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linéaires à l'aide de la géométrie stochastique**

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Par

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## **Optimization of Hybrid Broadcast/Broadband Networks for the Delivery of Linear Services Using Stochastic Geometry**

Thèse présentée et soutenue à Rennes, le 19/11/2019

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# Optimization of Hybrid Broadcast/Broadband Networks for the Delivery of Linear Services Using Stochastic Geometry

Ahmad SHOKAIR

A thesis is prepared for the degree of  
Doctor of Philosophy

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**Intitulé de la thèse :**

Optimisation des réseaux hybrides Broadcast/Broadband pour la fourniture de services linéaires à l'aide de la géométrie stochastique

**Ahmad SHOKAIR**

**En partenariat avec :**



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*"In questions of science, the authority of a thousand is not worth the humble reasoning of a single individual"*

Galileo Galilei

*"Science is a way of thinking much more than it is a body of knowledge"*

Carl Sagan





# Abstract

Modern mobile devices have the ability to connect to several types of networks to receive services, one of which is mobile TV. These types include digital terrestrial broadcast like Digital Video Broadcast (DVB) and cellular broadband networks like Long Term Evolution (LTE) and Fifth Generation New Radio (5G-NR). Yet each of these networks suffers from its own limitation ; broadcast networks lose efficiency when the number of users is low, and the broadband cellular network has limited spectral resources so it can be overloaded. To overcome the drawbacks of the two types, the hybrid network concept emerged. A hybrid network can be defined as the collaboration of two or more types of networks to deliver a service to the end user.

In this context, we aim to explore the possibilities for delivering modern resource-demanding services like the multimedia stream and mobile TV through conventional and hybrid networks. Herein, analytical studies are done to estimate the performance of the networks and to find the settings under which the adequacy is optimal.

The contributions in this thesis can be divided into four parts. The first part of the thesis introduces mobile TV as a service with all the opportunities it provides and the challenges it faces. It also surveys the conventional and hybrid network types and how the research community participated in studying and enhancing existing solutions. This is followed by a brief introduction to stochastic geometry and how it helps model and analyze cellular networks. The different models investigated in this work are then proposed.

The second part investigates first a hybrid broadcast/broadband network where a single high power high tower transmitter resembles the broadcast network, and where the cellular network operates in unicast mode. This model is then generalized by having multiple broadcasting transmitters in a much larger service area. In both cases, the hybrid model is analytically studied to find expressions that can estimate key performance metrics like the coverage probability, throughput, and power efficiency. The derived expressions are then used to find the set of parameters that optimize these metrics.

In the third part of the work, another operation mode is used in the cellular network side ; multicast. Since multicast in broadband networks is often accompanied by a Single Frequency Network (SFN) deployment, analytical study is conducted first to estimate the performance SFN multicast network. A multicast/broadcast hybrid model is then proposed to optimize the power efficiency of the network.

Finally, practical issues regarding the delivery of multimedia services to end users are discussed. The first issue is resource allocation, where a resource allocation scheme is proposed to maximize the success rate while maintaining a minimum acceptable quality of service. The second issue is the networks' power consumption. The hybrid broadcast/cellular network is studied from an energy efficiency point of view, and a set of operating conditions are fetched to maintain a green network.



# Résumé en Français

Après l'invention de l'imprimerie au XV<sup>e</sup> siècle, l'information est devenue de plus en plus accessible au public. Avant cela, si quelqu'un souhaitait diffuser une information, il devait soit parler assez fort à un large public, soit copier et faire circuler ces informations sur un support disponible, tel que le papier. La première méthode était peu coûteuse, mais limitée dans le temps et dans l'espace ; seules les personnes présentes à un endroit donné à un moment donné pouvaient recevoir le message. La seconde méthode nécessitait de reproduire de façon fidèle le même message plusieurs fois. Cela a rendu le message libre de temps et d'espace, mais le mécanisme de copie étant à la fois long et coûteux, les messages volumineux tels que les livres étaient confinés entre élites riches. Lorsqu'il s'agit de transmettre une information, il existe toujours un conflit entre efficacité de diffusion et personnalisation de l'information, faible coût et portée élevée. Cette dualité s'est maintenue entre le téléphone et la radio au début des années 1900, et récemment avec la diffusion télévisée et le flux multimédia sur des réseaux à large bande.

Au cours des dernières décennies notamment, les capacités des réseaux de communication et de diffusion n'ont eu de cesse de s'accroître pour faire face à l'explosion de la demande en nouveaux services, notamment dans le multimédia. Une grande partie des utilisateurs intéressés par ces services sont aujourd'hui ceux équipés d'appareils portables. Avec les progrès de l'industrie de l'informatique et des télécommunications et l'apparition de nouveaux supports de réception telles les tablettes, les smartphones, le nombre d'utilisateurs de télévision mobile a rapidement augmenté. Différents moyens de livraison du service sont aujourd'hui possibles parmi lesquels la diffusion TV terrestre (Terrestrial Broadcast - TBC), les réseaux cellulaires (Broadband - BB), la transmission par satellite, ou encore les réseaux locaux (Wireless Local Area Network - WLAN) ou régionaux (Wireless Metropolitan Area Network - WMAN). Néanmoins, chacune de ces méthodes d'accès possède ses avantages et ses limitations, entre caractéristiques souhaitables et les faiblesses tolérables.

Les réseaux TBC et BB sont deux des réseaux les plus performants dans la fourniture de services multimédias aux utilisateurs. La diffusion TBC est simple et efficace : un émetteur diffuse les informations et les utilisateurs intéressés se connectent et reçoivent le service. Cette méthode est très efficace pour une diffusion de masse vers un nombre important d'utilisateurs. Cependant, elle souffre d'un manque de personnalisation technique et de contenu et d'un accès limité aux utilisateurs équipés de récepteurs spéciaux. Au contraire, les réseaux cellulaires modernes BB sont capables de fournir les deux types de personnalisation et de gérer efficacement le partage des ressources entre utilisateurs tant que leur nombre reste modéré. De plus, ces réseaux connaissent un déploiement très large dans le monde entier. Néanmoins, ils peuvent subir une surcharge due à une largeur de spectre limitée rendant ces réseaux fragiles face à une demande massive de services.

Un réseau hybride TBC/BB peut constituer une solution pour améliorer la fourniture de services tels que la diffusion multimédia en continu et la télévision mobile, sans avoir à modifier profondément chaque réseau séparément. Différents modes de collaboration peuvent être élaborés, le plus pragmatique étant le partage par population d'utilisateurs, chaque réseau servant alors un sous-ensemble d'utilisateurs intéressés par un même service sur la base de critères prédéfinis.

L'objectif principal de cette thèse est d'explorer les capacités d'un réseau hybride TBC/BB dans un schéma de collaboration de partage d'utilisateurs pour des services linéaires. Cela inclut la fourniture d'outils permettant d'estimer les performances de différents déploiements dans différents modes opérationnels et d'adapter les paramètres système afin d'optimiser certains indicateurs de performances clés tels que la couverture radio ou l'efficacité énergétique par exemple. L'objectif est de fournir aux futurs concepteurs, opérateurs et chercheurs des éléments tangibles de réponse sur le potentiel de ce type d'hybridation.

Dans ce contexte, ce travail de thèse a permis d'étudier de nouvelles idées de collaborations entre réseaux TBC/BB, et de proposer de nouvelles solutions, analyses et algorithmes. Dans un premier chapitre, nous fournissons un état de l'art détaillé sur les technologies de télévision mobile, la nature du service, les opportunités qu'elle offre et les défis auxquels elle fait face. Les méthodes de livraison conventionnelles et hybrides sont ensuite discutées, en partant des normes disponibles, aux contributions de la communauté scientifique pour l'analyse et l'amélioration de ces techniques.

Dans un deuxième chapitre, une brève introduction à la géométrie stochastique est fournie, avec une description générale des modèles utilisés. Plus précisément, notre travail porte sur deux architectures de déploiements des réseaux BC : le cas avec une station BCT unique et celui à plusieurs stations. Par ailleurs, deux modes de transmission au sein des réseaux BB sont considérés : le mode Unicast (UC) et le mode Multicast (MC). Enfin, deux schémas de regroupement ou partage des utilisateurs sont mis en œuvre, à savoir la méthode par zone (ou géographique) et la méthode basée sur la qualité du signal reçu (eu égard au rapport signal sur interférence et bruit).

Dans les chapitres qui suivent, une analyse analytique approfondie est réalisée pour plusieurs combinaisons de déploiement en BC, de mode opérationnels BB et de stratégies d'allocation d'utilisateurs. Pour chaque scénario, la description du modèle est présentée et les mesures de performance clés sont recherchées de façon analytique à l'aide d'outils de la géométrie stochastique. Les expressions obtenues sont ensuite utilisées pour optimiser numériquement la configuration des réseaux.

Le résumé en français résume ici les principaux détails de chacun des chapitres de cette thèse.

## Chapitre 1 : Etat de l'art

Au cours de la dernière décennie, la généralisation du concept de réception en mobilité a poussé à la recherche de solutions technologiques permettant de prolonger l'expérience télévisuelle vers les appareils portables et mobiles. Le nombre considérable de détenteurs de téléphones portables et de clients potentiels représente aujourd'hui une énorme opportunité pour l'industrie de la télévision, tout en présentant plusieurs défis techniques et commerciaux. Sur le plan technique, il s'agit de gérer la mobilité des utilisateurs, assurer la couverture dans des zones de densité de population variée, d'utiliser efficacement la ressource spectrales et enfin de s'accommoder de récepteur ayant une alimentation électrique limitée. Sur le plan commercial, les fournisseurs de services doivent choisir judicieusement le contenu adapté aux utilisateurs mobiles et adopter un modèle commercial durable alors que les services de télévision sont pour la plupart associés à des offres gratuites.

Dans l'absolu, les services de télévision mobile peuvent être délivré à des récepteurs mobiles par le biais de l'une des technologies suivantes :

- Les réseaux de télévision terrestre «Terrestrial Broadcast» (TBC)
- Les réseaux satellites «Satellite Broadcast» (SBC)
- Les réseaux cellulaires «Broadband» (BB)
- Les réseaux locaux et régionaux (WLAN, WMAN)

Chacune de ces technologies offre un potentiel dans certains domaines. Cela inclut la large couverture de la transmission par satellite, l'efficacité du réseau terrestre, la personnalisation du réseau cellulaire, la fiabilité des réseaux d'accès sans fil. Cependant, chacun d'entre eux présente certains défauts qui le rendent sous-optimal ou fragile. On peut par exemple citer la forte latence et les effets de masquage pour les réseaux SBC, le manque d'efficacité en cas de nombre réduit d'utilisateurs pour les réseaux TBC, les ressources spectrales limitées dans les réseaux cellulaires et la difficulté de la gestion de la ressource et des interférences pour les réseaux d'accès sans fil.

Pour surmonter ces limitations, l'utilisation conjointe, coopérative ou par hybridation de plusieurs réseaux est une approche prometteuse. Un réseau hybride est celui qui utilise deux types de réseaux ou plus pour transmettre le contenu à un même type de récepteur. Cette collaboration peut prendre différentes formes. Les différents réseaux peuvent desservir différents types de services, servir différents utilisateurs, être responsable de différents blocs dans la chaîne de communication, transférer différentes parties du flux vidéo, etc.

Ainsi, dans le premier chapitre, nous traitons tout d'abord de la technologie de la télévision mobile elle-même. Nous commençons par décrire la nature et les exigences du service de TV mobile et les opportunités qu'il offre à la fois au secteur industrie mais aussi au grand public. De plus, les défis auxquels cette technologie est confrontée sont détaillés en incluant à la fois les verrous techniques et commerciaux. Pour mieux comprendre l'attitude des utilisateurs vis-à-vis de la technologie, les travaux de recherche sur les comportements et le comportement humain à cet égard sont présentés.

Dans la deuxième partie de ce chapitre, les réseaux d'accès de livraison classiques (TBC, BB, WLAN et WMAN) sont présentés, avec un descriptif synthétique des normes associées. Les défis auxquels chacune de ces méthodes est confrontée sont discutés avec un panorama des solutions proposées dans la littérature.

En tant que solution à la plupart des inconvénients des réseaux classiques, la troisième partie traite de l'approche des réseaux hybrides. Plusieurs combinaisons de ces réseaux sont considérées, expliquant les types de collaboration et les applications de chacun. En outre, les défis auxquels sont confrontés ces réseaux et les efforts de la communauté scientifique pour les résoudre sont mis en évidence.

## **Chapitre 2 : Introduction à la géométrie stochastique et présentation des modèles de réseaux hybrides utilisés**

### **La géométrie stochastique pour l'étude de performance de réseaux sans fil**

En réponse au besoin important d'expansion des réseaux, le célèbre modèle de réseau avec ses cellules de forme hexagonale a longtemps été utilisé pour modéliser et contrôler le déploiement des réseaux cellulaires. Cependant, une telle approche idéaliste manque de précision dans la description d'un réseau réel, en particulier dans des zones où la densité des utilisateurs varie de façon importante. De plus, l'analyse de ce modèle s'avère relativement compliquée, notamment lorsqu'il s'agit d'extraire des métriques de performance. En guise d'alternative, la géométrie stochastique se révèle être un outil mathématique souple permettant une analyse de réseau par calculs analytiques abordables. Dans cette section, une brève introduction à la géométrie stochastique et à son application dans les réseaux sans fil est présentée.

On peut définir la géométrie stochastique comme le domaine des mathématiques fournissant des méthodes et des modèles pour analyser les propriétés des points stochastiques dans un espace multidimensionnel. Ces modèles ponctuels aléatoires sont appelés processus ponctuels et sont les objets spatiaux les plus importants traités avec la géométrie stochas-

tique. La géométrie stochastique vise à décrire une collection aléatoire de points (noeuds) dans une ou plusieurs dimensions, et à en déduire des propriétés statistiques pour ces collections. De plus, en géométrie stochastique, une fonction du processus de points peut être conditionnée par la position du point ou moyennée sur toutes les positions possibles. Une autre cible est l'estimation d'un modèle statistique pour un ensemble de points existant.

Les réseaux sans fil sont l'un des domaines les plus connus pour l'application de la géométrie stochastique. Premièrement, la géométrie stochastique fournit un outil de modélisation en représentant les positions des noeuds dans un réseau sans fil avec l'un des processus ponctuels. Ceci s'applique aux noeuds fixes tels que les stations de base et aux noeuds mobiles (les terminaux). Deuxièmement, en partant des caractéristiques, propriétés et théorèmes associés, la géométrie stochastique peut aider à trouver certaines métriques de performance du réseau modélisé. Dans notre travail, nous nous concentrons sur la modélisation et l'analyse du réseau cellulaire, en utilisant un processus Ponctuel de Poisson (PPP) homogène. Un exemple de modèle de grille, le modèle de réseau PPP et une ressemblance avec un réseau réel sont illustrés sur la Fig.1.

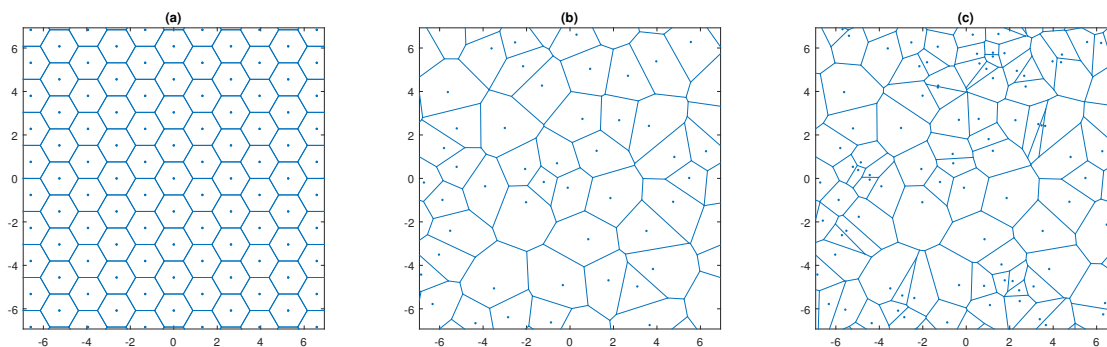


FIGURE 1 – Une comparaison entre le modèle de grille en (a), le modèle PPP en (c) et ce à quoi un réseau réel ressemble en (b)

## Modèles hybrides utilisés

Dans ce chapitre, nous présentons les modèles de réseau de base étudiés dans cette thèse. Comme mentionné précédemment, la thèse considère la fourniture de services linéaires aux utilisateurs via un réseau hybride de partage d'utilisateurs BC/BB. Néanmoins, ce type de réseau peut être étudié sous différentes contraintes en fonction du choix des facteurs suivants :

- Mode de fonctionnement du réseau cellulaire : le réseau cellulaire est capable de fournir le service soit en mode unicast ou multicast.
- Déploiement du réseau de diffusion comme réseau de délestage du réseau cellulaire : le cas avec un seul émetteur de diffusion au centre et le cas avec plusieurs émetteurs répartis sur une zone plus étendue.
- Attachement des utilisateurs au le réseau de diffusion ou réseau cellulaire selon deux stratégies possibles : attachement basé sur la position géographique ou sur la qualité de signal reçu par le terminal (au sens du rapport signal sur interférence plus bruit - SINR).

Dans la suite de cette thèse, plusieurs modèles de réseaux hybrides sont présentés. Chacun de ces modèles combine le choix d'une des deux options disponibles pour chacune des trois questions : dans quel mode le modèle BB fonctionne-t-il? Quel est le type de déploiement du réseau BC? Quelle est l'allocation utilisateur utilisée? La Fig. 2, utilisée en début de chaque nouveau cas traité permet de rapidement repérer la combinaison d'options activées pour chaque réseau étudié.

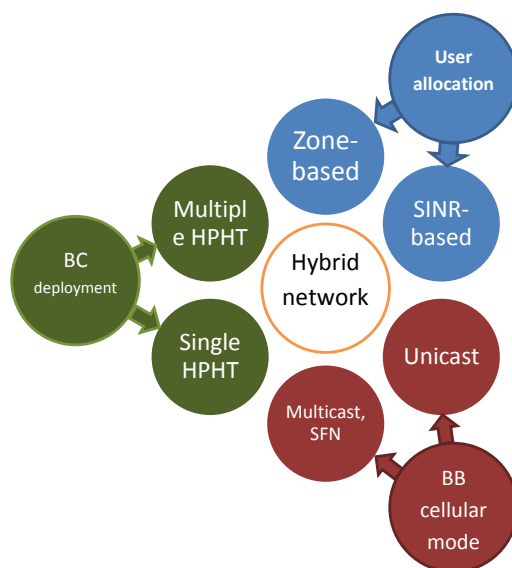


FIGURE 2 – Les différentes options et combinaisons du réseau hybride étudié

### Chapitre 3 : Etude du réseau hybride BC/UC

Le premier type de réseaux hybrides BC/BB étudié est celui qui met en oeuvre le mode BC à partir d'un émetteur unique et le mode UC dans un réseau BB cellulaire. Ce chapitre est divisé en deux parties. Dans la première partie, le modèle hybride basé sur la répartition et l'attachement des utilisateurs par zones géographique est présenté et analysé. La deuxième partie comprend l'analyse de modèle basée sur la qualité de signal reçu, sur critère de SINR. Dans les deux parties, l'analyse comprend la modélisation du réseau, la définition des principaux paramètres et les scénarios de coexistence, l'obtention des expressions pour la probabilité de couverture ainsi que d'autres mesures de performance. Dans chaque cas également, l'optimisation du réseau hybride est mise en oeuvre.

#### Réseau hybride avec répartition des utilisateurs par zones géographiques

La première partie de ce chapitre a été consacrée au réseau hybride basé sur la répartition par zones géographiques. Deux scénarios distincts pour la coexistence des réseaux BC et BB sont également introduits. Le premier est basé sur un accès à spectre partagé alors que le second est basé sur les spectres dédiés utilisant les zones blanches du spectre TV (TV white spaces TVWS). Une formulation analytique pour les deux modèles en termes de probabilité de couverture et de capacité a été obtenue, et des simulations numériques ont permis de vérifier l'exactitude de ces expressions. Un exemple de zone de service est présenté à la Fig. 3.

Les résultats ont montré que même si le scénario à spectre dédié produit une probabilité de couverture plus élevée, le scénario à spectre partagé reste plus efficace du point de vue de l'efficacité spectrale. Les résultats ont également indiqué qu'un rayon de diffusion optimal pouvant être atteint pour différentes conditions d'exploitation où la couverture ou la capacité pouvant être maximisée. Les résultats ont montré que ce point optimal change en fonction de la densité de UC BSs. Il est montré que, pour les deux scénarios, une valeur de densité de BS au-delà de laquelle il n'y a pas de gain significatif dans l'un ou l'autre scénario existe. De plus, il a été démontré que certaines annulations d'interférences éventuellement introduites au niveau de l'utilisateur final pouvaient améliorer considérablement la couver-



ture et l'expérience utilisateur. Les deux scénarios proposés ont également été comparés directement en termes d'efficacité spectrale, le scénario à spectre partagé s'étant révélé beaucoup plus efficace.

## Réseau hybride avec répartition des utilisateurs basée sur la qualité de signal reçu

Le modèle basé sur les zones décrit dans la section précédente peut être utile dans les cas où une séparation physique entre les réseaux est requise. Dans cette section, nous étudions une approche différente : l'association d'utilisateurs basée sur la meilleure qualité de signal. Ici, UC est toujours utilisé pour le réseau BB et un seul déploiement de HPHT est utilisé pour le réseau BC. La seule différence est que maintenant, l'allocation utilisateur est basée sur le SINR au lieu de la zone géographique.

Contrairement au modèle basé sur les zones, le modèle basé sur la SINR a des limites BC/UC qui dépendent grandement de la puissance de transmission de BC. Donc, pour optimiser les performances du réseau hybride, il est important de déterminer la valeur de la puissance de transmission BC qui minimise le facteur d'utilisation de la puissance. Cette optimisation a été effectuée numériquement pour différentes conditions et paramètres réseau.

Les résultats montrent qu'un mode de fonctionnement optimal peut être trouvé. L'emplacement et la valeur de ce point dépendent de plusieurs autres paramètres, tels que les qualités requises, les déploiements de réseau et la densité d'utilisateurs. La contribution nécessaire du réseau BC est souvent déterminante en ce qui concerne le placement de ce point de fonctionnement optimal.

Par exemple, la Fig. 4, montre que l'efficacité énergétique (mesurée ici en watts transmis par utilisateur servi) a une valeur optimale (minimale) obtenue pour une certaine valeur de la puissance transmise par la station BC (BC Tx power). Le régime de fonctionnement optimal du réseau hybride correspond donc à une situation intermédiaire entre l'utilisation exclusive du réseau BB (correspondant à l'extinction de l'émetteur BC, c'est-à-dire BC Tx Power = 0) et l'utilisation dominante du réseau BC (correspondant à une puissance très élevée de l'émetteur BC, c'est-à-dire BC Tx Power de plusieurs 10 kW). Les résultats montrent également comment les exigences de débit du service diffusé influencent la position du point optimal.

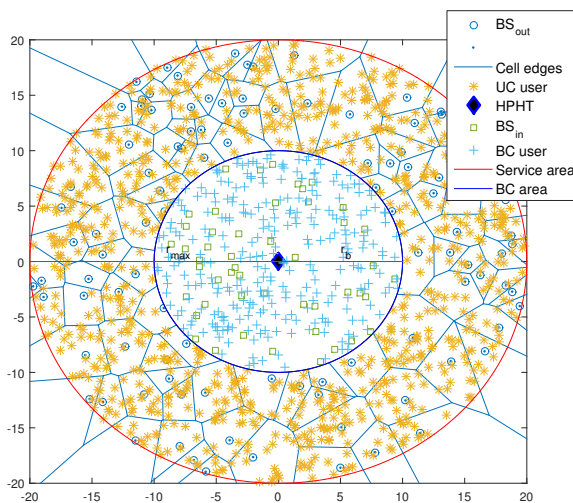


FIGURE 3 – Exemple de zone de service, avec un rayon de 20 km et un rayon de diffusion de 10 km

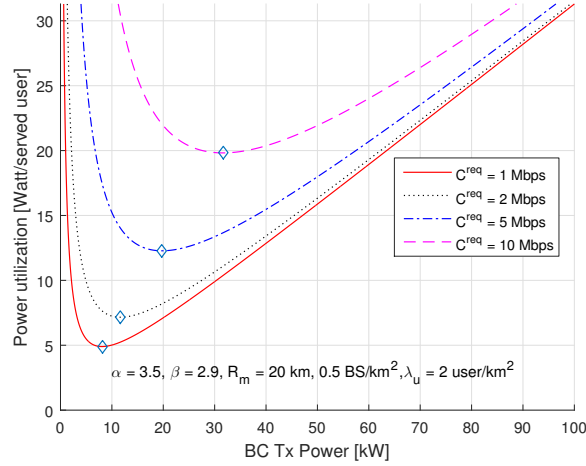


FIGURE 4 – Utilisation de l'énergie par rapport à la puissance transmise par le BC pour différentes capacités

## Chapitre 4 : Etude du modèle hybride multiple BC/BB

Dans ce chapitre, nous généralisons le modèle hybride BC/UC présenté dans le chapitre précédent dans une zone de service beaucoup plus large, dans laquelle de multiples BCT sont déployés. Ce chapitre sera consacré à l'étude du réseau hybride multiple BCT BC/UC basé sur des zones. Comme le scénario de coexistence s'est avéré plus efficace, il ne sera utilisé que dans ce modèle. Le modèle a été analysé à l'aide de la géométrie stochastique pour estimer la probabilité de couverture, la capacité et l'efficacité énergétique. Un exemple de la zone de service est illustré à la Fig. 5.

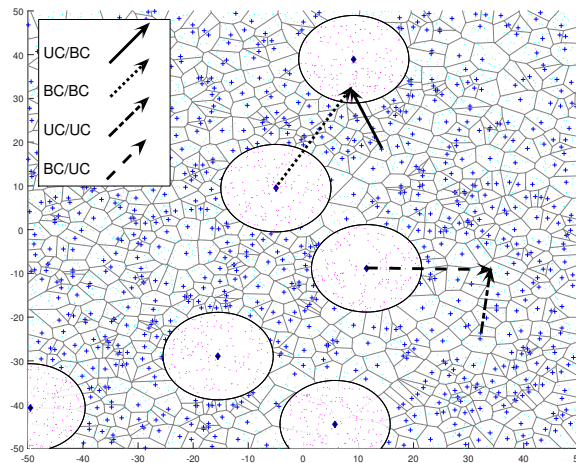


FIGURE 5 – Un exemple de zone de service

Dans ce document, deux approximations du «Poisson Hole Process» (PHP) obtenu ont été utilisées pour simplifier l'analyse (les PPP d'origine et modifiés) afin de déduire les limites supérieure et inférieure des métriques sélectionnées. Les expressions résultantes ont été vérifiées au moyen de simulations approfondies de Monte-Carlo, montrant une grande précision. Les expressions dérivées ont ensuite été utilisées pour optimiser numériquement les performances du réseau hybride en termes de couverture, d'efficacité spectrale et d'efficacité énergétique, en fonction des paramètres de conception clés, à savoir le rayon BC et la densité BCT. Les résultats ont montré que l'approche hybride apporte la meilleure performance en excluant les cas extrêmes d'un nombre d'utilisateurs très faible et très élevé. Il a été prouvé qu'il existait des points de fonctionnement optimaux régis par le rayon BC

et la densité BCT.

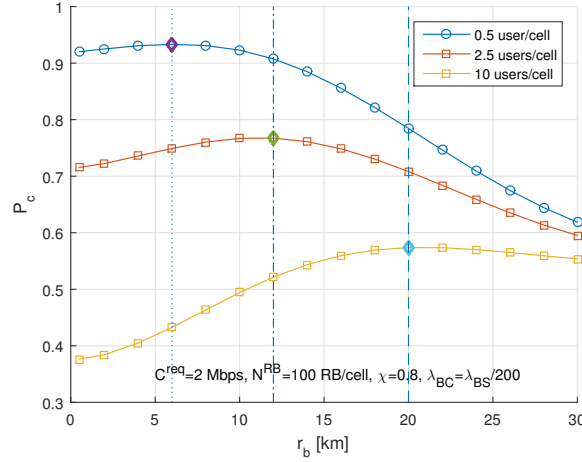


FIGURE 6 – Probabilité de couverture par rapport au rayon du réseau BC

Par exemple, Fig. 6 montre la probabilité moyenne de couverture en fonction du rayon de la BC  $r_b$  avec trois valeurs différentes de la densité de l'utilisateur. La figure montre qu'il existe un point optimal de maximisation de la couverture. Dans le réseau UC, une densité utilisateur plus élevée signifie une bande passante allouée moyenne inférieure pour chaque utilisateur, ce qui réduira le nombre d'utilisateurs couverts. Ensuite, une contribution plus importante du côté de la BC est nécessaire, ce qui se traduit par une valeur optimale de  $r_b$ .

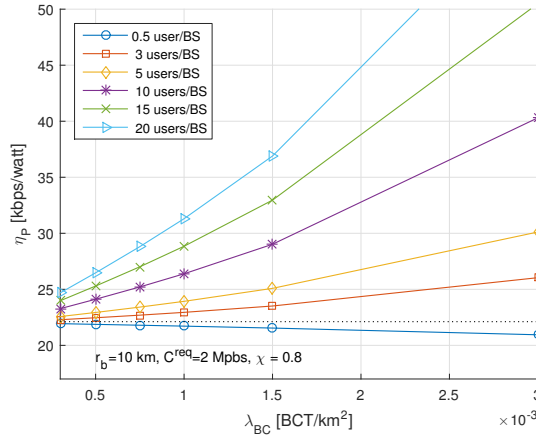


FIGURE 7 – L'efficacité énergétique d'une zone de service par rapport à la densité BCT

Un autre exemple est l'efficacité énergétique en termes de densité de réseau, comme indiqué dans la Fig. 7. Les résultats révèlent que l'augmentation de la densité BCT affecte l'efficacité énergétique de manière différente selon la densité des utilisateurs. Pour une faible densité d'utilisateurs (comme la courbe de 0,5 utilisateurs/BS), où le réseau BB peut fournir suffisamment de bande passante aux utilisateurs, augmenter le nombre de BCT ajoutera une énorme charge d'énergie sans apporter de valeur ajoutée significative à la couverture et à la capacité. Lorsque la zone est dense (comme dans les courbes de 15 et 20 utilisateurs/BS), l'ajout de plus de BCT déchargera les utilisateurs du réseau BC et supprimera les BS en raison de leur consommation électrique excessive. Par conséquent, cela augmente l'efficacité énergétique.

## Chapitre 5 : Intégration du mode de diffusion Multicast et de l'environnement SFN

Dans les deux chapitres précédents, le mode UC a été utilisé comme mode de fonctionnement pour le réseau BB du réseau hybride. Avec le mode UC, le réseau cellulaire peut personnaliser la transmission aussi bien techniquement que le contenu. Cependant, en raison de la bande passante limitée disponible dans chaque cellule le nombre d'utilisateurs servi est limité. Un tel nombre devient encore plus faible lorsque le service est exigeant en termes de «Bandwidth» (BW) comme le streaming vidéo.

Dans ce chapitre, nous portons notre attention sur le mode de fonctionnement MC du réseau BB et sur la manière de l'utiliser dans le contexte de réseaux hybrides. Le chapitre comprend deux parties principales. La première partie présente le déploiement SFN, déploiement qui accompagne généralement le mode MC, puis une borne inférieure de la probabilité de couverture est dérivée. La deuxième partie étudie un réseau hybride BC/MC, avec trois scénarios différents, et optimise son efficacité énergétique.

### Couverture dans un réseau cellulaire SFN

Dans la première partie, une nouvelle approche basée sur la géométrie stochastique est proposée pour dériver la probabilité de couverture pour un réseau SFN, avec une approximation appropriée pour simplifier l'analyse. L'analyse exacte, même si elle n'est pas traitable, constitue une base pour toute analyse ou approximation ultérieure. L'approximation proposée ici représente une limite inférieure pour les performances de couverture du réseau. Cela peut être considéré comme un compromis entre la faisabilité de l'analyse et la précision de l'estimation.

La probabilité de couverture par rapport au seuil SINR pour plusieurs valeurs de  $\alpha$ , et pour la simulation, l'analyse exacte et l'approximation de la limite inférieure, est illustrée à la Fig. 8. Les courbes obtenues montrent que l'analyse exacte, dont il a été prouvé qu'elle est pas calculable, décrit exactement les résultats de la simulation, alors que l'approximation représente une limite inférieure. La précision de l'analyse varie entre les différentes valeurs du coefficient de "pathloss" et du seuil SINR, mais elle est limitée à moins de 10% dans ces cas.

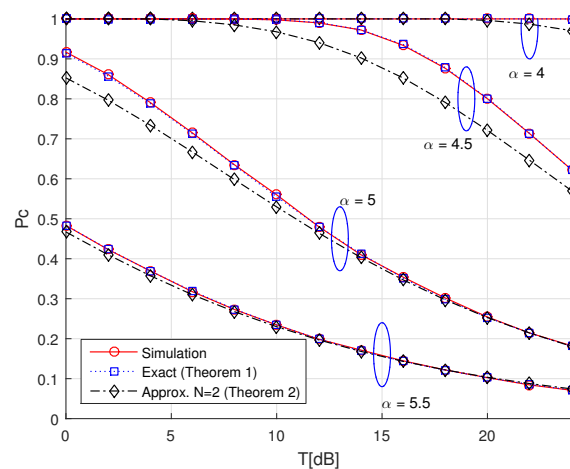


FIGURE 8 – Probabilité de couverture par rapport au seuil SINR  $T$  pour différentes valeurs de pathloss  $\alpha$ , pour la simulation, l'analyse exacte et l'analyse approximative

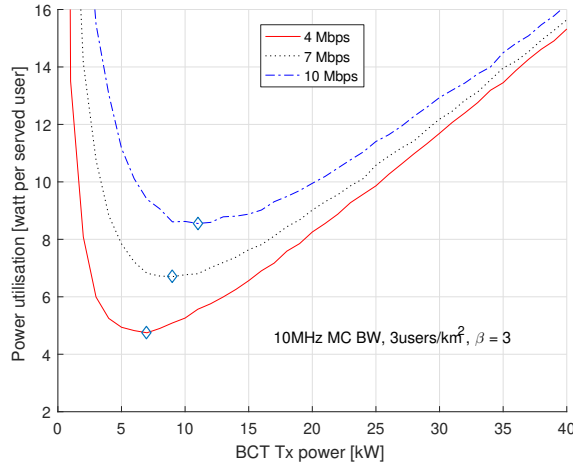


FIGURE 9 – Utilisation de l'énergie par rapport à la puissance transmise par le BC pour différentes capacités requises

## Etude du réseau hybride BC/MC

Dans la deuxième partie du chapitre, un nouveau modèle hybride est présenté : réseau hybride BC/MC basé sur le SINR avec un déploiement unique de BCT. Après avoir décrit le modèle, trois scénarios de fonctionnement sont proposés. Ces scénarios traitent de l'activation ou de la désactivation des «Resource Blocks» RBs sur lesquels le service MC est en cours de transmission. Les simulations numériques montrent que le scénario le plus efficace est celui où les RBs de MC sont utilisés pour d'autres services UC quand il n'y a pas d'utilisateur intéressé dans la cellule.

Les résultats montrent qu'un point optimal entre un réseau complet BC et un réseau complet MC peut être trouvé lorsque le système est traité du point de vue de l'efficacité énergétique. Il a également été conclu que même avec le partage des ressources dans le répertoire MC SFN, le réseau BC restait plus efficace. Cela s'est reflété dans la valeur du point optimal, qui augmente avec l'augmentation des exigences de qualité ou même en allouant plus de ressources à la transmission MC.

Par exemple, la figure 9 montre comment la puissance optimale du BC varie en fonction du débit de données requis. Les résultats montrent que, pour des exigences de qualité plus élevées, la puissance de transmission nécessaire augmente également. Le réseau BC plus économe en énergie apporte plus de contribution et couvre ainsi les utilisateurs demandeurs.

## Chapitre 6 : Considérations pratiques : gestion des ressources et consommation d'énergie

Les travaux présentés dans les chapitres précédents sont principalement analytiques et portent sur les aspects théoriques du déploiement du réseau. Dans ce chapitre, nous abordons certaines des questions pratiques relatives à la fourniture de services linéaires aux utilisateurs via des réseaux BB ou hybrides. Deux questions principales sont ici discutées, à savoir, l'allocation spectrale des ressources et l'efficacité énergétique du modèle hybride.

### Adaptation de l'allocation de ressources pour services linéaires

Dans la première partie, la gestion des ressources dans un réseau moderne BB opérant en mode UC et fournissant des services linéaires aux utilisateurs a été étudiée. Dans ce contexte, nous avons présenté un nouvel algorithme qui, contrairement aux autres algorithmes existants, est optimisé pour la fourniture de services linéaires. L'algorithme

proposé, à savoir LSORAS, vise à maximiser le nombre d'utilisateurs servis à qui est garanti un débit minimum requis permettant une réception correcte du service. L'algorithme LSORAS proposé pour chaque cellule est décrit dans Algorithme 1.

---

**Algorithm 1** LSORAS visant à maximiser SR

---

```

for  $n = 1 : N_{cell}$  do
  Select users in cell  $n$ 
  Sort users in descending order according to  $\max(\text{SINR})$ 
  Create a RB pool with all RBs
  Set  $M_{user,n}$  as the number of users in current cell  $n$ 
  for  $m = 1 : M_{user,n}$  do
    Sort available RB of user  $m$  in descending order according to SINR
    Select the RB of best SINR
    Eliminate the RB assigned to  $m$  from the RB pool
    Calculate the new  $C_m^{user}$ 
    if The RB are exhausted and  $C_m^{user} < C^{req}$  then
      Assign no RB to user  $m$ 
      Put back the assigned RB to the pool
      break
    end if
    if  $C_m^{user} \geq C^{req}$  then
      break
    end if
  end for
end for

```

---

La figure 10 montre la variation du taux de réussite par rapport à la densité dans une zone de service d'environ 100 stations de base. Les résultats montrent que le taux de réussite des méthodes "Maximum Throughput" (MT), "Proportional Fairness" (PF) et "Round Robin" (RR) décroît considérablement avec l'augmentation du nombre d'utilisateurs en attente de service. D'autre part, l'algorithme LSORAS permet d'obtenir des taux de réussite plus élevés même avec un taux de charge de 30 : 1 (utilisateurs par BSs), alors que la baisse n'est pas aussi sévère que pour les autres méthodes. La solution optimale produite par l'algorithme "Branch and cut" conserve un léger avantage par rapport à LSORAS. Néanmoins, pour une grande densité d'utilisateurs, l'algorithme "Branch and cut" devient très coûteux en termes de mémoire, de puissance et de temps de calcul par rapport à LSORAS.

## Evaluation de l'efficacité énergétique

Dans la deuxième partie, l'efficacité énergétique du réseau hybride basé sur la zone BC/UC est étudiée. L'objectif est de tester l'efficacité énergétique de l'approche hybride et de trouver l'ensemble de paramètres permettant de minimiser la consommation d'énergie par utilisateur servi. L'algorithme LSORAS est utilisé dans la partie BB du réseau. Les résultats indiquent qu'une taille de zone de diffusion optimale peut être trouvée et que l'effet de la densité de BSs sur cette taille est lié à la densité des utilisateurs. Les résultats montrent également que la densification du réseau améliore l'efficacité du système jusqu'à un certain niveau au-delà duquel l'efficacité est saturée. De plus, il a été démontré que, pour le même paramétrage de réseau, le réseau avec des densités d'utilisateurs plus élevée est plus efficace que celui avec des densités d'utilisateurs plus faibles. Les résultats montrent également que plus un réseau est dense, plus le gain d'un réseau hybride sera élevé par rapport à un réseau uniquement UC, tandis que réduire la densité augmentera le gain par

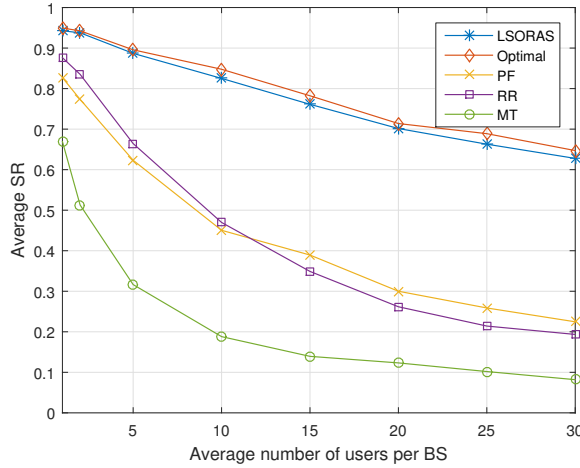


FIGURE 10 – SR moyen par rapport au nombre d'utilisateurs par BS dans la zone de service, avec  $C^{req} = 1,5 \text{ Mbps}$

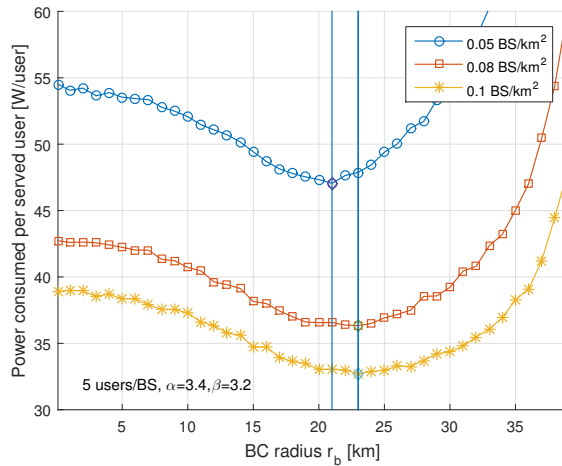


FIGURE 11 – Puissance consommée par utilisateur servi vs  $r_b$

rapport à un réseau uniquement BC.

La Fig. 11 montre cette variation de l'efficacité de la consommation d'énergie en fonction de la taille de la zone BC pour plusieurs valeurs de densité utilisateurs et de densité BS. Les résultats indiquent que l'on peut trouver un rayon de diffusion optimal minimisant l'efficacité énergétique. Cela confirme qu'une approche hybride permet d'optimiser le gain en énergie du système global.

## Conclusion

Les services de diffusion multimédia en continu, tels que la télévision mobile, suscitent un intérêt croissant dans le monde entier et représentent une excellente opportunité pour les acteurs du secteur et les fournisseurs de services. Des méthodes classiques telles que TBC, SBC, les réseaux cellulaires BB et sans fil sont généralement utilisées pour délivrer ces services, chacun présentant ses propres limites. L'approche hybride peut être une approche appropriée pour surmonter ces limites en exploitant les capacités de deux réseaux ou plus qui coopèrent pour servir les utilisateurs. Dans cette thèse, nous avons étudié l'approche hybride TBC/BB pour la fourniture de services linéaires. L'étude a été réalisée au moyen d'une analyse analytique approfondie à l'aide d'outils de géométrie stochastique.

Différents modèles hybrides ont été examinés, avec diverses combinaisons de déploie-

ment de BC, de modes de fonctionnement de BB et de stratégies d'allocation d'utilisateurs. Des indicateurs de performance clés ont été dérivés pour chaque modèle. L'optimisation numérique a été réalisée sur la base des expressions dérivées après vérification de leur précision avec des simulations.

Les résultats montrent que, pour toute une gamme de paramètres, l'approche hybride peut apporter un gain au réseau en termes de probabilité de couverture, de capacité, d'efficacité spectrale et d'efficacité énergétique.

le domaine de la télévision mobile et des services linéaires est très vaste et offre de nombreuses possibilités de recherche. Sur la base de cette thèse, de nombreux domaines et perspectives intéressants peuvent être approfondis.

Le reste des combinaisons du réseau hybride BC/BB peut être étudié. Comme indiqué sur la Fig. 2, nous avons introduit deux types de déploiements BCT, deux modes de fonctionnement BB et deux critères d'allocation des utilisateurs, qui permettent de créer 8 combinaisons différentes. Dans la thèse, nous avons étudié 4 de ces combinaisons, laissant les 4 autres pour des recherches futures. En outre, les travaux sur les déploiements de SFN sont ouverts à davantage de recherches.

Enfin dans cette thèse, nous avons utilisé des processus PPPs homogènes uniquement pour la modélisation du réseau BB. Plus généralement, d'autres types de processus ponctuels peuvent être utilisés, comme les processus PPP non stationnaires utiles à la modélisation de zones de densités variables. En outre, dans ce travail nous avons considéré les services linéaires comme une cible principale du réseau hybride. Le problème peut être étendu aux services non linéaires pour lesquels la demande est en très forte croissance depuis quelques années.





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# List of Symbols

## Operators and special functions

- $\Gamma(\cdot)$  Gamma function  
 $\gamma(\cdot, \cdot)$  lower incomplete gamma function  
 $\mathbb{E}[\cdot]$  Expected value  
 $\mathbb{P}[\cdot]$  Probability  
 $\mathcal{L}(\cdot)$  Laplace Transform  
 $s$  Laplace variable  
 ${}_2F_1(\cdot)$  Gaussian Hyper-geometric function

## Location modeling

- $\Lambda$  variable density of non-homogeneous Poisson Point Process  
 $\lambda$  constant density of homogeneous Poisson Point Process  
 $\lambda_{BCT}$  Density of BCT Poisson Point Process  
 $\lambda_{BS}$  Density of BS Poisson Point Process  
 $\lambda_U$  Density of users Poisson Point Process  
 $\Phi$  Poisson Point Process of the BB BSs  
 $\Psi$  Poisson Point Process of the users  
 $\Xi$  Poisson Point Process of the BCTs

## Channels

- $\alpha$  Path loss exponent for BB transmission  
 $\beta$  Path loss exponent for BC transmission  
 $\mu$  Rate of the distribution for BB transmission  
 $\nu$  Rate of the distribution for BC transmission  
 $g$  Channel random variable for BC transmission  
 $h$  Channel random variable for BB transmission

## Transmission parameters

- $\mathcal{P}_N$  Received noise power  
 $\mathcal{P}_{BC}$  Transmission power of BC  
 $\mathcal{P}_{MC}$  Transmission power of MC  
 $\mathcal{P}_{UC}$  Transmission power of UC

|            |                                       |
|------------|---------------------------------------|
| $B_R$      | Bandwidth ratio of BC and BB networks |
| $f_D$      | Frequency of BC transmission          |
| $f_L$      | Frequency of UC transmission          |
| $f_W$      | Frequency of TVWS                     |
| $W^{RB}$   | Bandwidth of a single resource block  |
| $W^{user}$ | Bandwidth allocated to a user         |
| $W_{BB}$   | Bandwidth of BB transmission          |
| $W_{BC}$   | Bandwidth of BC transmission          |
| $W_{MC}$   | Bandwidth of MC transmission          |

### **Distances**

|       |  |
|-------|--|
| $r_b$ | Radius of the BC zone                                |
| $r_d$ | distance between a BB user and the BCT               |
| $r_l$ | distance between a BB user and the serving BS        |
| $R_m$ | Radius of the service area                           |
| $r_q$ | distance between a BB user and the interfering BS    |
| $r_s$ | distance between a BC user and the interfering BB BS |
| $r_t$ | distance between a BC user and other BCTs            |
| $r_v$ | distance between a BC user and the serving BCT       |

### **Metrics**

|                 |   |
|-----------------|---|
| $\chi$          | weighting factor for the usefulness of the received BC power  |
| $\eta$          | Efficiency  |
| $\mathcal{U}_f$ | Spectral power utilization factor                             |
| $\mathcal{U}$   | Power utilization factor                                      |
| $\omega$        | Interference cancellation factor                              |
| $\zeta$         | Binary variable indicating whether a user is connected or not |
| $C$             | Probability of coverage                                       |
| $C_{BC}$        | Capacity for BC user  |
| $C_{MC}$        | Capacity for MC user  |
| $C_{UC}$        | Capacity for UC user  |
| $F$             | Received power from other BCTs on a BCT user                  |
| $I$             | Interference  |
| $I_{B/U}$       | Interference of BCTs on a UC user                             |
| $I_{U/B}$       | Interference of UC BSs on a BC user                           |
| $I_{U/U}$       | Interference of UC BSs on a UC user                           |
| $P_c$           | Probability of coverage                                       |
| $P_{cBC}$       | Probability of coverage for BC user                           |

|                |   |
|----------------|---|
| $P_{cMC}$      | Probability of coverage for MC user       |
| $P_{cUC}$      | Probability of coverage for UC user       |
| $P_i$          | Probability of a user to be a BC user     |
| $P_o$          | Probability of a user to be a BB user     |
| $S$            | Received SINR                             |
| $S_{BC}$       | Received SINR for a BC user               |
| $S_{MC}$       | Received SINR for a MC user               |
| $S_{UC}$       | Received SINR for a UC user               |
| $T$            | Received SINR threshold                   |
| $T_{BC}$       | Received SINR threshold for BC user       |
| $T_{MC}$       | Received SINR threshold for MC user       |
| $T_{UC}$       | Received SINR threshold for UC user       |
| <b>Others</b>  |   |
| $\mathbb{R}^d$ | Set of real vectors in the $d$ dimensions |
| $c$            | Speed of light                            |



# Acronyms

- 3G** Third Generation. 12
- 3GPP** Third Generation Partnership Project. 22, 24, 25, 35
- 3GPP2** Third Generation Partnership Project 2. 22, 25
- 4G** Fourth Generation. 12, 26
- 5G** Fifth Generation. 14, 22, 23, 25, 33, 36, 40, 122, 131, 141
- A4AI** Alliance for Affordable Internet. 10
- AL-FEC** Application-Layer FEC. 26
- AR** Augmented Reality. 22
- ARIB** Association of Radio Industries and Businesses. 19
- ATSC** Advanced Television System Committee. 18, 19
- ATSC-M/H** ATSC-Mobile/Hand-held. 19
- B2C** Business to Customer. 13
- BaC** Branch and Cut. 122, 126, 128, 129, 137, 140
- BB** Broadband. 1–4, 8, 10, 12, 13, 20, 22–24, 26, 28–32, 39–41, 48, 52, 53, 57, 59–63, 74, 80, 81, 84, 87, 88, 90, 91, 96–98, 106–108, 115–119, 121, 123, 128, 130–133, 135–137, 139–141
- BC** Broadcast. 1–4, 8, 11–13, 17–20, 23–25, 28–33, 35, 36, 39, 48, 51–53, 57, 59–81, 83–85, 87–99, 106, 107, 115–121, 131–137, 139–142, 147
- BCH** Bose–Chaudhuri–Hocquenghem. 20
- BCMCS** Broadcast and Multicast Services. 25
- BCT** Broadcast Transmitter. 51, 52, 57, 59, 81, 85, 88–96, 102, 106, 116, 120, 132, 139–141
- BER** Bit Error Rate. 34
- BS** Base Station. xxv, 2, 4, 5, 17, 21, 24, 25, 29, 30, 32, 33, 36, 37, 39, 46, 47, 49, 50, 52, 53, 56, 60–65, 68, 70, 71, 73, 75–77, 79–82, 84, 87, 91–99, 108–117, 123–126, 128, 129, 132–137, 140, 147
- BST-OFDM** Band Segmented Transmission-OFDM. 19
- BW** Bandwidth. 63, 85, 87, 107, 119, 124
- CBC** Cell Broadcast Center. 24
- CCDF** Complementary Cumulative Distribution Function. 64, 70, 110, 129
- CDF** Cumulative Distribution Function. 64, 65
- CP** Cyclic Prefix. 52
- CPU** Central Processing Unit. 12



**CRT** Cathode Ray Tube. 8

**DMB** Digital Multimedia Broadcasting. 18

**DPC** Dirty Paper Coding. 36, 37

**DSS** Dedicated Spectra Scenario. 60, 71, 73, 75

**DTMB** Digital Terrestrial Multimedia Broadcast. 18–20

**DTMB-A** DTMB-Advanced. 20

**DVB** Digital Video Broadcasting. 18, 28–30, 70, 75, 107

**DVB-H** DVB-Hand-held. 18, 28

**DVB-NGH** DVB-New Generation Hand-held. 18, 31

**DVB-SH** DVB-Satellite Hand-held. 32

**DVB-T** DVB-Terrestrial. 18, 107, 108

**DVB-T2** DVB-Terrestrial-2. 18, 19, 29–31

**EDGE** Enhanced Data rates for GSM Evolution. 22

**EE-HAS** Energy-Efficient HTTP adaptive streaming algorithm. 38

**eMBMS** enhanced-MBMS. 17, 25, 31, 35, 36, 107, 108, 119

**FCC** Federal Communications Commission. 7

**FDM** Frequency Division multiplexing. 37

**FEC** Foreword Error Correction. 20, 25

**FHD** Full High Definition. 11

**GI** Guard Interval. 108, 109

**GPRS** General Packet Radio Service. 22

**GSM** Global System for Mobile communication. 22

**HAS** Adaptive streaming. 14

**HD** High Definition. 2, 15, 25, 28, 31, 36

**HDTV** High Definition TV. 8, 18

**HPHT** High Power High Tower. 2, 17, 29, 51–53, 56, 59–64, 66, 70, 75–77, 79–81, 87–89, 91, 116, 131–133, 136, 145

**HSDPA** High-Speed Downlink Packet Access. 22

**HSPA** High Speed Packet Access. 22

**HSUPA** High-Speed Uplink Packet Access. 22

**ICI** Inter-Cell Interference. 2, 4, 23, 25, 29, 30, 36, 47, 49, 59–61, 63, 90, 107, 119, 130

**IMT-2020** International Mobile Telecommunication-2020. 22

**IoT** Internet of Things. 22

**IP** Internet Protocol. 17, 20, 25, 28, 30, 33

**IPTV** Internet Protocol TV. 15, 17, 26

**IS-95** Interim Standard 95. 22

**ISDB** Integrated Services Digital Broadcasting. 18, 20

**ISDB-T** ISDB-Terrestrial. 19

**ITU** International Telecommunication Union. 20, 22, 33

**LCD** Liquid Crystal Display. 8

**LDM** Layered Division Multiplexing. 19, 37

**LDPC** Low-Density Parity-Check. 18–20

**LED** Light Emitting Diodes. 8

**LSORAS** Linear Service Oriented Resource Allocation Strategy. 122, 127, 129–131, 134, 137, 140, 141

**LT** Laplace Transform. 47, 66, 68, 71, 82, 94–97, 99, 145, 147, 149

**LTE** Long Term Evolution. 17, 22–26, 28–31, 33, 35–38, 49, 56, 70, 75, 108, 122–124, 133

**LTE-A** LTE-Advanced. 22, 29, 107

**MBMS** Multimedia Broadcast Multicast Service. 17, 24, 25, 35

**MC** Multicast. 3, 4, 17, 21, 23–26, 28, 31, 35–37, 40, 48, 49, 52, 53, 57, 107, 108, 115–120, 140–142

**MCBCS** Multicast/Broadcast Service. 26

**MFN** Multi Frequency Network. 47, 107

**MIMO** Multiple Input Multiple Output. 11, 19, 22, 26, 37, 141

**MIP** Mixed Integer Programming. 122, 126, 128

**MISO** Multiple Input Single Output. 18, 19

**MPEG** Motion Picture Experts Group. 20

**MPEG-2** Motion Picture Experts Group-2. 19

**MT** Maximum Throughput. 122, 123, 128–130

**NOMA** Non-Orthogonal Multiple Access. 36

**NR** New Radio. 22, 23, 122

**NTSC** National Television System Committee. 7, 18

**OFDM** Orthogonal Frequency Division Multiplexing. 49, 50, 91, 108, 116, 132

**OTT** Over The Top. 9, 12, 13

**PA** Power Amplifier. 20, 56

**PAPR** Peak to Average Power Ratio. 20

**PDF** Probability Density Function. 29, 34, 64, 65, 93, 94, 108, 149

**PF** Proportional Fairness. 122, 123, 128–130

**PGFL** Probability Generating Functional. 45, 48, 147

**PHP** Poisson Hole Process. 94, 96, 98, 106

**PPP** Poisson Point Process. 30, 41, 43–46, 49, 51, 52, 59, 61, 62, 64, 76, 80, 82, 90, 91, 93, 94, 96–99, 106, 108, 109, 116, 123, 128, 131, 132, 141, 147

**PRBS** Pseudo-Random Binary Sequence. 20

**QoE** Quality of Experience. 8, 13–15, 22, 27, 30, 35, 39, 55, 57, 73, 74, 122, 141

**QoS** Quality of Service. 13, 14, 26, 29, 30, 35–37, 55, 56, 127, 131, 133, 140

**RB** Resource Block. 49, 116, 117, 120, 122–129, 131, 132, 134, 137, 140

**RR** Round-Robin. 122, 128–130

**RS** Reed-Solomon. 19, 20

**SBC** Satellite Broadcast. 8, 139

**SD** Standards Definition. 2, 28, 31

**SDN** Software Defined Networking. 38

**SDR** Software Defined Radio. 38

**SFN** Single Frequency Network. 3, 4, 17, 18, 25, 31, 35, 47, 49, 51–53, 57, 91, 92, 107, 108, 110, 111, 115, 116, 119, 120, 140, 141

**SINR** Signal to Interference and Noise Ratio. xxv, 11, 19, 25, 47, 48, 51–55, 57, 59, 62, 63, 66, 70, 71, 76–78, 80, 81, 83–85, 87, 88, 91–94, 106, 108–110, 113–120, 124, 126, 131, 132, 134, 139–141

**SIR** Signal to Interference Ratio. 29

**SISO** Single Input Single Output. 18, 19, 61, 141

**SMS** Short Messaging System. 24

**SNR** Signal to Noise Ratio. 51, 63, 80

**SR** Success Rate. 122, 125, 130, 133

**SSS** Shared Spectrum Scenario. 59, 71, 73, 75

**T-DMB** Terrestrial-DMB. 20, 28

**TBC** Terrestrial Broadcast. 1–4, 8, 11, 40, 41, 48, 56, 139

**TDM** Time Division Multiplexing. 19, 37

**TDMA** Time Division Multiple Access. 37

**TS** Transfer Stream. 20

**TVWS** TV White Space. 53, 60, 87, 91

**UC** Unicast. 2–4, 17, 21–26, 28–31, 35–37, 40, 48, 49, 53, 57, 59, 61–70, 73, 75–84, 87–99, 106, 107, 116, 117, 120, 121, 123, 125, 131–137, 139–141, 147

**UHD** Ultra High Definition. 2, 8, 11, 14, 15, 19, 22, 36

**UMTS** Universal Mobile Telecommunications System. 17, 22, 24

**VoD** Video on Demand. 9, 10, 15, 26, 30, 33

**VR** Virtual Reality. 22, 40

**WCDMA** Wideband CDMA. 22

**WLAN** Wireless Local Area Networks. 1, 4, 8, 12, 25, 26, 33, 37

**WMAN** Wireless Metropolitan Area Networks. 1, 4, 8, 25, 26, 33

# Introduction

This introduction is an overview of the thesis, explaining the context of the work done, and detailing the motivation behind this work and contributions made to the subject. The thesis organization is finally described.

## Context

Following the invention of the mechanical printing press in the fifteenth century, information has become more and more available for the public. Before that, if somebody wanted to deliver some kind of information to the masses, he or she needed to either speak loud enough to a large audience or to copy this information onto available writing material like paper. The first method was cheap, but both time and space limited; only people present at a specific location at a certain time was able to receive the message, and some special physical abilities were needed so that everybody can hear the message properly. The second method required careful re-writing of the same message several times. This made the message time and space free, but the copy mechanism was both labor-exhaustive and expensive, so large messages like books were confined between the rich elite.

The mechanical printing press helped deliver the information to a much larger number of people, with affordable costs, and without substantial time and distance constraints. This helped the circulation of ideas as a step toward democratizing knowledge, which had an enormous effect on human history. However, the information in published documents was limited to words and some drawings (and in the recent past pictures). It wasn't until the late 1800s and early 1900s that the first media, the human voice, was able to be transmitted in long distances, following the spread of both commercial telephones and radio broadcasting.

Yet, the duality continued. Telephone calls transferred personalized private messages between a small number of people (most often two). Besides, early switchboards had a limited capacity to redirect calls, especially between cities. On the other hand, radio Broadcast (BC) was able to reach many more users, but with the need for high-power transmission for just one unified message. Later in the 20th century, the audio-visual transmission came to life as well as the mobile telephony. TV sets became a standard in the majority of houses worldwide, and mobile phones grew to become an essential part of life.

The case for audiovisual multimedia transmission over modern networks is not different. There is always a conflict between efficiency and personalization, low cost and high reach... Meanwhile, a race was going on between network capabilities and the demand for the new services, especially in multimedia. A large portion of the users interested in such services were those with hand-held devices. With the advances in industries specialized in portable computers, tablets, smartphones, and even wireless TV systems, the number of mobile TV users grew rapidly. Terrestrial Broadcast (TBC), Broadband (BB) cellular networks, satellite transmission, Wireless Local Area Networks (WLAN), and Wireless Metropolitan Area Networks (WMAN) were trying to meet the increasing demand on services like video

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streaming for mobile devices, starting from Standards Definition (SD), High Definition (HD), and to Ultra High Definition (UHD) qualities.

Nevertheless, each of these methods had its own flows, and a choice has to be made -as always- between the desirable features and the tolerable weaknesses. At that point, the idea of a hybrid network emerged. A hybrid network is the one that includes two or more sub-networks collaborating to deliver a certain service. This hybridization in general aims at exploiting the capabilities of one network, while covering the flows with another one. The collaboration between the different networks can take several forms depending on the features each of the involved networks provides.

## Motivation and objectives

TBC and BB cellular networks are two of the most successful networks in the delivery of multimedia services to users. In TBC a ground High Power High Tower (HPHT) transmitter spreads the information at certain time, frequency, and power. Interested users, who are located within the reach of the transmission power, will tune in to the transmission frequency, at the time of transmission, and using compatible equipment he or she will be able to observe the content. This is similar to the orator example mentioned before and his speech. Virtually, the audience size can be infinite, since there is no limitation on the resources. The unlimited number of users makes the TBC a very efficient delivery method. Nonetheless, The reception needs having appropriate equipment, and it is limited in space and time. Moreover, in BC the communication is often one-way, *i.e.* the transmitters controls the whole stream, and usually there is no feedback from the receiver.

The lack of feedback prevents both content and technical personalization. Content personalization includes the ability to send slightly different content to each user depending on his preferences, *e.g.* different picture quality or different sound channels. Technical personalization, on the other hand, includes the transmitters' ability to change the transmission parameters like power, bandwidth, and modulation for each receiver depending on its condition. It can also include the ability to resend lost information. To overcome the lack of feedback, BC networks' parameters are often designed to serve the users with worst-case conditions, which degrades the network efficiency.

Contrarily, modern BB cellular networks are efficiently capable of providing both types of personalization. The fact that BB cellular networks have an uplink channel enables the mobile station to provide feedback to the BS including the channel conditions between the two ends. Using such information, and through power allocation and resource allocation, the transmitter can optimize the delivery to enhance the efficiency of the transmission. Moreover, the mobile user is then provided with a set of options with which he or she can control the viewing experience.

In addition to the personalization capabilities, modern cellular networks have a huge network deployment around the globe. Such widespread makes it easier to reach more users, and not limiting them to the areas around a HPHT. This, however, doesn't cover completely the cellular networks' flows. For instance, cellular networks suffer from extensive Inter-Cell Interference (ICI), since modern networks rely on frequency reuse in the cells. Yet the major limitation for this kind of networks is in the available spectrum. Most of the deployed networks nowadays use Unicast (UC) in the downlink. In UC, the BS allocates certain time and frequency resources for each user and delivers the information within these limits. The bottleneck here becomes the available spectral resources at each cell. The finite bandwidth limits the possible number of served users, especially when the requested service requires a large bandwidth like media streaming. When the number of users grows beyond the capability of the network, an overload occurs, and some users are dropped.

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To overcome the limited resources problem, modern cellular networks included Multicast (MC) to their specifications. In MC, a group of users, interested in the same content, share the same time-frequency resources in the download. The sharing helps to reduce the overload effect while maintaining an uplink for feedback. Yet, MC suffers from some drawbacks similar to that of TBC, which are the worst-case scenario transmission. This, as mentioned before, reduces the efficiency of the network.

A hybrid TBC/BB network can provide a solution to enhance the delivery of the service such as multimedia streaming and mobile TV to users, without having to deeply modify each network separately. One type of collaboration in this context is user sharing, where each network serves a subset of the interested users based on some pre-defined criteria. Other types of collaboration can be used such as service sharing and stream sharing, but it will not be considered since it is less credible in terms of implementation.

The main objective of this thesis is to explore the capabilities of a hybrid TBC/BB network in a user sharing collaboration scheme for linear services. This includes providing tools to estimate the performance of different deployments in various operational modes and to optimize the system settings to maximize some key performance metrics like coverage and efficiency. This aims at providing insight for future designers, operators, and researchers on the potential of this kind of hybridization.

## Contributions

According to the research environment, the thesis in hand claims novelty upon introducing new ideas, solutions, analysis, and algorithms. First, we provide a detailed survey on the mobile TV technology, the nature of the service, the opportunities it provides and the challenges that it faces. Besides, the conventional and hybrid delivery methods are then discussed, starting from the available standards, to the contributions of the scientific community in analyzing and improving these techniques.

To have a full understanding of the hybrid TBC/BB networks, different hybrid models are introduced and proposed. This includes different operational modes for the BB cellular network (both UC and MC modes), different TBC network deployments (both single transmitter and multiple transmitters deployments), and different user association schemes (both zone-based and signal-quality-based association). Throughout this work, stochastic geometry is used to model and analyze the cellular network.

Considering a UC mode of the cellular part and a single BC transmitter in the BC part, two frequency deployments are contemplated, one with coexistence between the two sub-networks in the frequency domain, and the other is without this coexistence. Using stochastic geometry, expressions for the probability of coverage and ergodic capacity for both scenarios are derived. The existence and the value of an optimal operation point for coverage and efficiency are then investigated in different network settings.

This model is also generalized into a multiple BC transmitters for the TBC part of the hybrid network. The new model is also analytically discussed to provide new expressions that can predict the coverage and capacity of the system using appropriate approximations.

Apart from the UC operational mode of the cellular network, MC is also studied. Since MC is usually accompanied with a Single Frequency Network (SFN) deployment, the performance of the SFN in a cellular network is analyzed. Again, using stochastic geometry tools, a lower bound for the probability of coverage is derived. Furthermore, three operational scenarios are proposed for a signal quality-based user association hybrid TBC/MC network, while the power efficiency of this hybridization is studied.

Finally, some practical concerns in BB and hybrid networks are explored. To optimize the delivery of linear services like live streams over a cellular BB network, a linear services-oriented resource allocation scheme is proposed. Moreover, the energy consumption and

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the energy efficiency of the hybrid TBC/BB network is studied after applying the resource allocation algorithm to the cellular sub-network.

## Thesis organization

The thesis is organized in 6 chapters excluding this introduction and the conclusion.

In Chapter 1, mobile TV, one of the modern demanding services, is introduced. We first investigate the key elements in the technology, the opportunities it provides to both the industry and the public, the challenges that face the technology industry both technically and commercially, and the human behavior regarding this service. Then, major conventional delivery methods like satellite, TBC, BB cellular, WLAN, and WMAN are discussed. Besides the most popular standards of these methods, the challenges and pitfalls of each are presented, with the solutions proposed by the research community. Withal, the hybrid approach is then presented, with different combinations of the conventional methods, and with various collaboration techniques. The efforts of the scientific community to study and enhance these hybrid networks are then surveyed.

In Chapter 2, a primer on stochastic geometry as a tool for modeling and analyzing a wireless network is first given. This represents a small introduction to the tools used throughout the thesis in the analysis. Then, the different network models that are used in the thesis are proposed and motivated. These models include different combinations of user association, BB operational modes, and TBC network deployment. Additionally, the key performance metrics that are used to evaluate the networks' operation are defined and explained.

In Chapter 3, The first hybrid TBC/BB models is considered, where the TBC is made out of a single BC transmitter, and the cellular network operate in UC mode. Two types of user associations are used here and are introduced in two sections. The first type is the zone-based user association, where the BC is responsible for serving a circular zone around the transmitter, and the rest of the area is covered by the cellular network. Two scenarios for frequency band utilization are used; coexistence in the frequency band and dedicated spectra for each network. The second type is the signal's quality-based association, where a user is served by the network that provides better signal quality. In the two sections, performance metrics such as coverage probability and power efficiency are derived. The derived expressions are verified by simulations and then used to find the optimal operating point (radius of the zone in the zone-based and the transmission power in the signal quality-based association). Finally, the effect of the system settings and network density on the performance is studied.

In Chapter 4, the zone-based hybrid model presented in chapter 3 is generalized to a one with multiple BC transmitters in a much larger service area. For this model, suitable approximations were made to derive some upper and lower bounds for the coverage probability. These approximations are then used to analyze the effect of some design parameters and environment variables on the performance. The existence and value of an optimal BC zone size are investigated.

In Chapter 5, we turn our attention towards the other transmission mode in the BB cellular network, which is MC. When operating in the MC mode, modern cellular networks apply a SFN deployment where all the BSs within a certain group transmit the service using the same band to avoid ICI. Therefore, we first analyze the SFN probability of coverage. But due to the complexity of the analysis, we use an approximation to find a lower bound for the coverage probability. In the second part of this chapter, we propose a hybrid BC/MC network, with three scenarios of operation. The power efficiency of one of the scenarios, which shows the best performance, is then numerically optimized in terms of BC transmission power.

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In Chapter 6, some practical issues regarding the operation of the hybrid networks are considered. This chapter discusses two issues in two sections. The first is the spectral resource management. To optimize the delivery of linear mobile TV services, a linear service-oriented resource allocation strategy is proposed. The proposed algorithm is then compared to existing resource allocation techniques in addition to the optimal solution of the optimization problem proposed by branch and cut. The second issue considered in this chapter is the energy efficiency of the hybrid network. We utilize an existing energy consumption model for modern cellular BSs and use it to numerically optimize the hybrid network's energy efficiency.

Finally, In the conclusion, the main contributions of the thesis are summarized and future perspectives are proposed.

## Publications

### Journals

- **A. Shokair**, M. Crussière, J.F. Héland, Y. Nasser, O. Bazzi, “Analysis of Hybrid Broadcast/Broadband Networks with Multiple Broadcasting Stations”, *IEEE Access*, 2019.
- **A. Shokair**, Y. Nasser, O. Bazzi, J.F. Héland, M. Crussière, “On the Coexistence of Broadcast and Unicast Networks for the Transmission of Video Services Using Stochastic Geometry”, submitted to *Springer’s EURASIP Journal on Wireless Communications and Networking (JWCN)*, 2019.
- **A. Shokair**, M. Crussière, Y. Nasser, J.F. Héland, O. Bazzi “Coverage and Efficiency of Signal-Quality-Based Hybrid Broadcast/Broadband Networks”, submitted to *IEEE transactions on wireless communications*, 2019.

### Conferences

- **A. Shokair**, J.F. Héland, O. Bazzi, M. Crussière, Y. Nasser, “Analysis of the Coverage Probability of Cellular Multicast Single Frequency Networks”, in *the IEEE International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, Barcelona, 2019.
- **A. Shokair**, Y. Nasser, M. Crussière, J.F. Héland, O. Bazzi, “Analytical Study of the Probability of Coverage in Hybrid Broadcast-Unicast Networks”, in *the IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Bologna, 2018.
- **A. Shokair**, M. Crussière, J.F. Héland, O. Bazzi, Y. Nasser, “Power Efficiency of the Hybrid Broadcast Unicast Network with Suitable Resource Allocation”, in *the IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, Valencia, 2018.
- **A. Shokair**, Y. Nasser, O. Bazzi, J.F. Héland, M. Crussière, “Near-Optimal Linear Service-Oriented Resource Allocation Strategy for LTE Networks”, in *the IEEE International Congress on Ultra Modern Telecommunications and Control Systems (ICUMT)*, Munich, 2017.
- **A. Shokair**, M. Crussière, J.F. Héland, Y. Nasser, O. Bazzi, “Mobile TV directed Resource Allocation Scheme for LTE Networks”, in *the IEEE International Symposium on Wireless Personal Multimedia Communications (WPMC)*, Yogyakarta, 2017.



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# Chapter 1

## State of the art review

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### 1.1 Introduction and historical background

Since the development of the first television set in the twentieth century, the industry of TV has never stopped advancing. The first TV concepts began to rise in the 1920s with pioneers such as Vladimir Zworykin and Philo Farnsworth. By the 1930s, with several laboratories working on different television concepts. Electric and Musical Industries and Marconi proposed a 405 line interlaced scanning system in 1934, and Baird presented a 240 lines progressive scanning system with 30 frames per second, both operating at 45 MHz. By 1937, and following the start of the regular BBC transmission, around 20000 TV sets were sold in the UK. Shortly after, in 1937, electronics TV sets began to be available for the public in the US, with companies like NBC and CBC broadcasting regularly. With such diversity in proposed systems, the Federal Communications Commission (FCC) decided to unify a television broadcasting standard. In 1941, FCC accepted a 525-line 30-frame black and white TV system. A few years after, in 1953, the National Television System Committee (NTSC) adopted the first color television standard with a frame rate of 29.97 Hz. In the same period, FCC was revising the allocation table and authorized the UHF TV transmission.

The search for higher picture quality continued, until the late 1960s, where the High Definition TV (HDTV) project began in Tokyo in 1968 at Nippon Hoso Nyokai with a 1500-line image target [1–3].

By 1988, 98 % of the houses in the US had at least one TV set. At that time, the research on the new digital TV instead of the conventional analog transmission had already started and fruited in the first digital platform in 1994, 1996 and 1998 for satellite, cable, and terrestrial transmissions respectively. The later years witnessed the emergence of new technologies for the TV sets to take the place of the Cathode Ray Tube (CRT) technology, like Plasma TVs, Liquid Crystal Display (LCD)s, and Light Emitting Diodes (LED)s. Besides, during the last few years, new quality levels have been reached with the rise of UHD TV as the new generational leap in the TV evolution [4, 5].

In the last decade, with the emerging of the mobile phones that are capable of screening videos, the attention was turned into “mobilizing” the TV experience by allowing these devices to receive the content, and the age of mobile TV started. Mobile TV presented a huge opportunity to the television industry following the enormous number of mobile phone holders and potential customers, yet it introduced several challenges both technically and commercially. The industry had to deal with the mobility of the users, coverage in urban and rural areas, limited spectral resources, and small power supply. The service providers, on the other hand, had to wisely choose the content that is suitable for mobile users, and adopt a sustainable business model.

Since mobile phones can’t be served by cables, and since they have built-in capabilities to access other wireless networks, mobile TV services are assumed to be delivered by one of the following technologies:

- TBC
- Satellite Broadcast (SBC)
- Cellular networks
- WLAN, and WMAN.

Each one of these technologies provides some potential in certain areas. This includes the wide coverage of satellite transmission, the efficiency of terrestrial BC, the personalization of the cellular network, the reliability of the wireless access networks. However, each one has certain flaws that make it sub-optimal. The examples include the latency and shadowing in SBC, lack of efficiency for a small number of users in TBC, limited spectral resources in cellular networks, and the limited range of wireless access networks.

To overcome these challenges, the hybridization approach has emerged. A hybrid network is the one that uses two or more types of networks to deliver the content to the mobile device. This collaboration can take different ways. The different networks can serve different areas, serve different users, be responsible about different blocks in the communication chain, transfer different parts of the video stream, and so on.

This first chapter represents a survey which focuses on the development of mobile TV and its access networks over the years, from both technical and commercial point of view. We will present the main advantages and drawbacks of each technology, provide the main challenges to overcome and the common pitfalls to avoid in the future.

The first part of this chapter discusses the mobile TV technology itself. Starting with the nature and requirements of the service to the opportunities it provides for both the industry and the public. Moreover, the challenges facing this technology are detailed. This includes both technical and commercial pitfalls and adversities. To better understand the users’ attitude of the users toward the technology, the research works conducted on the Quality of Experience (QoE) and human behavior in this regards are presented.

In the second part, the conventional delivery access networks are considered. The main features of the modern standards of TBC, BB cellular networks, WLAN, and WMAN are presented. The challenges facing each of these methods are discussed, with the proposed

solutions in the literature.

Being a promising solution for most of the pitfalls of conventional networks, the third part discusses the hybrid network approach. Several combinations of these networks are considered, explaining the types of collaboration and applications of each. Furthermore, the challenges facing these networks and the efforts of the scientific and industrial communities to face these difficulties are highlighted.

## 1.2 The Mobile TV technology

In this section, a general overview of the nature and requirements of a mobile TV service, with both the technical and commercial challenges, is presented.

### 1.2.1 Mobile TV service

As exposed in the sequel, the mobile TV is a slightly different service than the general services the mobile user usually requests. But as any other communication service, it will need a capable transmitter, either dedicated to this service or shared with other ones, capable receiver device, and a suitable protocol that can efficiently be used to deliver the information over the selected medium.

#### 1.2.1.1 What is the mobile TV service?

Mobile TV is the stream and display of video data in real time or near-real time manner to hand-held devices. In this case, the priorities and considerations for a system designer are different. For example, in such conditions, maintaining a bitrate suitable for the stream is more important than correcting all possible errors, *i.e.* a user will probably miss a small glitch in one of the frames, but will be annoyed if the video stops every few seconds to buffer.

In general, there are two types of mobile TV services [6]:

- **Linear services:** These services include the live TV stream from source to the viewer, where the transmission (start time, end time, sequence...) is fully controlled by the provider side. This type is useful for live events like music concerts, sport events, news...
- **Non linear services:** These services are the ones that are controlled by the user. Here, the user determines the content he wants to watch from a list of available programs, and determines the time of the start and the end, in addition to the sequence (when to pause, return, speed forward...). Video on Demand (VoD) services and Over The Top (OTT) services like Netflix and Amazon prime videos are fine examples of such type.

The efficient availability to reach any of these services is governed by numerous factors like the availability of the network, the compatibility with the device, the memory capacity, and the battery life.

#### 1.2.1.2 Major requirements

As mentioned earlier, certain requirements in the delivery technology are mandatory to keep the transmission applicable and efficient.

- **Efficient compression:** Video streams are composed of a series of frames rapidly displayed to give the impression of a moving picture. This amount of data requires an efficient compression algorithm that reduces the amount of data transmitted, but at the same time maintains the quality of video [7].

- Reliable and fast error correction: Transmitting in the wireless medium is challenging due to its lossy nature. With the high data rate of a video stream transmission and low latency requirements, a fast and reliable forward error correction is essential [8].
- Capable physical layer: The mobile nature of the users presents several challenges to the TV delivery such as shadowing, handover, fading and intensive interference. So a mobile TV delivery system needs to have a physical layer that can handle such effect, with a wide enough bandwidth.
- Power efficiency: In modern systems, green communication is one of the most important goals to achieve, for both economical and environmental reasons. Therefore, the energy efficiency of the system remains a very important factor [9].

### 1.2.2 Opportunities

According to [10], following the rapid increase in subscribers, especially in Asia, the mobile TV market is expected to significantly grow in the following years. Factors such as relatively low cost and usage convenience encouraged a large adoption of mobile TV in the last few years. Moreover, the growing smart phone and internet industries penetration in addition to the rise of average income will help the mobile TV industry flourish in the next decade.

From 27 thousand devices in 2001 to around 4.8 billion devices in 2017, the number of connected mobile BB devices is achieving an annual growth rate of around 113 % [11]. According to the 2018 Affordability Report by the Alliance for Affordable Internet (A4AI), most of the middle and high income countries have an affordable BB connection (1GB of data costs less than 5 % of the average income) [12]. The effect of pricing (among other factors) on the usage of BB services in Europe starting from 2008 was studied in [13]. Those factors lead to forecast a steady growth in the mobile TV market from 7.69 billion US dollars in 2005 to an estimated 17.02 billion US dollars in 2024 [14].

The nature of mobile TV services divides the market into two main categories: Live TV category, and VoD. In live TV usually a user would pay a subscription fee to have access to live content broadcasted by the operator through the cellular network or any other means. This category is particularly suitable for live events like sports competitions, music concerts, large social events, and breaking news. For example, the last five football world cups and the last five summer Olympic games had a TV audience that exceeded three billion viewer each [15–18]. It was reported in [16] that 38.7 million unique visitors used their mobile phones to watch the event in 27 national markets. The total increase of video views between the 2012 and 2016 Olympics was 131.6 % according to [17]. Moreover, according to news reports, Live 8 musical concerts in July 2005 had around 2 billion viewers and Micheal Jackson memorial service was watched by around 2 billion person as well.

On the other hand, the last decade witnessed the rise of several specialized VoD providers in addition to the conventional VoD cable providers. Netflix for example had a paying subscribers growth from 21.5 millions in 2011 to around 149 million in early 2019. The total revenue of the company was around 15.8 billion US dollars in 2018 [19]. Netflix is available for mobile devices, where its application was downloaded more than 500 million times on Android play Store. Amazon Video, a competitor to Netflix, had around 101 million subscribers in 2018. Hulu, in addition, had around 25 million subscribers at the beginning of 2019 with around 50 % increase from the same time in 2018.

In both cases (Live TV and VoD), either the content creator or the service provider is charging the users for access to the service. This can be seen as a direct profit for these two sectors. Nonetheless, the popularity of this kind of services makes users spend more time on their portable devices. This can help growing the market of mobile devices industry and electronic marketing. From 161 billion US dollars in 2011, the global smart phone revenues

for manufacturers grew into more than 419 billion US dollars in 2018 [20]. In addition, a global spending of 10 billion US dollars was recorded in 2017, and with the steady growth in the last years, more than 29 billion dollars is expected to be spent on video advertising by 2023 on smart phones only [21].

As can be seen, the existing and potential markets for mobile TV are considerably big. This creates opportunities to several parties like content makers, service providers, device manufacturers, advertisement agencies, and finally, end users. However, in such a competitive environment, it is essential to overcome the challenges introduced by the service nature, and understand the users' behaviour in order to make profit. These two aspects will be discussed in the following parts.

### 1.2.3 Challenges

Like every technology-related industry, mobile TV faces two kinds of challenges: (1) technical challenges to optimize the service itself, and (2) commercial challenges to adapt the service with the customers need in order to sell it. These two types are often correlated, for example the quality and accessibility of the stream will affect the number of customers. Yet, we will try to separate the two types in the discussion here.

#### 1.2.3.1 Technical challenges

One can classify the technical challenges for video delivery to end users into two types; those related to the delivery method, and those related to the receiving device.

**a) Delivery related challenges** The delivery related challenges are dependent on the chosen method of delivery. For example the handover problem is more severe in cellular networks than in satellite or terrestrial BC, and the shadowing effects the satellite transmission more than wireless access networks. In all cases, providing a seamless service is essential in mobile TV. Withal, the mobile nature of the receivers present the following problems:

- *Continuity*: Unlike other services, continuity is essential in a video stream. Having a lot of interruptions degrades severely the users experience. Theses interruptions can be sourced by Handover, where the mobile user is moving from one part of the network to another. This is particularly important between cells in cellular networks, or between sub-networks in a hybrid network. Shadowing can also interrupt the stream, especially when the transmission is done by satellite.
- *Reliability*: For a mobile TV service to be reliable, a user should have access wherever and whenever desired. This is directly related to the probability of coverage. Probability of coverage can be defined as the probability of a user device achieving certain threshold of signal quality. The coverage probability can be affected by fading, interference, and the allocated bandwidth. The weight of each one of these factors depends on the network type. For example, interference is more severe in cellular networks, while fading is the limiting factor for TBC transmission.
- *Quality*: The quality of a video stream is dictated by the frame rate and frame resolution. These two factors are related to the bit rate of the stream. Full High Definition (FHD), or 1080p, needs a bit rate between 5 and 6 Mbps, while providers like Netflix and Amazon recommend a bit rate between 15 Mbps and 25 Mbps for UHD, or 4K. Such data rates require careful planning of the network to maintain high SINR, sufficient spectral bandwidth, and efficient adaptable coding scheme. Multiple Input Multiple Output (MIMO) schemes are good solutions to enhance the spectral efficiency of the transmission. MIMO is already been included in fourth

generation cellular networks and beyond, and in broadcasting standards with simpler schemes, and proven a high improvement in the performance of the stream [22, 23].

All of this come with the increasing demand on BB services which creates an enormous traffic that the BB network operators need to handle. For more information on the network traffic for mobile devices the reader can refer to [24].

**b) Device related challenges** As for the device itself, its compact and portable nature present new challenges. Unlike fixed TV sets, mobile devices have limited size and energy supply. This will limit the available resources like processing power, memory size, and battery capacity, and therefore requires optimization of resource management. Here are some of the most relevant challenges for mobile devices:

- *Battery life*: A typical modern smartphone has a battery size that ranges between 2000 and 4000 mAh where lithium ion is the most common type. For years, the battery life has been a bottleneck for mobile devices. Live streaming is one of the most battery-exhausting services [25]. When video is being streamed to a device, high consuming peripherals in a device are operating, often in full capacity like at least one of the network interfaces operates, the display, the Central Processing Unit (CPU), and the memory. A detailed study on the battery consumption and temperature and CPU load in smartphones using different types of services is available in [26].
- *Memory*: It is known that memory chips are getting smaller and cheaper with time, but at the same time the sizes of the operating systems, applications, and files on a smartphone are getting larger. Memory capabilities is needed in one of two cases: buffering, and storage. Buffering is usually needed when a live stream is downloaded and displayed in real time. Both the size of the memory, and the read/write time is important, especially when the data rate gets higher. Storage, on the other hand, is needed when a content (or a group of contents) is pre-downloaded to the device in order to watch later. This is typical for OTT users who download content over a WLAN in order to save more expensive cellular data.
- *Speed and processing power*: Receiving, processing, and displaying high definition needs certain capabilities in a portable device. Modern smart phones and tablets in general has acceptable processing power and video processing competence. Nonetheless, current mobile phones market has a wide range of models with a large variance of capabilities. Too much load can create inconvenience to some users, like overheating, and overloading the device.
- *Compatibility*: As mentioned earlier, the market has a variety of smart phone and tablet models, with different network interfaces, processing power, display capacity, and operating systems. First it is essential for the device to have the network interface for the transmission method used. Nowadays 921 million smart phones have access to the Fourth Generation (4G) network and around 3.7 billions have access to the Third Generation (3G) networks [27], in addition to WLAN like Wi-Fi, but very few has access to terrestrial BC and satellite BC. For any delivery plan to succeed, it needs either to use the available capabilities in the market, or influence the manufacturers to install the required components in their new models. From processing power point of view, designing a service delivery based on the weakest devices will lead to dissatisfaction among advanced devices holders, and the opposite leads to overloading the slower devices. The same goes for video quality and display capacity. Providers will often be forced to transmit with different qualities in order to be backward compatible.

### 1.2.3.2 Commercial challenges

For any technology to flourish it has to be profitable. As important the technical perfection can be, the most important aspect is to be able to sell the technology to the masses and eventually make profit. This is essential to maintain the cycle of technological advancement: a new technology needs to be accepted in the mass market in order to make profit, this attracts more investments to develop the technology, and the cycle goes on.

**a) Understanding the market** To achieve a high market reach, the industry must first understand the market and user mentality, then optimize the service quality, and finally market the service properly. Since this kind of service is Business to Customer (B2C), understanding the customers behaviour and preferences is essential to have a high reach in the market. This will be discussed in details in the following parts. Based on this knowledge, the service is designed to meet certain technical requirements. The terms Quality of Service (QoS) and QoE emerge. QoS is a measure of the network behaviour, and is usually linked with factors like coverage, delay, packet loss, etc. QoE on the other hand is a subjective measure that is related to the users expectation, experience, and satisfaction. The correlation between QoS and QoE was studied in [28]. Since QoE is subjective in nature, several attempts were made to transform it into an objective metric based on QoS parameters like in [29–31].

Besides the performance of the technology, the other challenge for mobile TV is the experience of the users. The mobile TV experience is different from that of a fixed TV set, and the way a user receives the service is controlled by several factors such as user profile, mobility of the device, the context, the content, and the service cost [32].

**b) Profit sharing** In another context, profit sharing is another challenge for the mobile TV industrial community. For the end user to enjoy a content, and pay to watch it, several parties would have already contributed to the service: The content creators, the platform managers, the network operators, and the software developers. Most of the revenues usually comes from a payment done by the user (either fixed payment to gain access, or per view payment), and from advertisement. It is not always the case that each part is done by one separate entity. For OTT such as Netflix and Amazon, the platform manager also provides a part of the content and the required software. In the case of YouTube and Facebook, they provide only the platform and the software, while the content is open to be created by virtually anyone. In both cases, the network operator manages the delivery to the device. In other cases, especially for live events such as sports and musical events, the content provider usually manages the platform and provide the software, a separate BC or BB operator (or both) manages the delivery. Having a balanced profit sharing mechanism keeps all the involved parties operating and attracting investments.

Fig. 1.1 summarizes the challenges faacing the delivery of mobile TV to users.

## 1.2.4 QoE and human behaviour

The main focus in this part is the human perception and interaction with the mobile TV technology. It is to answer two main questions: How the users feel about the technology? And how the users react to the technology based on their perception and feelings?

### 1.2.4.1 Users' perception

To answer the first question, it is important to quantify how the users feel about the service they receive. For this purpose, the term QoE was introduced. Originally, QoE was a subjective metric that measures the perception of a service and the satisfaction of



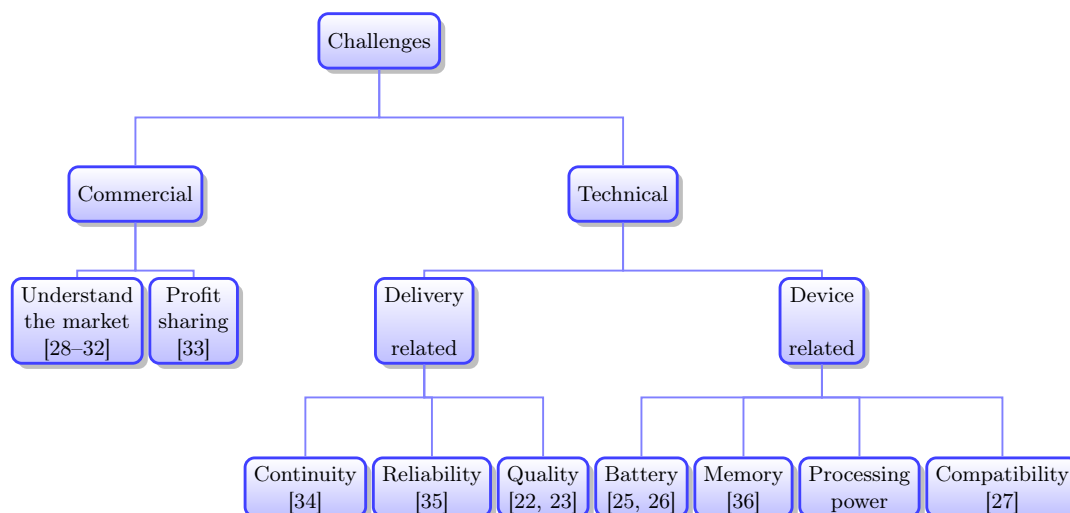


Figure 1.1 – The challenges facing mobile TV delivery

the users. As mentioned earlier, several attempts were conducted to link some objective metrics from QoS to QoE in order to simplify the optimization procedure especially for the technical part of the service.

QoE usually studies the satisfaction towards the whole service, or a part of the service, such as the effect of certain resolutions, for instance 4K and 8K. Due to its importance, it has been an important part of the literature when proposing, analyzing, and evaluating new technologies.

**a) QoE assessment** In the literature, several attempts were made to estimate the QoE for mobile TV technologies without the need to interview users every time a parameter changes. In [37], some features from the decoded video are used to estimate the users' experience, and in [38] a quality estimation method using distortion aggravation was proposed. Another quality assessment method for distorted images was suggested in [39].

Modelling the QoE is still an open issue in research. In [40], a novel modelling framework for QoE in the Fifth Generation (5G) networks for UHD media streaming is proposed. Such models try to predict the users' QoE under a verity of conditions related to the system and the users themselves.

Machine learning, on the other hand, provides advanced prediction tools. QoE management techniques were reviewed in [41] with a focus on machine learning application. The authors then highlighted the challenges for QoE modeling, monitoring, and control, proposing machine learning method for each. In [42], the packet loss distortion and its effect on the video perception was subjectively studied, and two models for estimating the subjective visibility of the artifacts were proposed using machine learning and analysis.

**b) QoE databases** For better analysis for QoE estimation methods, several databases for QoE indexing were created in the past few years, like the database for adaptive video streaming reported in [43], the live mobile quality assessment database in [44], the live QoE database for Adaptive streaming (HAS) in [45]. In addition, LIVE-Avvasi Mobile Video database presented in [46] is a result of a subjectively analyzing the effect of network impairments such as stalling on the QoE for mobile devices. In [47] and [48] Waterloo streaming QoE database I and II were respectively presented, and [49] introduced the Live-Netflix video QoE database that analyzes the effect of impairments such as buffering and compression on QoE for mobile devices.

Even though the mentioned databases provide a great assistant especially for machine

learning-based techniques for prediction, the choice of the training and testing pools, correlated observations, and sample sizes can create a pitfall for such methods. In [50], these effects were analyzed, and alternative procedures and guidelines were proposed to enhance the performance of the machine learning validation.

**c) Factors affecting the QoE** The effect of some of the viewing conditions is also being investigated in a QoE context. Authors in [5] studied the psychological effect of watching UHD images on users, especially with distances higher than usual. Moreover, the panoramic viewing of HD video and viewing angles were analyzed using a subjective quality assessment in [51]. A new model for QoE for olfaction-enhanced multimedia was proposed in [52]. Other system parameters like resource management [53], adaptive streaming [31], and rate adaptation [54] were also proposed in the literature based on QoE restrictions. More subjective studies on the QoE can be found in the surveys [55] and [56].

#### 1.2.4.2 Users' interaction

To answer the second question, how the users react to the technology, it is important first to understand their motives, then follow their behaviour, and finally understand what effects both.

Users often use mobile TV for entertainment and relaxation and to feel less lonely like when having a meal, as regular TV. But the mobile TV provides more personalized experience and gives the ability to easily share and exchange content. The desire to be up to date, and be the first to know also drives the need for the service. Mobile TV can also be used to kill time waiting in public transportation or for flights, helping in creating a private sphere [32, 57].

**a) Studying customers' behaviour** In [58], the authors studied the behaviour of mobile TV consumers in China for one month, recording more than one million unique users. The study demonstrated first the difference between watching patterns between land-line Internet Protocol TV (IPTV) and mobile TV, and second the difference in watching patterns being on different networks, Wi-Fi and cellular network in particular. The first difference was noticed in the content selection, where users tend to select more the high rated channels when on mobile TV. The usage time of mobile TV, being a random variable, follows a combination of Pareto and log-normal distribution, which is closer to the distribution of phone call time rather than IPTV usage time. The second difference is in the watching duration over Wi-Fi and cellular networks, where it is shorter on cellular network, mostly due to the higher price. A similar study was made for Hong Kong to study the viewing habits, interests, and willingness to adopt mobile TV based on the theory of planned behavior [59].

A study on the mobile TV watching behavior in the US was reported in [60] to answer questions like: what the American people are watching? and how the mobile TV changed their behavior regarding the TV experience in general. The results show that there is a tendency towards VoD at the expense of traditional linear services, and that mobile TV didn't take the place of the traditional TV set. The result also highlights some surprising findings like the fact that half of the surveyed pool watched mobile TV with at least one person on the same device.

The mobile TV users' behavior and watching patterns were analyzed in [61] with a special concentration on the content, and how it shapes these patterns. They were then used to generate estimation models to predict the traffic volume associated with a certain program. This allows operators to anticipate the load on the network, and therefore take suitable measures like resource reservation or change in operation mode.

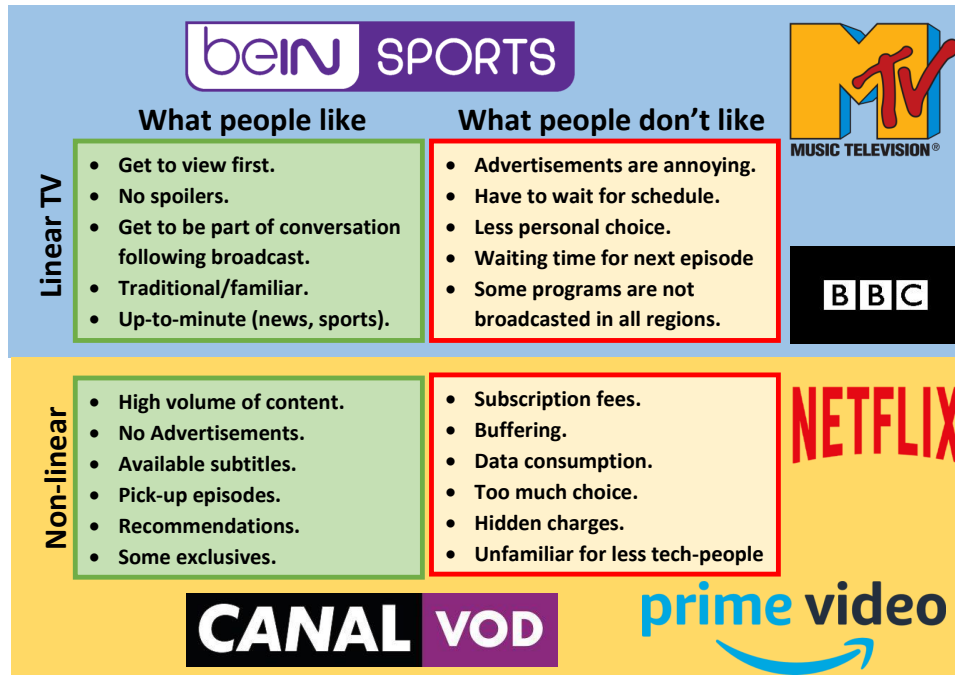


Figure 1.2 – Attractive and unattractive characteristics of linear and non-linear TV

**b) Factors controlling technology adoption** As any technology, it is essential to anticipate how the market will accept it, and whether potential costumers are read to adopt it. Several research works has been conducted on estimating the effect of some technology properties on its adoption by the users.

Users' profile can significantly influence the readiness to accept the technology and later pay to get access to it. Mobile TV adoption among collage student was studied in [62]. The study found that the need for information has a negative influence on the adoption rates, innovation attributes and adoption intention has a positive influence, and that demographics (gender, age) has low influence. This contradicts with the findings in [63] where the results suggests that the gender is an important factor for adoption intention. Another mobile TV user profiling attempt was conducted in [64] based on a study done in Korea.

Beside the users' characteristics found in the studies mentioned above, factors related to the technology itself were found to be influential in mobile TV adoption. Authors in [65] concluded that both media content and the cognitive concentration has significant effect on the willingness of users to adopt the mobile TV service. In [66], the technology readiness and technical support and training were the main focus when studying the behavioral intentions of potential mobile TV users. The findings show that the behavioral intentions are positively and significantly affected by performance expectancy and effort expectancy, while being negatively influenced by the technology readiness. In [67], the author found that flow experience, and consequently the usage intention, is majorly affected positively by content quality, perceived ease, and speed of access.

Fig. 1.2 summarize some of the aspects that users like and dislike about linear and non-linear services according to [68].

Some of the mentioned opportunities and challenges are common for any delivery method, and some are specific to some of these methods. In the next section, the conventional methods for mobile TV delivery are discussed.

### 1.3 Conventional methods for mobile TV delivery

One of the characteristics of mobile devices is connectivity. A mobile device has the ability to connect to several types of networks. Due to the advances in hardware and software-defined radio, the manufacturers are able to add more connectivity options to modern mobile devices. Conventionally, mobile TV is delivered in one of the following systems:

- **Terrestrial broadcast:** One of the oldest methods of TV delivery for fixed and mobile devices. Such networks usually consist of one or more HPHT transmitters forming an SFN. These transmitters deliver a number of programs over several channels on an allocated frequency band. All the users receive the same signal and select the channel they want to watch by filtering, making the network able to serve as many users as there are. One other characteristic of the terrestrial BC is that it is conventionally and natively unidirectional. Excluding a few new standards that try to implement an uplink, the stream flows always in the downlink. This creates a limitation for the personalization of both the transmission and the content.
- **Cellular network:** After the second generation of cellular networks, high-speed data became a requirement for new standards. Starting from the third generation mobile standards, the networks were able to deliver mobile TV stream with standard and high definition with high reliability. Generally, a connection in the cellular network is UC, *i.e.* each user connect with the BS separately with dedicated uplink and downlink, creating a limitation of the number of possible served users. However, MC specifications were added to some networks like Multimedia Broadcast Multicast Service (MBMS) in the Universal Mobile Telecommunications System (UMTS) and enhanced-MBMS (eMBMS) in Long Term Evolution (LTE). These methods allow multiple users to share the same spectral resources in the downlink making the network more efficient.
- **Satellite broadcast:** Due to the large distance creating large delay and path loss, the satellite services for mobiles remained limited to the emergency areas, airplanes, marine transportation, trains, and some rural area. Some attempts were made to deliver high data rate to mobile receivers via satellite, but the wireless channel conditions like shadowing make it almost impossible without a terrestrial component. This hybrid approach will be investigated in details in section 1.4.
- **Other wireless networks:** mobile TV can also be served through other networks over Internet Protocol (IP) in what is known as IPTV. Examples of these networks are the IEEE 802.11 known as Wi-Fi and IEEE 802.16 known as WiMAX. The high bit rate provided by such networks makes it possible to serve mobile TV for local users. However, IEEE standards fail in serving a high number of users in parallel, due to interface and multi-user access scheme limitations. This causes their poor performance in crowded areas.

In this section, these conventional methods will be discussed in details stating the main standards and technologies used and the enhancements introduced in the research world. Since all satellite transmission systems need a terrestrial complementary to serve users with services like mobile TV, satellite BC is not discussed in this section, it will rather be discussed in section 1.4 as a hybrid network with terrestrial and fixed networks.

#### 1.3.1 Terrestrial broadcast

Digital terrestrial BC started as a successor for the analog BC technologies for fixed TV sets with on-roof reception antennas and a HPHT for the transmission with line of sight link in most cases. This transition from analog to digital started in the early years of this century. Later, after the spread of handheld devices, several mobile-compatible

standards started to emerge. Currently there are five main players in the digital TV BC in the world: Digital Video Broadcasting (DVB) in Europe, Advanced Television System Committee (ATSC) in the United States, Integrated Services Digital Broadcasting (ISDB) in Japan, Digital Terrestrial Multimedia Broadcast (DTMB) in China, and Digital Multimedia Broadcasting (DMB) in South Korea [69–72].

Digital TV transmission standards need to define several blocks in the chain, like the error correction method, the media coding, the transfer protocol, the modulation scheme, the wireless access method, and the bandwidth occupied. In the following, the major mobile-compatible standards are described, with the challenges facing them.

#### 1.3.1.1 DVB

In 2004, DVB published their first standard targeting handheld devices like mobile phones and personal assistant devices namely DVB-Hand-held (DVB-H). This standard was based on the first generation terrestrial broadcasting standard DVB-Terrestrial (DVB-T) [73]. In fact, power consumption reduction for mobile devices, which was a major concern in DVB-H is still a main topic of research. In [74] authors designed and implemented a CMOS channel select filters for DVB-H receivers to optimize power consumption at the mobile front-end. Moreover, five cross-layer transmission schemes for scalable video over DVB-H networks are proposed in [75].

Later, in 2008, DVB published the second generation terrestrial broadcasting standard DVB-Terrestrial-2 (DVB-T2) as the successor of the first generation standard. The spectral resources were limited, so a more efficient transmission system was needed to increase the data rate and follow the emerging demand on HDTV.

The standard was designed to serve mobile devices as well as fixed TV sets through the availability of various system settings [76]. In addition, Multiple Input Single Output (MISO) was adopted in DVB-T2 to reduce destructive interference and enhance the SFN coverage compared to Single Input Single Output (SISO) [77]. Authors in [77] studied the performance of DVB under MISO and SISO concluding that the gain of using MISO is significantly high. In [78], the results of the DVB-T2 field measurements that took place in Seoul, South Korea, are presented. Authors analyzed the link budget factors and created a model for indoor coverage. The performance of DVB-T2 in an SFN deployment was further analyzed in [79]. Technical specifications for DVB-T2 are detailed in Table. 1.1

In 2010, DVB started a dedicated standard dedicated to handheld devices like the new generation and evolution of DVB-T2 under the name DVB-New Generation Hand-held (DVB-NGH), and in 2012 the standardization was finished [80]. The main goals for this new standard were to reduce the cost of the infrastructure and to enhance the coverage in the context of portable devices. Some requirements were added at the beginning of the standardization process like a minimum 50 % increase in the network efficiency, supporting moving mobiles up to 350 km/h, and supporting a return channel through the cellular network. To enhance the performance gain of DVB-NGH, Wu *et. al.* suggested in [81] a non-binary Low-Density Parity-Check (LDPC) coded modulation instead of the low-gain binary LDPC scheme used in the standard.

Regardless of the performance proofed by trials and the great potential, DVB handheld systems are finding problems penetrating to the mass production and to be adopted by manufacturers.

#### 1.3.1.2 ATSC

Similar to DVB, ATSC was the digital successor of the analog TV system in the United States approved by the NTSC. However, the system that emerged in 1996 and revised in

2009 was designed to serve fixed TV sets, and the coverage of mobile users, especially with high speeds, was almost impossible [69].

After the large spread of mobile phones at the beginning of the 2000s, ATSC introduced their mobile directed standard: ATSC-Mobile/Hand-held (ATSC-M/H). The standard was designed to be compatible with ATSC first generation, and inherited the same transmission scheme, becoming an official standard in 2008. Multiple tests were conducted for the standard as the one reported in [82], where authors studied the performance of the commercial ATSC-M/H receivers with different Doppler frequencies, evaluating also the Carrier to Noise (C/N) ratio threshold for mobile reception.

In the last few years, ATSC has been working on a revolutionary new generation of the terrestrial broadcasting systems: ATSC 3.0. The new system aims to deliver UHD TV to both fixed and mobile users. The work on the standard began in 2012 and the first completed specifications were issued in 2016. The new generation included MIMO as one of the three frame types alongside with SISO and MISO to overcome the capacity limits and to provide power gain [83]. ATSC 3.0 included an optional uplink connection for future interactive services. Technical details on ATSC 3.0 can be found in Table. 1.1.

The performance of ATSC 3.0 has been a subject for evaluation in the scientific community following the development of the new standard. The performance of the physical layer was studied in [84] by field trials, achieving around over 50 Mbps. Moreover, in [85], a performance comparison was conducted between Layered Division Multiplexing (LDM) and Time Division Multiplexing (TDM) based mobile delivery over ATSC 3.0, showing through simulation that compared to TDM, LDM can significantly lower the SINR reception threshold for the same rate especially at high speeds. The community is focusing now on finishing the work of important elements of the system so the mass implementation could start [86].

The aim is to overcome the limited spread of the ATSC standards beyond the US and have ATSC 3.0 as the global standard for future television broadcasting. The standard, however, is seen by many as a copy of the DVB-T2, especially in the physical layer.

### 1.3.1.3 ISDB

In the early 2000s, the Japanese Association of Radio Industries and Businesses (ARIB) issued the specifications of their new standard ISDB-Terrestrial (ISDB-T). The standard was adopted for both fixed and mobile transmission in Japan in 2003 and later in most of the South American countries. The Motion Picture Experts Group-2 (MPEG-2) stream is passed through an Reed-Solomon (RS) encoder before being separated to three hierarchical layers each with its own energy dispersal block, inner convolutional code, byte and bit interleavers, and mappers. The three layers are then combined, time and frequency interleaved, and then modulated by Band Segmented Transmission-OFDM (BST-OFDM) [69, 70]. The 6 MHz bandwidth is divided into fourteen segments, one of which is usually used for mobile transmission (which gave it the known as 1seg), twelve are used for fixed TV, and one guard segment [87]. This is known also as in-band mobile TV. The system doesn't use time slicing and thus it is more power consuming on the receiver side. Despite the 120 million devices sold by 2012, the mobile 1seg is not profitable anymore, but service providers are forced by regulations to transmit it [70].

### 1.3.1.4 DTMB

China, being the number one market in the world for terrestrial TV started the transfer from the analog to the digital BC in 2006, after the adoption of the DTMB standard. The standard uses RS and LDPC for outer and inner error correction coding, with byte and bit interleavers. The system is OFDM based and has three modulation options: BPSK,

QPSK and 16-QAM. The system was designed from the beginning to support both fixed and mobile users, and both indoor and outdoor [69, 70, 72, 88].

In July 2015, the International Telecommunication Union (ITU) accepted DTMB-Advanced (DTMB-A), the new generation of the DTMB standards. The new system can handle the traditional Motion Picture Experts Group (MPEG) Transfer Stream (TS) or other types of data such as IP packets but after pre-processing and encapsulating these packets into MPEG-TS. Then, the system uses an optional Bose–Chaudhuri–Hocquenghem (BCH) outer Forward Error Correction (FEC) coder and an LDPC inner coder and a Pseudo-Random Binary Sequence (PRBS) scrambler. The data are then mapped using QPSK, 16ASPK, 64APSK, or 256APSK and later modulated by OFDM. Laboratory tests and field test showed that DTMB-A has a good performance for both fixed and mobile users. However, the absence of time slicing caused the system to be power consuming as ISDB [89, 90].

#### 1.3.1.5 DMB

In 2005, the first commercialized mobile broadcasting system was announced in South Korea under the name Terrestrial-DMB (T-DMB), aiming to serve both fixed and mobile users with multimedia services. T-DMB uses MPEG-4 H.264 for source coding. RS code was used for FEC and a byte interleaver to increase the robustness. Despite the fact that T-DMB has low spectral efficiency and coverage compared to other first-generation broadcasting standards, it was one of the few that actually succeeded commercially [70, 72, 91].

#### 1.3.1.6 Challenges and pitfalls

Terrestrial broadcasting has an advantage in terms of the number of users: It can theoretically serve an infinite number of users compared to a limited number of users for cellular networks. Besides, it has a simple and easy to maintain infrastructure compared to satellite transmission. However, critical obstacles are facing such systems that lead for example to the commercial failure of most of the first generation mobile broadcasting services. Such obstructions can be either technical or user related.

One of the technical difficulties is the need for a dedicated frequency band for the transmission. Due to the digital dividend, which was majorly in favor of BB networks rather than BC operators, the number of available channels is reduced to only 28 in Europe and a similar cut is expected in the US [92]. This is one of the main issues of the telecommunication community in the last few years. Other technical problems are limiting the efficiency of the networks like the high power needed for the transmission. Besides the regulations on the power density and the effect on nearby humans, high transmission power reduces the efficiency of the Power Amplifier (PA) by forcing the operators to run at lower PA efficiency to avoid the saturation zone of the nonlinear PA. To avoid this problem, a lot of research has been conducted on Peak to Average Power Ratio (PAPR) reduction and digital predistortion.

Mobile terrestrial broadcasting also has difficulties dealing with modern users' needs and thus creating a profitable business model. A lot of research has been conducted on human behavior related to mobile TV as mentioned in the previous section. One of the main user-related issues is the lack of interactive services that a mobile user is used to with other services on the cellular network.

### 1.3.2 Cellular broadband

The first two generations of mobile cellular networks were designed and optimized for voice calls, not for data transmission. It wasn't until the 2.5 G that cellular networks be-

Table 1.1 – A comparison between different BC standards

| Standard             |            | DVB-T2                                      | ATSC 3.0                            | ISDB-T               | T-DMB         | DTMB-A                        |
|----------------------|------------|---|-------------------------------------|----------------------|---------------|-------------------------------|
| Source Coding        | Video      | MPEG-4 /H.264/QVC                           | HEVC Main 10                        | MPEG-2               | MPEG-4 H.264  | H.264, H.265                  |
|                      | Audio      | MPEG-4                                      | Dolby AC-4, MPEG-H-3D               | MPEG-2 AAC           | MPEG-2        | MPEG-4 BSAC                   |
|                      | TS         | Generic stream                              | MPEG-2 TS, Generic stream, IP       | MPEG-2 TS            | MPEG-2        | MPEG-2 TS, Generic stream     |
| Channel Coding (FEC) | Inner      | LDPC  | LDPC                                | Convolutional        | Convolutional | LDPC                          |
|                      | Outer      | BCH   | BCH                                 | RS                   | RS            | BCH                           |
| Interleavers         | Inner      | Bit, cell, time, freq.                      | Bit, group, block                   | Bit, symbol          | Time, freq.   | Bit, time                     |
|                      | Outer      | Bit   | Bit                                 | RS                   | Convolutional | Symbol                        |
| Transmission         | Scheme     | QPSK, 16QAM, 64QAM, 256 QAM                 | QPSK, (16, 64, 256, 1024, 4096)-QAM | QPSK, 16QAM, 64QAM   | DQPSK         | QPSK, 16APSK, 64APSK, 256APSK |
|                      | Modulation | OFDM  | OFDM                                | BST-OFDM             | OFDM          | TDS-OFDM                      |
|                      | FFT        | 1k, 2k, 4k, 8k, 16k, 32k                    | 8k, 16k, 32k                        | 2k, 4k, 8k           | 3.329 K       |                               |
|                      | GI         | 1/4, 19/128, 1/8, 19/256, 1/16, 1/32, 1/128 | 1/4 to 3/512                        | 1/4, 1/8, 1/16, 1/32 | 1/8 to 1/32   | 1/2 to 1/64                   |
|                      | BW (MHz)   | 1.7, 5, 6, 7, 8, 10                         | 6                                   | 6, 7, 8              | 1.712         | 6, 7, 8                       |
|                      | Antenna    | SISO, MISO, MIMO                            | SISO, MISO, MIMO                    | SISO                 | SISO          | MISO, MIMO                    |

came able of providing data services but with speeds limited to 144 kbps, making it almost impossible to transmit media stream like the mobile TV through it. With the emergence of third generation and fourth generation networks, with the potential of streaming tens of megabits per second, the idea of standard definition and even high definition mobile TV over the cellular network became possible.

Conventionally in cellular networks, each mobile terminal is connected to the serving BS through a dedicated uplink and downlink channels, and therefore, only one user has access to the data. This will allow a personalized service both content-wise and technical-wise. However, since the spectral resources are limited, UC is not efficient when a very large number of users are interested in the same content, especially if it is bandwidth-hungry like mobile TV. This is why in modern standards a MC option is often included, where multiple users share the same downlink channel.

Here, the mobile TV techniques, challenges, and solutions for both UC and MC methods are reviewed.

### 1.3.2.1 Unicast broadband

After the first generation of analog cellular network, the second generation of cellular networks (and the first digital generation) was introduced in the late 1980s with fairly low



bandwidth and limited data rate, just enough for digital voice and short messaging system. The two most dominant networks were Global System for Mobile communication (GSM) and Interim Standard 95 (IS-95), with maximum bit rate of 40kbps. A few years later, technologies as General Packet Radio Service (GPRS) and Enhanced Data rates for GSM Evolution (EDGE) were introduced by Third Generation Partnership Project (3GPP) to form what is known as the 2.5G, where for the first time, data rates of around 400 kbps are being transferred over the network [93–95]. However, such data rates are not enough for a reliable video stream and therefore, mobile TV was not an option.

In the early 2000s, the third generation of mobile networks started to develop aiming at providing high data rates to end users for applications like web browsing and multimedia streaming. 3GPP, which was responsible for GSM and EDGE, issued the Universal Mobile Telecommunication System UMTS. The early versions of UMTS used Wideband CDMA (WCDMA) technology with data rates up to 2 Mbps [93]. Modification and upgrades lead to the High Speed Packet Access (HSPA) a combination of High-Speed Downlink Packet Access (HSDPA) and High-Speed Uplink Packet Access (HSUPA) protocols, resulting in a 14.4 Mbps data rate [95]. With the introduction of MIMO and other modifications, HSPA+ emerged to achieved data rates around 23 Mbps in downlink [96]. On the other hand, Third Generation Partnership Project 2 (3GPP2) issued their CDMA2000 in 2002 that achieved data rates of 14.7 Mbps. Such speeds allowed for the first time the delivery of services like mobile TV over the UC links.

In 2009, 3GPP announced what is now the world standard for the fourth generation mobile networks under the name LTE. The motivation behind the new generation was to enhance the QoE for users, bringing data rates as high as 100 Mbps [93, 97]. Several enhancements were introduced to the original release, and LTE-Advanced (LTE-A) emerged after release 10 in 2011. The new release as the original one is OFDM based and used MIMO to enhance the capacity, achieving data rates as high as 500 Mbps for 4x4 antenna configuration [98, 99]. In [100], Rong *et.al.* studied the performance of the OFDM-based network like LTE in delivering mobile TV services in UC mode.

Few years ago the race towards a 5G cellular network started. In 2015, ITU issued the International Mobile Telecommunication-2020 (IMT-2020), which is the set of requirements for the new generation of cellular networks [101, 102]. The specifications aimed at three main objectives:

- Enhanced mobile BB: higher data rates up to 20 Gbps (100 Mbps user expected data rate), larger capacity up to 10 Mbps/m<sup>2</sup>, and more mobility tolerance up to 500 kmph.
- Massive machine type communication: Increasing the served devices to 10<sup>6</sup> device/km<sup>2</sup>.
- Ultra reliable and low latency communications: as low as 1 ms.

Achieving these technical goals allow for new and upgraded services and usage scenarios. This includes Internet of Things (IoT) with their applications in smart cities and smart homes, self driving cars, Augmented Reality (AR) and Virtual Reality (VR), and UHD media streaming. An illustration of these goals and usage scenarios was published by ITU and can be seen in Fig. 1.3.

In 2016 3GPP initiated the work on a new 5G radio access technology called New Radio (NR), which is now a part of release 15. NR included new features like the wide range of used frequency bands from below 1 GHz to around 50 GHz and supporting massive MIMO [103]. A summary of the min characteristics of the cellular network generations can be found in Table 1.2.

The New high data rates are promising for the mobile TV industry [104]. However, the demand is growing as well, and even if the network has a larger capacity now, handling a large number of users demanding bandwidth-consuming services like mobile TV requires a careful resource management strategy [105]. In OFDM-based transmission like in LTE and

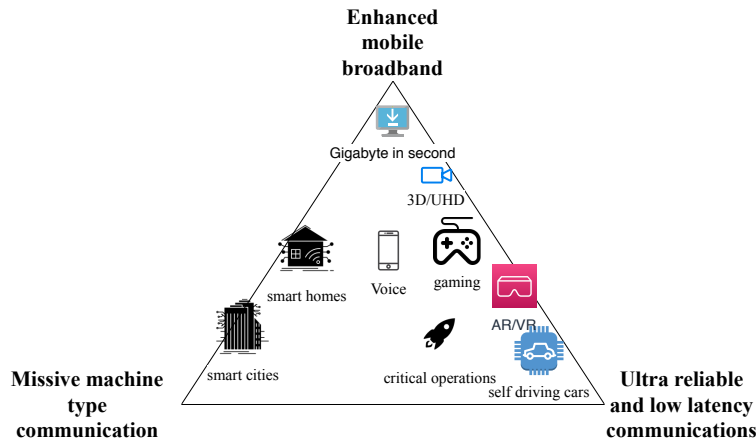


Figure 1.3 – IMT-2020 usage scenarios [101]

5G-NR, each user is allocated a number of resource blocks in the downlink. A resource block is defined as the smallest amount of time-frequency resources elements that are allocated for a user. Each resource block in LTE for example is 180 kHz wide (12 subcarriers, 15 kHz between each two subcarriers) and 0.5 ms in time (1 slot). The authors proposed in [106] a near-optimal resource allocation strategy dedicated to linear services such as mobile TV. The algorithm was then compared in [107] to other general-service algorithms like proportional fairness [108], round robin, and maximum throughput, and showed superior performance and robustness against user density and required data rate.

The other challenge in this context is the interference. One type of interference is the one between neighbor cells that are using similar frequencies due to frequency reuse, or what is known as ICI. The other type of interference is sourced by other technologies operating at the same frequency band, or on a neighboring band and leaking energy to the mobile network. In [109], the authors discussed the ICI coordination in heterogeneous networks. A heterogeneous network is a mix of cells of different sizes (from large macro cells to tiny femtocells), and might use different technologies for delivery. The interference between the uplink of LTE network allocated in 700 MHz bands and the digital terrestrial TV operating at the same band was analyzed in [110, 111], discussing the coexistence scenarios and presenting the protection measures. Cano *et.al* investigated in [112] the possible coexistence of LTE and Wi-Fi networks in the unlicensed spectrum, studying the current mechanisms considered for fair coexistence.

However, the limited spectral resources with the growing demand on data rates for the increasing number of users remains the main challenge for cellular networks, especially for multimedia streaming services. As a response to these challenges, the idea of a MC in the cellular network was proposed, this will be discussed next.

### 1.3.2.2 Multicast broadband

The main limitation for the delivery of BB services in the cellular network was the limited spectral resources. Even when an efficient resource allocation is used, the network will be able to serve a limited number of users with such spectrum-hungry service like mobile TV, and when the number of the interested users increase, an overload might occur. This forces the network either to block some users, or downgrade the quality of the stream. The direct solution was to serve multiple users, interested in the same content, with the same resources, and thus introducing MC instead of UC.

Even though both BC and MC use the same time-frequency to deliver the service, the nature of the two is quite different. In BC, the transmitter broadcasts the data using a

| Technology            | Commercial deployment | Frequency band (MHz)  | Radio access                              | Modulation                | Bandwidth                              | Peak rate                      |
|-----------------------|-----------------------|---|---|---------------------------|--|--------------------------------|
| GSM/<br>GPRS/<br>EDGE | 1992/ 2001/<br>2002   | 850, 900,<br>1800, 1900   | TDMA,<br>FDMA with<br>FDD                 | GMSK/<br>GMSK/<br>8PSK    | 200 kHz                                | 14.4/ 171.2/<br>473 kbps       |
| W-CDMA                | 2002 to 2004          | 700 to 900,<br>1400, 1700<br>to 1900,<br>3400                               | CDMA with<br>FDD                          | QPSK                      | 5 MHz                                  | 384 kbps                       |
| HSPA/HSPA+            | 2005                  | 700 to 900,<br>1400, 1700<br>to 1900,<br>3400                               | CDMA with<br>FDD                          | QPSK,<br>16QAM, 64<br>QAM | 5 MHz                                  | 14.4/336<br>Mbps               |
| LTE                   | 2009                  | 450, 700,<br>800, 900,<br>1500, 1800,<br>2100, 2300,<br>2600, 3500,<br>3700 | OFDM and<br>SC-FDMA                       | QPSK,<br>16QAM, 64<br>QAM | up to 20<br>MHz                        | 300 Mbps<br>(with 4x4<br>MIMO) |
| LTE-A                 | 2012                  | 450, 700,<br>800, 900,<br>1500, 1800,<br>2100, 2300,<br>2600, 3500,<br>3700 | OFDMA,<br>SC-FDMA,<br>clustard<br>SC-FDMA | QPSK,<br>16QAM, 64<br>QAM | up to 100<br>MHz                       | 1 Gbps<br>(with 4x4<br>MIMO)   |
| 5G NR                 | 2019                  | sub-6 GHz,<br>and<br>post-24GHz   | OFDMA,<br>NOMA                            | QPSK,<br>16QAM, 64<br>QAM | up to 400<br>MHz in<br>above-24<br>GHz | 20 Gbps                        |

Table 1.2 – Characteristics of most used cellular networks

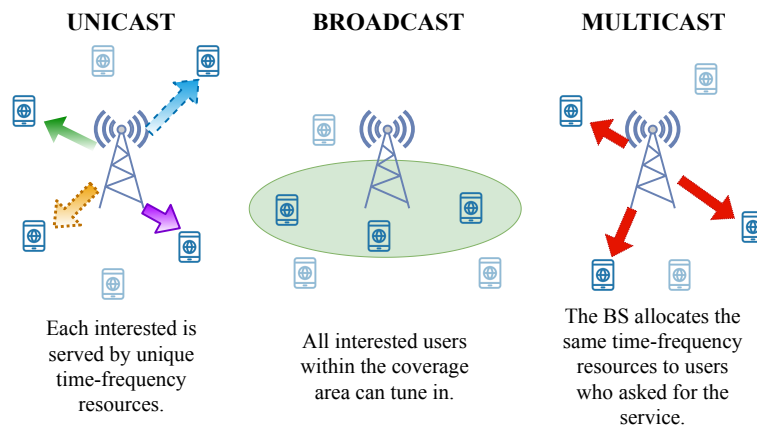


Figure 1.4 – The difference between UC, BC, and MC transmission in the downlink

setting known by the receiver side. If a user is interested, the receiver will tune in to get the transmission. MC, on the other hand, is initiated by the user. A user will declare interest in some content, and if the BS control finds that enough users have the same interest, it allocates certain time-frequency resources to be shared in downlink by all interested users. The difference between UC, BC, and MC is shown in Fig. 1.4. The comparison between the LTE MC services and the BC TV is further discussed in [113, 114].

The first introduction of MC was in 3GPP’s UMTS release 4, where the operator transmitted one-way information to all users like weather report and traffic report via Cell Broadcast Center (CBC). However, since such a system uses a Short Messaging System (SMS) for the delivery, it wasn’t usable for BB services. In release 6, MBMS was introduced

to BC IP packets to multiple users in a cell [115, 116]. To reduce ICI, a major obstacle in UC transmission, MBMS use an SFN where multiple neighboring cells MC the same content over the same frequencies, so the received power from other BSs will become useful rather than interference [100, 117]. The concept of MC was used also by 3GPP2 in the Broadcast and Multicast Services (BCMCS) included in CDMA2000.

3GPP release 9 included MBMS for LTE, where it is called eMBMS. eMBMS benefits from the new high bit rate and the improved H.264 codec and FEC of LTE systems to bring in higher resolution and higher frame rate in the end-to-end IP architecture system. While sharing a set of resource blocks in the downlink, eMBMS receivers achieves 3 bit/sec/Hz spectral efficiency, supporting 30 frames per second of 720p HD resolution [118].

The MC option can also be used for other services like software update and maps database update. Further enhancements were introduced in 3GPP release-14 in order to support the television services following broadcasting industry requirements, bringing on better interference enhancements, increasing the inter-site distance, dedicating carriers for eMBMS with full broadcasting resource allocation [119]. The capabilities of MC in the 5G network was also studied in the literature like in [120–122]

Several trial deployments were done in Europe, the United States and Australia, mainly for broadcasting sports events, between 2014 and 2016. South Korea was the first to deploy eMBMS commercially [71]. In [123], Awada *et.al.* studied the performance and the limitations of the LTE’s eMBMS implementations by conducting a field trial in Munich, Germany, showing that the simulation models provided succeed in predicting the performance of the network, and studying the effect of the cyclic prefix length on the coverage. Vargas *et.al.* conducted in [119] a physical layer performance testing in the lab, using different coding and modulation techniques to measure the SINR threshold.

New studies are being performed to enhance the performance of the MC capabilities of next-generation networks like in [124], where authors proposed Non-Uniform constellation as mapping techniques to narrow down the gap with Shannon limits and increase the network spectral efficiency.

Despite the advantage of MC over UC in terms of spectrum utilization efficiency, MC systems like eMBMS suffer from a major drawback, which is the lack of technical personalization (allocated bandwidth, power...). To overcome this, the BS transmits based on the worst case conditions, reducing power efficiency.

### 1.3.3 Fixed wireless networks

In addition to the BC and cellular networks, other wireless networks can also provide -in addition to other services- mobile TV. WLAN and WMAN are two of these methods. In this section, Wi-Fi and WiMAX are discussed as the most known examples of WLAN and WMAN respectively. These networks are not dedicated for mobile TV, but rather a general IP-based service infrastructure. However, their high achievable data rates qualify them to deliver such rate-demanding services.

#### 1.3.3.1 Wi-Fi

It is the commercial name of the wireless LAN networks that are based on the IEEE 802.11 standard. The system is very popular nowadays especially for indoor networks in homes and workplaces to interconnect devices and to connect those devices to the Internet. Since the first appearance, and for 20 years now, Wi-Fi continued to evolve, with new standards being established like 802.11a, 802.11b, 802.11g, 802.11n achieving maximum rates of 54, 11, 54, and 600 Mbps respectively. 802.11a operates at the 5 GHz unlicensed band and 802.11 b/g operates at 2.4 GHz unlicensed band [125]. The specifications of these standards are summarized in Table 1.3 [125–128].

Table 1.3 – Wi-Fi 802.11 standards and specifications

| Standard | Physical Access        | Max. rate (Mbps) | Band (GHz) | Bandwidth (MHz) | Multiple antenna |
|----------|------------------------|------------------|------------|-----------------|------------------|
| 802.11a  | OFDM                   | 54               | 5          | 20              | SISO             |
| 802.11b  | DSSS                   | 11               | 2.4        | 25              | SISO             |
| 802.11g  | OFDM<br>DSSS           | 54               | 2.4        | 20              | SISO             |
| 802.11n  | SDM/<br>OFDM           | 600              | 2.4/5      | 20/40           | MIMO             |
| 802.11ac | OFDM                   | 346/3466         | 5          | 20/160          | MIMO             |
| 802.11ad | OFDM<br>single carrier | 2160             | 60         | 2160            | MIMO             |
| 802.11ah | OFDM                   | 347              | 0.9        | 1/16            | MIMO             |

A Wi-Fi network can take one of two structures: (i) infrastructure mode; all users are connected to a controlling access point that is connected to a backbone network providing Internet connection, and (ii) Ad Hoc mode where there is no administrator for the network, and users are self-managed and interconnected. In general, the connection between the user and the access point is UC, but the standards also include MC capabilities. Application-Layer FEC (AL-FEC) can be used to protect the Wi-Fi MC against packet losses [129, 130]. Mostly in Wi-Fi networks, the access point is connected to the Internet by one of the numerous backhaul methods like copper wires, fiber optics, or another wireless networks like LTE and WiMAX.

Wi-Fi is one of the widest spread networks in the world, and as mentioned earlier, it is made for general services and not dedicated to mobile TV knowing that the achieved rates are promising for such application, so we will suffice with mentioned details in this regard.

Yet with the high data rates of Wi-Fi comes a major impediment, which is the limited coverage and weakness facing crowded areas. In general, the Wi-Fi range is between a few meters for indoor coverage, and a few tens of meters for the outdoor coverage. This limits the mobility of the connected users. An alternative for the limited WLAN range is the WMAN networks like WiMAX, which will be discussed next.

### 1.3.3.2 WiMAX

Worldwide Interoperability for Microwave Access, or WiMAX, is a set of wireless BB standards that are based on IEEE 802.16. These standards include mainly the physical layer and the MAC layer and cover fixed, portable, and mobile devices. This includes IEEE 802.16-2004 for fixed users, IEEE 802.16e for portable devices, IEEE 802.16a for both fixed and mobile as a complete WMAN, and IEEE 802.16m that was proposed as a 4G candidate [104]. It later used MIMO and reached rates up to 100 Mbps [125].

WiMAX offers high data rate with low latency and wide coverage area, making the technology suitable for real-time applications like video streaming and mobile TV. In addition, WiMAX has the capability to use MC to deliver the same content to a large number of users through what is known as Multicast/Broadcast Service (MCBCS) [131].

The QoS and system performance of the IPTV over WiMAX was studied extensively in the literature. In [132], authors studied the effect of different factors like transmission power, antenna gain, bandwidth, modulation techniques, coverage area and inter-node distances on the QoS of IPTV over WiMAX. Using OPNET simulator, Dager *et.al.* studied the QoS parameters that affect IPTV over WiMAX, like send and received packets per second, end-to-end packet delay, coverage region and number of users [133] concluding that WiMAX supports high coverage region and user density, and that it is a suitable technology to support IPTV. VoD services over WiMAX was also investigated in [134]. The performance of IPTV delivery over WiMAX with respect to key parameters was recently investigated in [135, 136].

|             | TBC  | Cellular UC   | Cellular MC  | Satellite  | WLAN  | WMAN  |
|-------------|--|---|--|--|---|---|
| TBC         |  | More efficient for large number of users                        | Higher delay spread and inter-site distance tolerance                          | More reliable (indoor/outdoor)                   | More efficient for large number of users                        | More efficient for large number of users                        |
| Cellular UC | Wide device spread, wide coverage, personalization, lower transmission power |   | Personalized content, adaptive transmission                                    | Wide device spread, reliability (indoor/outdoor) | Lower latency, wider coverage                                   | Higher mobility, wider coverage                                 |
| Cellular MC | Wide device spread, wide coverage  | Larger number of users, lower interference (SFN)                |  | Wide device spread, reliability (indoor/outdoor) | Lower latency, wider coverage                                   | Higher mobility, wider coverage                                 |
| Satellite   | Higher coverage areas, reliability in disasters and rural areas              | Higher coverage areas, reliability in disasters and rural areas | Higher coverage areas, reliability in disasters and rural areas                |  | Higher coverage areas, reliability in disasters and rural areas | Higher coverage areas, reliability in disasters and rural areas |
| WLAN        | Personalized content, higher rates   | Globally higher capacity (large number of access points)        | Globally higher capacity (large number of access points), personalized content | Higher indoor reliability                        |   | Globally higher capacity (large number of access points)        |
| WMAN        | Personalized content   | Relatively higher speeds  | Personalized content   | More reliable for urban areas and indoor         | Wider Coverage  |   |

Table 1.4 – Advantage of each conventional method over the others (the advantage of each row element over each column element)

Besides evaluating WiMAX for TV services, researchers have been suggesting improvements to the current standards especially in the scheduling in order to enhance the performance. For instance, a scheduling scheme was proposed in [137] as a trade-off between throughput and energy efficiency. Besides, a QoE-aware scheduling and layer selection mechanism was proposed in [138]

To conclude this section, Table 1.4 compares different delivery methods. It particularly indicates the advantage of each row element over each column element.

## 1.4 Hybrid Approach

As can be seen in the previous section, each type of networks has its own limitations, and that was the main motivation for the emergence of the hybrid approach. In a hybrid network, two types of networks jointly operate to deliver the service to the user, while each covers the limitations of the other. Different types of hybrid combinations that are the subject of the study of the scientific community are discussed here.

### 1.4.1 Broadcast/cellular broadband

The two major delivery methods are the BC networks and BB cellular networks. As seen in previous sections, each one from those networks has its own limitation. BC networks can provide the service for an unlimited number of users, but it lacks personalization due to the lack of feedback channel, and are inefficient for low densities. On the other hand, BB networks are well spread and adopted by the public, have high coverage, and can provide personalized services, but have limited spectral resources. The idea of a hybrid BC/BB network emerged to cover the pitfalls of each network alone. As we discussed earlier, mobile TV can be delivered over the mobile network by either UC or MC, and therefore the hybrid combination could be with both as well.

#### 1.4.1.1 Broadcast/unicast

BC/UC is one of the most studied hybrid combinations, due to the widespread of both parties. The collaboration between the two sides could take different approaches like the following:

- *Technical sharing*: Both networks serve the same users, and the collaboration is done in the communication parts, for example, the BC can provide downlink streaming while the cellular network can provide feedback, and so on.
- *Service sharing*: The users are served from both networks, but different services are transmitted through either one.
- *User sharing*: Each network serves a subset of the users or a part of the service area.

In addition to the research work in the literature on such approaches, the opportunities and challenges will be discussed later.

**a) Technical sharing** In technical sharing different collaborating networks run a part of the communication chain. Such hybridization studies started as soon as the cellular network became capable enough of handling the media stream. Barquero *et al.* discussed in [139] a hybrid DVB-centric DVB-H /cellular IP datacast to deliver TV services to mobile users, where expensive DVB-H towers are implemented to serve the crowded parts of the service area, and the mobile network will provide support in covering the rest of the area via UC, and by providing a feedback channel for error reporting and interactivity. A similar approach was proposed in [140], where authors analyzed the error characteristics, this time in T-DMB networks, and suggested a hybrid mechanism where the delivery of the content is still done by the BC side, while the error report and error correction is done by the mobile network. In [141] a hybrid DVB/LTE scheme was proposed, where LTE covers the DVB outage by re-transmitting the lost packets of the BC due to poor power budget for mobile devices. Such a solution is an alternative for the increase of BC power trying to cover the whole service area. The gain in power reduction is also analyzed in the work.

**b) Service sharing** In service sharing each part of the service is delivered by a different network, like different views from different cameras, unified video for all users and specified audio for each.

The collaboration in service sharing can be based on the conditions of the receiver. Abdel-Razzac *et al.* proposed in [142] some practical management algorithms for the reception of SD and HD mobile TV services. The algorithms concentrate on allocating users to either receive HD delivered by the UC network, or SD provided by the BC network, which is the concept they proposed in [143], where the LTE network only serves few HD channels, saving resources for other services and users. The proposed algorithms aim to reduce the ping-pong between HD and SD using a Kalman filter for predictive analysis.

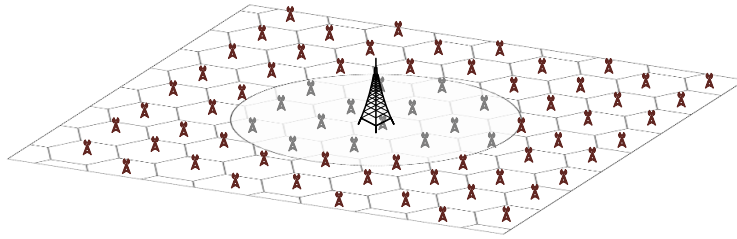


Figure 1.5 – A hybrid BC/cellular network with tower overlay

c) **User sharing** This type of collaboration can be seen as a traffic offload from the resource-limited UC network to the BC network, or an extension to the coverage of the BC to the widely spread mobile network. The studies that included such an approach focused on coverage and capacity optimization.

The impact of the hybrid DVB/LTE on the QoS of live mobile TV was studied in [144], where authors studied the service degradation due to the non-availability of service over LTE bearer, and the effect of traffic load on the duration and frequency of such degradation. The authors also considered a spatially separated hybrid model where each network serves a different part of the service area, typically inside and outside the circle surrounding the DVB HPHT transmitter.

This type of hybrid models was rather popular, and several attempts were made in the literature to find expressions that can estimate its performance. In [145], Bawab *et al.* derived expressions of the ergodic capacity for the coexistence case between LTE cell and DVB broadcasting station, in addition to the Probability Density Function (PDF) of the Signal to Interference Ratio (SIR) for users in both networks. The authors concluded that the global capacity is affected positively by increasing the mobile power, and negatively by the BC power, and that the maximization of mobile and BC capacities are opposite objectives. The authors then studied in [146] the spectral efficiency of such a hybrid network, in the cases of uniform and non-uniform power allocation, and for different spectral overlapping ratios. In both works, the ICI in the cellular network was not considered. In [147], Rother *et al.* investigated the tower overlay scenario, where a DVB-T2 HPHT covers the same area of the BB mobile network working with LTE-A+. Here, both networks operate with the same frequency bands and use future extension frames to deliver the popular content through BC instead of the overloaded BB network.

With different allocation criterion, Cornillet *et al.* proposed in [148] a hybrid DVB-T2/LTE network model, where both BC and mobile network operating over the same service area, and where the contents are transmitted either over the DVB-T2 BC network or by UC over LTE network. The allocation of the content to either network is based on the energy criterion, where the power gain for using each network for a particular service is first estimated. Authors show that for uniform user distribution, a threshold for the number of interested users controls the power efficiency gain and, therefore, the switch between the two systems at each time. Later in [149], authors studied the case of non-uniform user distribution in the service area, taking QoS difference between the two networks into consideration. The authors concluded that a full BC mode or a full UC mode do not always maximize energy efficiency and that the hybrid approach can provide an optimal solution.

Optimizing the collaboration parameters of the hybrid network has also been a subject of research. Fam *et al.* investigated in [150] the optimization of mobile TV hybrid BC/UC network from a planning point of view, where BC HPHT covers an area around it with some radius, and the rest of the users are served through UC by the nearest BS, showing, by simulation, that an optimal radius that maximizes the system throughput does exist. Then the authors provided in [151] a complete theoretical analysis, where a closed form



expression for the optimal BC radius was derived, and analyzing the performance of the proposed model under various conditions. However, in these studies, ICI was not taken into account in the analysis.

With ICI being an important limiting factor in a modern cellular network, the authors took it into consideration in [152] while proposing a hybrid BC/UC network. In the proposed model, a high power high tower covers a certain BC area, and the rest of the network is covered by the BB network. Two scenarios were introduced for frequency band utilization, one includes the use of TV white space, and one includes the sharing of the same band. Stochastic geometry was used to model and analyze the BB network by using a Poisson Point Process (PPP) to model the location of BSs and users. The expression for coverage probability and achievable throughput were also derived and used to optimize the performance in terms of BC zone size. Further analysis of the interference sources and suitable approximations were drawn in [153], and the optimization of network energy efficiency was analyzed in [154]. The model was then generalized in [155] to include numerous broadcasting transmitters distributed in the service area. Expressions of tight upper and lower bounds for coverage probability are derived and used to optimize the hybrid network in terms of system parameters like the density of BC transmitters.

**d) Opportunities, services and practical implementation** The hybridization between the BC network and the cellular network can create opportunities in new business areas and made new services possible. In [156], Lykourgiotis *et al.* discussed the convergence of BC and peer to peer communication within the context of the ROMEO project, which was founded by the European Commission to deliver 3D multi-view context to fixed and mobile devices, with a guaranteed level of QoE. Gil *et al.* proposed in [157] a tourism service that delivers touristic multimedia content to interested tourists using a collaboration between the mobile BB network and the BC network through IP. In [158], Hendrawa *et al.* built a test bed platform application for developing hybrid BC/UC interactive video applications for mobiles, and tested this platform with several cases such a VoD and poling.

Nevertheless, since making profit is the motive behind all the parties participating in such association, the hybrid model should be accompanied by a successful business plan to guarantee the continuity. Taking network infrastructure and operational costs and the subscription revenues into consideration, Authors developed in [33] a strategy for DVB and LTE operators to share profit from delivering mobile TV services for both the case of each network is managed by a separate operator, and the case when both networks are managed by the same operator. Authors used game theory techniques to derive closed form expressions for the profit of each side, and then found the optimal operating point maximizing each side's profit. The hybrid model used is similar to the one in [151] and described above, with increasing the density of LTE BSs to maintain the QoS required.

**e) Challenges and pitfalls** Away from the ICI produced by the mobile network, another kind of interference is particularly important when we are talking about different systems collaborating, which is the inter-network interference, where different networks operating at the same, or close enough, frequency bands could cause interference to each other. In [159], the coexistence between terrestrial BC and LTE deployed in the 470-490 MHz UHF spectrum was studied. The authors investigated the possible interference between DVB and LTE supplemental downlink based on a real case study in Finland, and drew some conclusions about the coexistence, such as indicating the availability of the LTE downlink in the lower UHF band. The coexistence between the LTE downlink and the DVB-T2 with partial overlapping between their spectra was also studied in [160], and the effect of such coexistence was furthermore elaborated in [161].

The other key challenge facing hybrid delivery is the synchronization between the dif-

ferent operating networks. Different parts in the communication chain will introduce some latency on the delivered data stream, and all parts combined producing an overall delay. And when the structure of two chains is different, the overall delay is different, and thus the media delivered will probably be out of synchronization. This is particularly important when parts of the service are delivered to the same user. One example is the application when the video is broadcasted to all users, and personalized audio is delivered by UC to each user, like different commentators over a sports event. To compensate for this effect, a synchronization technique is essential for such services. More on the importance of hybrid synchronization as an essential part of hybrid TV services can be found in [162].

#### 1.4.1.2 Broadcast/multicast

Unlike the UC case, mobile MC has several similarities with the terrestrial BC, and therefore suffer from similar drawbacks like the lack of personalization and channel adaptation. This is one of the reasons why the studies on the hybrid collaboration between terrestrial BC and BB MC are not as popular as hybrid BC/UC networks.

However, as mentioned earlier (and illustrated in Fig. 1.4), MC and BC maintain their discrepancy. BC is initiated by the transmitter, and MC is requested by the receiver. Moreover, since cellular networks acquire channel information for users, MC can use there information to adapt to the general conditions of the users. This is not the case with BC networks where the transmission is blind, and depends only on statistical analysis (worst case adaptation).

Nevertheless, researchers have worked on exploiting the collaboration between terrestrial BC networks and BB MC. Authors in [143] investigated the planning issues of a hybrid DVB-NGH/LTE-eMBMS network aiming at delivering both SD and HD mobile TV streams to users. The cases of full BC, full MC, and cooperative BC/MC were studied, showing that the cooperative schemes in both user offload and service offload scenarios introduce gain in terms of coverage and infrastructure cost. For example the needed number of LTE cells transmitting is reduced by more than 25%.

In [163], authors proposed a common physical layer based on LTE's eMBMS and DVB-T2 as a collaboration mechanism between the two networks. The authors provided the technical requirements and the design description, and proved the feasibility of the proposed approach through computer simulation, hardware implementation, laboratory tests, and field trials. The common physical layer was designed to (i) be scalable, to be able to work with different link sizes from few hundred meters cell to several kilometers BC, (ii) be compatible, to work with different existing technologies deployments like SFN, (iii) take advantage of the BC environment to transmit longer symbols, (iv) use suitable frame structure for point to multipoint transmission, which allows users to extract the necessary content and control information with complications. The specifications included framing, bandwidth control, coverage area extension, interleaving, and sounding pattern.

The collaboration between a BC and a MC network provides a gain in terms of system capacity, tolerance and immunity against users overload. Yet with this gain comes a cost that was inherited from the nature of both parties in such partnership. Both BC and MC are limited when it comes to personalization of content and channel adaptation. In both systems, the broadcasting component should take the worst user condition scenario, and thus loses power and spectral efficiency. This limitation continues with a hybrid model that contains only these networks. Moreover, the scenario that includes multiple networks operating at the same (or near enough) frequency bands can create additional interference between the two networks. These coexistence issues were discussed in [159].

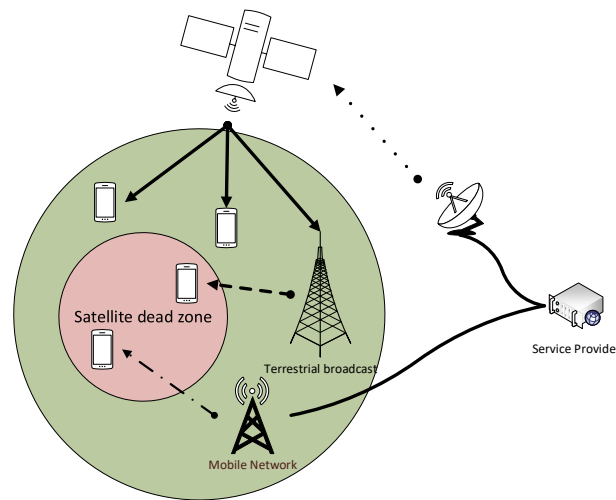


Figure 1.6 – A hybrid satellite/terrestrial broadcast/mobile BB network

### 1.4.2 Satellite/terrestrial and satellite/wireless

Satellite BC was mainly designed to fixed TV sets, which are usually equipped with high gain antennas, like the parabolic antenna, to compensate for the power degradation created by the huge distances. Therefore, it will be problematic for the satellite to deliver services like mobile TV alone, and the need for other "ground" networks becomes essential.

#### 1.4.2.1 Gap filling model

The mobile conditions like shadowing created a challenge for satellite communication in general, and TV delivery in particular, due to the real-time requirements of such service. These challenges highlighted the need to some ground "gap fillers" that help the service in reaching users with no line of sight with the satellite, and help enhance the received SNR, and here is where the hybrid satellite/terrestrial BC network emerged. Two types of gap fillers can be used, fixed gap fillers like terrestrial broadcasting BSs and cellular networks, and mobile gap fillers where the receivers can act as gap fillers for other receivers.

**a) Fixed gap fillers** DVB-Satellite Hand-held (DVB-SH) was one of the first standards that applied this approach. DVB-SH system is made from two components, a satellite component, and a complementary ground component. The complementary ground component can be either a BC transmitter for wide areas where the satellite signal is weak, personal gap fillers for smaller areas, especially indoor applications, or on-board mobile BC units which covers moving vehicles like trains [164].

Away from the official standards, several hybrid models have been proposed and studied. In [165], a hybrid TV delivery system that can provide the service to unlimited number of users is proposed. Such a system is required to have large coverage especially for indoor conditions, have a small infrastructure to reduce cost, and to target the mobile environment while providing comparable quality to that of fixed TV. In the proposed system, satellite high power transmission provides the BC for large areas, while terrestrial broadcasting transmitters cover the areas where the satellite signal is weak due to shadowing or multi-path like the urban areas. Both terrestrial and satellite links use DVB-SH for the radio interface and operate in the S-band. Moreover, the BB mobile network can be used to deliver unpopular services which high efficiency. It can also be used to provide interactivity

with services like VoD. The study also included detailed system architecture and network deployment. An example of such a network is shown in Fig. 1.6.

A similar approach was discussed in [166], where authors analyzed the performance of the hybrid model and derived closed-form expressions for the probability distribution function and the cumulative distribution function of the received SNR. Those expressions were then used to find the outage probability and the achieved symbol error rate. Ruan *et al.* proposed in [167] a hybrid satellite/terrestrial approach where the ground gap fillers operate at the same frequency band as the cellular network. Closed form expressions for the bit error rate and outage probability were also derived starting from the interference caused by the coexistence.

**b) Distributed gap fillers** Distributed or decentralized gap fillers can be useful to reduce the cost of the system by relying on receivers with good reception to provide help to other receivers in getting the stream. To increase the availability in urban areas, and to introduce interactivity to the satellite BC, Cocco *et al.* proposed in [168] a hybrid approach that instead of fixed gap fillers, relays on supporting the mobile devices with networking capabilities so that each user terminal operate as a mobile gap filler. Line of sight mobile terminals will provide a connection through ad-hoc to shadowed users, and two nearby line-of-sight devices can cooperate to create distributed antenna array to enhance capacity. Moreover, in [169] a hybrid model was proposed where users with better channel conditions act like relays to other users while using non-orthogonal multiple access. Expressions for the outage probability and ergodic capacity were derived.

#### 1.4.2.2 Wi-Fi/satellite hybridization

In the mentioned efforts, the satellite transmission, terrestrial BC and sometime the cellular networks were the participating sub-networks in the hybrid network. Nevertheless, other types of networks can be suitable for such merge. Wi-Fi for example can be helpful especially in two scenarios; fixed access points in urban areas, and on board access points for large transportation means.

**a) Fixed access points** Kumar *et al.* added in [170] fixed wireless access points like Wi-Fi to the hybrid satellite system. In their proposed deployment the content is injected to the satellite which will deliver the content to satellite antenna-equipped houses and LTE/5G BSs. The unequipped houses will receive the signal either from the equipped houses through Wi-Fi, or from the BSs via LTE/5G. Authors also formalized some optimization problems for the cost saving of the system and solved these problems using existing and developed optimization techniques. The proposed deployment was then evaluated, showing that it reduces the number of injection points by 85 % and the total cost of the system by 60 %.

In the S-2222 report issued by ITU, an IP based hybrid satellite/terrestrial network was discussed, where the terrestrial part decomposes of either WLAN networks like Wi-Fi, WMAN networks like WiMAX, or cellular networks like LTE. The report proposes a network architecture and a cross-layer protocol model. In the case of Wi-Fi and WiMAX based hybrid networks, the user is served by the wireless network, and the satellite connection role is to provide the service to the access points. These configurations can be used for multimedia streaming for wide areas as detailed in the later report [171]. This approach was also studied in [172] and [173] based on the ITU report. The hybrid satellite/Wi-Fi network for homes was further analyzed in [174] and [175].

**b) On board access points for transportation** Another application for this type of networks is providing the service to large moving transportation means like trains, boats,

and airplanes. Such vehicles usually move out of the reach of conventional methods due to large distances and tunneling. This was investigated in [176], where a hybrid satellite/Wi-Fi model with vertical handover procedure is proposed. In the studied model, a train receiving satellite signal will switch to a fixed Wi-Fi access point when approaching a tunnel. Authors also discussed the challenges that come with the handover, like the sudden change in round trip time, and proposed suitable solutions.

### 1.4.2.3 Performance enhancement

Research have been conducted on enhancing the performance and efficiency of the hybrid network. These enhancements can be applied on each network alone, or on the collaboration scheme of both networks.

**a) Individual enhancements** In general, enhancements to each sub-network can provide a better hybrid network overall. Improvements on either satellite or other wireless networks of course are too broad to be collected in this work, but we mention a couple of examples that can be applied in the hybrid model context. In [177], authors studied the cooperative satellite/terrestrial network, using multiple antennas and beamforming. However in this model, the main sub-network is the terrestrial component, and satellite component covers the areas with weak terrestrial coverage. The system capacity was optimized, and a time division scheme for multiple groups requesting different services was proposed. The proposed scheme provides a reduction in cost with respect to the traditional TV architectures that ranges between 38% and 61% for rural areas, between 47% and 60% for suburban areas, and between 53% and 65% in urban areas. Moreover, a theoretical study on the hybrid network was conducted in [178] for downlink with multiple antennas on the satellite end. An expression for the ergodic capacity was derived for the multi-user scenario while using fixed gain relaying.

**b) Group enhancements** Besides improvements introduced to each network alone, utilizing the diversity of the networks can be helpful to strengthen the hybrid group. Since the mobile terminal is receiving two versions of the signal, one from the satellite transmitter and one from the terrestrial repeater, spatial diversity can be achieved. Arti and Bhatnager approached this in [179, 180] using beamforming and combining based amplify-and-forward relaying. The PDF of the channel and the symbol error rate was also derived. Further studies on the cooperative delay diversity were conducted in [181]. The cooperative approach provided for a fixed Bit Error Rate (BER) a gain between 1 and 5 dB.

### 1.4.2.4 Challenges

Beside the conventional challenges for satellite networks like shadowing and fading, the hybridization with ground components can introduce new ones, like scheduling, resource management, and handover between networks.

The problem of handover and proper resource management was tackled in [182], where authors proposed a scheme based on the IEEE 802.21 standard. Authors in [183] proposed dynamic, context ware bandwidth allocation scheme in the frequency sharing scenario to face the challenges introduced by the mobile nature of the users.

In another context, authors in [184] investigated the effect of hardware impairments like power amplifiers' non-linearity and phase noise on the outage probability in a multi-user scenario. The outage probability was also derived in [185] in a scenario where both the satellite and terrestrial transmission coexist in the same band.

### 1.4.3 Cellular broadband hybrid network

MC or BC are in general efficient when addressing a large number of interested users due to spectrum sharing. This was the main motive behind introducing MC abilities to cellular networks like in eMBMS with LTE. However, the number of interested users in a certain service is fixed neither in time nor in space, and allocating a fixed bandwidth for MC all the time and in all the cells become less efficient. A hybrid UC/MC approach in a cellular network allows the UC and MC components to share transmission time, active cells, connected users or delivered services.

Use cases for the hybrid approach that were considered by 3GPP for the MBMS include the following[186]:

- Some media components are served through UC and others through MC to enhance efficiency.
- Use UC as a step between two MC streams to reduce switching time and enhance QoE.
- Extension of MC coverage through UC.
- Handover popular content to MC.
- Provide interactive TV using UC for uplink.
- Sending targeted content in addition to the main stream like ads and subtitles.

Different collaboration models have been proposed in recent years. Moreover, the performance of such models has been a subject of analysis in the literature. In [187], the performance of the hybrid UC/MC in LTE networks for the cases of media streaming and file transfer was analyzed. It was shown that the average eMBMS data rate increased with the size of the SFN from 1.2 Mbps for 1 cell to 5.8 Mbps for 37 cells, while the maximum rate decreased from 63 Mbps to 5 Mbps for the same range. It was also shown that an SFN of size 5 is the optimal for download time. A model where popular TV channels are delivered through MC and less popular channels are delivered through UC was analytically studied in [188]. The results show that a small number of MC radio bearers is needed for mobile TV.

Several aspects are to be closely considered to optimize the performance of the hybrid approach, like user association, resource management, interference management, and multiple access techniques.

#### 1.4.3.1 User association

In cases where user can receive the service from one of the two networks, a user association scheme become critical. Such schemes create rules on how each user is either linked through UC or served by MC. Araniti *et al.* proposed in [189, 190] an LTE based algorithm for users association to either UC or MC in a hybrid network that serves a user-dense area. The proposed algorithm considers the presence of MC groups with similar channel conditions for MC and represents a trade-off between energy efficiency and performance.

#### 1.4.3.2 Resource management

In modern cellular network, each cell has a pool of available time and frequency resources. In OFDM based transmission for example, a number of resource blocks is available for allocation. Now allocating a number of resource blocks to MC will reduce the available resource blocks for all the other users in that cell. This require careful planning so that the network can serve mobile TV efficiently while maintaining the QoS for other users in the network.

A dynamic resource allocation scheme between the UC and MC in LTE was proposed in [191]. The proposed algorithm tune the number of sub-frames assigned to MC in order to minimize the time difference between UC and MC streams. The case under study was

a main multicasted stream (a sports game for example), with alternative view angles, are served through UC upon request. Another possible case is the delivery of 3-D stream, where the left channel is delivered through eMBMS, and the right channel is delivered through UC to interested users. This work is extended in [192] to include multi-stream multimedia, where the content with high demand is transmitted over MC, and enhancements to the main stream are delivered through UC, like delivering additional layer to interested users via UC to provide HD and UHD quality. An extension to the LTE simulation platform presented in [193] was made to test the proposed BC resource allocation and content adaptation algorithms. The spectral requirements were also analyzed in [194], where an algorithm to adapt the transmission mode to the popularity of the TV channel is proposed in order to minimize the needed bandwidth.

#### 1.4.3.3 Power allocation

Power allocation in the hybrid approach is another main design issue. Transmitting low power for MC users for example can leave some users on the edges out of coverage, while too high transmission power will leak too neighboring cells causing additional ICI. Aiming at maximizing the UC throughput and MC coverage, Hu *et al.* proposed in [195] a power allocation algorithm to guarantee certain QoS threshold for both MC and UC users in a network where BSs transmit both signals over the same band. In [196], two power allocation algorithms for Non-Orthogonal Multiple Access (NOMA) hybrid UC/MC networks were proposed and compared. The first algorithm prioritizes MC users and the second prioritize UC users. Closed form expressions were derived in both cases for the outage probability of the hybrid network.

#### 1.4.3.4 Interference cancellation

Modern cellular networks often use a frequency reuse factor of 1, *i.e.* all cells use the same band for serving their users, which creates ICI. Interference cancellation in this case become essential to maintain an efficient transmission. In [197], authors derived ergodic capacity and the optimal Dirty Paper Coding (DPC) interference pre-cancellation order for a hybrid UC/MC network for the case of (i) single MC and single UC signals and (ii) single MC and multiple UC signals. Applications to big data systems for 5G networks using hybrid UC/MC wireless networks were discussed in [198]. To compensate for the extensive interference caused by reusing the frequency band, null space-based interference cancellation is to discriminate UC from MC.

#### 1.4.3.5 Multiplexing and multiple access

Finally, multiplexing techniques are to be considered especially with such resource-hungry applications. Non-orthogonal techniques gained particular interest in the scientific community. For example, in [199], a hybrid UC/MC cooperation strategy based on NOMA, where both UC and MC overlap in time-frequency, and space. In the proposed scheme, the initial stream is sent for both UC and MC, then a MC user is selected to relay the message to users who didn't receive the initial stream correctly. The power allocation for the relaying transmission could either be fixed or dynamic. The power allocation coefficients and the outage probability were also derived. This idea was extended in [200] by proposing non-orthogonal layered MC multiple access schemes to improve the spectral efficiency, especially for multimedia streaming in 5G networks. The proposed designed transmits the video information in high priority and low priority streams, where regular users near the edges of the cell decode the high priority only, and the users near the transmitter decode both streams to get higher QoS. The users with good channel condition receiving both streams can work as relays for other users.

The non-orthogonal hybrid MC/UC was also studied in [201] and was compared to both UC and MC transmissions by deriving expressions for the probability of coverage, capacity, spectral efficiency, and energy efficiency for each case. Results have shown that non-orthogonal hybrid approach and the MC approach has better performance in all BS density deployments except the case of an extremely dense network. The hybrid approach was studied this time from an energy efficiency point of view in [202]. Two different schemes are considered: DPC and Time Division Multiple Access (TDMA) comparing their energy efficiency performance. Different QoS metrics were used in the study for the hybrid network: Outage probability for MC, and effective capacity for UC. The study concluded that DPC will always outperform TDMA when energy is considered.

In contrary to traditional TDM and Frequency Division multiplexing (FDM), LDM was considered in [203] to increase the coverage of the MC and the throughput of the UC through a non-orthogonal transmission hybrid network. Beamforming and MIMO were used in the analysis in addition to power allocation aiming at minimizing the total power. After tackling these optimization problems under QoS constraints, the study concluded that LDM outperforms TDM, especially in dense deployments.

#### 1.4.4 Cellular broadband/wireless networks

Cellular networks provide mobility and wide coverage area for users and less power consumption as tests have shown in [204], while other wireless networks like Wi-Fi can provide higher rates for smaller areas. A hybrid cellular/wireless network can provide both opportunities for a user. Moreover, the hybrid approach can offload traffic from the limited cellular network into the wireless networks that usually serve a smaller number of users, and have a reliable backhaul. Since most modern mobile phones come with Wi-Fi built-in, it became an obvious and easy method for offloading traffic from the cellular network especially for services that require high bandwidth.

##### 1.4.4.1 Collaboration techniques

Like in other cases of hybrid combination of networks, the collaboration can take different forms.

**a) User sharing, (Switching)** The most popular approach for the hybrid cellular/WLAN is what can be called the switching approach, where the stream goes entirely through either one of the two networks. This kind of collaboration needs a decision making mechanism to associate a user to one of the two networks based on certain criteria. This kind of data offloading for mobile networks like LTE to Wi-Fi and WiMAX networks (among others) is addressed in [205]. In [206], a switching algorithm between LTE and Wi-Fi based on the available bandwidth of each network, and the throughput required by the video stream was proposed.

A comparison between a network-centric (the network optimizes and controls the stream management of each user) and a user-centric (each user controls the stream proportion going through each network) approaches is shown in [207]. The results obtained show that the network-centric approach achieved better throughput but at the cost of increased overhead.

Other allocation mechanisms have been proposed based on optimization criterion. For example authors in [208] proposed a new scheme that combines the data from the user equipment and the data from the BSs, and present them to decision-making mechanism that allocates the user into the network that achieves the best data rate.



**b) Stream sharing** In this kind of hybrid models, different parts of the stream are delivered to a user through different networks. One example of stream sharing was demonstrated in [209] for LTE and Wi-Fi.

Here also the network (or the mobile device) needs a decision making mechanism to control the portions of data going through each sub-network. Recently in [210], an offloading system for video streaming between LTE and Wi-Fi based on game theory is proposed. The proposed mechanism controls the data quantity transmitted through each network in order to maintain the quality of the streamed media. The authors modeled the offloading with a progressive second price auction game, where multiple users share the same LTE resource blocks, proposed a low complexity algorithm to solve the problem and adopted the fountain code for packet reordering and error correction to add flexibility. The authors then proposed in [211] a Software Defined Radio (SDR) based architecture that applies path diversity through LTE and Wi-Fi networks for better traffic offloading while maintaining the transmission stability, and framed the problem as a Nash bargaining game to design a resource allocation scheme.

Other scheduling mechanisms to control the flow through each network based on different priorities have been proposed in the literature. A scheduling system that maximizes the hybrid LTE/Wi-Fi network utility based on Software Defined Networking (SDN) was proposed in [212]. The usage of SDN allows capture information about data flow, which is used then to control the flow scheduling. The battery life of a smartphone device was the main concern in [213] where a request policy for video streaming over LTE/Wi-Fi stream sharing that achieves near-optimal throughput was proposed. The new mechanism show superiority when compared to other schemes such as the Energy-Efficient HTTP adaptive streaming algorithm (EE-HAS).

In a different approach, a new hybrid network model was demonstrated in [214] to deliver massive video streams to users with access to LTE and a single Wi-Fi network. For  $N$  interested users, the LTE will send a portion of the stream to each user ( $\frac{1}{N}$  of the data), and the users will exchange the data over the Wi-Fi network for each to get the whole stream.

#### 1.4.4.2 Coexistence in the unlicensed band

Operators and regulators of cellular networks are in continues quest for new bands to expand the capacity. One solution is to operate over the unlicensed band, where other networks like Wi-Fi operate. In this context, a hybrid cellular/Wi-Fi network faces the hurdle of overcoming the mutual interference between its two sub-networks. In [215], it was shown that the centric nature of LTE resembles the main challenge for the coexistence scenario, and different mechanisms that assure a fair coexistence were discussed and analyzed.

The interference between cellular networks operating in the unlicensed band and Wi-Fi was modeled and characterized in [216], and the performance of the downlink in such a hybrid network was analytically studied in [217].

Different schemes to avoid this interference have been proposed. Most of these schemes organizes the transmission time for each network to achieve minimum collision. A non-collaborative "listen before talk" scheme suggested here to be added to LTE in order to reduce the effect of the coexistence on Wi-Fi, reduces the coverage probability for LTE itself. Equal throughput for Wi-Fi and LTE was achieved with the enhanced listen before talk scheme proposed in [218], and a "joint proportional fair" rate allocation for both networks is proposed and analyzed in [219]. Alternately, Almeida *et al.* suggested in [220] a collaborative, time-sharing mechanism, where Wi-Fi uses the LTE almost blank sub-frames for transmission.

### 1.4.5 Common challenges and pitfalls

As one can observe from the various hybrid combinations, all share some common challenges for different collaboration techniques. Some of these challenges have been tackled before, where suitable solutions have been proposed by researchers. Some of them, however, need more work to enable an efficient delivery mechanism.

When dealing with stream sharing or technical sharing in any type of hybrid networks, the data passes through different communication chains in different networks. To guarantee a certain level of QoE, a capable synchronization technique is needed to ensure that different parts of the stream reach the mobile station within an acceptable time range, which depends on the buffers' sizes and the used queuing system at the receiver.

Other types of collaboration create their own challenges to the designers. In user sharing, the users are divided into subsets based on pre-defined criteria, and each subset is allocated to one of the participating networks. To optimize cooperation, the allocation criteria have to be well defined and well-chosen to ensure maximum performance. Moreover, a user allocation mechanism is needed to effectively use the selected criteria in allocating users to networks. Such a mechanism has to take into account several QoE-related topics, like how often do a handover between networks occurs, how efficient the handover protocol is, and how different the qualities between the networks are.

This brings in another related challenge to this kind of collaboration; handover. In conventional networks, the handover occurs when a mobile station moves from the service of one BS to another. Due to the often homogeneous nature of the transmitters, the effect of the handover is reduced. Yet in a hybrid network, another type of handover occurs, where the switch between networks can take place based on the user association scheme discussed earlier. The heterogeneous nature of the two sides of such a handover requires a carefully designed protocol that does not degrade the QoE by interrupting the viewing experience or changing severely either the quality or the parameters of the reception.

In a different context, the limited available spectrum can project its own limitations on the hybrid wireless networks. From one side, a resource allocation scheme is needed to manage the allocated time and spectral resources to each service, network, and user. An efficient resource allocation system should be service-aware, QoE-aware, and network-aware. This creates the need for other sources for information for the decision making block like channel estimation and content related data acquisition. Certain types of hybridization may allow more than one network to share the same frequency band, which bring us to coexistence.

## 1.5 Summary and motivation

Following the increasing availability of mobile and handheld devices like smartphones and tablets, applications like mobile TV are getting more and more popular, and are predicted to flourish more in the near future. This caused the subject to attract researchers from different disciplines. In this work, the mobile TV technology is discussed. The opportunities provided by the new service, which motivate the industry to invest in it, are detailed, and the challenges driving the scientific research community to find solutions are examined. Nowadays, there exist different types of networks that are capable of delivering the service to mobile devices, such as terrestrial BC, cellular BB, satellite, and wireless local (and metropolitan) area networks. Each of these networks can provide an added value, but at the same time has some pitfalls. To overcome these limitations, hybrid approaches, with combinations of the conventional delivery methods have been proposed. In this chapter, the conventional methods were presented, with the challenges facing each, and the work done by the research world to surmount these challenges. Then, different feasible hybrid

Table 1.5 – Hybrid networks summary

| Hybrid network              | Type                           | Collaboration                               | Challenges and proposed solutions   |
|-----------------------------|--------------------------------|---|---|
| Broadcast/Cellular          | BC/UC                          | Technical sharing [139–141]                 | Inter-Network Interference [159–161] .<br>Sync [162].<br>Handover [143]. Coverage [152]           |
|                             |                                | Service sharing [142, 143, 148, 149]        |   |
|                             |                                | User sharing [144, 146, 147, 151, 152, 155] |   |
|                             | BC/MC                          | Service offload [143]                       | Personalization.<br>Channel adaption.<br>Coexistence [159].                                       |
|                             |                                | User offload [143]                          |   |
| Common Physical layer [163] |                                |   |   |
| Satellite                   | Sat/TBC/Cell.<br>(Gap fillers) | Centralized gap fillers [165–167]           | Hardware impairments [184].<br>Handover [182].<br>Resource management [183].                      |
|                             |                                | Distributed gap fillers [168, 169]          |   |
|                             | Sat/Wi-Fi                      | Fixed AP [170–172, 175]                     |   |
|                             |                                | On-board AP [176]                           |   |
| Cellular Broadband          | UC/MC                          | Service sharing [188, 191, 192]             | Handover. ICI [197, 198].<br>User association [189, 190].<br>Resource management [191, 193, 194]. |
|                             |                                | User sharing (range extension) [186]        |   |
|                             |                                | Technical sharing (stream filling) [186]    |   |
| Cellular/wireless           | Cell./Wi-fi                    | User sharing (switching) [205, 206]         | Coexistence in unlicensed band [215, 220],<br>Handover.   |
|                             |                                | Stream sharing [209, 214]                   |   |

approaches were detailed, with a review of the work presented in the literature on how to optimize these models, and the gain they can provide.

With the exploding demand on higher quality service, and the emergence of new technologies in the industry (3D, VR, 8K), these hybrid approaches can be the solution to the future challenges with limited energy and spectral resources. Currently, extensive work is being done on the development of new standards especially in 5G and new broadcasting networks. Moreover, new projects aiming to provide BB connection to the whole globe via a massive satellite network are being developed.

Nevertheless, the hybrid approach will still be a clear choice to enhance performance and efficiency in future networks. The common challenges discussed in the context of this work are issues that the scientific community needs to tackle. This includes the optimization of handover protocols, user association algorithms, and resource management schemes.

Moreover, due to the increasing need for the already limited spectrum available for wireless networks, coexistence between networks in the frequency domain, especially collaborating networks can be an efficient solution to better exploit the available bandwidth. However, additional management schemes are needed to handle the coexistence to reduce inter-network interference.

In addition to the technical challenges, other aspects of the mobile TV service is to be further studied. For instance, the development of new technologies both in the networks and in the devices necessitate a better understanding of the users' behavior, especially the readiness to adopt these new services. Quantifying what users need can immensely help researchers and developers answer to the requests of the future market.

As we can see, this domain is very broad, from the verity of network types, to the numerous challenges facing each. In this thesis, we will focus on two types of these networks: TBC, and cellular BB networks. We will try to exploit the capabilities of a hybrid between these two types for the delivery of linear services. This will be done for different operation modes for BB like UC and MC. These networks will be deeply analyzed using suitable mathematical tools to provide methods for estimating the performance of such deployments. Besides, some of the challenges facing such networks are tackled, like coexistence in time and frequency, resource allocation, and energy efficiency.

## Chapter 2

# A preface on stochastic geometry and the used hybrid network models

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To simplify the reading of the rest of the thesis, we introduce in this chapter some concepts and definitions that will be used throughout this work. As mentioned earlier, stochastic geometry tools are used to model, simulate, and analyze cellular networks. In the first section, we will present a small introduction to stochastic geometry and its applications in wireless networks. In particular, we discuss PPP and how it can be used to model the cellular network, in addition to an insight into the properties and the analysis procedure.

Different hybrid TBC/BB cellular network models are presented in the thesis. In the second section of this chapter, we present the basics of these models. This includes the descriptions, the assumptions made, and the definitions needed for each of the deployments. In the third section, we define the main evaluation metrics that are used to assess the performance of the network models analyzed here.

## 2.1 Stochastic geometry for wireless networks

Following the spread of cellular networks, the famous grid model, with its hexagonal shaped cells, was used to model the deployment of the network. However, such an idealistic approach lacks accuracy in describing a real-world network, especially in areas with different densities. Moreover, the analysis of this model was rather complicated. As an alternative, stochastic geometry emerged as a flexible mathematical tool that allows a tractable network analysis. In this section, a brief introduction to stochastic geometry and its application in wireless networks is presented.

### 2.1.1 Introduction

#### 2.1.1.1 What is stochastic geometry?

One can define stochastic geometry as the area of mathematics that provides methods and models to analyze the properties for stochastic points in multidimensional space. These random point patterns are called point processes, and they are the most important spacial objects stochastic geometry deals with. Stochastic geometry aims at describing a random collection of points (nodes) in one or more dimensions, and derive statistical properties for such collections. Moreover, in stochastic geometry, a function of the point process can be conditioned on the position of the point, or averaged over all possible positions. Another target is estimating a statistical model for an existing set of points [221].

#### 2.1.1.2 Applications

Stochastic geometry, being a flexible and tractable tool, found applications in a wide spectrum of disciplines, from astronomy [222] and material science [223], to image analysis [224] and industrial planning [225].

Nevertheless, wireless networks remain one of the most popular applications of stochastic geometry. It has been used to model and analyze different types of networks, like ad hoc networks [226] and WLAN networks [227]. Moreover, several studies have approached the cellular networks from a stochastic point of view. Both heterogeneous networks [228] and homogeneous networks [229] have been subjects to such studies.

The aim of the stochastic approach in a random network is to find statistical figures that reflect the performance of this network. Different types of point processes are being used to model different types of deployments, based on the correlation between the characteristics of the network and that of the point process.

### 2.1.2 Point processes

#### 2.1.2.1 What is a point process?

A point process is a collection of points randomly distributed in a certain space of one or more dimensions. Haenggi defined the point process in [221] as the countable random collection of points that resides in some measure space.

Without going into deeper details, a simple point process can also be defined as follows [230]:

Let  $\mathbb{N}$  be the set of all sequences  $\vartheta = \mathbb{R}^d$  satisfying:

1. Finite: Any bounded set  $A \subset \mathbb{R}^d$  contains finite number of points,
2. Simple: for any two elements  $x_i$  and  $x_j$ ,  $x_i \neq x_j$  if  $i \neq j$ , *i.e.* no two points are located at the same position,

A simple point process in  $\mathbb{R}^d$  is a random variable taking values in the space  $\mathbb{N}$ .

Based on this definition, a point process, denoted by  $\Theta$  can be simply defined as follows:

$$\Theta = \sum_i \delta_{x_i} \quad (2.1)$$

where  $\delta$  is the Dirac measure. An instance of the point process  $\Theta$  is denoted by  $\vartheta$ , and the number of points in a set  $A$  is denoted by  $\Theta(A)$

### 2.1.2.2 Properties and characterizations

Here we define some of the important characterizations and properties of the point processes in general. These are the probability distribution, the void probability, and the stationarity.

- Distribution: A point process can be characterized first by its distribution. This is the probability of finding  $n$  points in certain space  $A$ :  $\mathbb{P}[\Theta(A) = n]$ , where  $\mathbb{P}$  denotes the probability.
- Void probability: A point process can be defined by its void probability. Void probability is the probability to find zero points in a certain space  $A$ :  $\mathbb{P}[\Theta(A) = 0]$ . Two point processes are said to be equivalent if both have the same void probability.
- Stationarity [231]: A point process  $\Theta = \{x_n\}$  is said to be stationary if the translated process  $\Theta_x = \{x_n + x\}$  has the same distribution as  $\Theta$  for all values of  $x$ .

### 2.1.2.3 Examples of point processes

Different distributions (or null probabilities) will produce different point processes. Here are some examples:

- Binomial: A binomial point process is formed of  $n$  points uniformly distributed in a compact set  $W$ .
- Poisson point process: A PPP is formed of a random number of independent points over possibly infinite space. It will be detailed in the next part.
- Matern hard-core: Matern hard-core is the result of thinning another point process such as a PPP. Thinning is the removal of some points of the original point process to comply with certain constraints like the minimum distance between points.
- Cluster process: A cluster process is a result of performing clustering over another point process like PPP (Poisson Cluster Process). Clustering is replacing each node of the original point process with a cluster of nodes. The new cluster process is the union of all the clusters.
- Determinantal: The distribution of a determinantal point process is the determinant of a function called a kernel.

The nature of the application determines which point process is the appropriate one to be used for modelling. An example of a PPP and a Matern hard-core process is shown in Fig. 2.1.

## 2.1.3 Primer on Poisson point processes

A PPP is one of the most used point processes in studying wireless networks. Derivatives of the PPP are also used, *i.e.* like after thinning or clustering.

### 2.1.3.1 Definition

The PPP can be defined as follows [221]: A PPP  $\Theta$  with intensity  $\Lambda$  is a point process in  $\mathbb{R}^d$  such that:

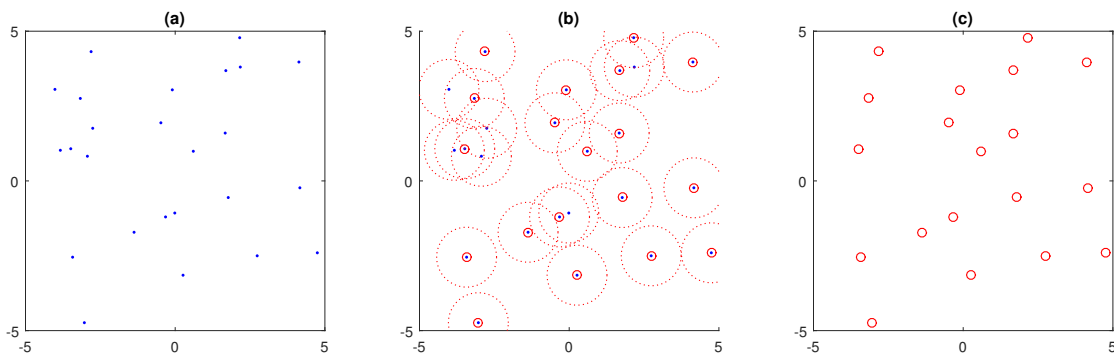


Figure 2.1 – An example of thinning a PPP to obtain a Matern hard-core process. The original PPP is shown in (a), the thinning process is shown in (b) where a minimum distance of 1 is used, and the final Matern hard-core process is shown in (c).

- for each compact set  $A \subset \mathbb{R}^d$ ,  $\Theta(A)$  has a Poisson distribution with mean  $\Lambda|A|$ , where  $|\cdot|$  denotes the  $d$  Lebesgue measure, or the  $d$ -dimensional volume. The distribution then becomes:

$$\mathbb{P}[\Theta(A) = k] = \exp\left(-\int_A \Lambda(x)dx\right) \frac{\left(\int_A \Lambda(x)dx\right)^k}{k!} \quad (2.2)$$

- for any disjoint bounded sets, say  $A_1, A_2, \dots, A_i$ , the number of points in the sets  $\Theta(A_1), \Theta(A_2), \dots, \Theta(A_i)$  are independent random variables.

Notice that the intensity of the point process is variable, and depends on the location. A special case of the general definition is when the density is constant over the whole space. This produces what is known as the homogeneous or uniform PPP.

A uniform PPP  $\Theta$  with intensity  $\lambda$  is a point process in  $\mathbb{R}^d$  such that:

- for each compact set  $A$ ,  $\Theta(A)$  has a Poisson distribution with mean  $\lambda|A|$ . The distribution can then be as follows:

$$\mathbb{P}[\Theta(A) = k] = \exp(-\lambda|A|) \frac{(\lambda|A|)^k}{k!} \quad (2.3)$$

- for any disjoint bounded sets, say  $A_1, A_2, \dots, A_i$ , the number of points in the sets  $\Theta(A_1), \Theta(A_2), \dots, \Theta(A_i)$  are independent random variables.

Since in the homogeneous PPP the distribution is the same over the whole space, the uniform PPP is said to be stationary, and therefore can be identified by the unique intensity value  $\lambda$ . Throughout this thesis, whenever a PPP is mentioned, it refers to the uniform PPP in  $\mathbb{R}^2$ .

### 2.1.3.2 Properties

Based on the definitions above, here are some properties of the homogeneous PPP:

- Density: The density of a uniform PPP is  $\lambda$ , which is also equal the expected value of the distribution in a set (Area in  $\mathbb{R}^2$ )  $A$ , normalized to the volume of the set:

$$\lambda = \frac{\mathbb{E}[\Theta(A)]}{|A|} \quad (2.4)$$

where  $\mathbb{E}$  denotes the expected value.

- Stationarity: As mentioned above, a homogeneous PPP is stationary since the distribution is fixed over the whole space, *i.e.*  $\Theta = \{x_n\}$  and  $\Theta_x\{x_n + x\}$  have the same distribution.

- Void probability: The void probability is the probability of finding no nodes in a certain set. By substituting  $k$  with 0 in (2.3), the resulting void probability is given by:

$$v_A = \mathbb{P}[\Theta(A) = 0] = \exp(-\lambda|A|) \quad (2.5)$$

- Conditioning: For a uniform PPP  $\Theta$ , if a restriction is made on  $\Theta$  to a compact set  $S$ , and the number of points of  $S$  is conditioned to be exactly  $n$ , then  $S$  is considered to be a binomial point process with  $n$  points.

### 2.1.3.3 Distances

In a uniform PPP, the distances between nodes are also considered as random variables. In our application, these distances are of special interest. The distribution of the distances between nodes in an infinite PPP has been found in multiple pieces of work.

The probability distribution function of the distances  $r$  from a node to its  $i^{\text{th}}$  closest neighbor in a PPP with intensity  $\lambda$  in the  $d$ -dimensional space can be expressed as follows:

$$f_{R_i}(r) = \exp(-\lambda c_d r^d) \frac{d(\lambda c_d r^d)^i}{r \Gamma(i)} \quad (2.6)$$

where  $c_d r^d$  is the volume of the  $d$ -dimensional ball of radius  $r$ , and  $\Gamma(\cdot)$  denotes the gamma function. The reader can refer to [232] for the proof.

Moreover, the joint distribution of the distances can also be of good use. The joint distribution of the distances to the closest  $n$  BSs in a PPP in  $\mathbb{R}^2$  with intensity  $\lambda$  is given by [233]:

$$f(r_1, r_2, \dots, r_n) = e^{-\lambda \pi r_n^2} (2\pi\lambda)^n r_1 r_2 \dots r_n \quad (2.7)$$

These distributions or some special cases of them will be used in the proofs in the thesis.

### 2.1.3.4 Operations over a PPP

Here, we mention a couple of operations over a PPP; sum and product using some famous existing theorems. Note that we will limit the theorems to the case in hand, which is the uniform PPP, knowing that the theorems cover more general cases. We will also exclude the proofs for compactness. Interested readers can refer to [221, 231] for more details.

- Summation (Campbell's theorem): Campbell's theorem state that the expected value of a summation of a function  $f(x) : \mathbb{R}^d \rightarrow \mathbb{R}$ , over a uniform PPP  $\Theta$  of density  $\lambda$  is given by:

$$\mathbb{E} \left[ \sum_{x \in \Theta} f(x) \right] = \lambda \int_{\mathbb{R}^d} f(x) dx \quad (2.8)$$

- Product (Probability Generating Functional (PGFL)): For a a uniform PPP  $\Theta$  of density  $\lambda$ , the expected value of a product of a function  $f(x) : \mathbb{R}^d \rightarrow \mathbb{R}$  over  $\Theta$  can be calculated as follows:

$$\mathbb{E} \left[ \prod_{x \in \Theta} f(x) \right] = \exp \left( -\lambda \int_{\mathbb{R}^d} (1 - f(x)) dx \right) \quad (2.9)$$

## 2.1.4 Cellular network modeling and analysis

Wireless networks are one of the most well-known domains for applying stochastic geometry. First, stochastic geometry provides a tool for modelling, by representing the positions of nodes in a wireless network with one of the point processes. This applies for



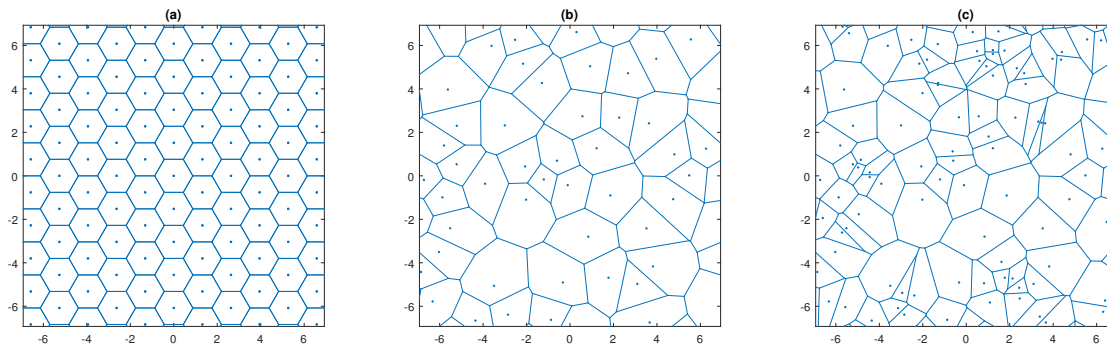


Figure 2.2 – A comparison between the grid model in (a), the PPP in (c), and what an actual network will look like in (b)

fixed nodes like BSs, and mobile nodes (users). Second, starting from the characteristics, properties, and related theorems, stochastic geometry can help find some performance metrics of the modelled network. In our work, we focus on the modelling and analysis of the cellular network, using a homogeneous PPP.

#### 2.1.4.1 Modeling and accuracy

Conventionally, several models have been used to represent the cellular network. The most well-known form was the grid model, with its famous hexagonal-shaped cells. Even though this model was easy to use and provided acceptable accuracy that enables the evaluation of new techniques, it suffers from some major flaws. For instance, the grid model is over-simplistic, and does not emulate an actual deployment. This affects the estimated coverage regions and interference impact. Moreover, this model lacks supporting mathematical tools, partially due to the high correlation between its points, and it is difficult to scale with different parameters.

Random spatial models can provide an alternative solution. In particular, a PPP has been proposed as a possible candidate [226, 228, 229, 234]. First, a PPP bears more resemblance to the actual deployment, allowing it to emulate a real network more accurately. Moreover, stochastic geometry, with all the mathematical tools provided, allows more detailed studies and allows some insight on the performance under a variety of conditions. An example of the grid model, the PPP network model, and a resemblance of an actual network are shown in Fig. 2.2. In the examples given, and throughout the thesis, Voronoi tessellation under Euclidean distance measure is used to mark the boundaries of the cells.

The users, moreover, can be modeled with an independent PPP. However, since the PPP is assumed to be stationary, a single user at the center of this homogeneous process can act as a typical user in a large-enough network. This can simplify both the simulation and the analysis if no other component is affecting the network.

Generally, in such network models, the user receives transmitted signals from all the operating BSs. Based on the network architecture, this signal is counted as either useful signal or an interference signal. The analysis can then be done taking several topics into consideration. This will be discussed next.

#### 2.1.4.2 Analytical analysis

To analyze a network using stochastic geometry tools, a few points have to be defined first:

- Power model: Several power models have been proposed during the past decades. One of these models is the path loss model, in which the received power for a

receiving node is given by:

$$\mathcal{P}_R = \mathcal{P}_T h r^{-\alpha} \quad (2.10)$$

where  $\mathcal{P}_R$  and  $\mathcal{P}_T$  denote the received and the transmitted power respectively. Moreover,  $h$  is a random variable that represents the randomness of the channel,  $r$  is the link distance, and  $\alpha$  is the path loss exponent. Note that the distribution of  $h$ , based on the nature of the channel, is essential in the analysis process.

- Transmission mode: By transmission mode we mean either a Multi Frequency Network (MFN) or an SFN. In an MFN, the receiver receives power from a single BS, namely the serving BS. All other transmitting BSs at the same frequency band at the same time are sources of interference. Contrarily, in an SFN, multiple BSs cooperatively transmit the same signal. In that case, more than one signal is considered to be a useful signal.
- Frequency reuse: In cellular networks, an operator can divide the available bandwidth into multiple sub-bands, and each cell operates at one of those sub-bands to reduce ICI. The number of sub-bands is called the reuse factor, and it affects the number and distribution of the interfering BSs with a user.
- Duty cycle: The duty cycle is the portion of the time where a certain BS is transmitting. This also affects the average interference power at the receiver.

Based on the selected parameters, and using the properties of the point process, with the tools provided by stochastic geometry, performance metrics can be derived. Probability of coverage and the ergodic capacity are two of the main measures, which will be defined among others in the coming sections.

The last point in this section is the interference. ICI is a very important factor in cellular network, and it is commonly the limiting factor. This follows the selection of the frequency reuse factor, which is often selected to be one. And because of the stochastic nature of the network model, the statistics of the interference become more important in the analysis, especially since the SINR is the basis of most of these analytic studies. In particular, the Laplace Transform (LT) of the interference is of a special significance. This importance came from the fact that in many derivations, using stochastic geometry theorems, the expected value of the exponential of the interference is needed, knowing that the LT can be defined as follows:

$$\mathcal{L}_I(s) = \mathbb{E}_I[e^{-sI}] \quad (2.11)$$

### 2.1.4.3 General expressions of the LT of the interference

In most of the analytical analysis, the complexity of the LT terms determines the complexity of the final expressions. A general term can be found for several cases of the LT and stated in Theorem 2.1.

**Theorem 2.1.** *The general expression for an interference sourced from a homogeneous PPP  $\Omega$  of density  $\lambda$ , starting from a distance  $R$  from the user, where the interference is given by:*

$$I = \sum_{\Omega \setminus b} P h d^{-\alpha} \quad (2.12)$$

and where  $\Omega \setminus b$  is the set of all BSs excluding the serving BS,  $P$  is the transmission power,  $h$  is the channel with exponential distribution of rate  $\rho$ ,  $d$  represents the distance, and  $\alpha$  denotes the path loss exponent, is given by:

$$\mathcal{L}_I(s) = \exp\left(\frac{-2\pi\lambda R^{2-\alpha} s P}{\rho(\alpha-2)} {}_2F_1\left(1, 1 - \frac{2}{\alpha}; 2 - \frac{2}{\alpha}; \frac{-sP}{\rho R^\alpha}\right)\right) \quad (2.13)$$

where  ${}_2F_1(\cdot)$  is the Gaussian hyper-geometric function.

*Proof.*

$$\begin{aligned}
 \mathcal{L}_I(s) &= \mathbb{E}_{\Omega,h}[\exp(-sI)] \\
 &= \mathbb{E}_{\Omega,h}[\exp(-s \sum_{n \in \Omega} Ph_n d_n^{-\alpha})] \\
 &= \mathbb{E}_{\Omega,h}[\prod_{n \in \Omega \setminus b} \exp(-sPh_n d_n^{-\alpha})] \\
 &\stackrel{(a)}{=} \mathbb{E}_{\Omega}[\prod_{n \in \Omega \setminus b} \mathbb{E}_h[\exp(-sPh_n d_n^{-\alpha})]] \\
 &= \mathbb{E}_{\Omega \setminus b}[\prod_{n \in \Omega \setminus b} \frac{1}{1 + \frac{sP}{\rho d^\alpha}}] \\
 &\stackrel{(b)}{=} \exp\left(-\lambda \int_{\mathbb{R}^2} \frac{1}{1 + \frac{\rho d^\alpha}{sP}}\right) \\
 &\stackrel{(c)}{=} \exp\left(\frac{-2\pi\lambda}{\alpha} \int_{R^\alpha}^{\infty} \frac{x^{\frac{2}{\alpha}-1}}{1 + \frac{\rho}{sP}x} dx\right)
 \end{aligned} \tag{2.14}$$

where (a) follows the independence of the point distribution and the channel effect, and (b) follows the PGFL of the product over a PPP as stated in (2.9). The integral in (b) is applied on the whole 2-D plane starting at a distance  $R$  from the serving point. This results in (c) where the coordinates are switched to polar system, and by substituting  $x = d^\alpha$ . Now using equation 3.194 from [235] that states that:

$$\int_w^\infty \frac{x^{u-1}}{(1 + \beta x)^v} dx = \frac{w^{u-v}}{\beta^v(v-u)} {}_2F_1\left(v, v-u; v-u+1; -\frac{1}{\beta w}\right) \tag{2.15}$$

to solve the integral,  $\mathcal{L}_I(s)$  is reduced into (2.13) ■

The result expression introduced in Theorem 2.1 is fairly simple, and includes a single tabulated special function that can be quickly evaluated numerically.

## 2.2 Hybrid models used

In this section, we will present the basic network models that will be studied in this work. As mentioned before, the thesis considers the delivery of linear services to the users through a user-sharing hybrid BC/BB network. Nevertheless, this kind of networks can operate under several conditions depending on the selection of the following factors:

- Operation mode of the cellular network: The BB cellular network is capable of delivering the service either by UC or MC.
- BC network deployment: Two cases are examined, the case with a single TBC transmitter at the center, and the case with multiple transmitters distributed over a larger area.
- User allocation strategy: Allocating users to either BC or BB network is done through one of two considered strategies: Zone-based allocation, and SINR-based allocation.

In the following chapters, combinations of these cases are used to investigate the performance of the hybrid approach. Here we will state the basic features of these models.

## 2.2.1 Broadband cellular networks model

The cellular network is a common component for all the hybrid models that will be investigated, therefore we will start by describing briefly the modeling and operation of this network. As we stated earlier, cellular networks normally operate in UC mode but can turn on MC mode if needed. We also discussed in Chapter 1 the pros and cons of each one. In the following chapters, both modes are used.

### 2.2.1.1 Common features

The cellular network is modeled by a homogeneous PPP in  $\mathbb{R}^2$  with a constant density. A user in the network will be served by the nearest BS, creating a Voronoi tessellation. In all the presented and proposed models, it is assumed that all the base stations are always transmitting, *i.e.* a duty cycle of 1. Therefore, at all times, a receiver, randomly placed in the service area, will receive signals from all the BSs in the network. The received power from each BS is estimated according to (2.10). Yet the power being useful or interference depends on the planning and operational mode.

Besides, the cellular network is assumed to be transmitting in Orthogonal Frequency Division Multiplexing (OFDM). Each user is allocated a number of Resource Block (RB)s. A RB is defined as the smallest time-frequency resources that can be allocated to a user in a network. In OFDM, a RB is made of a set of subcarriers in frequency, for 1 frame in time. For example, an LTE RB is made of 12 subcarriers, 15 kHz apart, making a total of 180 kHz bandwidth, for a slot of 0.5 ms. To simplify the analysis, and unless otherwise indicated, the spectrum is assumed to be flat for all the allocated RBs per user.

### 2.2.1.2 Unicast operational mode

In unicast mode, the BS allocates a number of RBs in the downlink to each user in the cell. These RBs are unique for each user, *i.e.* no two users share the same RB. This enables personalized transmission for each user, but limits the total number of served users.

It is assumed that the network operates with a frequency reuse factor of 1, *i.e.* all BS transmit at the same frequency band. This will significantly increase the ICI but will allow more efficient usage of the available spectrum. Based on the two assumptions of the duty cycle and the frequency reuse factor, the serving BS will be the only source of useful power, and all the other BS will always be sources of interference.

Since a user in the network is served by the closest BS, and since the network is modeled by a uniform PPP, the distribution of the distance to the closest point in the process is of special interest. By setting the space to  $\mathbb{R}^2$ , and the neighbor index to 1 in (2.6), the expression is reduced to:

$$f_R(r) = 2\pi\lambda r \exp(-\lambda\pi r^2) \quad (2.16)$$

Fig. 2.3 shows an example of a receiver with three transmitters, the closest BS provides the useful signal (green), while the others transmit interference power (red).

### 2.2.1.3 Multicast mode and SFN

In multicast mode, the BS allocates some RBs to be shared in the downlink by multiple users. This eliminates the advantage of personalization, but relatively reduces the spectral cost on the network. Moreover, the MC mode is usually accompanied by an SFN deployment. In such a deployment, all the received signals from BSs of the same SFN can be considered as useful power depending on their time of arrival.

To be specific, in an OFDM-based transmission in an SFN deployment, multiple signals arrive at the receiver side with some delays to each one. In OFDM, The guard intervals are usually used to insure that multiple arriving copies of the same signal do not interfere

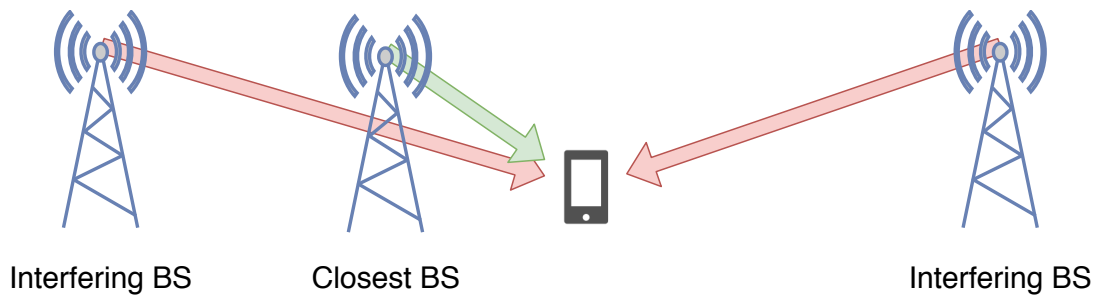


Figure 2.3 – An illustration on a UC signal reception

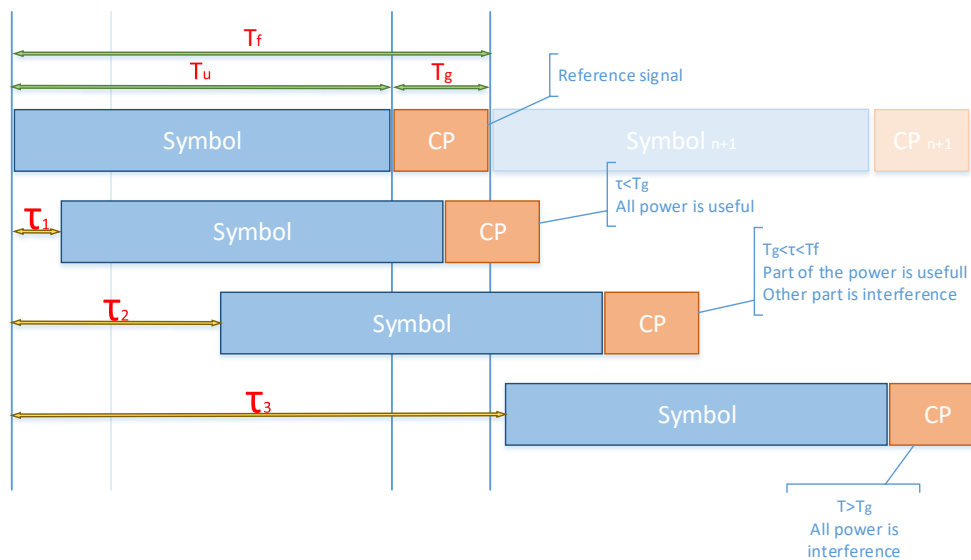


Figure 2.4 – An example of four received signals, the first is the reference signal, and the other three fall under the three mentioned categories

with one another. Now supposing that the receiver is synchronized with the first received signal (usually from the closest BS), the other received signals will arrive with a delay that falls under one of the following three cases:

- The delay is less than the guard interval of the symbol: in this case, all the signal power is counted as useful power.
- The delay is larger than the guard interval of the signal, but less than the symbol time: in this case, part of the received power is counted as useful power, and the rest is counted as interference.
- The delay is larger than the symbol duration: in this case, the received signal is completely out of phase, and all the power is counted as interference.

An example of this effect is illustrated in Fig. 2.4. In this figure, the delay is denoted by  $\tau$ ,  $T_u$  is the useful OFDM symbol duration,  $T_g$  is the cyclic guard interval, and  $T_f = T_u + T_g$  is the total symbol duration. The portion of the useful power and the interference power is quantified in some models like in [236], and will be detailed in Chapter 5.

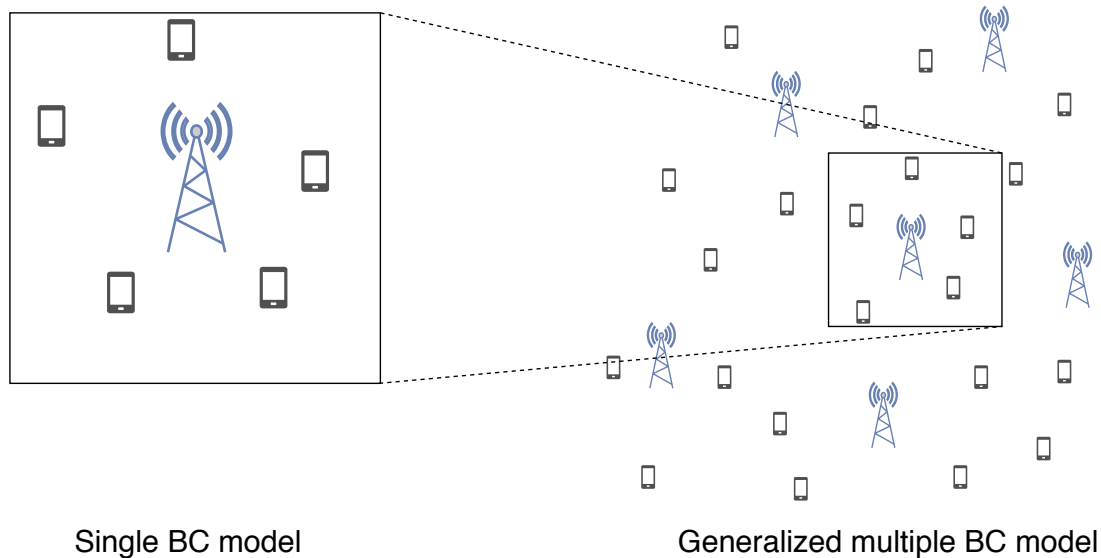


Figure 2.5 – The single BC deployment and the generalized multiple BC deployment

## 2.2.2 Broadcast network deployments

Two cases for the BC network deployment are considered here. The first is made out of a single BC HPHT serving surrounding users. The second consists of multiple BC HPHT operating as an SFN.

### 2.2.2.1 Single BC transmitter

The single BC transmitter is fairly simple. A HPHT located at the center of the service area transmits a signal with high power at a certain frequency. All interested users tune in to receive the service. These users are modeled by a PPP. The path loss model is used to estimate the received power at the receiver side as in (2.10). In the lack of outside interference, the network becomes noise limited, and the Signal to Noise Ratio (SNR) is used to evaluate the performance.

A user is said to be covered by the BC network if the SINR (or SNR) are greater than a certain threshold. In this case, the HPHT-receiver channel achieves the required capacity, and the receiver achieves the data rate of the transmission. It is important to note that beyond the required capacity, enhancing the signal quality will not change the data rate on the receiver side. The transmission is fully controlled by the transmitter, and therefore unified for all served user regardless of the channel conditions, as long as the SINR threshold for the reception is reached.

### 2.2.2.2 Multiple BC transmitters

The multiple BC transmitters is a generalization of the single BC transmitter model. It can be seen as zooming-out from the transmitter to a much wider area, where multiple BC HPHTs are deployed. This is illustrated in Fig. 2.5.

The Broadcast Transmitter (BCT)s are modeled by a PPP with a low density. Normally, random processes are not the first option to model the positions of the BCTs, considering that their locations are often well planned. However, since the studied area is large, with varying geographic and demographic nature, a random process can be accurate enough for representing the network. Moreover, future networks -as the model presented herein- can be more dense, which increases the accuracy of the random process modeling. This also brings in the advantage of making the analysis tractable.

The coverage, capacity, and rate have the same conditions as for the single BCT case. The only difference is in the SINR calculations. As mentioned, the BC network operates in an SFN mode, which means that a user will receive multiple versions of the signal from several BCTs with a certain delay. This is similar to the case of MC in cellular network discussed earlier. Yet in the BC deployment the inter-site distances are much larger. To simplify the analysis we re-categorize the received signals from HPHTs other than the closest one into two categories:

- Signals from near HPHTs: These signals will arrive with some delay, and therefore will provide partially useful power.
- Signals from far HPHTs: These signals will arrive with a much larger delay, so it will be counted as interference. However, due to the enormous distances and the path loss, the received interference power due to these signals is negligible compared to the noise and other interference sources

Therefore, we used a coefficient that will be multiplied by the total received power from other HPHTs. This coefficient is between 0 and 1, and it depends on the transmission settings like the Cyclic Prefix (CP), and the density of the transmitters.

### 2.2.3 Hybrid broadcast/broadband model

Starting from the BB and BC models in the two previous parts, we define a user sharing hybrid BC/BB network model. In such a hybrid model, a user will be allocated to either network based on some criteria, which results in a user allocation scheme. Two of these criteria are discussed here: The users' relative position, and the received signal quality.

It is assumed that all users have the capability to receive both BC and cellular BB transmission, with a priority to BC. It is also assumed that both networks are transmitting the same service at the whole time (we are considering the time of the live feed), *i.e.* a duty cycle of 1 for both networks.

#### 2.2.3.1 Zone-based user association

In the zone-based scheme, the criterion for the user allocation is the position of the user with respect to the BCT. The HPHT is associated with a circular zone, namely BC zone, within which all users are considered to be BC users. As a result, the users set, which are as mentioned modeled with a uniform PPP with a certain density, are divided into two subsets: BC users and BB users. Moreover, all the cellular BSs within the BC zone are not transmitting the service, and thusly are not taken into account in the analysis.

This type of user association scheme is useful for scenarios where a certain area needs to be covered, like the surrounding of some event, or a small city. Moreover, the zone-based allocation is essential in the scenarios where the BC and BB networks coexist in the frequency domain. This will be detailed in the coming parts.

It is important to note that such a scheme is network controlled. The network, having all the information about users' locations will set the BC zone, and add each user to one of the two subsets based on the position.

To optimize the network performance, the network controller can calibrate the zone size, or in our case the zone radius. Increasing the zone radius will quadratically increase the portion of the BC users. Increasing the number of BC users enhances efficiency by reusing the spectrum for multiple receivers. But due to the upper limit transmission power a HPHT can tolerate, enlarging the zone will add users that are supposed to be served by BC, but out of the transmission's reach.

### 2.2.3.2 SINR-based user association

In the SINR-based scheme, a user receives both BC and BB transmissions, and based on the quality of the signal, *i.e.* the received SINR, the receiver decides to join either networks, with a priority for the BC network. The decision-making mechanism will be as follows: if the received SINR from the BC is enough to well decode the transmission, then the receiver will go forward and use the BC transmission (join the BC users subset), else, the user will connect to the BB network, and ask for the service from there.

In contrary to the zone-based user allocation, the SINR-based scheme is receiver-controlled (or at least partially controlled). The receiver decides to join either network. This reduces the overhead on the network control but reduces the possibilities to have coexistence between the two networks like in the zone-based model, where a marginal geographic separation can be achieved.

### 2.2.3.3 Coexistence scenarios

The available spectrum for wireless networks is getting more and more crowded. Moreover, the expensive price tag on the licensed spectrum is high and increases the cost of the network. One solution is to use the same spectrum for multiple networks, on what is called coexistence in frequency.

Coexistence in frequency adds extensive interference to both networks, but significantly reduces the needed bandwidth, which improves the global spectral efficiency of the network. In our zone-based hybrid network models, we consider two cases for used frequency bands:

- Shared spectrum scenario: In the shared spectrum scenario, both networks use the same frequency band for transmission, thus coexist in frequency. In this case, cellular BSs will act as sources of interference for BC users, and the HPHTs will act as interference sources for cellular users. This coexistence can take place in TV White Space (TVWS) or any other band.
- Dedicated spectra scenario: In dedicated spectra, each network operates on its own frequency band, and therefore no interference occurs between the two networks.

Note that for the zone-based scheme, in both cases of frequency usage (with and without coexistence), the BSs within the BC zone are set to operate at a different frequency than the BSs outside the BC zone. This allows the coexistence to be possible in the first place. On the other hand, in the SINR-based scheme, only the dedicated spectra scenario is used.

To optimize the performance of the SINR-based hybrid network, and since the allocation is user-centered as we mentioned, the network can control the BC transmission power to control the portion of the users that will join the BC network. Rising the BC transmission power can increase the coverage and the spectral efficiency, but after a certain point, a large increase in power will not be reflected in an equal increase in served users, and the power efficiency starts to drop.

## 2.2.4 Summary of the hybrid combinations

In this section, the different options of the parts that form the hybrid network are detailed. The BB network can operate either in UC or MC SFN modes, the BC network can have a single HPHT or multiple HPHT deployments, and the user allocation can be zone-based or SINR-based.

In the rest of this thesis, several hybrid network models are presented. Each one of these models is a combination of choosing one of the two options available for each of the three questions: What mode is the BB model is operating in? What is the BC network deployment? And what is the user allocation used? This is illustrated in Fig. 2.6. In each model, one ball of each color will be chosen to enter the hybrid mix. This figure will be repeated at the beginning of each proposed model while highlighting the chosen options.



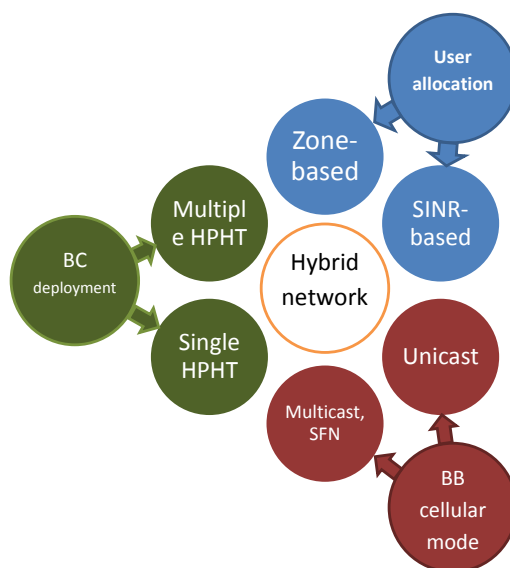


Figure 2.6 – The different options and combinations of the studied hybrid network

## 2.3 Evaluation metrics

In this section, we define the main assessment metrics that will be used throughout the thesis to evaluate the performance of different network models and proposed algorithms.

### 2.3.1 SINR

SINR is a measure of signal quality. By definition, it is equal to the total received useful power divided by the total received interference power plus noise, and can be expressed as follows:

$$SINR = \frac{\sum_i \mathcal{P}_{R_i}}{\mathcal{P}_N + \sum_j \mathcal{P}_{R_j}} \quad (2.17)$$

where  $\mathcal{P}_N$  is the noise power, and  $\mathcal{P}_R$  are the received power as defined in (2.10).

### 2.3.2 Probability of coverage

The probability of coverage considered here is the SINR-based coverage, *i.e.* the probability that a user in the service area achieves an SINR not less than a certain threshold  $\mathcal{T}$ . It can be written as follows:

$$P_c = \mathbb{P}[SINR > \mathcal{T}] \quad (2.18)$$

The probability of coverage can also be interpreted as the portion of the service area that is covered by the network, or the portion of the users that are covered as well.

### 2.3.3 Ergodic capacity

The capacity is the maximum achievable rate of a certain link, and it is defined based on a modification of the original Shannon's limit. Instead of the signal to noise ratio, SINR is used to calculate a link's capacity. And with SINR being a stochastic process, the ergodic capacity can be defined by:

$$\mathcal{C} = \mathbb{E}[\log(1 + SINR)] \quad (2.19)$$

The capacity itself will not measure the actual rate a user will have, but it gives an indication on the average QoS in the network. Moreover, as can be seen in the definition, the metric is normalized by the bandwidth, so it can be seen as a measure of the spectral efficiency.

### 2.3.4 Power efficiency and power utilization

Besides the user-centered metrics mentioned above, power efficiency is an important factor when evaluating a network's performance. Achieving a high coverage probability by transmitting an immense amount of power will create a set of problems; technically for the transmitters, economically for the operator, and environmentally for the surrounding population. Two metrics related to the networks ability to invest the transmitted power are used in this thesis.

The first metric is power efficiency, which is the ratio of the network capacity and the transmitted power:

$$\eta_P = \frac{\sum_i \mathcal{C}}{\sum_j \mathcal{P}_{T_j}} \quad (2.20)$$

Note that the sum over  $i$  is over all the users, while the sum over  $j$  is over all the transmitters.

The second metric is power utilization, which is the average needed transmitted power to successfully serve a single user. We define the power utilization as follows:

$$\mathcal{U}_P = \frac{\mathbb{E}[\sum_j \mathcal{P}_{T_j}]}{\mathbb{E}[\sum_i \zeta_i]} \quad (2.21)$$

where  $\zeta_i$  is a binary variable that is equal to 1 if user  $i$  is connected and equal to 0 otherwise.

### 2.3.5 QoE

QoE is a measure of the users' satisfaction with the service provided. The personal nature of this metric has driven most of the research done on QoE to be subjective. It depends on the opinion of users often collected through a questionnaire or a survey. This complicated the task of evaluating the QoE in the design phase. As we mentioned in Chapter 1, several models were proposed to map QoS results, which are easier to evaluate objectively, into QoE.

We consider in this work two of the proposed models in the literature, with some modifications on the used QoS measures. The first was proposed in [30]. Using the exponential interdependency of quality of experience and quality of service hypothesis, QoE is linked to the packet loss ratio. This resulted in the following expression:

$$Q_1 = 3.01 \exp(-4.473 (1 - p)) + 1.065 \quad (2.22)$$

where  $p$  is the packet loss ratio. In our work, we replaced the packet loss ratio by the probability of coverage, based on the assumption that a packet is lost when the receiver is out of coverage (SINR less than the required threshold for that packet). The first QoE metric can be written as follows:

$$QoE_1 = 3.01 \exp(-4.473 (1 - P_c)) + 1.065 \quad (2.23)$$

The second QoE measure was recently proposed in [31]. This score is more general and it is equal to a weighted sum of three sub-scores: freezing score, bitrate switch score, and video bitrate score. The original model is given by:

$$QoE_2 = Q_v + \varepsilon Q_f + \varpi Q_s; \quad (2.24)$$

where  $Q_v$  is the rate score given by:

$$Q_v = \ln(\text{rate}) \quad (2.25)$$

$Q_f$  is the freezing score defined as:

$$Q_f = -\frac{\exp(-1 + t_f)}{1 + \exp(-1 + t_f)} \quad (2.26)$$

where  $t_f$  is the freezing time. A freezing time is the time where the capacity is below the minimum rate required for a video stream. Finally  $Q_s$  is the change in video quality category, and it is defined as:

$$Q_s = \frac{-\nu |cat_k - cat_{k-1}|}{cat_k} \quad (2.27)$$

where  $cat_k$  and  $cat_{k-1}$  are the quality categories for current and previous time slots, and,  $\varepsilon$ ,  $\varpi$  and  $\nu$  are all positive weight coefficients.

To adapt the proposed mapping to our QoS metrics, we slightly modified each one of the sub-scores. For instance, the bit rate in the rate score is substituted by the total user capacity ( $W \log_2(1 + SINR)$ ), where  $W$  is the allocated bandwidth. Moreover, since the freezing time is directly related to the time where the signal quality is less than the required threshold,  $t_f$  is replaced by the coverage probability. Besides, to classify the video quality into categories, we used a table presented by mLAB in [237] that links the video resolution to the minimum required data rate for proper reception. The constants in this model are set as follows:  $\varepsilon = 8$ ,  $\varpi = 1$ , and  $\nu = 2$ . Note that due to the complicated evaluation of some scores, this metric is only evaluated through simulations.

### 2.3.6 Energy efficiency

The last metric we considered is energy efficiency or energy utilization. It is a measure of the networks' competence of using electrical feed power while delivering the service. This metric is close to the power utilization factor discussed earlier, but with one major difference: The power consumption of a BS or a HPHT is considered instead of the transmission power. It is defined as follows:

$$\mathcal{U}_E = \mathbb{E} \left[ \frac{\sum_j \mathcal{E}_j}{\sum_i \zeta_i} \right] \quad (2.28)$$

where  $\mathcal{E}_j$  is the energy consumption of the  $j^{\text{th}}$  transmitter. Remember that  $\zeta_i$  is a binary variable indicating whether a user is connected or not. To estimate the energy consumption of a BS and a HPHT, we used the model proposed in [238]. This model was designed for LTE BSs, but due to the lack of appropriate model for TBC HPHTs, the same model is used for both cases, but with different parameters. The power consumption of a BS is given by:

$$\mathcal{E} = N_{TRX}(\mathcal{P}_0 + \Delta_p \mathcal{P}_{out}) \quad (2.29)$$

where  $\mathcal{P}_{out}$  is the output power of the PA,  $\mathcal{P}_0$  represents the power consumption with no power transmitted, and  $\Delta_p$  is the load dependent power consumption slope.  $N_{TRX}$  is the number of transmit/receive chains. The reference also provides a table of numerical values for those constants depending on the nature of the BS being a macro cell, micro cell, femto cell...

## 2.4 Summary

In this chapter, we presented a small introduction to stochastic geometry and how it can be used in the context of studying wireless networks. It was shown that using point processes to model the cellular networks adds accuracy to the representation, and provides mathematical tools to conduct a tractable analysis. Such analysis provides expectations for major performance metrics such as SINR, probability of coverage, capacity, QoE, and efficiency. Those metrics are defined here, and major indications of each are stated.

Moreover, we presented the basics for the major models for the networks that are used in the thesis. In the cellular network, both UC and SFN MC modes are discussed. Besides, in the BC, both the single and multiple BCTs are detailed. Finally, the two used user allocation schemes, zone-based and SINR-based, are presented, with the possible coexistence scenarios.

In the following chapters, we will use different combinations of BB operation modes, BC deployments, and user allocation techniques to explore the capabilities of such hybridization. Moreover, for each combination, we will use different sets of simulation settings and system parameters to reveal the characteristics of each model, and help highlight the optimal deployment in each case.



# Chapter 3

## Hybrid BC/UC network

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The first type of hybrid BC BB networks that will be studied is the one with single BCT, and UC mode for the BB network.

This chapter is divided into two parts. In the first part the zone-based hybrid model is presented and analyzed. The second part includes the SINR-based model analysis. In both sections, the analysis includes modeling the network, setting the main parameters and coexistence scenarios, deriving expressions for coverage probability and other performance metrics, and numerically optimize the hybridization.

### 3.1 Zone-based hybrid network

In this section, we introduce the hybrid BC/BB network with single HPHT, UC mode for the cellular network, and zone-based user allocation for the collaboration scheme (See Fig. 3.1). Such a model can be useful for targeted areas like the surrounding of a sports arena, a venue of a musical or political event, or just a small city. Besides, this deployment, as we'll see later, allows the coexistence between the BC and BB networks with some arrangements.

In contrary to the previous works in [150, 151, 239] where a grid model was used to model the BB network, a PPP is used. Moreover, our work considers the ICI which has not been considered in the literature for such kind of deployments. The main contributions of this section could be summarized as follows:

- Proposing two scenarios for the user-sharing zone-based hybrid network. The first scenario, namely Shared Spectrum Scenario (SSS) states that both the BCTs and

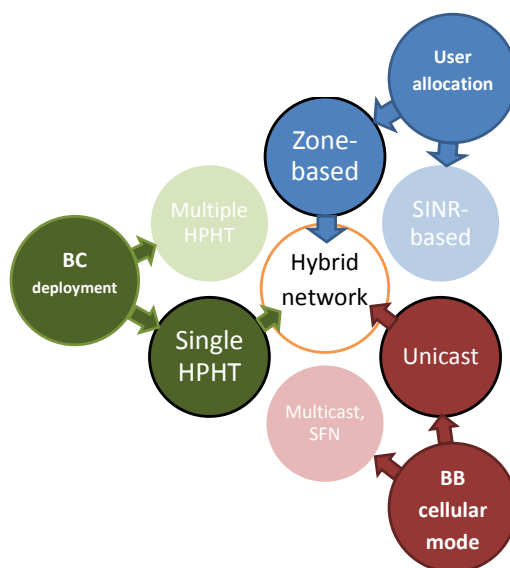


Figure 3.1 – The combination of the first studied model: zone-based single BC/UC hybrid network

BB BSs operate over the same frequency band. The second scenario, namely Dedicated Spectra Scenario (DSS), states that the BB BSs outside the BC zone operate at a different frequency such as the TVWS. The two scenarios are compared over their efficiency.

- Using stochastic geometry tools in modeling the BB network, compared to the conventional grid model used in the literature.
- Taking ICI into consideration as a limiting factor for the BB network in the analysis, and as a major influence in the performance of the hybrid network.
- Deriving analytical expressions that estimate the coverage probability for the BC users, BB users, and any user in the network. A similar procedure was made for the average capacity. The average metrics were studied as well as the metrics that correspond to the relative positions of the users.
- Numerically optimizing the hybrid network in terms of the key design parameters, particularly the BC zone radius and the BB network density.

### 3.1.1 The hybrid system model

The model follows the general description stated in Chapter 2 with the choices illustrated in Fig. 3.1. We consider linear TV<sup>1</sup> serviced to users, distributed uniformly over a wide circular service area, resembling a typical metropolitan area, as shown in Fig. 3.2. The BC zone is assumed to be occupying the center of the considered area.

#### 3.1.1.1 General description

The hybrid network consists of two Orthogonal Frequency Division Multiplexing (OFDM) systems:

1. A BC system composed of a single HPHT site located at the center of the service area.

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1. This model is suitable for any linear service that needs to be delivered to large number of users.

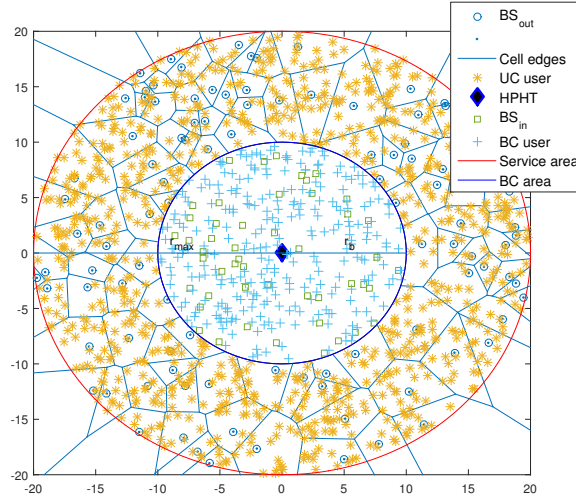


Figure 3.2 – An example of a service area, with 20 km radius, and 10 km broadcast radius

2. A mobile BB UC system composed of a number of BSs uniformly distributed over the service area.

It is assumed that all the BB BSs transmit with the same power  $\mathcal{P}_U$ , and the HPHT transmits with a power  $\mathcal{P}_B$  such that  $\mathcal{P}_B > \mathcal{P}_U$ . The BSs are located according to a PPP  $\Phi$  with a density  $\lambda_{BS}$ . The users are distributed according to another, independent, PPP  $\Psi$  with a density equal to  $\lambda_U$ .

As mentioned in Chapter 2, it is also assumed that a user has the ability to connect to either system depending on its position. If the user is within the coverage area of the HPHT, *i.e.* the distance to the HPHT is less than the BC zone radius  $r_b$ , then the user will be connected to it. Else, the user will be outside the BC region hence connected to the nearest UC BS. This will result in a disk with broadcast users inside, and a Voronoi tessellation for UC users. An example of this network is shown in Fig. 3.2. For both transmission systems, the standard power loss propagation model is used as in (2.10), and it is assumed that all transmitter/receiver couples use SISO antennas.

The HPHT will operate over a frequency  $f_D$ . The cellular BSs outside the BC zone will operate on one of two frequencies based on the selected scenario that will be discussed shortly. The operational frequency for the BSs inside the BC zone is  $f_L$ . It is different from the frequencies used by the BSs outside the BC zone in both scenarios and they will not delivering the service. Hence, they will not be interfering with the system and have no particular interest, and therefore will not be further discussed.

### 3.1.1.2 Shared spectrum scenario

In this scenario, the UC operates at two frequency bands: (i)  $f_L$  for BSs within the BC zone as mentioned earlier, and at (ii)  $f_D$ , the same frequency used by the HPHT, for BSs outside the BC zone. This is briefed in Fig. 3.3a. This arrangement will result in the following points:

- The ICI originated from BSs inside BC zone to outside UC users is avoided. In other words, we consider that the BSs inside the BC area are not delivering the TV service. This schematic is indeed interesting in the sense that it reduces the total interference received by a UC user. The average level of interference for UC users depends on the ratio of broadcast zone area to the service area.
- BC users fed by the HPHT suffer from interference from BSs outside the BC zone. However, this interference is variable depending on the distance from HPHT and can be significantly small for non-edge users.



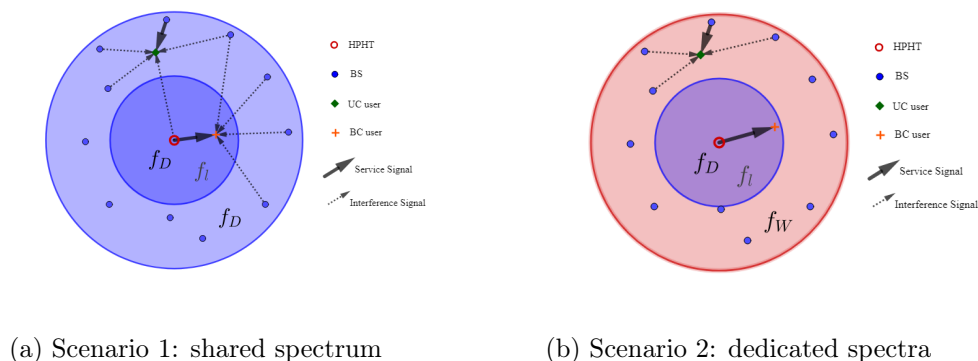


Figure 3.3 – Different proposed scenarios

- BB users fed by the UC BSs suffer from interference from the HPHT even if they are out of the BC coverage. Indeed, these BB users are receiving signals from both BSs and the HPHT at the same frequency. However, the level of interference perceived by an UC user from a HPHT depends on the distance in between. Particularly, it can be significantly small if (i) the broadcast area is large enough, and the power of the HPHT is properly designed or (ii) the UC receiver is far from the HPHT. It is worth mentioning that the signals received from the HPHT and the BSs are not synchronized hence a UC user will consider the HPHT signal as interference.
- The interest of this scheme is clearly seen in terms of bandwidth allocation as inside and BB users (of the broadcast area) with TV services are operating at the same frequency. This will be at the detriment of additional interference level as explained above.

Based on these points, we can now define the SINR for BC and UC users. Starting from the pathloss model as stated in (2.10), the SINR for BC users is given by:

$$S_{BC} = \frac{\mathcal{P}_B g r_v^{-\beta}}{\mathcal{P}_N + I_{U/B}} \quad (3.1)$$

where  $\mathcal{P}_B$  is the transmission power by the HPHT,  $g$  represents the random channel effect between the HPHT and the user, including shadowing and fading. Assuming Rayleigh fading for all our channels,  $g$  is an exponentially distributed random variable with rate  $v$ .  $r_v$  is the distance between the HPHT and the BC user,  $\beta$  represents the path loss exponent for BC,  $\mathcal{P}_N$  is the noise power, and  $I_{U/B}$  denotes the interference on an BC user from outside BSs. The interference is the sum of the powers of the received interfering signals. For a user in the broadcast area operating at frequency  $f_D$ , all BSs in the UC area are considered as interferers, then  $I_{U/B}$  is given by:

$$I_{U/B} = \sum_{j \in \Phi'} \mathcal{P}_U h_j r_{s_j}^{-\alpha} \quad (3.2)$$

where  $\mathcal{P}_U$  is the transmission power of UC BS and  $r_{s_j}$  is the distance between a user and interfering BS  $j$ . The random channel effect between BS  $j$  and the user is denoted by  $h_j$ , which is also assumed to be exponentially distributed with a rate  $\mu$ .  $\Phi'$  is the set of all BSs outside the BC zone, which is a subset of the original PPP  $\Phi$ .

On the other hand, the SINR for UC users is given by:

$$S_{UC} = \frac{\mathcal{P}_U h r_l^{-\alpha}}{\mathcal{P}_N + I_{U/U} + I_{B/U}} \quad (3.3)$$

where  $r_l$  is the distance between the serving BS and the user,  $\alpha$  represents the path loss exponent for UC,  $\mathcal{P}_N$  is the noise power, and  $I_{U/U}$  and  $I_{B/U}$  denote the interference on a BB user from BSs and the HPHT respectively. The interference on a UC user from interfering BSs is given by:

$$I_{U/U} = \sum_{j \in \Phi/b} \mathcal{P}_U h_j r_{q_j}^{-\alpha} \quad (3.4)$$

and from the HPHT transmitter is given by:

$$I_{B/U} = B_R \mathcal{P}_B g r_d^{-\beta} \quad (3.5)$$

where  $\Phi/b$  denotes the set of all BSs in the UC area excluding the serving BS for user under consideration.  $r_{q_j}$  is the distance from a UC user and the interfering BS  $j$ , and  $r_d$  is the distance from a UC user to the HPHT transmitter.  $B_R$  is the ratio between the Bandwidth (BW) of the BC and that of UC. Since in general, the BW of the BB network is higher than that of the BC where both are overlapping, the ratio can be written as follows:

$$B_R = \min(1, \frac{W_{BC}}{W_{UC}}) \quad (3.6)$$

where  $W_{BC}$  and  $W_{UC}$  are the BW of BC and UC respectively. This term is added to count only the overlapping spectrum when calculating the total interference power. If the BW allocated to the UC user is less than the BW of the BC, all the interference power is counted. Else, a portion of the received BC power is counted as interference.

### 3.1.1.3 Dedicated spectra scenario

The dedicated spectra scenario differs from the first scenario in the spectrum allocation. In this scenario, the BC HPHT operates at frequency  $f_D$ , UC BSs inside the BC zone operate at  $f_L$  (always irrelevant to the study herein), while the BSs outside the BC zone operate at  $f_W$ , a sub-band of the TV white space, where  $f_L$ ,  $f_W$  and  $f_D$  don't overlap. This scenario is summarized in Fig. 3.3b.

This will result in the following points:

- Compared to shared spectrum scenario, ICI for UC is significantly reduced due to the usage of three different frequencies.
- Contrarily to Scenario 1, BC users, fed by the HPHT will only be limited by path loss and noise, and will not suffer from any interference.
- UC users fed by the BB BSs suffer only from ICI produced by BSs outside the BC zone.
- The interference is limited at the expense of additional bandwidth allocation.

Starting from the assumptions in this scenario, the SNR for BC users is given by:

$$S_{BC} = \frac{\mathcal{P}_B g r_v^{-\beta}}{\mathcal{P}_N} \quad (3.7)$$

Similarly, the SINR for UC users is given by:

$$S_{UC} = \frac{\mathcal{P}_U h r_l^{-\alpha}}{\mathcal{P}_N + I_{U/U}} \quad (3.8)$$

The difference from shared spectrum scenario is that  $I_{U/B}$ , the interference from the BSs on BC users, and  $I_{B/U}$ , the interference from the HPHT on UC users, are both eliminated from the equations.

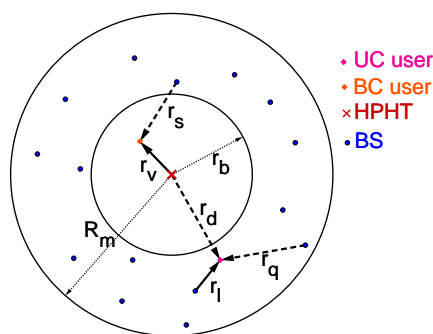


Figure 3.4 – Important distances used in the model

### 3.1.1.4 PDFs of main link distances

Three distances shown in figure 3.4 are particularly important in the analysis that will follow: (1) the distance  $r_d$  between the UC user and the HPHT transmitter, (2) the distance  $r_v$  between a BC user and the center, and (3) the distance  $r_l$  between a UC user and its serving BS. Since both BS and users positions are random, those distances are random as well, and their distributions are needed in the derivation of coverage and capacity. The distributions will be a function of the BC zone radius  $r_b$ , and the service area radius  $R_m$ .

We start with  $r_d$ . The Cumulative Distribution Function (CDF) of  $r_d$  is given by:

$$\begin{aligned}
 F_{r_d}(R_d) &= \mathbb{P}[r_d < R_d] \\
 &= \frac{A(R_d, r_b)}{A_{UC}} \\
 &= \frac{\pi R_d^2 - \pi r_b^2}{\pi R_m^2 - \pi r_b^2} \\
 &= \frac{1}{R_m^2 - r_b^2} R_d^2 - \frac{r_b^2}{R_m^2 - r_b^2}
 \end{aligned} \tag{3.9}$$

where  $A(R_d, r_b)$  is the area limited by the two concentric circles of radii  $R_d$  and  $r_b$ . The PDF of  $r_d$  will then be:

$$\begin{aligned}
 f_{r_d}(r_d) &= \frac{dF_{r_d}(r_d)}{dr_d} \\
 &= \frac{2}{R_m^2 - r_b^2} r_d, \quad r_d \in [0, R_m]
 \end{aligned} \tag{3.10}$$

Using similar procedure, the PDF of  $r_v$  can be found to be as follows:

$$f_{r_v}(r_v) = \frac{2}{r_b^2} r_v, \quad r_v \in [0, r_b] \tag{3.11}$$

Note that both distributions are linear and independent of the density of the BSs. The last distance distribution to be calculated is the one of  $r_l$ , the distance from a UC user to the serving BS.

If a BS is serving a user at a distance  $r_l$ , and starting from the definition that a user is served by the closest BS, then one can conclude that there is no BSs with a distance less than  $r_l$  to that user. And since the network is modeled by a PPP, the probability of that happening (finding no nodes within a certain area) is equal to the void probability given in (2.5). Therefore, the Complementary Cumulative Distribution Function (CCDF) of  $r_l$ ,

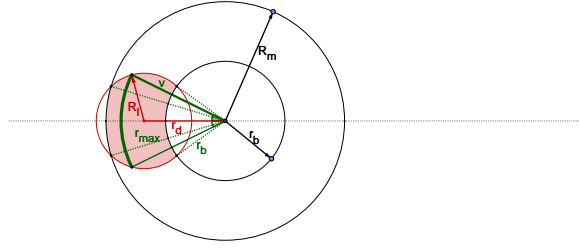


Figure 3.5 – Calculation of area limited by the circle of radius  $R_l$ , service area circle, and broadcast area circle

which is the probability of  $r_l > R_l$  is equal to the void probability that is equal to  $\lambda A$ , where  $A$  is the area highlighted in Fig. 3.5. Now, the CDF of  $r_l$  is as follows:

$$\begin{aligned}
 F_{r_l}(R_l) &= \mathbb{P}[r_l < R_l] \\
 &= 1 - \exp(-\lambda_{BS} A) \\
 &= 1 - \exp(-\lambda_{BS} \int_{\max(r_b, r_d - R_l)}^{\min(R_m, r_d + R_l)} 2\theta v \, dv) \\
 &= 1 - \exp(-2\lambda_{BS} \int_{\max(r_b, r_d - R_l)}^{\min(R_m, r_d + R_l)} \arccos\left(\frac{v^2 + r_d^2 - R_l^2}{2v r_d}\right) v \, dv)
 \end{aligned} \tag{3.12}$$

Then, the PDF of  $r_l$  is given by:

$$f_{r_l}(r_l) = \frac{d}{dr_l} \left[ \exp\left(-2\lambda_{BS} \int_{\max(r_b, r_d - r_l)}^{\min(R_m, r_d + r_l)} \arccos\left(\frac{v^2 + r_d^2 - r_l^2}{2v r_d}\right) v \, dv\right) \right] \tag{3.13}$$

**Approximation of the PDF of  $r_l$ :** (3.13) is very complicated to express and interpret, and therefore will be hard to be used in the sequel. This exact expression is needed in the following cases:

- The density of the BSs is extremely low, so that the cell sizes are comparable to the large BC zone.
- For the users on the BC/BB border.
- For the users on the edge of the service area.

In all of these cases, the BC zone disturbs the user arrangement around the BS. Now since the first case is impractical, and the number of users on the border is relatively small, and since the service area edge is hypothetical for calculation purposes, an approximation with the conventional PDF stated previously in (2.16) can be made. Thus the PDF of  $r_l$  could then be reduced to:

$$f_{r_l}^*(r_l) = 2\pi\lambda_{BS} r_l \exp(-\pi\lambda_{BS} r_l^2) \tag{3.14}$$

It can clearly be seen that even though the approximation is much simpler than the exact value, it completely ignores the relative position to the center and the broadcast radius  $r_b$ .

In the sequel, this approximation will be used when necessary, like in the estimation of coverage probability for BC users in (3.15) and (3.33) and UC users in (3.24) and (3.35), where both the exact formula and the approximation could be used.

### 3.1.2 Probability of coverage

The first evaluated performance metric is the coverage probability. Herein, we derive analytical expressions for the probability of coverage of BC users, UC users, and the probability of coverage of any user at any position. Since shared spectrum scenario and dedicated spectrum scenario have slight differences in the initial and final expressions, the derivation for the first scenario is detailed, while in the second scenario, only the final result is stated with indication on the differences. Note that the procedure of the derivation is standard, and only model-related adjustments differ.

#### 3.1.2.1 Shared spectrum scenario

##### a) Coverage for BC users

We start with the coverage probability for BC users. Starting from the definition of the probability of coverage in (2.18), and using the expression of the received SINR for BC users defined in (3.2), the coverage probability for a BC user is given by:

$$P_{cBC} = \frac{2}{r_b^2} \int_0^{r_b} \exp\left(\frac{-vT_{BC}r_v^\beta \mathcal{P}_N}{\mathcal{P}_B}\right) \mathcal{L}_{I_{U/B}}\left(\frac{vT_{BC}r_v^\beta}{\mathcal{P}_B}\right) r_v dr_v \quad (3.15)$$

The complete proof is in Appendix B.

As can be seen in (3.15), the expression for the coverage probability is straightforward. The complexity of the calculation depends on the complexity of the LT expression inside the integral. The next step is to evaluate that LT term.

Let  $s = \frac{vT_{BC}r_v^\beta}{\mathcal{P}_B}$ ,  $\mathcal{L}_{I_{U/B}}(s)$  is calculated as follows:

$$\mathcal{L}_{I_{U/B}}(s) = \exp\left(-2\lambda_{BS}\left(\int_0^{R_m-r_v} \frac{\pi r_s}{1 + \frac{\mu r_s^\alpha}{s\mathcal{P}_U}} dr_s + \int_{R_m-r_v}^{R_m+r_v} \frac{\arccos\left(\frac{r_v^2+r_s^2-R_m^2}{2r_v r_s}\right)}{1 + \frac{\mu r_s^\alpha}{s\mathcal{P}_U}} r_s dr_s\right.\right. \\ \left.\left. + \int_0^{r_b-r_v} \frac{\pi r_s}{1 + \frac{\mu r_s^\alpha}{s\mathcal{P}_U}} dr_s + \int_{r_b-r_v}^{r_b+r_v} \frac{\arccos\left(\frac{r_v^2+r_s^2-r_b^2}{2r_v r_s}\right)}{1 + \frac{\mu r_s^\alpha}{s\mathcal{P}_U}} r_s dr_s\right)\right) \quad (3.16)$$

The complete derivation is in Appendix C, and by substituting  $s$  by its value we get the final expression:

$$\mathcal{L}_{I_{U/B}}\left(\frac{vT_{BC}r_v^\beta}{\mathcal{P}_B}\right) = \exp\left(-2\lambda_{BS}\left(\int_0^{R_m-r_v} \frac{\pi r_s}{1 + \frac{\mu \mathcal{P}_B r_s^\alpha}{vT_{BC} \mathcal{P}_U r_v^\beta}} dr_s + \int_{R_m-r_v}^{R_m+r_v} \frac{\arccos\left(\frac{r_v^2+r_s^2-R_m^2}{2r_v r_s}\right)}{1 + \frac{\mu \mathcal{P}_B r_s^\alpha}{vT_{BC} \mathcal{P}_U r_v^\beta}} r_s dr_s\right.\right. \\ \left.\left. - \int_0^{r_b-r_v} \frac{\pi r_s}{1 + \frac{\mu \mathcal{P}_B r_s^\alpha}{vT_{BC} \mathcal{P}_U r_v^\beta}} dr_s - \int_{r_b-r_v}^{r_b+r_v} \frac{\arccos\left(\frac{r_v^2+r_s^2-r_b^2}{2r_v r_s}\right)}{1 + \frac{\mu \mathcal{P}_B r_s^\alpha}{vT_{BC} \mathcal{P}_U r_v^\beta}} r_s dr_s\right)\right) \quad (3.17)$$

As explained in the derivation steps, the first two integrals correspond to the integration over the whole service area, while the second two integrals correspond to the integration over the BC zone, where there is no interference. The expression is then the difference between the first two and the second two.

**Approximation 1 of (3.17):** Here, it is assumed that due to high BC transmission power, interference is not effective beyond certain point, so the effective interference could be reduced to the disk surrounding a user, with a radius equal to the distance of HPHT from that user. In this case, (3.16) can be written as:

$$\mathcal{L}_{I_{U/B}}^*(s) = \exp\left(-2\lambda_{BS} \int_{r_b-r_v}^{\min(R_m-r_v, r_v)} \frac{\pi - \arccos\left(\frac{r_v^2+r_s^2-R_m^2}{2r_v r_s}\right)}{1 + \frac{\mu r_s^\alpha}{s\mathcal{P}_U}} r_s dr_s\right) \quad (3.18)$$

Substituting  $s$  by its value gives the final expression:

$$\mathcal{L}_{I_{U/B}}^* \left( \frac{vT_{BC}r_v^\beta}{\mathcal{P}_B} \right) = \exp \left( -2\lambda BS \int_{r_b-r_v}^{\min(R_m-r_v, r_v)} \frac{\pi - \arccos\left(\frac{r_v+r_s-R_m}{2r_v r_s}\right)}{1 + \frac{\mu\mathcal{P}_B r_s^\alpha}{T_{BC}v\mathcal{P}_U r_v^\beta}} r_s dr_s \right) \quad (3.19)$$

The derivation follows the same procedure in (C.1) until (d). Next step will be by similar yet opposite approach as in appendix A part (B), integrate over the disk of radius  $r_v$  and trimmed by the BC disk, this will produce (3.19).

**Approximation 2 of (3.17):** A second approximation could be obtained by assuming that interference is produced by a single interferer placed on the closest point to a user directly on the BCUC border. This approximation is not generally accurate, but it significantly reduces the complexity of the calculations. The Laplace transform yields:

$$\mathcal{L}_{I_{U/B}}^{**} \left( \frac{vT_{BC}r_v^\beta}{\mathcal{P}_B} \right) = \frac{1}{1 + \frac{v\mathcal{P}_U T_{BC} r_v^\beta}{\mu\mathcal{P}_B (r_b-r_v)^\alpha}} \quad (3.20)$$

As for this approximation, the derivation steps are as following:

$$\begin{aligned} \mathcal{L}_{I_{U/B}}^{**}(s) &= \mathbb{E}[\exp(-sI_{U/B})] \\ &= \mathbb{E}_h[\exp(-s\mathcal{P}_U h(r_b-r_v)^{-\alpha})] \\ &= \frac{1}{1 + \frac{s\mathcal{P}_U}{\mu(r_b-r_v)^\alpha}} \end{aligned} \quad (3.21)$$

Finally, substituting  $s$  by its value, will produce formula in (3.20).

### b) Coverage for UC users

The derivation of the coverage probability for UC users is similar to that of the BC users (stated in Appendix C) but with two major differences: (1) there are two sources of interference instead of one, and (2) the coverage depends on both  $r_l$  and  $r_d$ . The coverage probability conditioned on the relative position of the user can be derived as follows:

$$\begin{aligned} P_{c_{UC}|r_l, r_d} &= \mathbb{P}[S_{UC} > T_{UC}|r_l, r_d] \\ &= \mathbb{P}\left[\frac{\mathcal{P}_U h r_l^{-\alpha}}{\mathcal{P}_N + I_{B/U} + I_{U/U}} > T_{UC}|r_l, r_d\right] \\ &\stackrel{(a)}{=} \mathbb{E}_{I_{B/U}, I_{U/U}} \left[ \exp\left(\frac{-\mu T_{UC} r_l^\alpha (\mathcal{P}_N + I_{B/U} + I_{U/U})}{\mathcal{P}_U}\right) \right] \\ &= \exp\left(\frac{-\mu T_{UC} r_l^\alpha \mathcal{P}_N}{\mathcal{P}_U}\right) \mathcal{L}_{I_{B/U}} \left[\frac{-\mu T_{UC} r_l^\alpha}{\mathcal{P}_U}\right] \mathcal{L}_{I_{U/U}} \left[\frac{-\mu T_{UC} r_l^\alpha}{\mathcal{P}_U}\right] \end{aligned} \quad (3.22)$$

where (a) again follows the exponential distribution of  $h$ , and the final step follows the independence between  $I_{B/U}$  and  $I_{U/U}$ . To get the general coverage probability, we average on both  $r_l$  and  $r_d$ :

$$P_{c_{UC}} = \int_{r_d} f_{r_d}(r_d) \int_{r_l} f_{r_l}(r_l) \exp\left(\frac{-\mu T_{UC} r_l^\alpha \mathcal{P}_N}{\mathcal{P}_U}\right) \mathcal{L}_{I_{B/U}} \left[\frac{-\mu T_{UC} r_l^\alpha}{\mathcal{P}_U}\right] \mathcal{L}_{I_{U/U}} \left[\frac{-\mu T_{UC} r_l^\alpha}{\mathcal{P}_U}\right] dr_l dr_d \quad (3.23)$$

Substituting the expressions and limits for  $r_d$  from (3.10), and for  $r_l$  from (3.14) we obtain the final expression:

$$\begin{aligned} P_{c_{UC}} &= \frac{4\pi\lambda BS}{R_m^2 - r_b^2} \int_{r_b}^{R_m} r_d \int_0^\infty r_l \exp(-\pi\lambda BS r_l^2) \exp\left(\frac{-\mu T_{UC} r_l^\alpha \mathcal{P}_N}{\mathcal{P}_U}\right) \\ &\quad \mathcal{L}_{I_{B/U}} \left[\frac{-\mu T_{UC} r_l^\alpha}{\mathcal{P}_U}\right] \mathcal{L}_{I_{U/U}} \left[\frac{-\mu T_{UC} r_l^\alpha}{\mathcal{P}_U}\right] dr_l dr_d \end{aligned} \quad (3.24)$$

As for the LTs, they can be calculated in a similar manner to  $\mathcal{L}_{I_{U/B}}(s)$ . For  $\mathcal{L}_{I_{U/U}}\left[\frac{-\mu T_{UC} r_l^\alpha}{\mathcal{P}_U}\right]$ , the exact expression is found to be as follows:

$$\begin{aligned} \mathcal{L}_{I_{U/U}}\left(\frac{\mu T_{UC} r_l^\alpha}{\mathcal{P}_U}\right) = & \exp\left(-2\lambda BS\left(\int_{\min(r_l, R_m - r_d)}^{R_m - r_d} \frac{\pi r_q}{1 + \frac{1}{T_{UC}}\left(\frac{r_q}{r_l}\right)^\alpha} dr_q\right.\right. \\ & + \int_{\max(r_l, R_m - r_d)}^{R_m + r_d} \frac{\arccos\left(\frac{r_d^2 + r_q^2 - R_m^2}{2r_d r_q}\right)}{1 + \frac{1}{T_{UC}}\left(\frac{r_q}{r_l}\right)^\alpha} r_q dr_q \\ & \left.\left. - \int_{\max(r_l, r_d - r_b)}^{r_d + r_b} \frac{\arccos\left(\frac{r_d^2 + r_q^2 - r_b^2}{2r_d r_q}\right)}{1 + \frac{1}{T_{UC}}\left(\frac{r_q}{r_l}\right)^\alpha} r_q dr_q\right)\right) \end{aligned} \quad (3.25)$$

The first two integrals refer to the interference generated by the whole service area (from the serving BS up to closest edge, then from the closest edge to the furthest edge). The third integral is over a distinct disk, which is the gap generated by the BC zone.

**Approximation of the LT in (3.25):** In order to reduce the complexity of (3.25), an approximation could be made, by assuming that the major source of interference is due to the first term which represents the disk limited by the BC disk and the service area circle. From the above formula, this will lead the following:

$$\mathcal{L}_{I_{U/U}}^*\left(\frac{\mu T_{UC} r_l^\alpha}{\mathcal{P}_U}\right) = \exp\left(-2\lambda BS \int_{\min(r_l, R_m - r_d)}^{R_m - r_d} \frac{\pi r_q}{1 + \frac{1}{T_{UC}}\left(\frac{r_q}{r_l}\right)^\alpha} dr_q\right) \quad (3.26)$$

The other LT,  $\mathcal{L}_{I_{B/U}}(s)$  is simpler to evaluate since it is originated by a single transmitter:

$$\begin{aligned} \mathcal{L}_{I_{B/U}}(s) &= \mathbb{E}_g \left[ \exp(-s I_{B/U}) \right] \\ &= \mathbb{E}_g \left[ \exp(-s B_R \mathcal{P}_B g r_d^{-\beta}) \right] \\ &= \frac{1}{1 + \frac{s B_R \mathcal{P}_B r_d^{-\beta}}{v}} \end{aligned} \quad (3.27)$$

then

$$\mathcal{L}_{I_{B/U}}\left(\frac{\mu T_{UC} r_l^\alpha}{\mathcal{P}_U}\right) = \frac{1}{1 + \frac{B_R T_{UC} \mu \mathcal{P}_B r_d^{-\beta} r_l^\alpha}{v \mathcal{P}_U}} \quad (3.28)$$

From the three terms in (3.25) or from the approximation made in (3.26) one can conclude that the UC transmission power doesn't affect the Laplace transform of the inter-cell interference. However, increasing  $\mathcal{P}_U$  boosts the overall coverage by increasing the other two terms in (3.24). Moreover, taking into account the approximations done in (3.14) and (3.26), the effect of the BS density  $\lambda_{BS}$  is not similarly clear. From one point, increasing  $\lambda_{BS}$  increases the linear part in (3.14), but decreases the exponential parts in (3.14) and (3.26). Thus the overall effect of  $\lambda_{BS}$  depends on other factors that appear in the exponential and control the decay rate like  $T_{UC}$  and  $\alpha$ . Note that for the case of  $B_R$  equal to 0, indicating no overlapping, the equation returns to the case where no interference from the BC on the UC exists, and  $\mathcal{L}_{I_{B/U}}\left(\frac{\mu T_{UC} r_l^\alpha}{\mathcal{P}_U}\right)$  is meaningless, and the coverage probability will be similar to that scenario 2, which will be later shown in (3.35).

### c) Coverage for general users

Since the users are randomly and uniformly distributed over the service area, then the probability of a user being in the BC zone is the ratio of the BC zone area to the total

service area:

$$\begin{aligned} P_i &= \frac{A_{BC}}{A_{total}} \\ &= \frac{r_b^2}{R_m^2} \end{aligned} \quad (3.29)$$

where  $A_{BC}$  is the BC area, and  $A_{total}$  is the service area. Consequently, the probability of a user to be a UC user is the complementary:

$$P_o = 1 - \frac{r_b^2}{R_m^2} \quad (3.30)$$

Therefore, general probability of coverage for a general user in the service area will be the linear combination of the two coverage probabilities of the BC and UC users weighted by their corresponding probabilities:

$$P_c = P_i P_{c_{BC}} + P_o P_{c_{UC}} \quad (3.31)$$

### 3.1.2.2 Dedicated spectra scenario

The derivation steps of Scenario 2 are similar to that of Scenario 1 with one major difference: the elimination of the mutual interference between the networks  $I_{U/B}$  and  $I_{B/U}$ , and their related equations. Thus the probability of coverage for BC users will be as follows:

$$P_{c_{BC}} = \frac{2}{r_b^2} \int_0^{r_b} \exp\left(\frac{-\mu T_{BC} r_v^\beta \mathcal{P}_N}{\mathcal{P}_B}\right) r_v dr_v \quad (3.32)$$

Using equation 3.381/8 in [240] this equation could be written in the form:

$$P_{c_{BC}} = \frac{2}{r_b^2} \frac{\gamma\left(\frac{2}{\beta}, \frac{\mu T_{BC} \mathcal{P}_N r_b^\beta}{\mathcal{P}_B}\right)}{\beta \left(\frac{\mu T_{BC} \mathcal{P}_N}{\mathcal{P}_B}\right)^{2/\beta}} \quad (3.33)$$

where  $\gamma(a, x)$  is the lower incomplete gamma function given by:

$$\gamma(a, x) = \int_0^x e^{-t} t^{a-1} dt \quad (3.34)$$

In addition, the probability of coverage of UC users could be written as:

$$P_{c_{UC}} = \frac{2}{R_m^2 - r_b^2} \int_{r_b}^{R_m} r_d \int_0^{R_m} f_{r_l}(r_l) \exp\left(\frac{-\mu T_{UC} r_l^\alpha \mathcal{P}_N}{\mathcal{P}_U}\right) \mathcal{L}_{I_{U/U}}\left(\frac{\mu T_{UC} r_l^\alpha}{\mathcal{P}_U}\right) dr_l dr_d \quad (3.35)$$

In Scenario 2, one can notice that coverage of BC users is related only to the parameters of the BC, and it is independent of the UC parameters. In addition, the coverage of UC users is dependent only on UC parameters and  $r_b$ . This means that in general, the coverage of BC and UC users will increase with this model, but at the expense of using an additional frequency band.

### 3.1.2.3 Simulation verification

To compare the formulations derived previously with simulations, numerical and Monte-Carlo simulations have been conducted.



Table 3.1 – Simulation setting for the zone-based hybrid BC/UC model

| Parameter                      | Value        | Parameter        | Value         |
|--------------------------------|--------------|------------------|---------------|
| $R_m$                          | 30 km        | $\alpha, \beta$  | 3.4, 3.2      |
| $r_b$                          | 10 km        | $\mathcal{P}_N$  | -141 dBm/Hz   |
| $\mathcal{P}_B, \mathcal{P}_U$ | 33 kW, 1.2kW | $\lambda_{BS}$   | $0.15BS/km^2$ |
| $W_{BC}, W_{UC}$               | 8 MHz, 10MHz | $\lambda_U$      | $5user/km^2$  |
| $\mu, \nu$                     | 1, 1         | $T_{BC}, T_{UC}$ | 0 dB, 0 dB    |

**a) Simulation setting** The service area selected is of 30 km radius, with variable BC radius. Unless otherwise mentioned, the density of BSs is equal to  $0.15BS/km^2$ . Default simulation settings are summarized in Table 3.1. The isotropic transmission power of BSs is set to 1200 W, and the isotropic transmission power of the HPHT is set to 33 kW. The noise power is set to  $-105dBm$  corresponding to 8 MHz of bandwidth. It is worth mentioning that despite the general framework of our work, the parameters in this section were selected in line with LTE and DVB specifications. [239]

**b) Verification of the expressions** Firstly, to compare the analytical expressions with Monte-Carlo simulation results, the CCDF of the SINR, which is equal to the probability of coverage is calculated for BC users, UC users, and any user in the service area as shown in Fig. 3.6a, 3.6b, and 3.6c respectively for shared spectrum scenario, and in Fig. 3.7a, 3.7b, and 3.7c respectively for dedicated spectra scenario.

Both Fig. 3.6a and 3.7a show a very good convergence between the simulation and the analytical results. Fig. 3.6b and 3.7b show a very high accuracy as well, with error ranging from 1 to 2%. Fig. 3.6c and 3.7c verify the derived formulations and the different probability expressions in the previous sections. The first approximation for BC users presented in equation (3.19), and the approximation for UC users provided by (3.26) produce very close values to both simulation results and derived equations. The second approximation for the BC users provided by (3.19) is accurate for high threshold values, and loses its accuracy for low threshold values, *i.e.* below  $3dB$ . However, the use of these approximations reduces significantly the processing time for the analytical derivations. Fortunately, these approximations work well with the practical transmission parameters.

**c) Effect of relative position** Since the average values, in general, could be misleading, and in order to highlight the effect of the position on the coverage, a test was done without the last averaging over position with respect to the center in Eq. (3.15) and (3.24) for Scenario 1, and Eq. (3.33) and (3.35) for Scenario 2. Fig. 3.8a and 3.8b show a cross-section of the service area, from the center to the edge, with the coverage probability at each point with distance  $R$  from the center of the service area, for two different values of  $\lambda_{BS}$ , and their corresponding optimal BC radius  $r_b$  for both scenarios. Results show that BC users have excellent coverage for both cases near the HPHT as expected, but this value drops dramatically for scenario 1 on the BC border due to interference, and the drop is more skewed when the density is higher. In the second scenario, the drop is smoother, and it is not affected by the density of BSs. Moreover, UC has a stable coverage value over most of its region except at both boundaries, with a higher average for higher density network, and with a slight outperformance for the dedicated spectrum scenario. One could mention the main changes in the BC/UC border region. In shared spectrum scenario, users on both sides of the BC/UC borders suffer from severe interference levels, which results in the gap seen in Fig.3.8a with a probability of coverage that drops down to 0.05. In contrary, this gap is not as significant in Fig. 3.8b that corresponds to dedicated spectra scenario, as it

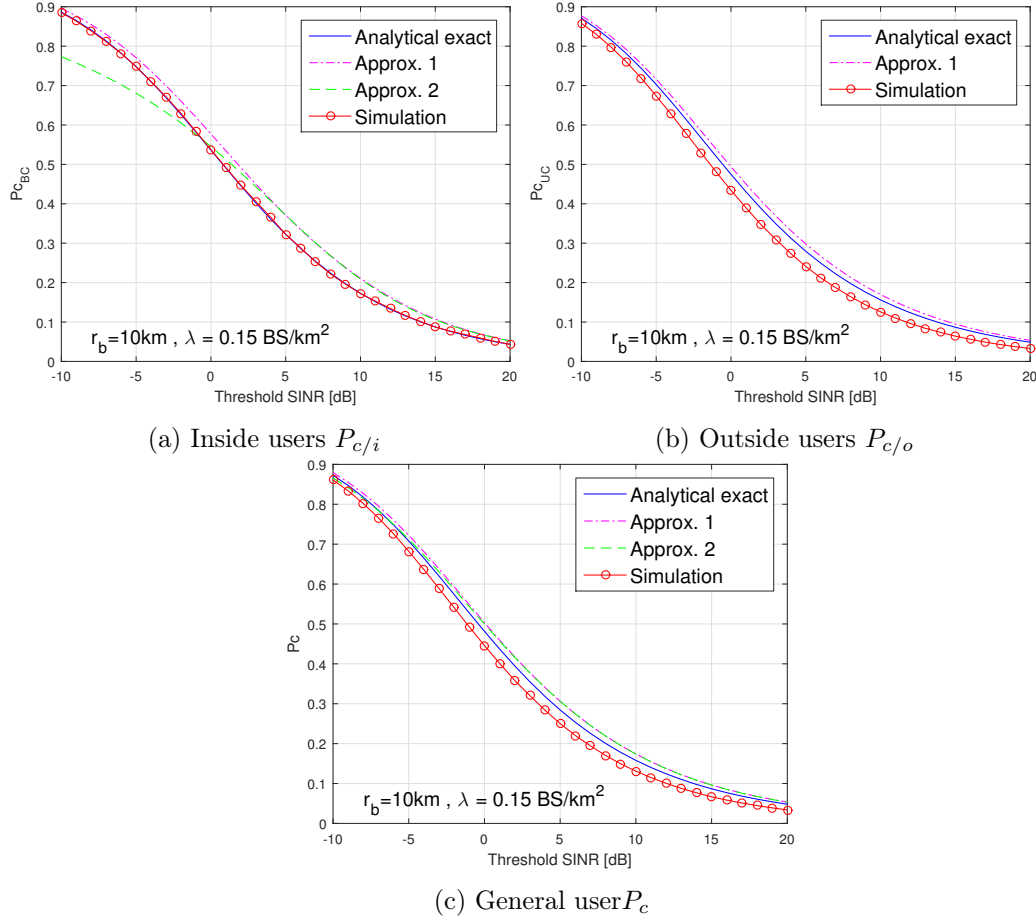


Figure 3.6 – CCDF of the SINR, or the probability of coverage  $P_c$  for shared spectrum scenario

is limited by the slight change in operating BSs density near the border.

### 3.1.3 Throughput and users' experience

#### 3.1.3.1 Ergodic capacity

In this section, we consider the average capacity for a unit bandwidth. As in the previous section, derivations for the SSS are described, and the final results of the DSS follow. We consider the average capacity for a bandwidth unit to be as follows:

$$C = \mathbb{E}[\log_2[1 + SINR]] \quad (3.36)$$

#### a) Capacity for BC users

Starting from the stated definition of the capacity, and using the definition of the received SINR for a BC user, the normalized ergodic capacity for a BC user is given by:

$$C_{BC} = \frac{2}{r_b^2} \int_0^{r_b} r_v \int_0^\infty \exp\left(-\frac{v(2^t - 1)r_v^\beta \mathcal{P}_N}{\mathcal{P}_B}\right) \mathcal{L}_{I_{U/B}}\left(\frac{v(2^t - 1)r_v^\beta}{\mathcal{P}_B}\right) dt dr_v \quad (3.37)$$

The complete derivation is detailed in Appendix D.

The LT terms  $\mathcal{L}_{I_{U/B}}(s)$  are the same as the ones in (3.16). The same approximations in (3.18) and (3.21) can be applied here as well. It could be used by substituting  $s$  by  $\frac{v(2^t - 1)r_v^\beta}{\mathcal{P}_B}$ .

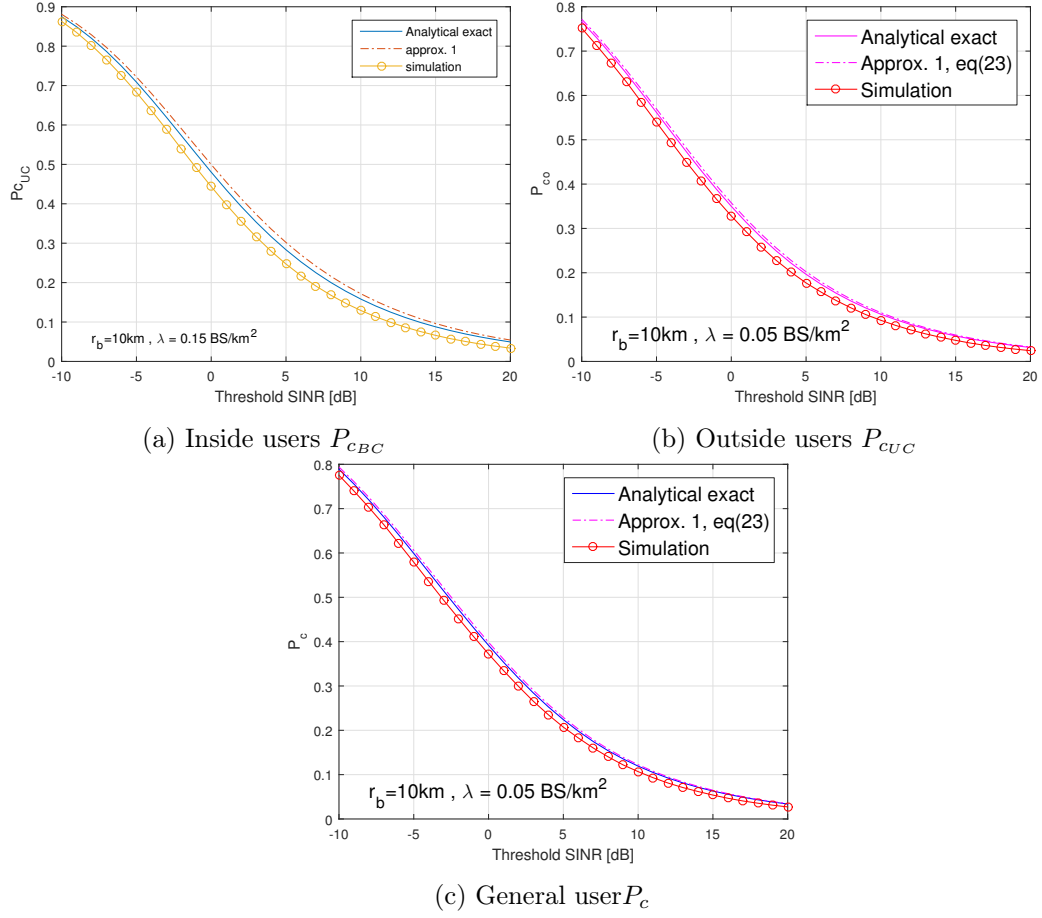


Figure 3.7 – CCDF of the SINR, or the probability of coverage  $P_c$  for dedicated spectra scenario

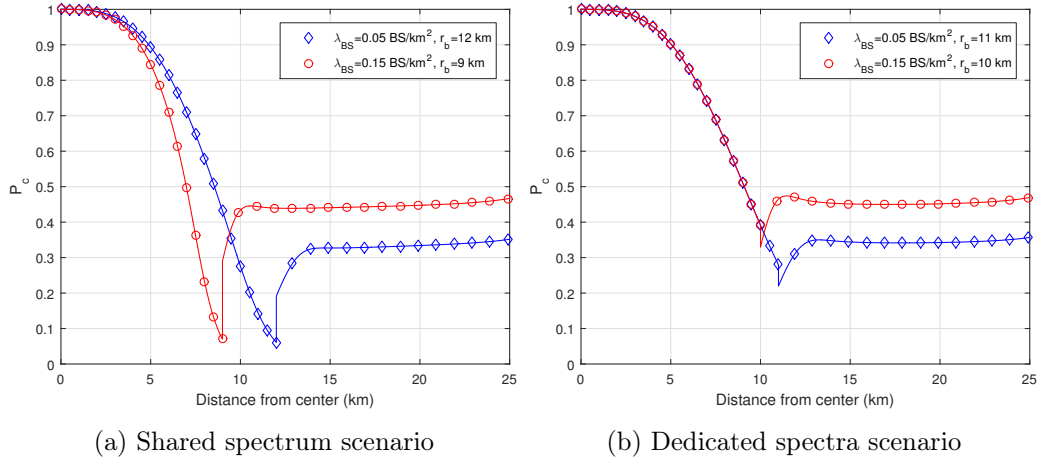


Figure 3.8 – Probability of coverage as a function of distance from center for  $-105\text{dBm}$  noise power and  $T = T_{BC} = T_{UC} = 0\text{ dB}$

**In scenario 2**, the capacity for BC users are similar to that of model 1, but again, with the elimination of terms related to  $I_{U/B}$ . The capacity of the BC users could then be derived and written as:

$$C_{BC} = \frac{1}{\ln(2)} \frac{2}{r_b^2} \int_0^{r_b} r_v \int_0^\infty \exp\left(\frac{-v(e^t - 1)r_v^\beta \mathcal{P}_N}{\mathcal{P}_B}\right) dt dr_v \quad (3.38)$$

By some rearrangement, and the use of equation 3.327 in [240], the capacity can be written as:

$$C_{BC} = \frac{1}{\ln(2)} \frac{2}{r_b^2} \int_0^{r_b} r_v \exp\left(\frac{v\mathcal{P}_N r_v^\beta}{\mathcal{P}_B}\right) - E_i\left(-\frac{v\mathcal{P}_N r_v^\beta}{\mathcal{P}_B}\right) dr_v \quad (3.39)$$

where  $E_i(x)$  is the exponential integral function given by:

$$E_i(x) = -\int_{-x}^{\infty} \frac{e^{-u}}{u} du \quad (3.40)$$

### b) Capacity for UC users

Using similar analysis, the average capacity for outside users is given by:

$$\begin{aligned} C_{UC} &= \mathbb{E}_{r_d, r_l, h} \left[ \log_2(1 + S_{UC}) \right] \\ &= \int_{r_b}^{R_m} f_{r_d}(r_d) \int_0^{2R_m} f_{r_l}(r_l) \mathbb{E} \left[ \log_2 \left( 1 + \frac{\mathcal{P}_U h r_l^{-\alpha}}{\mathcal{P}_N + I_{U/U} + I_{B/U}} \right) / r_d, r_l \right] dr_l dr_d \\ &= \frac{2}{R_m^2 - r_b^2} \int_{r_b}^{R_m} r_d \int_0^{2R_m} f_{r_l}(r_l) \int_0^{\infty} \exp\left(\frac{-\mu(2^t - 1)r_l^\alpha \mathcal{P}_N}{\mathcal{P}_U}\right) \\ &\quad \mathcal{L}_{I_{U/U}/r_d} \left( \frac{\mu(2^t - 1)r_l^\alpha}{\mathcal{P}_U} \right) \mathcal{L}_{I_{B/U}/r_d} \left( \frac{\mu(2^t - 1)r_l^\alpha}{\mathcal{P}_U} \right) dt dr_l dr_d \end{aligned} \quad (3.41)$$

The final step follows the independence between  $I_{U/U}$  and  $I_{B/U}$ .  $\mathcal{L}_{I_{U/U}/r_d} \left( \frac{\mu(2^t - 1)r_l^\alpha}{\mathcal{P}_U} \right)$  can be found by replacing  $s$  (3.25) by  $\frac{\mu(2^t - 1)r_l^\alpha}{\mathcal{P}_U}$  instead of  $\frac{\mu T_{UC} r_l^\alpha}{\mathcal{P}_U}$ . The approximation in (3.26) applies here in a similar manner. In addition,  $\mathcal{L}_{I_{B/U}/r_d} \left( \frac{\mu(2^t - 1)r_l^\alpha}{\mathcal{P}_U} \right)$  is found by replacing  $s$  in (3.27) by  $\frac{\mu(2^t - 1)r_l^\alpha}{\mathcal{P}_U}$ .

For scenario 2, the average capacity can be similarly derived, and can be written as:

$$\begin{aligned} C_{UC} &= \frac{2}{R_m^2 - r_b^2} \int_{r_b}^{R_m} r_d \int_0^{2R_m} f_{r_l}(r_l) \int_0^{\infty} \exp\left(\frac{-\mu(2^t - 1)r_l^\alpha \mathcal{P}_N}{\mathcal{P}_U}\right) \\ &\quad \mathcal{L}_{I_1/r_d} \left( \frac{\mu(2^t - 1)r_l^\alpha}{\mathcal{P}_U} \right) dt dr_l dr_d \end{aligned} \quad (3.42)$$

### c) Capacity for general users

Similar to the probability of coverage of a user at any position, the average capacity is as well a linear combination between the two calculated average capacities, weighted by the probability of a user being connected to either BC or UC. The general average capacity will then be as follows:

$$C = P_i C_{BC} + P_o C_{UC} \quad (3.43)$$

#### 3.1.3.2 Quality of experience

Based on the definitions of the two proposed QoE scores in (2.23) and (2.24), we evaluate the performance of the two proposed scenarios.

Fig. 3.9 shows the average QoE score 1 of the network as a function of the BC radius  $r_b$ . The results show that the DSS scenario outperforms the SSS for both BS density values, and that the optimal value of  $r_b$  is slightly smaller for more BS-dense areas.

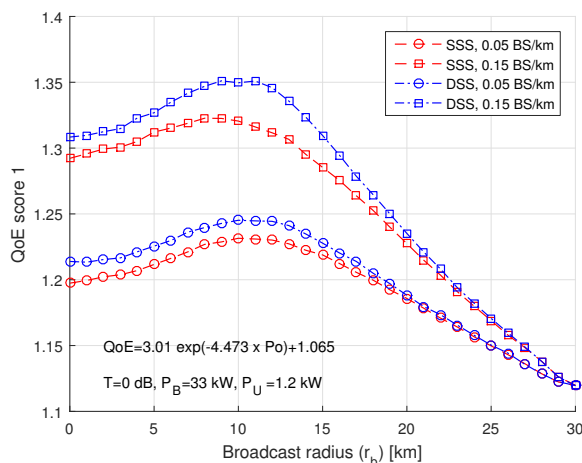


Figure 3.9 – A comparison between the two scenarios based on the QoE score 1

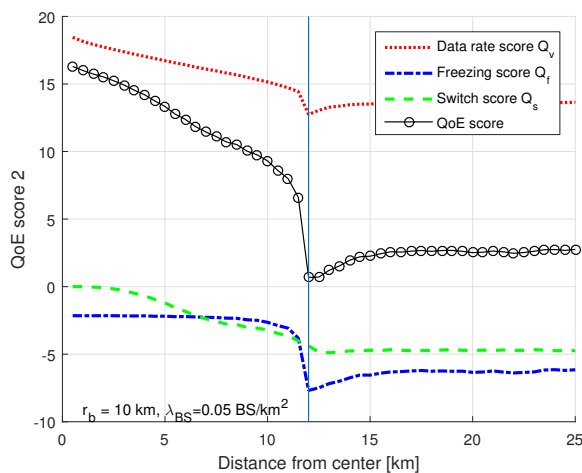


Figure 3.10 – The QoE versus the relative position from the center of the service area for SSS

Fig. 3.10 shows the QoE as indicated in  $QoE_2$  at each user's position relative to the coverage area center. In this example, we have considered  $\varepsilon = 8$ ,  $\varpi = 1$ , and  $\nu = 2$ . The figure shows the different QoE sub-scores and the final score. It can be seen that the users at the edge of the BC area (marked by a blue line in the figure) suffer the most from the degradation of QoE. Note that the results are provided for the SSS scenario only for simplicity.

### 3.1.4 Optimal operating point

The derived expressions for the coverage probability and capacity are quite complicated, so an analytic optimization is prohibitive. Alternatively, in this part we perform numerical optimization by exhaustive search. The relative simplicity of the derived expressions allows this process to be executed quickly. Two main system parameters are particularly important: the BC zone radius  $r_b$  and the BB network density  $\lambda_{BS}$ .

#### 3.1.4.1 Optimal BC radius

Among the different design parameters, it is very clear that the first parameter to optimize is the radius (i.e. the coverage) of the broadcast zone for both scenarios. Fig.

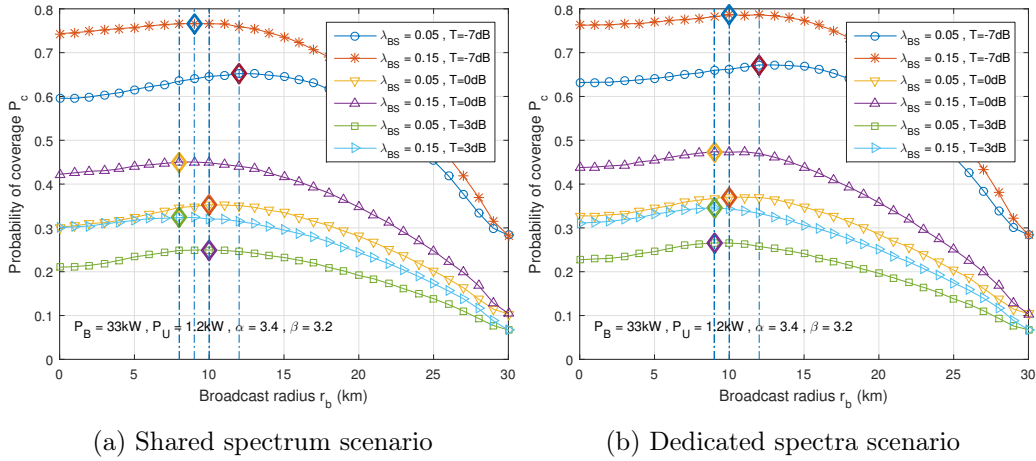


Figure 3.11 – Probability of coverage for both scenarios vs. the BC radius  $r_b$  for  $-105$  dBm noise power

3.11a and 3.11b show the probability of coverage vs the BC radius for a general user in the service area for UC BS densities of  $0.05\text{BS}/\text{km}^2$  and  $0.15\text{BS}/\text{km}^2$  for both scenarios. The results show that for a small value of  $r_b$ , where most users are UC users, the probability of coverage  $P_c$  will be limited by the achievable  $P_c$  in the UC network. When the BC radius  $r_b$  increases, more users are being covered by the BC network and thus the total  $P_c$  increases. However, when  $r_b$  is increased too much, edge users associated with BC become out of coverage due to high interference, pathloss and noise levels. Optimal values of  $r_b$  vary between 8 and 12 km.

Both figures show that the required threshold  $T$  ( $T = T_{BC} = T_{UC}$ ) has a huge effect on the coverage probability, but a limited effect on the optimal radius of BC area. In addition, results show that for shared spectrum scenario, increasing  $\lambda_{BS}$  pushes the optimal point towards smaller values. This effect is not as clear in scenario 2. The main reason could be that in Scenario 1, adding more UC BS add more interference to BC users, and consequently, limits the BC sub-network efficiency. Moreover, a comparison between the two plots shows that there is no significant difference between the two cases in terms of the optimal radius, and it is limited to a shift of around one kilometer in some cases. Excluding the edge users, BC users in general have a better QoE compared to the UC users.

It is worth mentioning that the extreme values of the broadcast radius  $r_b$  in each scenario (i.e. SSS and DSS) depict one of the stand-alone networks behaviors. For instance, in the DSS scenario, setting  $r_b$  to  $0\text{km}$  is equivalent to broadband network alone while a very large value of  $r_b$  depicts the broadcast network. In both extreme cases of  $r_b$ , it is very clear that the standalone networks could not provide the best coverage performance. One should also notice that, even though the framework in this section is applicable to any hybrid solution of networks, the simulation parameters have been selected according to LTE and DVB specifications. In other words, the hybrid proposed solution outperforms each of these networks operating alone.

The results so far correspond to a certain fixed value of the HPHT BC transmission power  $\mathcal{P}_B$ . To study the effect of  $\mathcal{P}_B$  on the optimal setting, the optimal BC radius is calculated for different values of  $\mathcal{P}_B$ . The results for shared spectrum scenario are shown in Fig. 3.12. The results show that as the transmission power increases, the optimal radius increases as well. A larger transmission power for the BC produces more coverage in the BC zone, and consequently, a bigger contribution is needed from the BC network, which increases the optimal radius.

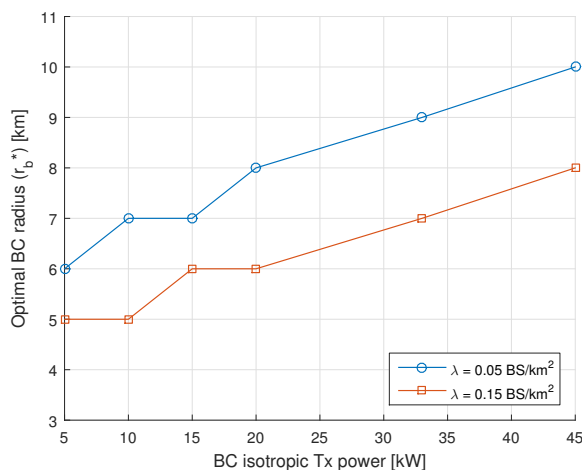


Figure 3.12 – The Effect of BC transmission power on the optimal BC radius in shared spectrum scenario

### 3.1.4.2 Optimal BS density

The second main design parameter for the hybrid network is the density of the BS providing unicast. To study the effect of the BS's density, probabilities of coverage for inside, outside, and general user are calculated for different values of  $\lambda_{BS}$  for both scenarios under study. For this study  $r_b$  is selected to be around the optimal values found in the previous section. The results are shown in Fig.3.13

For shared spectrum scenario, in general a low-density network will produce less interference on BC users, and thus those users will have better coverage and capacity. Nevertheless, low-density network means that UC users are on average far from their BS and thus have less coverage and capacity. The growth of coverage for UC users with the increase of  $\lambda_{BS}$  is faster than the decay of the coverage for BC users, thus the total coverage increases, until a point where further increase doesn't produce additional capacity or coverage since the interfering BSs are becoming closer to typical UC user. In the setting used here, one can conclude that  $0.15BS/km^2$  is enough for nearly maximum coverage.

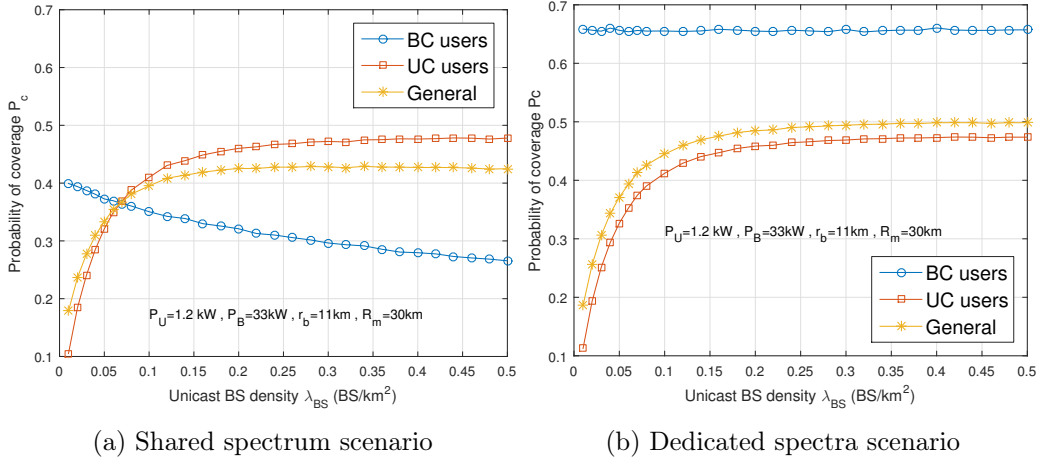
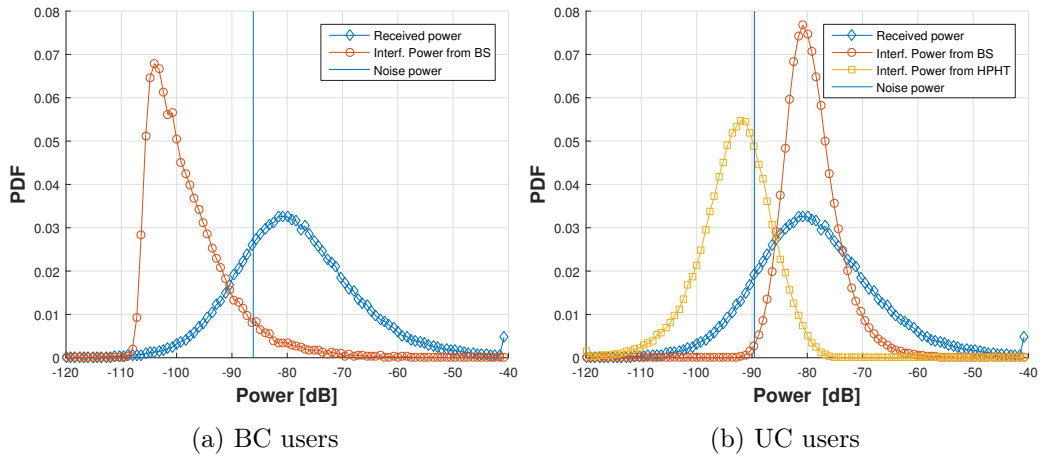
In dedicated spectrum scenario, however, the density doesn't affect the inside users' coverage, and consequently the total coverage is higher in general. However, Scenario 2 doesn't significantly shift the value on which the coverage becomes stable. In practice, the control of BS density can be done by turning off the service transmission of selected BSs but this leads to a new model of a PPP network which is out-of-scope in this chapter. The results for average user capacity and system capacity are highly correlated with that of coverage, so they are not shown.

### 3.1.5 Interference effect

$P_c$  is directly related to the achievable SINR, and consequently to the interference a user experiences. Fig. 3.14 shows the distribution of the interference power, the useful received power, and the noise power for BC and UC users. Note that the noise power values used follow the difference in BW between BC and UC modes.

Fig. 3.14a shows that the power received by the BC users is on average higher than both the noise power and the interference from BSs. Moreover, the impact of noise is much higher than interference, making it the limiting factor for SINR of BC. This is mainly due to the limited power transmitted by the UC BS compared to the HPHT, which limits its effect to the BC edge users.

On the other hand, Fig. 3.14b shows that the impact of the interference initiated by


 Figure 3.13 – Effect of the BSs' density  $\lambda_{BS}$  on the probability of coverage

 Figure 3.14 – The PDF of the received power and interference power for BC and UC users, with  $r_b = 12\text{km}$  and  $0.1\text{ BS}/\text{km}^2$  in SSS

the other UC BSs is much more severe than that initiated by the HPHT transmitter, with a difference of around 11 dB between their means, making it the limiting factor for UC SINR. The effect of the noise is on average higher than the HPHT interference as well. In fact, the effect of the HPHT interference is limited to the users near the BC area, since even if the power transmitted is high, the pathloss and the huge distances cause the received power negligible for far users.

The results shown are related to the system setting chosen, especially the pathloss exponent, therefore the numerical values, especially the relative power of the noise will change for different settings. These results show that appropriate interference cancellation mechanisms should be included in the UC receiver.

In all the testings performed so far, the induced interference was fully taken into account as no interference cancellation was supposed to be carried out. Here the effect of potential interference cancellation technique, modeled with a cancellation factor  $\omega$  is studied. In fact, the SINR formulas of (3.2) and (3.3) are slightly modified to include the new factor. For shared spectrum the modified formulas for BC and UC users will be respectively as follows:

$$S_{BC} = \frac{\mathcal{P}_B g r_v^{-\beta}}{\mathcal{P}_N + \omega I_{U/B}} \quad (3.44)$$



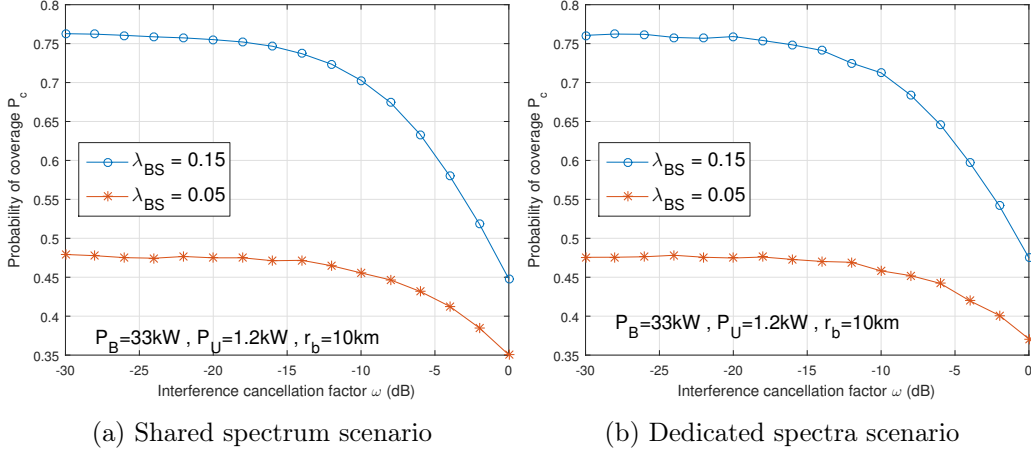


Figure 3.15 – Effect of interference cancellation factor  $\omega$  on coverage and capacity for both scenarios

and

$$S_o = \frac{\mathcal{P}_U h r_l^{-\alpha}}{\mathcal{P}_N + \omega(I_{U/U} + I_{B/U})} \quad (3.45)$$

Similarly, for dedicated spectra scenario, SINR will be modified but with reduced effect. SINR of BC users will remain unchanged as in (3.7), while SINR of UC will be a modification of (3.8), and will be as following:

$$S_{UC} = \frac{\mathcal{P}_U h r_l^{-\alpha}}{\mathcal{P}_N + \omega I_{U/U}} \quad (3.46)$$

where  $\omega$  is the reduction factor, and  $\omega \leq 1$ . Fig. 3.15 shows the coverage probability for shared spectrum scenario (3.15a) and dedicated spectra scenario (3.15b).

Fig. 3.15 shows that for both scenarios, coverage could be enhanced by more than 67% for  $\lambda = 0.15\text{BS}/\text{km}^2$  and around 37% for  $\lambda = 0.05\text{BS}/\text{km}^2$  with a cancellation factor of -15 dB. Further cancellation increase, i.e. lower values of  $\omega$ , will not be as effective as noise becomes the dominant limiting factor. Further simulations show that the 15 dB cancellation can achieve around 130% increase in average capacity for a user, and around 250% increase in achievable capacity for 90% of users.

### 3.1.6 Comparison between the two scenarios

The two presented scenarios share most of the design criteria, except the frequency bands occupied by each. While the difference in probability of coverage and system capacity is not significant, edge users in the two scenarios experience very different conditions as can be seen in Fig. 3.8a and 3.8b. As can be concluded from Fig. 3.6c and 3.7c for Coverage Probability, dedicated spectra scenario has a slight advantage due to fewer sources of interference. However, this slight advantage comes with a very expensive price in terms of occupied bandwidth, due to the usage of two frequency bands instead of one. For a fair comparison, let us analyze the two scenarios from the perspective of the global area spectral efficiency defined as

$$A_e = \frac{C^{sys}}{W_{total} \pi R_m^2} \quad (3.47)$$

where  $W_{total} = W_{BC} + W_{UC}$  is the total bandwidth.  $W_{total} = 18$  MHz for the dedicated spectra scenario, and  $W_{total} = 10$  MHz in the case of shared spectrum scenario because of the overlapping of the bands. The global area spectral efficiency as a function of the BC radius is shown in Fig.3.16.

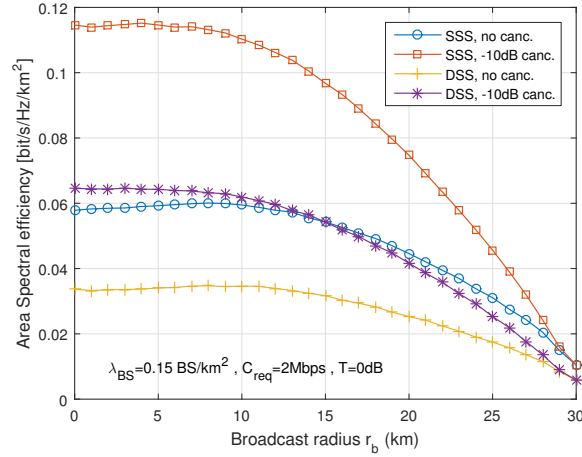


Figure 3.16 – Global area spectral efficiency comparison between the two proposed scenarios with and without interference cancellation (SSS=Shared Spectrum Scenario, DSS= Dedicated Spectra Scenario).

Table 3.2 – Comparison between the SSS and DSS scenarios

| Parameter                  | SSS               | DSS               |
|----------------------------|-------------------|-------------------|
| Coverage                   | slightly lower    | slightly higher   |
| Average capacity           | slightly lower    | slightly higher   |
| Edge users coverage        | very low coverage | better conditions |
| Used BW                    | 1 frequency band  | 2 frequency bands |
| Global spectral efficiency | much higher       | much lower        |

The results show that even though dedicated spectrum scenario achieves higher capacity and coverage, but globally, shared spectrum scenario is more efficient. The large distances between the HPHT and UC users from one side, and the BS and BC users from the other side, cause the mutual interference to be limited to the edge users. Hence, cancelling this interference by using dedicated spectra scenario has a limited effect on the coverage and capacity, while the bandwidth used is hugely increased (doubled, or even more depending on the used networks) to attain such goal. This eventually leads to a severe drop of the efficiency in the second scenario. The results also show that dedicated spectral scenario with -10 dB of interference cancellation can reach the efficiency level of shared spectrum scenario with no interference management. Moreover, It can be noticed that the use of more advanced receivers with better interference management has more effect on the shared spectrum scenario doubling the efficiency, whereas the effect on the dedicated spectra scenario is limited because of the fewer number of interference sources in that case.

However, it remains up to the designer to use either choice depending on the available resources and their cost. For example, if the state of the edge users is critical, and the additional BW is available and not costly, then dedicated spectra scenario could again be the preferable network option.

Table 3.2 briefs the comparison between the shared spectrum scenario (SSS) and the dedicated spectra scenario (DSS)

## 3.2 SINR-based hybrid network

The zone-based model discussed in the previous section can be useful in cases where a physical separation between the networks is required. In this section, we study a different

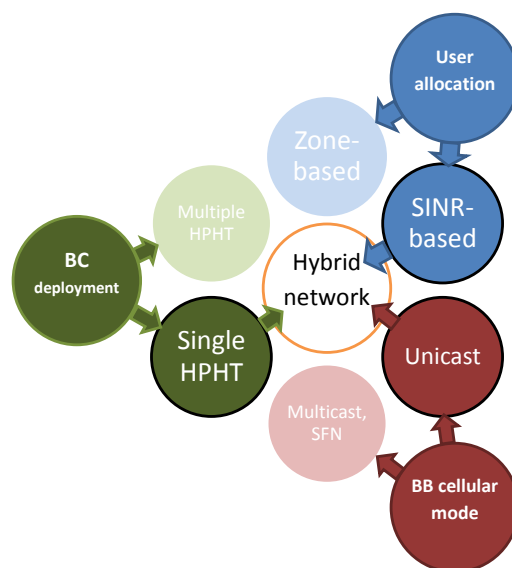


Figure 3.17 – The combination of the second studied model: SINR-based single BC/UC hybrid network

approach: the user association based on the best signal quality. As can be seen in the illustration in Fig. 3.17, UC is still used for the BB network, and a single HPHT deployment is used for the BC network. The only difference is that now the user allocation is SINR-based instead of zone-based.

### 3.2.1 The hybrid model

Similar to the model presented in the previous section, the network is made out of two sub-networks: a BC network with a single HPHT at the center of the service area, and a BB network with a number of BSs distributed uniformly over the service area.

The BB network operates in UC mode, and is modeled by a PPP  $\Phi$  with density  $\lambda_{BS}$ . The users are also distributed uniformly according to an independent PPP  $\Psi$  with density  $\lambda_U$ .

The HPHT transmits with a power  $\mathcal{P}_B$  over a frequency  $f_D$ , and all the BSs transmit with a power  $\mathcal{P}_U$  at a frequency  $f_L$  (a frequency reuse factor of 1) where  $\mathcal{P}_B > \mathcal{P}_U$ , and where  $f_D$  and  $f_L$  do not overlap. This frequency selection, with no overlapping between the networks' frequency bands, eliminates the coexistence possibilities, and therefore, no interference will occur between the two sub-networks.

All the users are assumed to have the capability to connect to either network, with a priority to the BC network. If the received SINR from the BC transmission exceeds a certain threshold required for proper reception of the service, then the user is connected to the BC network, and is referred to as a BC user. Else, if the received BC SINR is lower than the required threshold, the user is considered to be a UC user, and will be served by the closet BS. We consider any BS that has no UC users interested in the services as non-active. The BS will still be on, creating interference, but it will not transmit the service, and therefore will not be included in the power efficiency calculations.

In an SINR-based hybrid scheme, the first step is to properly formulate the SINR for both BC and UC. For a BC user, the useful power comes from the HPHT solely, and since there is no overlap in frequency with the BB network, there is no interference sources counted in the analysis. Therefore, the SINR here is actually an SNR, and based on the

pathloss model stated in (2.10), it can be written as:

$$S_{BC} = \frac{\mathcal{P}_B g r_v^{-\beta}}{\mathcal{P}_{N_{BC}}} \quad (3.48)$$

where  $r_v$  is the distance between a user and the HPHT. Here, the channel random variable  $g$  is also exponentially distributed with a rate  $v$ .

As for the UC received SINR, it can be defined as follows:

$$S_{UC} = \frac{\mathcal{P}_U h r_l^{-\alpha}}{P_{N,UC} + I_{U/U}} \quad (3.49)$$

where  $r_l$  is the distance between the user and the serving BS.

The interference sourced by other BSs in the UC network is given by:

$$I = \sum_{i \in \Phi/b} \mathcal{P}_U h_i q_i^{-\alpha} \quad (3.50)$$

where  $\Phi/b$  is the set of all BSs excluding the serving BS, and  $q_i$  is the distance to the  $i^{\text{th}}$  interfering BS.

Since both the positions of the users and the BSs are random, then the distances between a user and a BS, and between a user and the center (where the HPHT is located) is also random. The distribution of the distance between a user and the HPHT is derived in a similar manner to that distance in the previous section, and it is as follows:

$$f_{r_v}(r_v) = \frac{2}{R_m^2} r_v, \quad r_v \in [0, R_m] \quad (3.51)$$

On the other hand, the distribution of the distance between the user and the serving BS is the same as explained in (2.16), and it is again as follows:

$$f_{r_l}(r_l) = 2\pi\lambda_{BS} r_l \exp(-\lambda_{BS}\pi r_l^2) \quad (3.52)$$

### 3.2.2 The coverage probability

In this scenario, the coverage probability is the probability that the user is covered at least by one of the networks (BC or BB), which is the complementary of the outage probability from both networks. We will start with the coverage probability of each network separately, then use the expressions to find the total coverage probability.

#### 3.2.2.1 Probability of coverage for a BC user

Starting from the probability of coverage definition in (2.18), the probability of coverage for a BC user at a distance  $r_v$  from the BCT is given by:

$$\begin{aligned} P_{c_{BC}|r_v} &= \mathbb{P}[S_{BC} > T_{BC}|r_v] \\ &= \mathbb{P}\left[\frac{\mathcal{P}_B g r_v^{-\beta}}{\mathcal{P}_{N,BC}} > T_{BC}|r_v\right] \\ &= \mathbb{P}\left[g > \frac{T_{BC} \mathcal{P}_{N,BC} r_v^\beta}{\mathcal{P}_B} | r_v\right] \end{aligned} \quad (3.53)$$

Now, averaging over  $r_v$  to get the general coverage probability:

$$\begin{aligned}
 P_{cBC} &= \mathbb{E}_{r_v} \left[ \exp \left( - \frac{vT_{BC}\mathcal{P}_{N,BC}r_v^\beta}{\mathcal{P}_B} \right) \right] \\
 &= \int_0^{R_m} f_{r_v}(r_v) \exp \left( - \frac{vT_{BC}\mathcal{P}_{N,BC}r_v^\beta}{\mathcal{P}_B} \right) dr_v \\
 &= \frac{2}{R_m^2} \int_0^{R_m} r_v \exp \left( - \frac{vT_{BC}\mathcal{P}_{N,BC}r_v^\beta}{\mathcal{P}_B} \right) dr_v
 \end{aligned} \tag{3.54}$$

Substituting  $x = vT_{BC}\frac{\mathcal{P}_{N,BC}}{\mathcal{P}_B}r_v^\beta$ , the above integral can be reduced into:

$$P_{cBC} = \frac{2\mathcal{P}_B\gamma\left(\frac{2}{\beta}, \frac{vT_{BC}\mathcal{P}_{N,BC}R_m^\beta}{\mathcal{P}_B}\right)}{vT_{BC}\mathcal{P}_{N,BC}R_m^2\beta} \tag{3.55}$$

where  $\gamma(z, s)$  is the lower incomplete gamma function.

### 3.2.2.2 Probability of coverage for a UC user

The coverage probability for a UC user at a distance  $r_l$  from the serving BS can be evaluated as follows:

$$\begin{aligned}
 P_{cUC|r_l} &= \mathbb{P}[S_{UC} > T_{UC}|r_l] \\
 &= \mathbb{P}\left[\frac{\mathcal{P}_U h r_l^{-\alpha}}{\mathcal{P}_{N,UC} + I_{U/U}} > T_{UC}|r_l\right] \\
 &= \mathbb{P}\left[h > \frac{T_{UC}(\mathcal{P}_{N,UC} + I_{U/U})r_l^\alpha}{\mathcal{P}_U} | r_l\right]
 \end{aligned} \tag{3.56}$$

Now averaging over  $r_l$  to get the general coverage probability:

$$\begin{aligned}
 \mathcal{P}_{cUC} &= \mathbb{E}_{r_l} \left[ \exp \left( - \frac{\mu T_{UC}(\mathcal{P}_{N,UC} + I_{U/U})r_l^\alpha}{\mathcal{P}_U} \right) \right] \\
 &= \int_0^\infty f_{r_l}(r_l) \mathbb{E}_{I_{U/U}} \left[ \exp \left( - \frac{\mu T_{UC}(\mathcal{P}_{N,UC} + I_{U/U})r_l^\alpha}{\mathcal{P}_U} \right) \right] dr_l \\
 &= 2\pi\lambda_{BS} \int_0^\infty r_l \exp(-\lambda_{BS}\pi r_l^2) \exp \left( - \frac{\mu T_{UC}\mathcal{P}_{N,UC}r_l^\alpha}{\mathcal{P}_U} \right) \mathcal{L}\left(\frac{\mu T_{UC}r_l^\alpha}{\mathcal{P}_U}\right) dr_l
 \end{aligned} \tag{3.57}$$

Substituting  $f_{r_l}(r_l)$  by its value from (3.52) gives the final expression:

$$\mathcal{P}_{cUC} = 2\pi\lambda_{BS} \int_0^\infty r_l \exp(-\lambda_{BS}\pi r_l^2) \exp \left( - \frac{\mu T_{UC}\mathcal{P}_{N,UC}r_l^\alpha}{\mathcal{P}_U} \right) \mathcal{L}\left(\frac{\mu T_{UC}r_l^\alpha}{\mathcal{P}_U}\right) dr_l \tag{3.58}$$

Since the network is modeled by a homogeneous PPP, and the user is receiving interference from all the BSs in the network excluding the serving BS, then Theorem 2.1 can be applied to calculate the LT. This results in the following expression:

$$\mathcal{L}_{I_{U/U}}(s) = \exp \left( \frac{-2\pi\lambda_{BS}r_l^{2-\alpha}s\mathcal{P}_U}{\mu(\alpha-2)} {}_2F_1\left(1, 1 - \frac{2}{\alpha}; 2 - \frac{2}{\alpha}; \frac{-s\mathcal{P}_U}{\mu r_l^\alpha}\right) \right) \tag{3.59}$$

Substituting  $s = \frac{\mu T_{UC}r_l^\alpha}{\mathcal{P}_U}$  into the equation results in the final form:

$$\mathcal{L}_{I_{U/U}}\left(\frac{\mu T_{UC}r_l^\alpha}{\mathcal{P}_U}\right) = \exp \left( \frac{-2\pi\lambda_{BS}T_{UC}r_l^2}{\alpha-2} {}_2F_1\left(1, 1 - \frac{2}{\alpha}; 2 - \frac{2}{\alpha}; -T_{UC}\right) \right) \tag{3.60}$$

Table 3.3 – Simulation setting for the SINR-based hybrid BC/UC model

| Parameter                      | Value          |
|--------------------------------|----------------|
| $R_m$                          | 30 km          |
| $\mathcal{P}_B, \mathcal{P}_U$ | 17 kW, 1.3kW   |
| $BW_{BC}, BW_{UC}$             | 8 MHz, 20MHz   |
| $\mu, \nu$                     | 1, 1           |
| $\mathcal{P}_N$                | -141 dBm/Hz    |
| $\lambda_{BS}$                 | $0.5BS/km^2$   |
| $\lambda_U$                    | $1.5user/km^2$ |

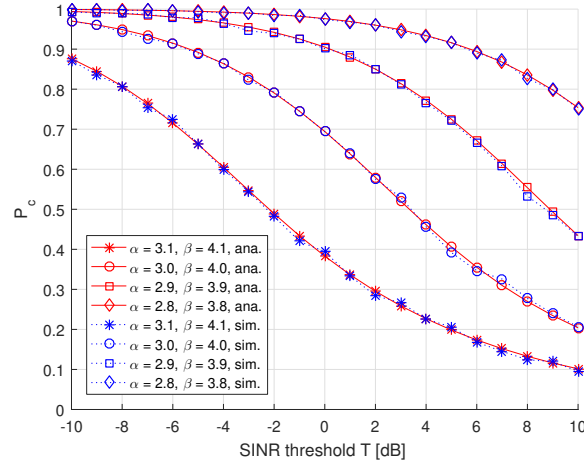


Figure 3.18 – The probability of coverage for the SINR-based hybrid BC/UC model

### 3.2.2.3 Probability of coverage for any user

The general coverage probability can be seen as the complementary of the general outage probability. A user is said to be out of coverage if it is not covered by either network, *i.e.* the product of the outage probability of BC and UC networks.

Therefore, the coverage probability will be as follows:

$$P_c = 1 - P_{o_{BC}}P_{o_{UC}} \quad (3.61)$$

where  $P_o$  denotes the outage probability. The final coverage probability will then be:

$$P_c = 1 - (1 - P_{c_{BC}})(1 - P_{c_{UC}}) \quad (3.62)$$

### 3.2.2.4 Verification of the derived expressions

To verify the obtained expressions, we compared them with the Monte-Carlo simulations. The testing was done under the setting shown in Table 3.3. Fig. 3.18 shows this comparison for different path loss values.

The results show that the derived expressions succeeded in matching the simulation results perfectly for different SINR thresholds and different path loss exponents. Besides, the results show that as the path loss increases, the coverage probability decreases as expected.

### 3.2.3 The power efficiency optimization

#### 3.2.3.1 The power utilization expression

Starting from the definition in (2.21), the power utilization in this model can be written as:

$$\mathcal{U} = \frac{\mathbb{E}\left[\mathcal{P}_B + \sum_{i \in \Psi} \mathcal{P}_{U_i}\right]}{\mathbb{E}\left[\sum_{i \in \Phi} \zeta_i\right]} \quad (3.63)$$

where  $\zeta_i$  is a binary variable that is equal to 1 if user  $i$  is connected and 0 otherwise.

The sum of transmitted power from the BSs is equal to the average number of BSs in the service area multiplied by the probability that the BS is actually transmitting. The average number of BSs is equal to the density multiplied by the total area which is  $A\lambda_{BS}$ . The probability of a BS to be transmitting is the outage probability of the BC network which is equal to  $1 - \mathcal{P}_{c_{BC}}$ . The total power of the UC network is then the average number of transmitting BSs multiplied by the individual transmitted power. As for the number of served users, it is equal to the average number of users in the service area  $A\lambda_U$  multiplied by the probability of coverage. This results in the following expression:

$$\mathcal{U} = \frac{\mathcal{P}_B + A\lambda_{BS}(1 - \mathcal{P}_{c_{BC}})\mathcal{P}_U}{\mathcal{P}_c A\lambda_U} \quad (3.64)$$

#### 3.2.3.2 Optimization of power utilization

In the zone-based model, an optimal BC zone radius was the goal of the optimization problem. In the SINR-based model, the BC transmission power is what controls the portion of the users that goes to each network. The transmission power ranges from zero, indicating a full BB network, to 100 kW, theoretically indicating a very large coverage area.

However, other factors control both the optimal  $\mathcal{P}_B$  and the power efficiency at these values. These include design parameters like the BS density  $\lambda_{BS}$ , service-related parameters like the required capacity for proper reception  $C^{req}$ , service area parameters like the pathloss exponent  $\beta$  and the service area radius  $R_m$ , and user density  $\lambda_U$ . These results are reported in Fig. 3.19, 3.20, 3.21, 3.22, and 3.23 respectively.

The common, and most obvious, conclusion from these figures is that an optimal point, where the power transmitted per served user is minimum, exists. The optimal value is shown to be a function of the studied parameter, and it ranges from a few kW to more than 30 kW in some cases.

For all the shown figures, the power utilization factor is high at both ends of the transmission power line but for different reasons. At very low  $\mathcal{P}_B$ , most of the users are UC users, and due to interference, these users have generally lower coverage than BC users. When we increase  $\mathcal{P}_B$  more users join the BC subset, and therefore, the overall efficiency is enhanced. After a certain point, adding more power will no longer add coverage at the same rate for new users, and the excessive power used degrades the efficiency (increases the power utilization factor). So at the high end of the transmission power line, the high  $\mathcal{U}$  is due to unnecessary transmission power.

Fig. 3.19 shows the power utilization versus the BC transmission power for different values of BC density  $\lambda_{BS}$ . The results show that adding more BSs to the network reduces its efficiency (increases  $\mathcal{U}$ ). The added BSs might enhance the coverage for the UC users, but the power cost seems to be higher on the hybrid network. The results also indicate that the optimal  $\mathcal{P}_B$  increases with BB network density. That means that more contribution is needed from the BC sub-network to take over more users and reduce the contribution of the less efficient UC network as more unnecessary BSs are added. The optimal transmission

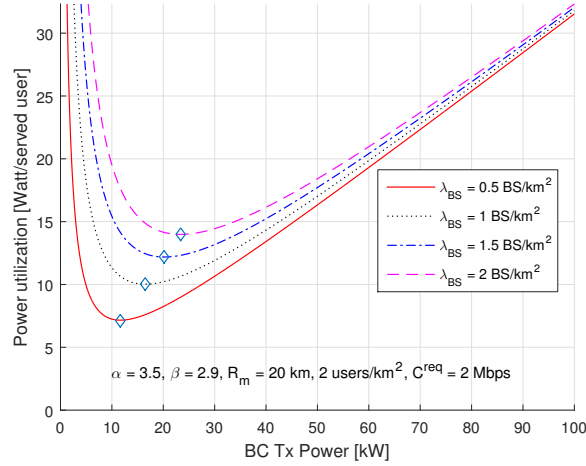


Figure 3.19 – Power utilization versus the BC transmitted power for different BS densities

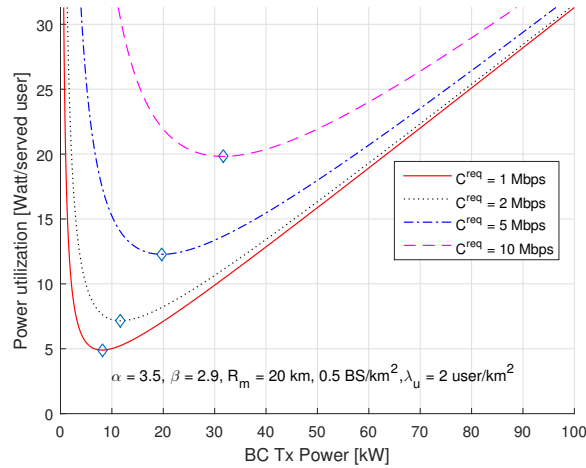


Figure 3.20 – Power utilization versus the BC transmitted power for different required capacities

power ranges from 11 kW for lower densities of  $0.5 \text{ BS/km}^2$  to 22 kW for higher densities of  $2 \text{ BS/km}^2$ .

In Fig. 3.20, the  $\mathcal{U}$  curves for different required capacity values  $C^{req}$  are compared.  $C^{req}$  is the needed link capacity for a user to properly receive the service. Although the term  $C^{req}$  doesn't appear in the equations, but it controls other parameters like the SINR threshold  $T$ . For a certain assigned BW  $W$ , the  $T$  and  $C^{req}$  are related as follows:

$$C^{req} = W \log_2(1 + T) \quad (3.65)$$

As expected, for higher required capacity (indicating higher SINR threshold), the coverage probability is reduced, and therefore the power efficiency for the same transmission power is reduced as well. The results indicate that the higher the service requirements are, the more contribution is needed from the BC network, which is reflected in the higher optimal  $\mathcal{P}_B$  for higher  $C^{req}$ .

The nature and the size of the service area have their own effect on the optimal operation point. In Fig. 3.21 the path loss exponent for BC is studied. In areas with higher path loss, more power is needed from the BCT to maintain the performance. The same effect is noticed in Fig. 3.22 that studies the service area radius: as the service area gets bigger, more BC power is needed. In both cases, higher path loss and higher service area size, the coverage probability for the same  $\mathcal{P}_B$  is reduced, and therefore the efficiency is reduced



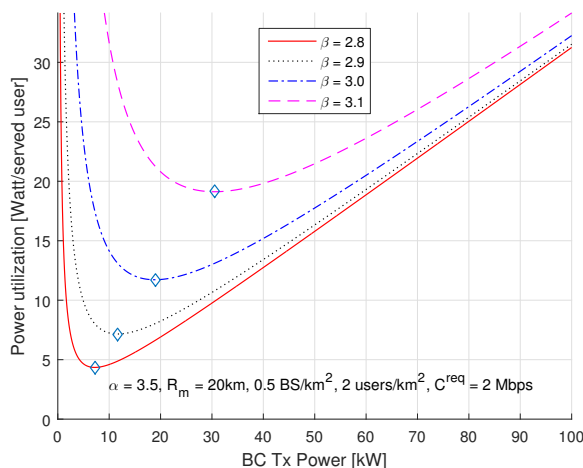


Figure 3.21 – Power utilization versus the BC transmitted power for different values of BC pathloss exponent  $\beta$

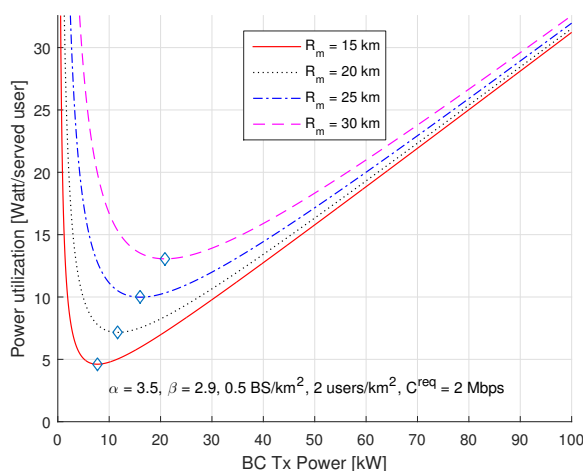


Figure 3.22 – Power utilization versus the BC transmitted power for different sizes of service areas

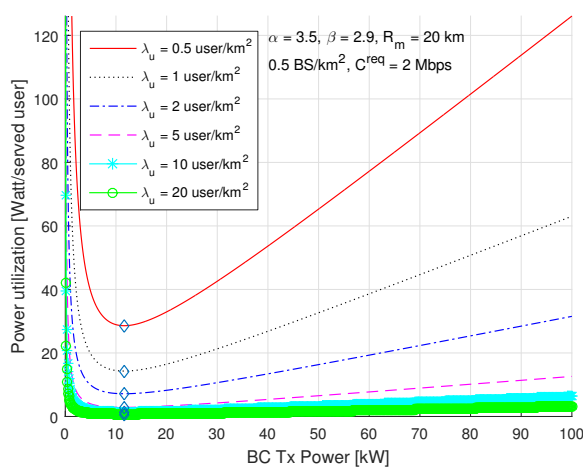


Figure 3.23 – Power utilization versus the BC transmitted power for different user densities

also.

Finally, Fig. 3.23 shows the effect of the user density on the power utilization curves.

The user density appears in the denominator of the expression of power utilization. Nevertheless,  $\lambda_U$  affects other parameters in the analysis. The user density controls the allocated bandwidth in the UC network, and consequently, the needed SINR threshold and the coverage probability. Since the available BW in a BS is limited, the more users we have, the less BW we can allocate for each user. Therefore, the needed SINR for the same capacity becomes higher. A resource allocation scheme is introduced in Chapter 6, but for now, we assume that the available bandwidth in a BS  $W^{BS}$  is equivalently allocated to all users in the cell. To simplify the problem, we define the user BW as the ratio between of the user density and BS density, multiplied by the available BW in a cell:

$$W = \frac{\lambda_{BS}}{\lambda_U} W^{BS} \quad (3.66)$$

substituting (3.66) into (3.65) allows us to find the needed SINR threshold  $T$  for a certain  $C^{req}$ .

The results show that the more users are in the network, the more the power-efficient the network is. This indicates that the hybrid network is capable of handling the users without a drop in the coverage. It can also be noticed that for low user density, any increase in BC power beyond the optimal value will result in an increase in  $U$  with a much higher rate than the case of higher densities. The reason is that beyond the optimal  $\mathbb{P}_B$ , any additional power will reduce the efficiency, and having fewer users in the network aggravates the problem by increasing the denominator for  $\mathcal{U}$ . One can also notice that the optimal transmission power is almost the same whatever the user density is, indicating that beyond that point there is no need for additional contribution from the BC network since the majority of the users are then served by the HPHT under these conditions.

### 3.3 Summary and conclusions

In this chapter we introduced a hybrid BC/UC network with single HPHT, and under two forms of user allocation: zone-based and SINR-based user allocation. The two schemes can be used in different conditions or under different constraints and objectives.

The first part of the chapter discussed the zone-based hybrid network while introducing two different scenarios for BC and BB coexistence. The first was based on shared spectrum access while the second was based on the dedicated spectra using TVWS. An analytical formulation for both models in terms of probability of coverage and capacity has been derived, and numerical simulations have verified the accuracy of the derived expressions.

The results showed that in general, the dedicated spectra scenario produces higher coverage probability for a user in the service area by few percents and higher system capacity as well, with similar percentages. However, since it requires an additional frequency band adopted from the TV white space, a compromise could be made between coverage and spectral resources. Even though the compromise, i.e. the choice of Scenario 1 or Scenario 2, could be hard to find, a soft solution where Scenario 1 is applied in general, but TV white space is used for BS on the BC/UC boundaries, can be proposed in the future.

The results also indicated that an optimal broadcast radius could be reached for different operation conditions where coverage or capacity could be maximized. The results showed that this optimal point changes depending on the density of UC BSs. It is shown that, for both scenarios, a value of BS density beyond which there is no significant gain in either scenario exists. Moreover, it is shown that some interference cancellation possibly introduced at the end-user level could significantly enhance both coverage and user experience. The two proposed scenarios were also directly compared in terms of the spectral efficiency, where the shared spectrum scenario proved to be much more efficient.

In the second part of the chapter, the SINR based hybrid BC/UC network was introduced. First, the hybrid model and the user allocation criteria are described. The user

is served by the BC if the BC SINR is high enough, and if not, the user will be served by the BB network. Based on these definitions, the probability of coverage of BC user, UC users, and finally, any user in the service area were derived and then verified through Monte-Carlo simulations. Using the derived coverage probability, the power utilization metric was found.

Unlike the zone-based model, the SINR-based model has soft BC/UC boundaries which greatly depend on the BC transmission power. So to optimize the hybrid network performance, it was important to find the value of the BC transmission power that minimizes the power utilization factor. This optimization was done numerically for different network conditions and settings.

The results show that an optimal operation mode can be found. The location and value of this point depend on several other parameters like the required qualities, network deployments, and user density. The needed contribution from the BC network is often the controller of this optimal point.

From both user allocation hybridization techniques, one can see that for a range of system parameters, the hybrid network introduces gain in performance when compared to the full BC and full BB networks. This gain is a function of the settings of both networks, and of the conditions the network is operating in. The hybrid network settings have to be carefully tuned to extract the maximum gain from this hybridization.

While we focused on the single BCT in this chapter, in the next chapter, a generalization of the zone-based model is introduced. Instead of zooming in to just one BCT, we zoom out to include multiple HPHTs and BC zones. The performance of the network will be analyzed similarly to what was done here.

# Chapter 4

## Hybrid Multiple BC/BB Model

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In the previous chapter, the zone-based hybrid BC/UC network was analyzed. However, a single HPHT deployment was considered. This model is useful for scenarios where a specific area is needed to be covered. In this chapter, we generalize this idea into a much wider service area, where multiple BCTs are deployed. So, as can be seen from the illustration in Fig. 4.1, the focus of this chapter will be on studying the zone-based hybrid multiple-BC/UC network. Since the coexistence scenario proved to be more efficient, it will solely be used in this model.

Unlike previous works that discuss heterogeneous and multi-tier networks (such as in cellular), the work here focuses on the nature of the broadcast service. Indeed, contrary to other services, BC is characterized by the pre-fixed rates while the design is based on the worst-case user service. The importance of our work resides in the consideration of the

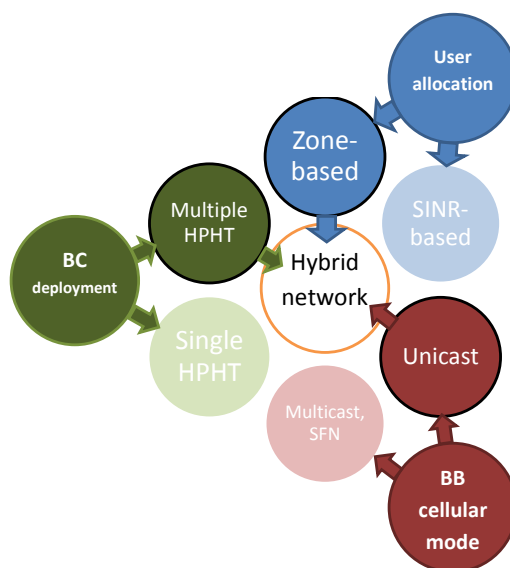


Figure 4.1 – The combination of the third studied model: zone-based multiple BC/UC hybrid network

ICI in the network analysis as it represents a major factor affecting the quality of service of such hybrid network but was neglected in previous works such as [150, 151, 239].

Moreover, this chapter gives deeper insights and conclusions of this hybrid model as: (i) it considers the coexistence between the two services over the same frequency band causing mutual interference in a spread BC deployment, (ii) it simplifies the user association to either network (BC or BB) to have much simpler expressions, and (iii) takes the nature of the service into account when calculating the system rate and efficiency.

The main contributions of this chapter could be summarized as follows:

- Proposition of a zone-based user sharing hybrid BC/UC model where the BC and the BB networks share the same band.
- Inclusion and analysis of ICI as a major factor in the design of the hybrid network. Here, ICI of both networks is considered. The interference due to coexistence between the two networks is also studied.
- Derivations of the novel analytical expressions of the probability of coverage for BC, UC, and any user in the service area, as well as the average normalized capacity for those cases, using stochastic geometry tools for modeling and analysis, with two approaches for simplification: normal and reduced PPP.
- Optimization of the hybrid network by maximizing selected evaluation metrics like the probability of coverage, spectral efficiency, and power efficiency, in terms of the main design parameters such as the density of BCTs and the size of the BC zone represented by the BC radius.

## 4.1 Generalized hybrid BC/BB model

In this section, the proposed model of the hybrid network is first presented and then followed by the main derivations. The derived expressions will be used in the next sections for numerical optimization and analysis.

### 4.1.1 System description

The system parameters, notations, and general modeling are similar to the ones in Chapter 3. However, we re-state these basic descriptions for completeness. This chapter considers the delivery of linear services to a number of users, distributed uniformly over the service area. The users' distribution is modeled by a PPP  $\Psi$  with density  $\lambda_U$ . The users are served by one of the two networks:

- BB UC network: it consists of number of BSs uniformly distributed over the service area. The positions of the BSs are modeled by a PPP  $\Phi$  with density  $\lambda_{BS}$ . The BSs are transmitting OFDM data with isotropic power  $\mathcal{P}_U$ .
- BC network: it consists of a number of BCTs or HPHTs, uniformly distributed over the service area. This time, the HPHTs are also modeled with another independent PPP  $\Xi$  with a density  $\lambda_{BC}$ , which is much smaller than  $\lambda_{BS}$ . The BCTs are broadcasting OFDM data with isotropic power  $\mathcal{P}_B$ , where  $\mathcal{P}_B > \mathcal{P}_U$ .

An example of the service area is shown in Fig. 4.2. The coverage area for the BCT is clearly larger than that of the BSs due to a larger transmitted power. To simplify the analysis procedure, it is assumed that a BCT has a circular coverage area centered at the BCT and with radius  $r_b$ . Any user within any of the BC areas is served by the nearest BCT. The users that are not covered by any of the BC areas are served by the nearest BS.

In this chapter also, it is assumed that the BCTs operate at frequency  $f_D$ . The UC BSs outside the BC covered areas also operate at the same frequency  $f_D$ , while the UC BSs located within any of the BC areas operate at frequency  $f_L$ . Those BSs are not transmitting linear services and will have no role in our model, and they will not cause any interference to other parts of the system. Even though such coexistence between two networks is not currently implemented, such deployment may be a solution for better usage of the spectrum. As we mentioned before the TVWS or the unlicensed bands can be the domain where such coexistence can take place. On the other side, since all the BSs (outside of the BCTs' areas) and all the BCTs operate at the same frequency, a mutual interference will be created between the two networks that have to be quantified and evaluated. In fact, one of the key technological bottlenecks in this work is to optimize the service area of the BCTs, among others.

In Chapter 3, three cases of interference were considered: from BC on UC users  $I_{B/U}$ , from UC on UC users  $I_{U/U}$ , and from UC on BC users  $I_{U/B}$ . In this chapter, there is one more signal type that is introduced by the nature of deployment of the BC network. It is the signal power received by a BC user and sent from a BCT other than the closest one. Here, we use the SFN configuration to minimize the utilization of the spectrum despite the need to synchronize all the BCTs (out of the scope of the thesis). The received power is partially useful and will be added to the received signal. This will be detailed later.

### 4.1.2 SINR definitions

Based on the defined hybrid network, and starting from the path loss model for the calculation of the received power, and to calculate the coverage probability and capacity, we start by the definitions of the SINR for the two networks.

For a typical BC user, we define the SINR as follows:

$$S_{BC} = \frac{\mathcal{P}_B g r_v^{-\beta} + \chi F}{\mathcal{P}_N + I_{U/B}} \quad (4.1)$$

where  $\mathcal{P}_B$  represents the transmitted power by the BCT,  $g$  is a random variable that represents the random behavior of the BC channel and has an exponential distribution, *i.e.*  $g \sim \exp(v)$  with  $v$  being the rate of the distribution,  $r_v$  represents the distance between the user and the closest BCT,  $\beta$  is the path loss exponent for BC transmission,  $\chi$

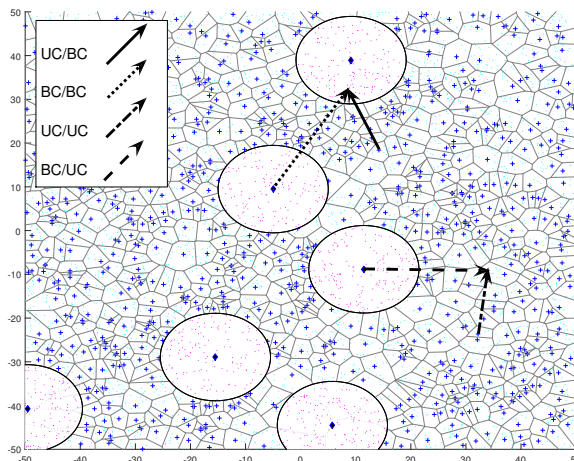


Figure 4.2 – An example of a service area, with  $\lambda_{BC} = \lambda_{BS}/200$  and  $r_b = 10$  km. The discs are BC zones (with BCTs in the middle), and the boxes with Voronoi tessellation are UC cells, with BSs in the middle of each (distances in km)

is a weighting factor for the usefulness of the received BC power and it will be discussed later, and  $\mathcal{P}_N$  is the noise power.  $I_{U/B}$  is expressed as follows:

$$I_{U/B} = \sum_{n \in \Phi'} \mathcal{P}_U h_n r_{s_n}^{-\alpha} \quad (4.2)$$

where  $\Phi'$  is the set of all UC BSs outside the BC zones,  $r_{s_n}$  is the distance between the user and the  $n^{\text{th}}$  interfering UC BS,  $h$  is a random variable that represents the random behavior of the UC channel and has an exponential distribution, *i.e.*  $h \sim \exp(\mu)$ , and here  $h_n$  refers to the channel between the user and the  $n^{\text{th}}$  interfering BS.  $\alpha$  is the path loss exponent for UC transmission.

On the other hand,  $F$  is the summation of all received signals from other BCTs. As stated in Chapter 2 (see Fig. 2.4), due to multiple received signals with different arrival times from SFN transmitters, the received signal from a transmitter arrives with a delay (with respect to the signal from the nearest BCT) that falls under one of the following cases:

- The delay is less than the guard interval. In this case, all received power is useful.
- The delay is larger than the guard interval but smaller than the total symbol time (symbol time+guard interval): a portion of the power is useful and the other is interference.
- The delay is larger than the total symbol duration, and thus all the received power is seen as interference.

The third case happens when the distance between the SFN transmitter and receiver is very large. Hence, the received power is very small, so it will not be included in our SINR expression. Even though it is well known that the non-useful power is counted as interference, but due to the small effect of such interference compared to other interference sources, it is neglected in the SINR definition we have introduced in (4.1) for simplification. The first two cases are approximated and modeled by a weighting factor  $0 \leq \chi \leq 1$  of the total received power  $F$  as an approximation to simplify the analysis. The latter is defined as:

$$F = \sum_{k \in \Xi \setminus i} \mathcal{P}_B g_k r_{t_k}^{-\beta} \quad (4.3)$$

where  $\Xi \setminus i$  is the set of all BCTs, excluding the serving BCT.  $r_{t_k}$  and  $h_k$  are the distance and channel from the BC user to the  $k^{\text{th}}$  BCT respectively.

On the other hand, for a typical UC user, the SINR is given by:

$$S_{UC} = \frac{\mathcal{P}_U h r_l^{-\alpha}}{\mathcal{P}_N + I_{U/U} + I_{B/U}} \quad (4.4)$$

where  $r_l$  is the distance between the user and the serving BS, and  $I_{U/U}$  is the total interference received by a UC user from the interfering BS, given by:

$$I_{U/U} = \sum_{n \in \Phi \setminus b} \mathcal{P}_U h_n r_{q_n}^{-\alpha} \quad (4.5)$$

where  $\Phi \setminus b$  is the set of all UC BSs excluding the serving BS,  $r_{q_n}$  is the distance between the user and the  $n^{\text{th}}$  interfering UC BS. In addition,  $I_{B/U}$  is defined by:

$$I_{B/U} = \sum_{k \in \Xi} \mathcal{P}_B g_k r_{d_k}^{-\beta} \quad (4.6)$$

where  $r_{d_k}$  is the distance from the  $k^{\text{th}}$  BCT. One can notice that the SINR models for both BC and UC look similar, but differences exist in the magnitude of the interference, path loss exponent and transmitted power.

### 4.1.3 PDF of link distances and useful probabilities

Before deriving the expressions for the PDFs of the link distances, it is important first to find the probabilities that a user is in BC and in UC networks. The probability of a user to be within a UC area, i.e. UC user, is to have no BCTs with a distance  $r_b$  or less. Thus it is given by the void probability of the BC PPP:

$$P_{UC} = \exp(-\lambda_{BC} \pi r_b^2) \quad (4.7)$$

Consequently, the probability of a user to be a BC user, the complementary of the probability being a UC user, is given by:

$$P_{BC} = 1 - \exp(-\lambda_{BC} \pi r_b^2) \quad (4.8)$$

Two essential PDFs must be calculated: (i) the PDF of  $r_v$ , the distance between a BC user and the serving BCT, and (ii) the PDF of  $r_l$ , the distance between a UC user and its serving BS.

The distribution of  $r_v$  needs more effort to be obtained so it will be discussed first. The related PDF is stated in the following Lemma.

**Lemma 4.1.** *Considering a hybrid network with multiple BCTs each having a circular coverage area with radius  $r_b$ , the PDF of the distance  $r_v$  between a typical BC user and its serving BCT is:*

$$f_{r_v}(r_v) = \frac{2\pi\lambda_{BC}r_v \exp(-\lambda_{BC}\pi r_v^2)}{1 - \exp(-\lambda_{BC}\pi r_b^2)} \quad (4.9)$$

*Proof.* The probability of a user to be a BC user and with distance  $r_v > R_v$  is the probability that there is no BCT closer to that user than  $R_v$ , and that there is at least one BCT in the strip between the circle of radius  $R_v$  and the circle with radius  $r_b$ . This probability is given by:

$$\begin{aligned} \mathbb{P}[(r_v > R_v) \cap BC] &= \exp(-\lambda_{BC}\pi R_v^2)(1 - \exp(-\lambda_{BC}\pi(r_b^2 - R_v^2))) \\ &= \exp(-\lambda_{BC}\pi R_v^2) \exp(-\lambda_{BC}\pi r_b^2) \end{aligned} \quad (4.10)$$



Now the probability of having  $r_v > R_v$  is given by:

$$\mathbb{P}[(r_v > R_v) | BC \text{ user}] = \frac{\mathbb{P}[(r_v > R_v) \cap BC \text{ user}]}{P_{BC}} \quad (4.11)$$

Substituting (4.8) and (4.10) in (4.11) gives the CCDF of  $r_v$ , and differentiating it will give the PDF stated in (4.9). ■

On the other hand, the PDF of  $r_l$  has been discussed in several previous works addressing stochastic geometry based network models and in this thesis. It is obtained based on (2.16), and by ignoring the cases of users at the edge of the BC area. It can be expressed as follows:

$$f_{r_l}(r_l) = 2\pi r_l \lambda_{BS} \exp(-\lambda_{BS} \pi r_l^2) \quad (4.12)$$

## 4.2 Probability of coverage

The probability of coverage, being defined as the probability that the SINR is larger than some threshold, is to be calculated here. The procedure for derivation is close to what was done in Chapter 3. However, since the structure of the network is more complicated, some approximations can be used to reduce the complexity of the derived formula. In fact, both UC BSs and BCTs are distributed according to a PPP, and the (UC/UC) interference is generated by the whole UC PPP except the gaps generated by BC areas in the interference points. For that reason, the UC network can be seen as a Poisson Hole Process (PHP) [241]. Analyzing a PHP can be done with different approaches. One approach is to consider the PHP as a new PPP with reduced density [221]. Another approach is to ignore the holes completely, leading to a lower bound for the probability of coverage by overestimating the interference [242]. In this section, the derivation for the general probability of coverage for BC and UC users is detailed. The general expressions of the LT of the interference are also calculated.

### 4.2.1 General expressions of probability of coverage

Let us first derive the probability of coverage  $P_{cBC}$  for **BC users**. It can be expressed in the following lemma.

**Lemma 4.2.** *The average probability of coverage  $P_{cBC}$  for BC users is given by:*

$$P_{cBC} = \frac{2\pi\lambda_{BC}}{1 - \exp(-\lambda_{BC}\pi r_b^2)} \int_0^{r_b} r_v \exp(-\pi\lambda_{BC}r_v^2) \exp\left(\frac{-vT_{BC}r_v^\beta \mathcal{P}_N}{\mathcal{P}_B}\right) \mathcal{L}_{I_{U/B}}\left(\frac{vT_{BC}r_v^\beta}{\mathcal{P}_B}\right) \mathcal{L}_F\left(\frac{-v\chi r_v^\beta}{\mathcal{P}_B}\right) dr_v \quad (4.13)$$

where  $T_{BC}$  is the SINR threshold for acceptable coverage in BC, and  $\mathcal{L}(\cdot)$  denotes the LT operator.

*Proof.* For BC network, the probability of coverage is the average probability that the SINR for a BC user  $S_{BC}$  is greater than a certain threshold  $T_{BC}$ . It can be derived as follows:

$$P_{cBC} = \mathbb{E}_{r_v} \left[ \mathbb{P}(S_{BC} > T_{BC} | r_v) \right] \quad (4.14)$$

$$= \int_0^{r_b} \mathbb{P}\left[g > \frac{T_{BC}r_v^\beta}{\mathcal{P}_B} (\mathcal{P}_N + I_{U/B} - \frac{\chi F}{T_{BC}}) | r_v\right] f_{r_v}(r_v) dr_v \quad (4.15)$$

But

$$\begin{aligned} \mathbb{P}[g > \frac{T_{BC}r_v^\beta}{\mathcal{P}_B}(\mathcal{P}_N + I_{U/B} - \frac{\chi^F}{T_{BC}}) \mid r_v] &= \mathbb{E}_{F, I_{U/B}} \left[ \exp \left( \frac{-vT_{BC}r_v^\beta}{\mathcal{P}_B}(\mathcal{P}_N + I_{U/B} - \frac{\chi^F}{T_{BC}}) \right) \right] \\ &= \exp \left( \frac{-vT_{BC}r_v^\beta \mathcal{P}_N}{\mathcal{P}_B} \right) \mathcal{L}_{I_{U/B}} \left( \frac{vT_{BC}r_v^\beta}{\mathcal{P}_B} \right) \mathcal{L}_F \left( \frac{-v\chi r_v^\beta}{\mathcal{P}_B} \right) \end{aligned} \quad (4.16)$$

The first step is valid if and only if  $(\mathcal{P}_N + I_{U/B} - \frac{\chi^F}{T_{BC}}) > 0$  and it follows the exponential distribution of the random variable  $g$ . In fact, the first step will lose some accuracy when the power from other BCTs is higher than the sum of the noise power and the (UC/UC) interference, and this will happen only when the BCTs are very close to each other, which is not the case in practice. Substituting in (4.14), and replacing  $f_{r_v}(r_v)$  by its value provides the final expression. ■

The derived expression averages the probability of coverage over two random components of the SINR: the random channel, and the random relative position of the user, *i.e.* the random distances to BSs and BCTs. The first LT corresponds to the interference power from UC BSs on the BC users, and the second LT corresponds to the received power from other BCTs. Expressions for both LTs are derived in the coming sections.

For **UC users**, the probability of coverage  $P_{cUC}$  has a similar definition as that of BC users, but using a dedicated threshold  $T_{UC}$ . This leads to Lemma 4.3.

**Lemma 4.3.** *The probability of coverage  $P_{cUC}$  of a UC user is as follows:*

$$P_{cUC} = 2\pi\lambda_{BS} \int_0^\infty r_l \exp(-\pi\lambda_{BS}r_l^2) \exp\left(\frac{-\mu T_{UC}r_l^\alpha \mathcal{P}_N}{\mathcal{P}_U}\right) \mathcal{L}_{I_{U/U}}\left(\frac{-\mu T_{UC}r_l^\alpha}{\mathcal{P}_U}\right) \mathcal{L}_{I_{B/U}}\left(\frac{-\mu T_{UC}r_l^\alpha}{\mathcal{P}_U}\right) dr_l \quad (4.17)$$

where  $T_{UC}$  is the SINR threshold for sufficient signal reception quality in UC.

*Proof.* The proof follows the same steps as for BC coverage probability. ■

Also for UC users, the probability of coverage is averaged over the random channel effect and the relative position of the users. The first LT corresponds to the interference power transmitted by the interfering UC BSs, while the second LT corresponds to the interference conducted by all the BCTs. Even though the two expressions for the probability of coverage for BC and UC users are not in closed forms, the integration is fairly straightforward since most of the LT expressions are in well tabulated special functions.

Finally, for a **general user** randomly positioned in the service area, the probability of coverage  $P_c$  can be seen as the linear combination between probabilities  $P_{cBC}$  and  $P_{cUC}$  previously calculated. This result is stated in Corollary 4.1.

**Corollary 4.1.** *The probability of coverage for a general user randomly located in the service area is as follows:*

$$P_c = (1 - \exp(-\lambda_{BC}\pi r_b^2))P_{cBC} + \exp(-\lambda_{BC}\pi r_b^2)P_{cUC} \quad (4.18)$$

*Proof.* The total probability of coverage for a given user is given by:

$$P_c = P_{BC}P_{cBC} + P_{UC}P_{cUC} \quad (4.19)$$

where  $P_{BC}$  is the probability that a user is within a broadcast domain, and  $P_{UC}$  is the probability that a user is not in any BC domain.  $P_{BC}$  is as shown in (4.8), and  $P_{UC}$  is its complementary shown in (4.7). Substituting both in (4.19) gives (4.18). ■

### 4.2.2 Evaluation of the LTs of the BC signals

The target here is to give the LTs of the BC signals, i.e.  $F$  and  $I_{B/U}$  as they are easily deduced from Theorem 2.1. The LT of  $F$  on a BC user is independent from the BB network, and thus is independent from the BS density. It is given by the following corollary.

**Corollary 4.2.** *The LT of the additional received BC power by BC users can be expressed as:*

$$\mathcal{L}_F\left(\frac{-v\chi r_v^\beta}{\mathcal{P}_B}\right) = \exp\left(\frac{2\pi\lambda_{BC}\chi r_v^2}{\beta-2} {}_2F_1\left(1, 1 - \frac{2}{\beta}; 2 - \frac{2}{\beta}; \chi\right)\right) \quad (4.20)$$

*Proof.* Since the received power is due to the BCT distribution, and knowing that the nearest source is  $r_v$  away, the general formula introduced in Theorem 2.1 can be used. Starting from the definition of the added power in (4.3), and substituting  $s = \frac{-v\chi r_v^\beta}{\mathcal{P}_B}$ , the expression in (4.20) is obtained. ■

The problem turns out to find the LT of BCT interference on UC users, i.e.  $I_{B/U}$ . It is given by the following corollary.

**Corollary 4.3.** *The LT of the interference originated by the BCT on a UC user is expressed as:*

$$\mathcal{L}_{I_{B/U}}\left(\frac{\mu T_{UC} r_l^\alpha}{\mathcal{P}_U}\right) = \exp\left(-\frac{2\pi\lambda_{BC}\mu\mathcal{P}_B T_{UC} r_b^{2-\beta} r_l^\alpha}{v\mathcal{P}_U(\beta-2)} {}_2F_1\left(1, 1 - \frac{2}{\beta}; 2 - \frac{2}{\beta}; -\frac{\mathcal{P}_B\mu r_l^\alpha T_{UC}}{\mathcal{P}_U v r_b^\beta}\right)\right) \quad (4.21)$$

*Proof.* The interference is originated by a PPP modeling of the BCTs, and since the user is served by UC, then the nearest interference source is at least beyond the distance  $r_b$ , then the expression derived in Theorem 2.1 also applies here. By using the interference definition in (4.6), and with substituting  $s = \frac{\mu T_{UC} r_l^\alpha}{\mathcal{P}_U}$ , the expression in (4.21) is obtained. ■

## 4.3 Simplified expressions for the probability of coverage

The expressions of the LTs given in (4.20) and (4.21) are easily handled. However, this is not the case for BS interference signals  $I_{U/B}$  and  $I_{U/U}$  in (4.13) and (4.17), which makes the probability of coverage expression harder to evaluate. To simplify the problem, we adopt two different approaches for these interference terms, detailed next.

### 4.3.1 Approach 1: Evaluation of the LT of the BS interference using a reduced PPP

As mentioned earlier, the PPP of the UC network with density  $\lambda_{BS}$  can be seen as a PHP due to the void areas created by the BC zones. In this approach, the PHP is approximated by a new PPP with a reduced density  $\lambda'_{BS}$  (approximation 1). It gives an underestimate for the interference, since in the new reduced-density area all the interfering BSs are farther on average. Hence, the probability of coverage will be overestimated (upper-bound). The new density  $\lambda'_{BS}$  is given by:

$$\lambda'_{BS} = \lambda_{BS} e^{-\lambda_{BC}\pi r_b^2} \quad (4.22)$$

A complete derivation of this can be found in III-B in [241].

Let us first start with the case of the UC BS interference on BC users, i.e.  $I_{U/B}$ . Since the distance from the nearest interfering BS is not fixed, and since the density of the interference sources is not constant in the area around the user because of the random relative position of the user, the derived final expression in Theorem 2.1 can't be used. However, a similar approach for the derivation can be made and yields the following result of Lemma 4.4.

**Lemma 4.4.** *Assuming a reduced density PPP model for the UC sub-network of a hybrid network with multiple BC stations, the LT of interference of UC BSs on BC users is as follows:*

$$\begin{aligned} \mathcal{L}_{I_{U/B}}^u \left( \frac{vT_{BC}r_v^\beta}{\mathcal{P}_B} \right) &= \exp \left( \lambda'_{BS} \int_{r_b-r_v}^{r_b+r_v} \frac{2r_s \arccos \left( \frac{r_s^2 - r_v^2 - r_b^2}{2r_s r_v} \right)}{1 + \frac{\mu \mathcal{P}_B r_s^\alpha}{v \mathcal{P}_U T_{BC}}} dr_s \right) \\ &\exp \left( - \frac{2\pi \lambda'_{BS} v \mathcal{P}_U T_{BC} (r_b - r_v)^{2-\alpha}}{\mu \mathcal{P}_B (\alpha-2)} {}_2F_1 \left( 1, 1 - \frac{2}{\alpha}; 2 - \frac{2}{\alpha}; \frac{-\mathcal{P}_U v T_{BC}}{\mathcal{P}_B \mu (r_b - r_v)^\alpha} \right) \right) \end{aligned} \quad (4.23)$$

The superscript  $u$  stands for upper-bound.

*Proof.* Let  $s_1 = \frac{vT_{BC}r_v^\beta}{\mathcal{P}_B}$ . The first LT can be evaluated as following:

$$\begin{aligned} \mathcal{L}_{I_{U/B}}(s_1) &= \mathbb{E}_{\Phi, h} [\exp(-s_1 I_{U/B})] \\ &= \mathbb{E}_{\Phi, h} [\exp(-s_1 \sum_{n \in \mathcal{N}} \mathcal{P}_U h_n r_{s_n}^{-\alpha})] \\ &= \exp \left( -\lambda'_{BS} \int_{\mathbb{R}^2 \setminus \mathcal{G}} \frac{1}{1 + \frac{\mu r_s^\alpha}{s_1 \mathcal{P}_U}} \right) \end{aligned}$$

The steps are identical to standard LT calculation. The integral is applied on the whole 2-D plane excluding the gap created by the absence of any interferer inside the BC zone. The result will then be:

$$\mathcal{L}_{I_{U/B}}(s_1) = \exp \left( -\lambda'_{BS} \int_{r_b-r_v}^{\infty} \frac{2\pi r_s}{1 + \frac{\mu r_s^\alpha}{s_1 \mathcal{P}_U}} dr_s + \lambda'_{BS} \int_{r_b-r_v}^{r_b+r_v} \frac{2r_s \arccos \left( \frac{r_s^2 - r_v^2 - r_b^2}{2r_s r_v} \right)}{1 + \frac{\mu r_s^\alpha}{s_1 \mathcal{P}_U}} dr_s \right) \quad (4.24)$$

Substituting  $s_1$  by its value, and applying (2.15) on the first term gives the final expression as in (4.23).  $\blacksquare$

The derivation is done by calculating the interference produced by the entire service area, then subtracting the interference from the BC zone (as it does not cause interference), hence creating the additional exponential term in the expression.

Now we focus on the LT of UC BS interference on UC users, i.e.  $I_{U/U}$ , which is calculated in the following corollary.

**Corollary 4.4.** *Starting from approximation 1, the LT of the interference of UC BS transmission on the UC users is given by:*

$$\mathcal{L}_{I_{U/U}}^u \left( \frac{\mu T_{UC} r_l^\alpha}{\mathcal{P}_U} \right) = \exp \left( - \frac{2\pi \lambda'_{BS} r_l^2 T_{UC}}{\alpha - 2} {}_2F_1 \left( 1, 1 - \frac{2}{\alpha}; 2 - \frac{2}{\alpha}; -T_{UC} \right) \right) \quad (4.25)$$

*Proof.* Based on PPP modeling and since the nearest interference source is at least at distance  $r_l$  (the serving distance), Theorem 2.1 applies. Starting from the definition of the interference stated in (4.5), and setting  $s = \frac{\mu T_{UC} r_l^\alpha}{\mathcal{P}_U}$ , the expression in (4.25) is obtained.  $\blacksquare$

### 4.3.2 Approach 2: Evaluation of the LT of the BS interference by ignoring gaps

In this approach, the gaps (areas) of the BB interference sources are completely ignored, i.e. the interferers are considered to be in the whole plane (approximation 2). This will overestimate the interference, and thus give a lower bound for the probability of coverage for BC, UC, and general users. Here, the analytical derivations are the same as with approach 1, but with one minor change: the density of the original PPP is used instead of the modified density, i.e.  $\lambda_{BS}$  instead of  $\lambda'_{BS}$ .

**Corollary 4.5.** *Based on the second approach, the LT of the interference sourced by the BB network on a BC user is expressed as:*

$$\begin{aligned} \mathcal{L}_{I_{U/B}}^l \left( \frac{vT_{BC}r_v^\beta}{\mathcal{P}_B} \right) &= \exp \left( \lambda_{BS} \int_{r_b-r_v}^{r_b+r_v} \frac{2r_s \arccos \left( \frac{r_s^2 - r_v^2 - r_b^2}{2r_s r_v} \right)}{1 + \frac{\mu \mathcal{P}_B r_s^\alpha}{v \mathcal{P}_U T_{BC}}} dr_s \right) \\ &\exp \left( -\frac{2\pi \lambda_{BS} v \mathcal{P}_U T_{BC} (r_b - r_v)^{2-\alpha}}{\mu \mathcal{P}_B (\alpha-2)} {}_2F_1 \left( 1, 1 - \frac{2}{\alpha}; 2 - \frac{2}{\alpha}; \frac{-\mathcal{P}_U v T_{BC}}{\mathcal{P}_B \mu (r_b - r_v)^\alpha} \right) \right) \end{aligned} \quad (4.26)$$

The superscript  $l$  stands for lower-bound.

*Proof.* Same steps as in Lemma 4.4 ■

The same applies for  $I_{U/U}$  by changing  $\lambda'_{BS}$  to  $\lambda_{BS}$ :

**Corollary 4.6.** *Starting from the second approximation by ignoring the gaps in the BB network, the LT of the inter-cell interference of UC BSs on a UC user is as follows:*

$$\mathcal{L}_{I_{U/U}}^l \left( \frac{\mu T_{UC} r_l^\alpha}{\mathcal{P}_U} \right) = \exp \left( \frac{2\pi \lambda_{BS} r_l^2 T_{UC}}{\alpha-2} {}_2F_1 \left( 1, 1 - \frac{2}{\alpha}; 2 - \frac{2}{\alpha}; -T_{UC} \right) \right) \quad (4.27)$$

*Proof.* Based on PPP modeling and since the nearest interference source is at least at distance  $r_l$  (the serving distance), Theorem 2.1 applies. Starting from the definition of the interference stated in (4.5), and setting  $s = \frac{\mu T_{UC} r_l^\alpha}{\mathcal{P}_U}$ , the expression in (4.25) is obtained. ■

### 4.3.3 Evaluation of the upper and lower bounds of the coverage probability

As mentioned earlier, the expressions of the probability of coverage for BC and UC users in (4.13) and (4.17) respectively are too complicated if the LT terms are to be evaluated exactly. However, the two approximations allow less complex expressions, that correspond to a lower and upper bounds of the interference terms.

**Theorem 4.1.** *The upper bound of the probability of coverage for the BC user is given by:*

$$P_{c_{BC}}^u = \frac{2\pi \lambda_{BC}}{1 - \exp(-\lambda_{BC} \pi r_b^2)} \int_0^{r_b} r_v \exp(-\pi \lambda_{BC} r_v^2) \exp \left( \frac{-v T_{BC} r_v^\beta \mathcal{P}_N}{\mathcal{P}_B} \right) \mathcal{L}_{I_{U/B}}^u \left( \frac{v T_{BC} r_v^\beta}{\mathcal{P}_B} \right) \mathcal{L}_F \left( \frac{-v \chi r_v^\beta}{\mathcal{P}_B} \right) dr_v \quad (4.28)$$

and the upper bound of the probability of coverage for UC users is given by:

$$P_{c_{UC}}^u = 2\pi \lambda_{BS} \int_0^\infty r_l \exp(-\pi \lambda_{BS} r_l^2) \exp \left( \frac{-\mu T_{UC} r_l^\alpha \mathcal{P}_N}{\mathcal{P}_U} \right) \mathcal{L}_{I_{U/U}}^u \left( \frac{-\mu T_{UC} r_l^\alpha}{\mathcal{P}_U} \right) \mathcal{L}_{I_{B/U}} \left( \frac{-\mu T_{UC} r_l^\alpha}{\mathcal{P}_U} \right) dr_l \quad (4.29)$$

*Proof.* In the first approximation, the PHP is approximated by a PPP with a reduced density. The reduction in density means that the point process will be stretched, interfering points will be further away from the user in all directions. Assuming the actual interference to be (general notation that can apply to both BC and UC cases):

$$I^{actual} = \sum_{n \in \Theta \setminus b} \mathcal{P} l_n r_{a,n}^{-\alpha} \quad (4.30)$$

where  $r_{a,n}$  and  $l_n$  are respectively the actual distance and the channel to the  $n^{th}$  interferer, and the calculated interference to be:

$$I^{calc} = \sum_{n \in \Theta \setminus b} \mathcal{P} l_n r_{c,n}^{-\alpha} \quad (4.31)$$

where  $r_{c,n}$  is the calculated distance from the  $n^{\text{th}}$  interferer, and since in both cases the size of the sum, the transmission power, and channel coefficient are the same, the only difference lies in the distance. Because of the approximation by changing the density and the expansion of the PPP, the calculated distance will be higher on average than the actual one:

$$r_c > r_a \implies I^{\text{calc}} < I^{\text{actual}} \implies \mathcal{L}_{I^{\text{calc}}}(s) > \mathcal{L}_{I^{\text{actual}}}(s)$$

The last step follows from the non-negative  $s$ . Applying this to both  $\mathcal{L}_{I_{U/U}}(s)$  and  $\mathcal{L}_{I_{U/B}}(s)$  gives:

$$\mathcal{L}_{I_{U/U}}^u(s) > \mathcal{L}_{I_{U/U}}(s) \quad (4.32)$$

and

$$\mathcal{L}_{I_{U/B}}^u(s) > \mathcal{L}_{I_{U/B}}(s) \quad (4.33)$$

and since the rest of the terms in the coverage probability expressions are the same, then  $P_{cBC}^u$  and  $P_{cUC}^u$  provides upper limits for the coverage probability for BC and UC users respectively. ■

**Theorem 4.2.** *The lower bound of the probability of coverage for the BC user can be written as:*

$$P_{cBC}^l = \frac{2\pi\lambda_{BC}}{1 - \exp(-\lambda_{BC}\pi r_b^2)} \int_0^{r_b} r_v \exp(-\pi\lambda_{BC}r_v^2) \exp\left(\frac{-vT_{BC}r_v^\beta \mathcal{P}_N}{\mathcal{P}_B}\right) \mathcal{L}_{I_{U/B}}^l\left(\frac{vT_{BC}r_v^\beta}{\mathcal{P}_B}\right) \mathcal{L}_F\left(\frac{-v\chi r_v^\beta}{\mathcal{P}_B}\right) dr_v \quad (4.34)$$

and the lower bound of the probability of coverage for UC users can be expressed:

$$P_{cUC}^l = 2\pi\lambda_{BS} \int_0^\infty r_l \exp(-\pi\lambda_{BS}r_l^2) \exp\left(\frac{-\mu T_{UC}r_l^\alpha \mathcal{P}_N}{\mathcal{P}_U}\right) \mathcal{L}_{I_{U/U}}^l\left(\frac{-\mu T_{UC}r_l^\alpha}{\mathcal{P}_U}\right) \mathcal{L}_{I_{B/U}}\left(\frac{-\mu T_{UC}r_l^\alpha}{\mathcal{P}_U}\right) dr_l \quad (4.35)$$

*Proof.* In this approximation, the gaps are ignored. This leads to count more BSs as interfering sources than the actual number. Denote the actual interference by (general notation that can apply for both BC and UC users):

$$I^{\text{actual}} = \sum_{n \in \Theta'} \mathcal{P}l_n r_n^{-\alpha} \quad (4.36)$$

and denote the calculated interference in this approximation by:

$$I^{\text{calc}} = \sum_{n \in \Theta} \mathcal{P}l_n r_n^{-\alpha} \quad (4.37)$$

Since the terms in the sum are the same and always positive, the value of the sum depends on its size. Since  $\Theta' \subset \Theta$ , then  $I^{\text{calc}} \geq I^{\text{actual}}$ , and consequently:

$$\mathcal{L}_{I^{\text{calc}}}^l(s) \leq \mathcal{L}_{I^{\text{actual}}}(s) \quad (4.38)$$

for non-negative  $s$ . Applying this to both  $\mathcal{L}_{I_{U/U}}(s)$  and  $\mathcal{L}_{I_{U/B}}(s)$  gives:

$$\mathcal{L}_{I_{U/B}}^l(s) \leq \mathcal{L}_{I_{U/B}}(s) \quad (4.39)$$

and

$$\mathcal{L}_{I_{U/U}}^l(s) \leq \mathcal{L}_{I_{U/U}}(s) \quad (4.40)$$

Plugging the lower limits of the LTs in the coverage expressions creates a lower bound for the coverage as in (4.34) and (4.35). ■

Table 4.1 – Simulation parameters for the multi-BC/UC model

| Parameter                                  | Value                   | Parameter       | Value       |
|--|-------------------------|-----------------|-------------|
| $\mathcal{P}_U, \mathcal{P}_B$ (isotropic) | 1.2 & 17 kW             | $r_b$           | 10 km       |
| $W_{BC}, W_{UC}$                           | 8 & 20 MHz              | $\mathcal{P}_N$ | -141 dBm/Hz |
| $\alpha, \beta$                            | 3.4 & 3.2               | $\mu, \nu$      | 1 & 1       |
| $\lambda_{BS}, \lambda_U$                  | 0.15, 1/km <sup>2</sup> | $N^{RB}$        | 100 RB/cell |

### 4.3.4 Verification of the derived expressions

Therein, the expressions derived for the coverage probability are compared to the Monte-Carlo simulation results.

#### 4.3.4.1 Simulation setting

The service area is selected to be a square area of side equal to 100 km, with variable BC radius and BC density. Throughout this section,  $\chi$  is set to 0.8. This value was concluded from simulations based on the model presented in [236] for DVB-T2 in 8 MHz bandwidth and 8K mode (often used for mobile reception) reported in [243]. Default simulation settings are summarized in Table 4.1. These settings will result in a similar deployment as the example in Fig. 4.2.

#### 4.3.4.2 Comparison and verification

Fig 4.3 shows that the derived expressions for the probability of coverage match perfectly with the simulation results whatever the threshold  $T$  is, except for very low thresholds for BC users. These limitations were explained through the derivation of the coverage probability in Appendix A. Furthermore, it can be seen that approximation 1 (from expressions (4.28) and (4.29) ) represents an upper bound while approximation 2 (from expressions (4.34) and (4.35) ) represents a lower bound for the actual coverage as expected in the theorems. Both approximations have good accuracy, with an advantage to the lower bound, which almost overlaps the simulation results.

## 4.4 Capacity and network efficiency

In this section, we consider the capacity, or the maximum achievable rate. The maximum spectral efficiency is firstly derived. Then, the average capacity of the hybrid network is considered, followed by the system capacity and a power efficiency metric.

### 4.4.1 Ergodic capacity

The normalized user capacity is related only to the SINR of the received signal. For BC users, it is given by the following lemma.

**Lemma 4.5.** *The ergodic capacity of a BC user is given by:*

$$\begin{aligned}
C_{BC} &= \frac{2\pi\lambda_{BC}}{1 - \exp(-\lambda_{BC}\pi r_b^2)} \int_0^{r_b} r_v \exp(-\lambda_{BC}\pi r_v^2) \int_0^\infty \exp\left(\frac{-\nu u r_v^\beta \mathcal{P}_N}{\mathcal{P}_B}\right) \\
&\quad \mathcal{L}_{I_{U/B}}\left(\frac{\nu u r_v^\beta}{\mathcal{P}_B}\right) \mathcal{L}_F\left(\frac{\nu \gamma r_v^\beta}{\mathcal{P}_B}\right) \frac{1}{\ln(2)(u+1)} du dr_v
\end{aligned} \tag{4.41}$$

*Proof.* Same steps as in D.1. Since  $F$  is independent of  $I_{U/B}$ , the final step is applicable. An additional substitution with  $u = 2^t - 1$  is done at the last step to simplify the expression. ■

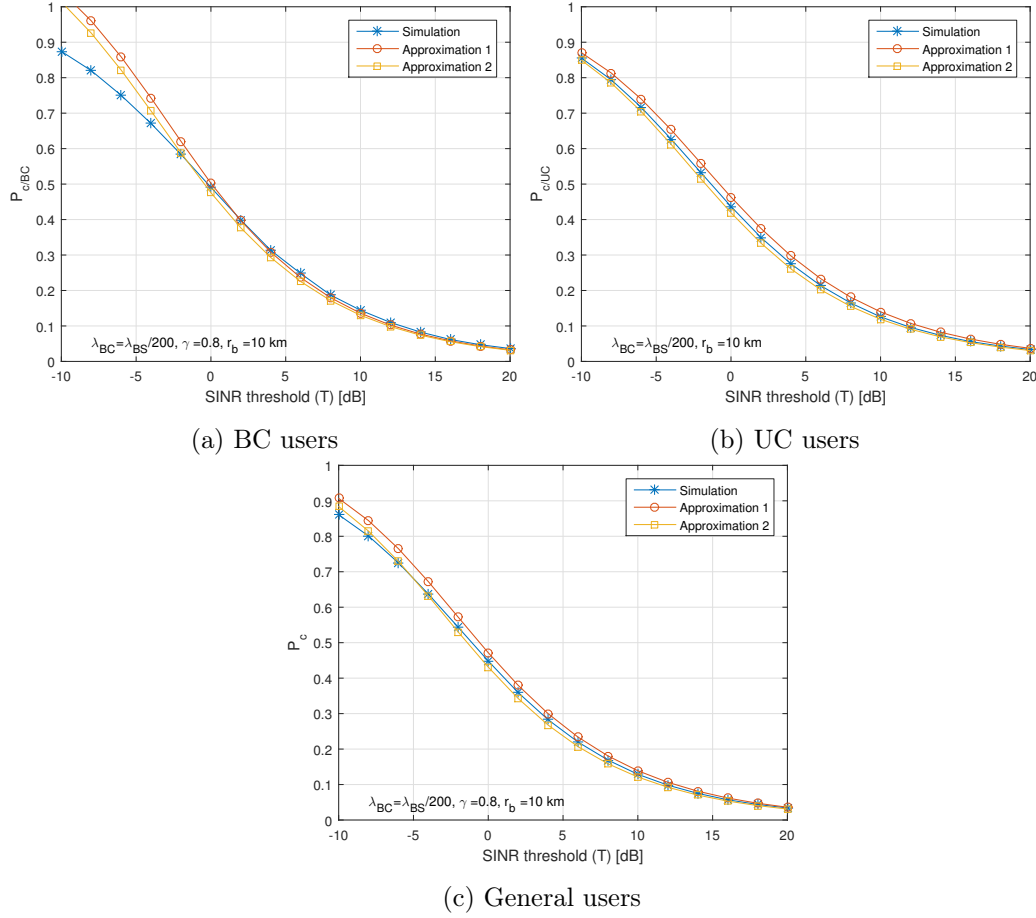


Figure 4.3 –  $P_c$  for BC, UC and general users for  $r_b = 10$  km,  $\chi = 0.8$  and  $\lambda_{BC} = \lambda_{BS}/200$

The LT terms in (4.41) are the same as in (4.13), hence they are used in the derivations. Similarly, the ergodic capacity for UC users can be calculated.

**Lemma 4.6.** *The ergodic capacity for a UC user is given by:*

$$\begin{aligned}
 C_{UC} &= 2\pi\lambda_{BS} \int_0^\infty r_l \exp(-\lambda_{BS}\pi r_l^2) \int_0^\infty \exp\left(\frac{-\mu u r_l^\alpha \mathcal{P}_N}{\mathcal{P}_U}\right) \\
 &\quad \mathcal{L}_{I_{U/U}}\left(\frac{\mu u r_l^\alpha}{\mathcal{P}_U}\right) \mathcal{L}_{I_{B/U}}\left(\frac{\mu u r_l^\alpha}{\mathcal{P}_U}\right) \frac{1}{\ln(2)(u+1)} du dr_l
 \end{aligned} \tag{4.42}$$

*Proof.* Similar steps to that of the BC capacity are followed. ■

The form of (4.42) is close to that of the probability of coverage for UC users presented in (4.17), but with one more averaging level. The LT therein can be evaluated using (4.25) and (4.21) with a simple change of parameters.

For a general user, the capacity is the combination between the two capacities, given by:

$$C = P_{BC}C_{BC} + P_{UC}C_{UC} \tag{4.43}$$

#### 4.4.2 Average system capacity

The derivations above are given for the average spectral efficiency. However, it is useful to calculate the average system capacity, or the total capacity achieved by all the users in



the service area. The system capacity is the sum of capacities of the two networks, and it could be defined as following:

$$C^{sys} = C_{BC}^t + C_{UC}^t \quad (4.44)$$

where  $C_{BC}^t$  is the total capacity of the BC network and  $C_{UC}^t$  is the total capacity of the UC network.

**Corollary 4.7.** *Following the definition in (4.44), the system capacity of a hybrid network with multiple BCTs is given by:*

$$C^{sys} = A \exp(-\lambda_{BC}\pi r_b^2) C_{UC} \lambda_{BS} N^{RB} W^{RB} + \lambda_U A (1 - \exp(-\lambda_{BC}\pi r_b^2)) P_{c,i} C^{req} \quad (4.45)$$

where  $A$  is the service area,  $N^{RB}$  is the total number of resource blocks available for a cell BS, and  $W^{RB}$  is the bandwidth of a single resource block.

*Proof.* The capacity of the UC network is the sum of the UC users' capacities, or the product of the average user capacity and the number of users:

$$\begin{aligned} C_{UC}^t &= M_{UC} C_{UC} W^{user} \\ &= \lambda_U A P_{UC} C_{UC} N^{RB/user} W^{RB} \\ &= \lambda_U A \exp(-\lambda_{BC}\pi r_b^2) C_{UC} \frac{\lambda_{BS}}{\lambda_U} N^{RB} W^{RB} \end{aligned} \quad (4.46)$$

where  $M_{UC} = \lambda_U A$  is the number of users in the service area,  $W^{user}$  is the bandwidth allocated to a user, and  $N^{RB/user} = \frac{\lambda_{BS}}{\lambda_U} N^{RB}$  is the average number of resource blocks allocated to a user following a uniform allocation for resources. The second step follows the uniform distribution of users, and the final step follows the assumption of a uniform allocation of resource and substituting the UC probability by its expression. As for the total capacity of the BC network, its derivation is done differently. Indeed, as the BCT is broadcasting with a predetermined data rate, the total capacity is the number of connected users multiplied by the predefined rate, which is in this case, the minimum required capacity for a user to be connected ( $C^{req}$ ):

$$\begin{aligned} C_{BC}^t &= N_U^{BC} C^{req} \\ &= \lambda_U A P_{BC} P_{c/BC} C^{req} \\ &= \lambda_U A (1 - \exp(-\lambda_{BC}\pi r_b^2)) P_{cBC} C^{req} \end{aligned} \quad (4.47)$$

Adding the two expressions completes the proof. ■

Note that the total UC capacity is independent of user density, since the available resources in a cell will be allocated for whatever the number of users would be in that cell. For BC, however, the total capacity depends on the user density, and it is independent of the average user capacity.

### 4.4.3 Power efficiency

The power efficiency of the system, or the normalized system capacity is defined as the ratio between the system capacity and the total transmitted power as defined in (2.20). In this model, it is given by:

$$\begin{aligned} \eta_P &:= \frac{C^{sys}}{\sum \mathcal{P}_B + \sum \mathcal{P}_U} \\ &= \frac{\lambda_U P_{BC} P_{cBC} C^{req} + P_{UC} C_{UC} \lambda_{BS} N^{RB} W^{RB}}{\lambda_{BC} \mathcal{P}_B + \lambda_{BS} \mathcal{P}_U} \end{aligned} \quad (4.48)$$

This metric includes all the important design parameters: the BC radius  $r_b$  which is embedded in  $P_{UC}$ ,  $P_{BC}$ ,  $P_{cBC}$ , and  $P_{cUC}$ , the BCT density  $\lambda_{BC}$ , the BS density  $\lambda_{BS}$ , the

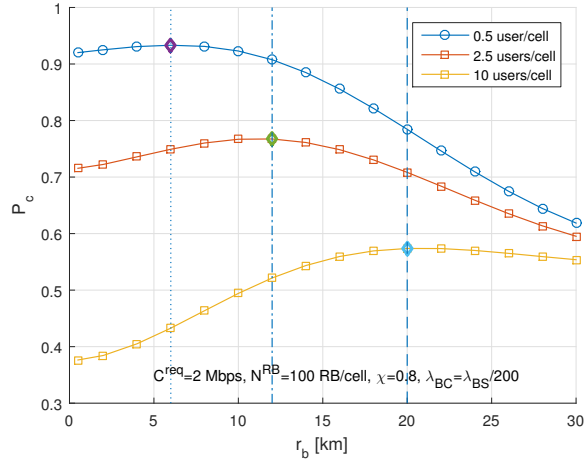


Figure 4.4 – Probability of coverage versus the BC radius

transmission powers  $\mathcal{P}_B$  and  $\mathcal{P}_U$  and also depends on the density of the users in the service area  $\lambda_U$ .

In fact, it will be extremely complicated to calculate the optimal operation point directly from this formula. Instead, numerical evaluation of the above equation will be given later for different working conditions.

## 4.5 Network optimization

In this part, we aim at finding an optimal point of operation for the hybrid network in terms of two of the key design parameters: BC radius  $r_b$ , and BCT density  $\lambda_{BC}$ . The metrics used for evaluation are the probability of coverage, the spectral efficiency, and the network power efficiency. Since the derived expressions are proved to be accurate (lower bounds in particular), they will be exclusively used for the rest of the chapter.

### 4.5.1 Optimization of coverage

Maximizing the probability of coverage is a key design goal. Fig. 4.4 shows the average probability of coverage as a function of the BC radius  $r_b$  with three different values of user density. The figure shows that an optimal point where the coverage is maximized does exist.

In a UC network, higher user density means lower average allocated bandwidth for each user, which will reduce the number of covered users. Then, more contribution is needed from the BC side, which results in a higher optimal  $r_b$ .

Fig. 4.5 shows that increasing the density of BCT enhances the coverage except the case with very low user density, as expected. The higher the number of BCT, the more users are connected to the BC, and because of the relatively higher coverage of the BC, the higher the coverage will be. Moreover, it can be noticed that the rate of growth for the coverage probability increases with the user density of the network. As expected, for low user density, the BB network can handle the service alone, and any additional BCT density will not affect the coverage.

### 4.5.2 Optimization of spectral efficiency

Spectral efficiency gives an indication on the capability of the system to properly use spectral resources. With the limited available band in the BB network, it is important to optimize the spectral efficiency of the hybrid network.

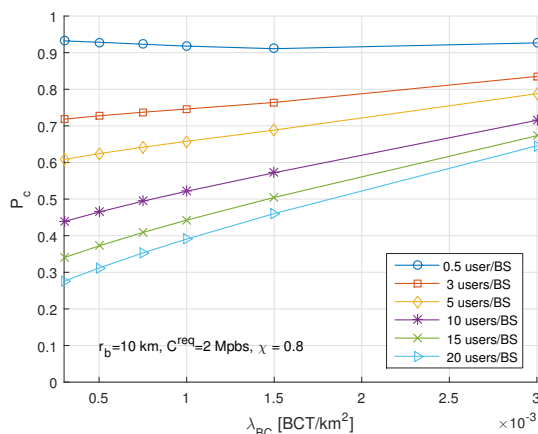


Figure 4.5 – Probability of coverage versus the density of BCT

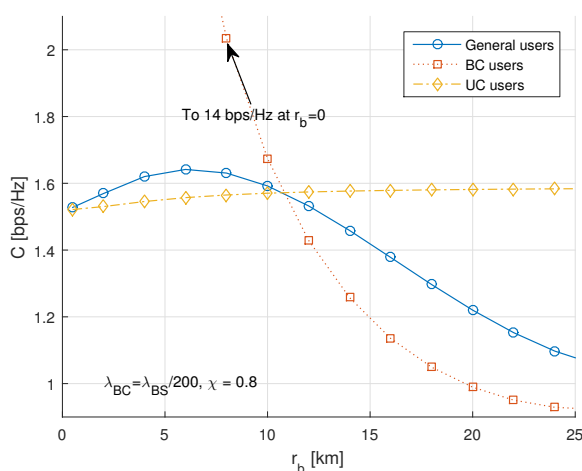


Figure 4.6 – Spectral efficiency versus the BC radius

Fig. 4.6 provides the optimum BC radius that maximizes the average spectral efficiency of the users. Note that the normalized capacity is independent of the SINR threshold and consequently from user density. Results in Fig. 4.6 indicate that adding the BC component to a BB network increases the spectral efficiency, especially for users that are within an optimum radius of the BCT (note that  $r_b = 0$  corresponds to BB network). However, after a certain point of the BCT radius, the edge users whose number increases with the radius  $r_b$  become far from the BCT, and consequently get lower capacity.

For the same BC radius, the effect of BCT density on the spectral efficiency is studied next. Note that the total BC power is maintained, so the transmission power of a single BCT decreases as we increase the BCT density. It can be seen from Fig. 4.7 that increasing the number of BCTs degrades the BC spectral efficiency. Even though increasing the BCT density will reduce the interference from the UC BSs and enhance the received power for BC users, the reduction in transmission power for each BCT appears to be a dominant factor, therefore reducing the global spectral efficiency. The results show that the best capacity-wise performance is achieved when the density of the BCT is low (around 1.63), in contrary to that of the BB BSs. This indicates that scale diversity of the hybrid approach (combination of the dense and sparse networks) is a key factor in the design.

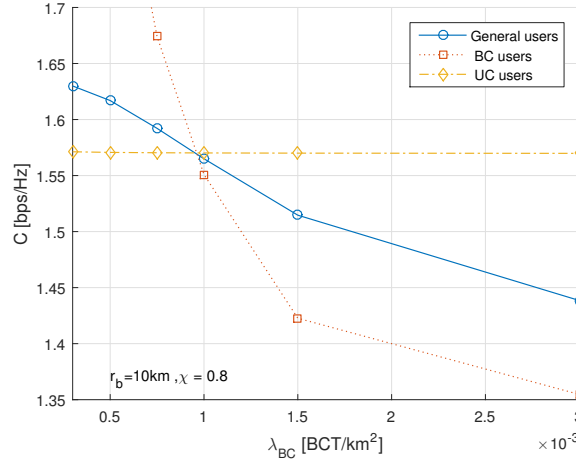
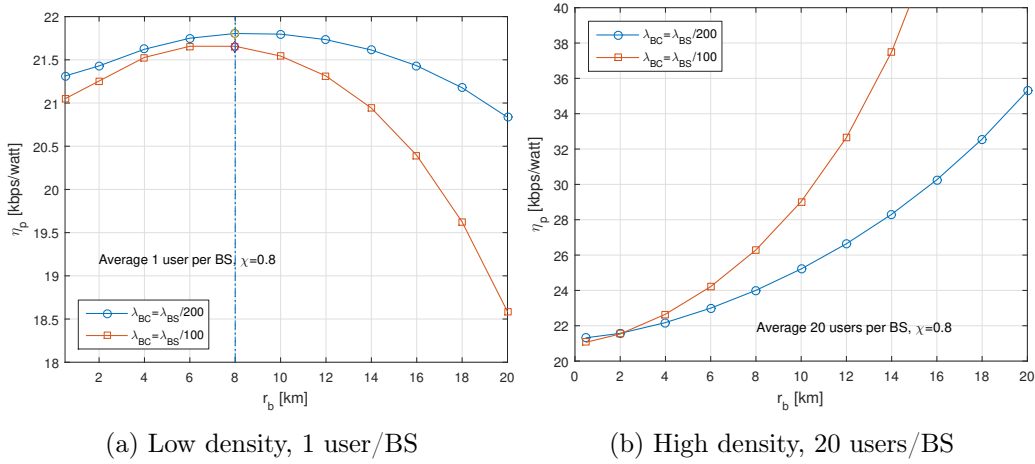


Figure 4.7 – Spectral efficiency versus the density of BCT



(a) Low density, 1 user/BS

(b) High density, 20 users/BS

 Figure 4.8 – Power efficiency of a service area with  $\gamma = 0.8$  and for different loading scenarios

### 4.5.3 Optimization of power efficiency

Maximum coverage can theoretically be achieved by covering the whole service area by a large number of BCTs with small BC radius. However, such a solution requires a huge amount of energy, and thus is not feasible. The power efficiency derived in (4.48) is a suitable metric to assess achievable system capacity taking power consumption into consideration. Fig. 4.8 illustrates the variation of power efficiency as a function of BC radius for two values of BCT density, and for low and high user density.

In a service area with low user density, as shown in Fig. 4.8a with an average of 1 user per BS (requesting mobile TV service), increasing the BC radius enhances the power efficiency of the network until the optimal radius is reached. Beyond this point, expanding the BC zone will add more edge BC users, without introducing any gain in coverage and capacity, which reduces the power efficiency.

In contrary, Fig. 4.8b shows that for a service area with high user density, higher  $r_b$  will always produce greater efficiency, due to the overload on the BB network. Expanding the BC contribution in a user-dense area by rising  $r_b$  will take out power consuming UC BSs, and serve more users by including them in the BC network, and consequently increases the efficiency.

Results in Fig. 4.9 reveal that rising the BCT density affects the power efficiency differently depending on the user density. For low user density (like the curve of 0.5

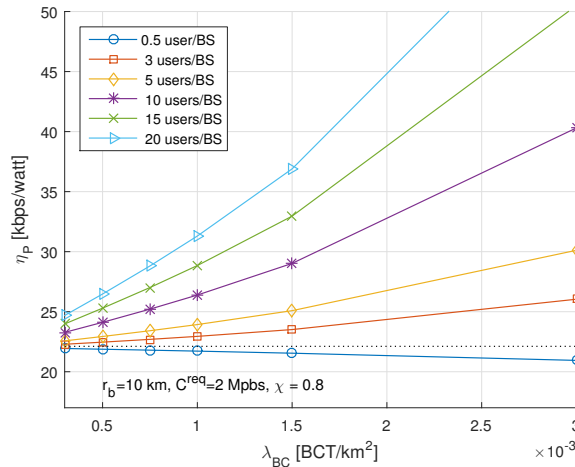


Figure 4.9 – Power efficiency of a service area versus BCT density

users/BS), where BB can manage to deliver enough bandwidth to the users, increasing the number of BCTs will add a huge amount of power load without having a significant added value to the coverage and capacity. When the area is dense (like in the curves of 15 and 20 users/BS), adding more BCT will offload the users to the BC network, and take out the BSs because of their excessive power consumption. Consequently, this increases the power efficiency.

## 4.6 Summary and conclusion

In this chapter, we introduced and evaluated a zone-based hybrid BC/BB network, with multiple BCTs deployment in the BC network, and UC mode used in the BB network. The model was analyzed using stochastic geometry to estimate the coverage probability, capacity, and power efficiency.

Therein, two approximations for the obtained PHP were used to simplify the analysis (the original and the modified PPPs) in order to derive upper and lower bounds for the selected metrics. The resulting expressions were verified through extensive Monte-Carlo simulations, showing a high accuracy. The derived expressions were then used to numerically optimize the hybrid network performance in terms of coverage, spectral efficiency, and power efficiency, as a function of the key design parameters, that is the BC radius and the BCT density. Results showed that the hybrid approach brings in the best performance excluding the extreme cases of a very low and very high number of users. Hereby, it was proved that optimal operating points exist, which are governed by the BC radius and BCT density.

As can be noticed, unlike Chapter 3, this chapter studied only the zone-based hybrid model. The SINR-based model can be studied in future work. It is worth mentioning that the work presented in this chapter resulted in an accepted paper to IEEE access, and it is under review at the time of writing the thesis.

# Chapter 5

## Multicast and the SFN Environment

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In the previous two chapters, UC was used as an operating mode for the BB side of the hybrid network. In UC, the cellular network can personalize the transmission both technically, and content-wise. However, due to the limited bandwidth available at each cell and the extensive ICI, the number of served users is limited. Such a number becomes even smaller when the service is demanding in terms of BW like video streaming.

In this chapter, we turn our attention into the MC operating mode in the BB network, and how it can be used in the context of hybrid networks. The chapter has two main parts. The first part introduces the SFN deployment, a deployment that usually accompanies the MC mode, then derives a lower bound coverage probability. The second part studies a BC/MC hybrid network, with three different scenarios, and optimizes its power efficiency.

### 5.1 Coverage in an SFN cellular network

With multiple users mutually exploiting the same spectral resources, BC and MC technologies are considered as key solutions to address a large audience with a resource-hungry service. For instance, the second generation of the terrestrial DVB standards, DVB-T2, adopts a full broadcast strategy while on the other hand, a multicast mode is envisaged in the eMBMS of the LTE-A standard [100].

Despite the interest in MFN in many countries, broadcast and multicast technologies have widely been deployed in practice within SFN thus offering a reduction of the ICI. In an SFN, a group of neighboring transmitters uses the same band to deliver the service, while keeping a synchronization between them so that the received power from all the transmitters can be constructively exploited by the receiver [118].

The analysis of SFN networks has attracted some research effort from the system level and deployment evaluation point of view. Yet, the analytical derivations in terms of instance of the probability of coverage have not been thoroughly considered. In [244] and

[245], the authors have conducted some analysis for both DVB-T2 and eMBMS through extensive simulations. In [123], field trials for eMBMS coverage performance were reported. Nonetheless, the analytical derivations of the average coverage probability for a mobile TV network is still an open question. Some attempts can be found in [117, 236, 246, 247]. Therein, the received power was modeled with a log-normal distribution with a certain mean and variance, causing the sum of the received powers to have a log-normal distribution as well. However, the analysis doesn't include the distribution of the BSs and doesn't consider the path loss in the derivation of the final expression.

In another context, so-called joint transmission or multi-point access was considered in the literature as in [248]. In joint transmission models, a user is served by multiple BSs so that the received power from all the transmitters is considered as useful power. However, such models fail to capture the effect of the delay reception on the performance, especially when this delay creates partial interference. Moreover, coordinated multi-point access assumes that all BSs can adjust the transmission for each user, which is not the case in multicast SFNs.

In this section, a new approach for the derivation of the probability of coverage is presented using stochastic geometry tools. As in the previous chapters, the studied network is modeled as a PPP. On this basis, two main contributions are provided: first, an analytical expression of the probability of coverage is derived; second, a suitable approximation of the coverage probability based on the closest base stations is proposed as a trade-off between derivations accuracy and theoretical analysis tractability. The obtained expressions are validated by Monte Carlo simulations.

We first describe the system model with the basic definitions and some useful derivations. Then we state the analysis for the SFN network and the obstacles facing a complete analytic derivation. Next, we detail the approximation made to get a lower bound expression. Finally, we study the effect of some parameters on the performance of the model and the accuracy of the derived expressions.

### 5.1.1 The SFN Model

In this part, we detail the model description, define the SINR of the users, and state some PDFs that will later be used in the derivations.

#### 5.1.1.1 The model description

Let us consider the delivery of mobile TV services to users in the downlink of a BB cellular network such as LTE network.

Formally, the considered network model consists of a number of BSs uniformly distributed over a given service area according to a PPP  $\Phi$  with density  $\lambda_{BS}$ . All BSs are assumed to be transmitting OFDM signals at the same power and using the same frequency band, *i.e.* with frequency reuse factor of 1. MC transmission is used to deliver a common data stream to the users, meaning that spectral resource is jointly used by all the interested users in the downlink. In addition, perfectly synchronized SFN deployment is assumed, where all the considered cells belong to a common SFN area. In the analysis, a single user at the center of the service area is considered as a typical user.

#### 5.1.1.2 SINR definitions

In an SFN scenario, all BSs synchronously transmit the same signal. Assuming that the receiver is perfectly time-synchronized to the signal from the nearest BS, the received signals from other BSs will arrive with some delay that falls within three cases: (1) the delay is less than the Guard Interval (GI) of the reference OFDM signal; in this case all the

received signal power is useful, meaning that the receiver is able to constructively exploit the delayed versions of the signal, (2) the delay is larger than the GI and less than the useful symbol time; in this case part of the received signal power is useful and the other part outside the GI is interference, and (3) the delay is larger than the symbol time; in this case the whole received signal power represents interference. This was illustrated in Chapter 2, especially in Fig. 2.4.

On this basis, the SINR for a user in the network can be defined as:

$$S = \frac{\sum_{i \in \Phi} \delta_i h_i r_i^{-\alpha}}{\mathcal{P}'_N + I} \quad (5.1)$$

where  $r_i$  is the distance from the user to BS  $i$  and  $h_i$  represents the Rayleigh channel to that BS with  $h$  having an exponential distribution, *i.e.*  $h \sim \exp(\mu)$ ,  $\mu$  being the rate, and  $\alpha$  is the path loss exponent. Since all BSs are assumed to be transmitting at the same power, the power term is eliminated from both the useful power and the interference, and the noise power  $\mathcal{P}_N$  is normalized by the transmission power  $\mathcal{P}_M$  to get the used normalized noise power  $\mathcal{P}'_N$ . Based on the previous discussion about delayed signal arrival, Eq. (5.1) also involves a coefficient, noted  $\delta_i$ , which reveals the portion of the power that is considered as useful according to the arrival time of the signal from BS  $i$ . Following the same idea,  $I$  represents the interference power, which is sourced by the delayed signals' power, and writes:

$$I = \sum_{i \in \Phi} (1 - \delta_i) h_i r_i^{-\alpha} \quad (5.2)$$

According to [236],  $\delta_i$  can be expressed in terms of delay time  $\tau_i$  with respect to the nearest transmitter as follows:

$$\delta_i(\tau_i) = \begin{cases} 1 & 0 \leq \tau \leq T_g \\ \left( \frac{T_u + T_g - \tau_i}{T_u} \right)^2 & T_g < \tau \leq T_f \\ 0 & \text{otherwise} \end{cases} \quad (5.3)$$

where  $T_u$  is the useful OFDM symbol duration,  $T_g$  is the cyclic prefix duration, and  $T_f = T_u + T_g$  is the total symbol time. To simplify the analysis, we substitute the time with the ratio of the distance and velocity  $c$ , and  $\delta(r, r_i)$  ( $\delta(r, r_i)$  will denote  $\delta_i$  in the rest of this work) is given by:

$$\delta(r, r_i) = \begin{cases} 1 & 0 \leq r_i - r \leq cT_g \\ \left( 1 + \frac{T_g}{T_u} + \frac{r - r_i}{cT_u} \right)^2 & cT_g < r_i - r \leq cT_f \\ 0 & r_i - r > cT_f \end{cases} \quad (5.4)$$

where  $r$  is the distance from the user to the nearest BS (the reference signal), and  $r_i$  is the distance to the  $i^{\text{th}}$  nearest BS. The substitution of the delay time by the ratio of distance difference and speed is based on the fact that the variations in propagation distances are small compared to the actual distances between BSs.

### 5.1.1.3 Link distance distributions

As in the previous chapters, the distances between users and BSs are random, and their probability distribution is essential in finding the average coverage probability over any position. However, in this section, the joint distribution of the distances to the BSs is needed. The joint distribution is a requirement in the derivation since the distances from a point in a PPP to the other points (from nearest to the farthest) are correlated.



The joint distribution of the distances to the closest  $n$  BSs, as stated earlier in (2.7), is given by:

$$f(r_1, r_2, \dots, r_n) = e^{-\lambda_{BS}\pi r_n^2} (2\pi\lambda_{BS})^n r_1 r_2 \dots r_n \quad (5.5)$$

We will eliminate the derivation here, but interested readers can refer to [233] for more details.

### 5.1.2 General probability of coverage expression

The probability of coverage under study here is solely related to the received SINR. Indeed, the SINR is a random variable that depends on the random channel coefficients and the random distance to the serving BSs. A user is said to be covered if its SINR is larger than a threshold  $T$ . In the following theorem, the first contribution of this chapter is stated.

**Theorem 5.1.** *The probability of coverage for an SFN is given by:*

$$P_c = \mathbb{E}_\Phi \left[ \sum_{i \in \Phi} \left( \prod_{j \in \Phi, j \neq i} \frac{1}{1 - \frac{\Delta(r_1, r_j) r_j^{-\alpha}}{\Delta(r_1, r_i) r_i^{-\alpha}}} \right) e^{-\mu \frac{T \mathcal{P}'_N r_i^\alpha}{\Delta(r_1, r_i)}} \right] \quad (5.6)$$

where  $\mathbb{E}$  denotes the expected value, and

$$\Delta(r_1, r_i) = (1 + T)\delta(r_1, r_i) - T$$

*Proof.* Starting from its definition, the coverage probability for a given position can be written as:

$$\begin{aligned} P_{c|\mathbf{r}} &= \mathbb{P}[S > T | \mathbf{r}] \\ &= \mathbb{P} \left[ \frac{\sum_{i \in \Phi} \delta(r_1, r_i) h_i r_i^{-\alpha}}{\mathcal{P}'_N + \sum_{i \in \Phi} (1 - \delta(r_1, r_i)) h_i r_i^{-\alpha}} > T | \mathbf{r} \right] \\ &= \mathbb{P} \left[ \sum_{i \in \Phi} \delta(r_1, r_i) h_i r_i^{-\alpha} > T \mathcal{P}'_N + \sum_{i \in \Phi} T (1 - \delta(r_1, r_i)) h_i r_i^{-\alpha} | \mathbf{r} \right] \\ &= \mathbb{P} \left[ \sum_{i \in \Phi} h_i r_i^{-\alpha} \Delta(r_1, r_i) > \mathcal{P}'_N | \mathbf{r} \right] \end{aligned} \quad (5.7)$$

where  $r$  is the set of all distances to all the BSs. Now let the left hand-side of the inequality be represented by a random variable  $G$ , the coverage will then be as follows:

$$P_c = \mathbb{E}_\Phi [CCDF_G(\mathcal{P}'_N)] \quad (5.8)$$

Starting from the assumption that the channel is a Rayleigh channel, and  $h$  has an exponential distribution with rate  $\mu$ , then  $\Delta(r_1, r_i) h_i r_i^{-\alpha}$  also has an exponential distribution with modified rate  $\mu r_i^\alpha / \Delta(r_1, r_i)$ . Thus, the problem turns out to write the CCDF of the summation in (5.7).

The summation of independent exponentially distributed random variables  $X_i$  with rates  $\xi_i$  such that  $Y = \sum_{i=1}^n X_i$ , is a random variable with hypoexponential distribution with the CCDF given by:

$$F'_Y(y) = \sum_{i=1}^n \left( \prod_{j=1, j \neq i}^n \frac{1}{1 - \frac{\xi_i}{\xi_j}} \right) e^{-\xi_i y} \quad (5.9)$$

In the case considered in (5.8), we have a set of exponentially distributed random variables that have the modified rates  $\xi_i = \mu r_i^\alpha / \Delta(r_1, r_i)$ , and therefore, the CCDF of  $G$ , the sum

of all those random variables is given by:

$$F'_G(g) = \sum_{i \in \Phi} \left( \prod_{j \in \Phi, j \neq i} \frac{1}{1 - \frac{\Delta(r_1, r_j) r_j^{-\alpha}}{\Delta(r_1, r_i) r_i^{-\alpha}}} \right) e^{-\mu \frac{r_i^\alpha}{\Delta(r_1, r_i)} g} \quad (5.10)$$

Substituting (5.10) in (5.8) gives the final expression.  $\blacksquare$

It is clear that the CCDF function in (5.10) is very complicated and includes Lagrangian basis polynomials that are hard to evaluate. The problem is even more complicated if we consider the additional expectation in (5.7). Indeed, let us define the function  $f(x)$  as:

$$f(x) = \left( \prod_{j \in \Phi, j \neq i} \frac{1}{1 - \frac{\Delta(r_1, r_j) r_j^{-\alpha}}{\Delta(r_1, r_i) r_i^{-\alpha}}} \right) e^{-\mu \frac{r_i^\alpha}{\Delta(r_1, r_i)} x} \quad (5.11)$$

then the expected value of the sum of that function using PPP follows Campbell's theorem:

$$\mathbb{E}_\Phi \left[ \sum_{i \in \Phi} (f(x)) \right] = \int_{\mathbb{R}^2} f(x) dx \quad (5.12)$$

Eventually, the problem of the obtained expression in Theorem 5.1 is its lack of tractability as seen in (5.12). Hence, a suitable approximation is needed as proposed next.

### 5.1.3 Probability of coverage lower limit

Since finding the coverage probability from (5.6) requires either prior knowledge of all the distances or evaluating the Lagrange basis polynomial for all values of  $r$ , we introduce herein an approximation that simplifies the analysis. The approximation is based on reducing the set of BSs providing useful signals into the  $N$  closest BSs. While this reduction might be penalizing in terms of accuracy, it provides a suitable analytical derivation that is easy to assess. In other words, the sum in (5.6) will then reduce into  $N$  terms, and the product will be much simpler to solve.

Now since the interference and noise, the limiting factors for the coverage, remain the same in this approximation, while the useful power is reduced to be sourced from just  $N$  BSs instead of the whole set, then the approximation in hand provides a lower bound for the coverage probability.

**Theorem 5.2.** *Taking the closest  $N$  BSs as the only useful power providers, the probability of coverage for SFN can be approximated by:*

$$P_c > \int_{r_1} \int_{r_2} \dots \int_{r_N} \sum_{i=1}^N \left[ \left( \prod_{j=1, j \neq i}^N \frac{1}{1 - \frac{\delta(r_1, r_j) r_j^{-\alpha}}{\delta(r_1, r_i) r_i^{-\alpha}}} \right) e^{-\mu \frac{r_i^\alpha}{\delta(r_1, r_i)} T \mathcal{P}'_N} \right. \\ \left. \mathcal{L}_I \left( \mu \frac{T r_i^\alpha}{\delta(r_1, r_i)} \right) \right] f(r_1, r_2, \dots, r_n) dr_1 dr_2 \dots dr_N \quad (5.13)$$

*Proof.* Starting from its definition, the coverage probability can be written as:

$$P_{c|\bar{r}} = \mathbb{P}[S > T | \bar{r}] \\ = \mathbb{P} \left[ \sum_{i=1}^N \delta(r_1, r_i) h_i r_i^{-\alpha} > T (\mathcal{P}'_N + I) | \bar{r} \right] \quad (5.14)$$

where  $\bar{r}$  is the vector of the distances to all contributing BSs (closest  $N$  BSs). The later steps follow the assumption that the closest few BSs will be within a distance where the

delay is lower than the guard interval, and so, there will be no correlation between the useful power and the interference. Now let the left-hand-side of the inequality be represented by a random variable  $J$ , the coverage will then be as follows:

$$P_c = \mathbb{E}_{\bar{r}, I} [CCDF_J(T(\mathcal{P}'_N + I))] \quad (5.15)$$

Using a similar derivation to the one conducted for  $G$ ,  $J$  will also have hypoexponential distribution, and consequently the CCDF will be as follows:

$$F'_J(T(\mathcal{P}'_N + I)) = \sum_{i=1}^N \left( \prod_{j=1, j \neq i}^N \frac{1}{1 - \frac{\delta(r_1, r_j) r_j^{-\alpha}}{\delta(r_1, r_i) r_i^{-\alpha}}} \right) e^{-\mu \frac{r_i^\alpha}{\delta(r_1, r_i)} T(\mathcal{P}'_N + I)} \quad (5.16)$$

Now substituting (5.16) in (5.15), and following the independence of  $\bar{r}$  and  $I$ , the coverage probability expression becomes:

$$P_c = \mathbb{E}_{\bar{r}} \left[ \sum_{i=1}^N \left( \prod_{j=1, j \neq i}^N \frac{1}{1 - \frac{\delta(r_1, r_j) r_j^{-\alpha}}{\delta(r_1, r_i) r_i^{-\alpha}}} \right) e^{-\mu \frac{r_i^\alpha}{\delta(r_1, r_i)} T \mathcal{P}'_N} \mathcal{L}_I \left( \mu \frac{r_i^\alpha}{\delta(r_1, r_i)} T \right) \right] \quad (5.17)$$

Now taking the first  $N$  BSs and the ones providing the useful power, and averaging over the distances to these BSs (using the joint distance distribution since the distances are not independent) gives the final result.  $\blacksquare$

To evaluate (5.13), we now turn our attention to the LT term. From the definition, the LT can be written as

$$\begin{aligned} \mathcal{L}_I(s) &= \mathbb{E}_I[\exp(-sI)] \\ &= \mathbb{E}_{\Phi, h} \left[ \exp\left(-s \sum_{i \in \Phi} (1 - \delta(r_1, r_i)) h_i r_i^{-\alpha}\right) \right] \\ &\stackrel{(a)}{=} \mathbb{E}_{\Phi} \left[ \prod_{i \in \Phi} \mathbb{E}_h[\exp(-s(1 - \delta(r_1, r_i)) h_i r_i^{-\alpha})] \right] \\ &\stackrel{(b)}{=} \mathbb{E}_{\Phi} \left[ \prod_{i \in \Phi} \frac{1}{1 + \frac{s(1 - \delta(r_1, r_i))}{\mu r_i^\alpha}} \right] \end{aligned} \quad (5.18)$$

where (a) follows the independence of the channel and the point process, (b) follows the exponential distribution of  $h$ . Using the probability generating functional which states that

$$\mathbb{E}_{\Phi} \left[ \prod_{\Phi} f(x) \right] = \exp \left( -\lambda_{BS} \int_{\mathbb{R}^2} 1 - f(x) \right)$$

and by changing to polar coordinates, the LT will be:

$$\mathcal{L}_I(s) = \exp \left( -2\pi\lambda_{BS} \int_{r_N}^{\infty} \frac{u}{1 + \frac{\mu u^\alpha}{s(1 - \delta(r, u))}} du \right) \quad (5.19)$$

Since  $\delta(r, u)$  is a conditional function over three regions, (5.19) can be expanded. By substituting  $p = u - r$ , the distance difference, the LT can be expressed as:

$$\mathcal{L}_I(s) = \exp \left( -2\pi\lambda_{BS} \left( \int_{T_g c}^{T_f c} \frac{p+r}{1 + \frac{\mu(p+r)^\alpha}{s(1 - \left(1 + \frac{T_g}{T_u} - \frac{p}{cT_u}\right)^2)}} dp + \int_{T_f c}^{\infty} \frac{p+r}{1 + \frac{\mu(p+r)^\alpha}{s}} dp \right) \right) \quad (5.20)$$

Table 5.1 – Simulation setting for the MC SFN model

| Parameter                | Value                        |
|--------------------------|------------------------------|
| $\mathcal{P}_U$          | 1.3kW                        |
| $W_{BC}, W_{BB}, W_{MC}$ | 8 MHz, 20 MHz, 7 MHz         |
| $T_u, T_g$               | 66.7 $\mu s$ , 16.67 $\mu s$ |
| $\mu, \nu$               | 1, 1                         |
| $\mathcal{P}_N$          | -141 dBm/Hz                  |
| $\lambda_{BS}$           | 0.25BS/km <sup>2</sup>       |
| $\lambda_U$              | 2.5user/km <sup>2</sup>      |

Note that the integral that ranges from 0 to  $T_g c$  is eliminated since within this range  $\delta = 1$ , and therefore the integral equals to zero.

The resulting expressions in (5.13), which represents the lower bound (since only  $N$  BSs are considered) for the coverage probability, can be seen as a trade-off between the tractability and accuracy of the estimation. Increasing the number of the included BSs for useful power will exponentially increase the complexity of the calculation but will reduce the error with the exact expression in (5.6).

The approximation done to obtain the lower bound explained above depends on the assumption that the closest  $N$  BSs provide the great majority of useful power. This assumption makes the approximation prone to a variance in accuracy against path loss exponent and BS density. The effect of these two factors on the accuracy of the analysis and the performance of the network is studied in the next section.

### 5.1.3.1 Verification of the derived expressions

In this section, the derived expressions for the coverage probability are verified through Monte Carlo simulations and are then used to study the effect of the BS density on the coverage of the network.

The simulations are done under typical LTE network conditions. The symbol time, the guard interval and the values used in the LTE standard were applied, *i.e.* 66.7  $\mu s$  and 16.67  $\mu s$  respectively. The noise power is set to -100 dBm for 5 MHz BW allocated for the streaming, and 0.25BS/Km<sup>2</sup> is selected as network BS density. As mentioned earlier, the complexity of the analysis grows rapidly with  $N$ . Therefore only the nearest two BSs are considered in the analysis, *i.e.*  $N = 2$ . The simulation settings are summarized in Table 5.1.

The probability of coverage versus the SINR threshold for several values of  $\alpha$ , and for the simulation, exact analysis, and the lower bound approximation, are shown in Fig. 5.1.

The obtained curves show that (5.6) describes exactly the simulation results, while the approximation provided by (5.13) represents a lower bound. The accuracy of the analysis varies between different values of  $\alpha$  and  $T$  but it is limited to less than 10% in these cases. It is important to remember that the results of theorem 5.1 are not tractable and can't be analytically found, so they were obtained by numerical computation.

It can be noticed from the results that as  $\alpha$  gets higher the approximation better approaches the simulation results. This can be explained by the fact that the approximation relies on taking into consideration only the signals' power from the two nearest BSs while ignoring the rest. Therefore, when  $\alpha$  increases, the received power from far BSs becomes negligible, and consequently the approximation becomes more accurate.

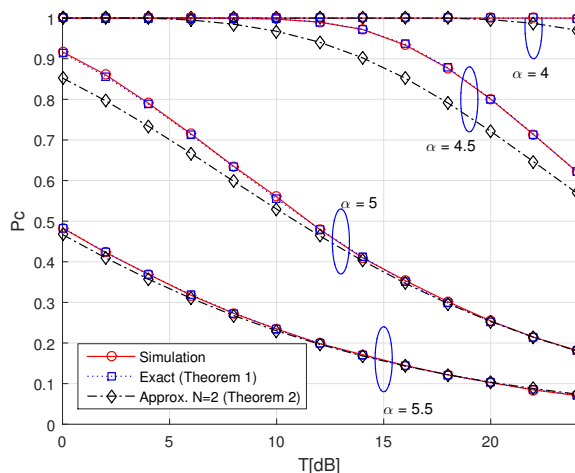


Figure 5.1 – Probability of coverage versus SINR threshold  $T$  for different values of  $\alpha$ , for simulation, exact analysis (5.6) and approximation analysis (5.13)

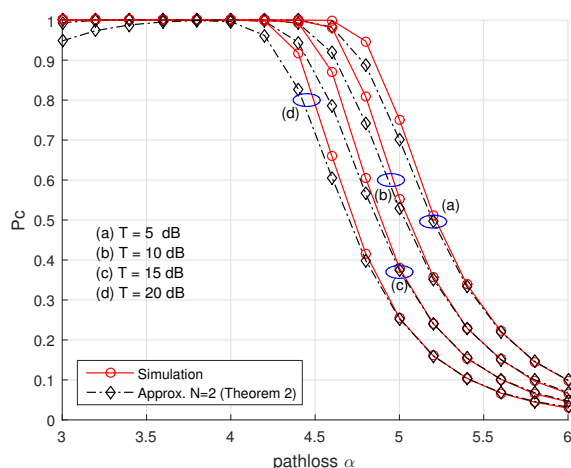


Figure 5.2 – Probability of coverage versus pathloss exponent  $\alpha$  for different values of  $T$

#### 5.1.4 Effect of the design parameters and the environment

Here, the effect of some parameters on the model's performance are further investigated. This includes the nature of the service area reflected in the path loss exponent, and the network deployment reflected in the BS density.

First, the effect of  $\alpha$  can be further investigated in Fig. 5.2. The figure shows the variation of the coverage probability against the path loss exponent  $\alpha$  for different SINR thresholds, while comparing the lower bound and the simulation. Away from the direct implication of the reduction of the coverage probability as  $\alpha$  increases, it can be seen that the error between simulation and the lower bound is reduced. Yet, it can be noticed that at low path loss values, the coverage starts to decay. At these values, the interference effect becomes significant and becomes the limiting factor instead of noise (noise is the limiting factor in high path loss environment). The derived approximation, being a lower bound, starts this decay before the actual simulation as can be seen in the top left corner of Fig. 5.2.

After validating the derived lower bound, we turn our attention into studying the effect of BS density on the performance, using the derived expressions for the lower bound. The probability of coverage as a function of the BS density  $\lambda_{BS}$  while maintaining the total transmission power of the network is shown in Fig.5.3. Maintaining the total network

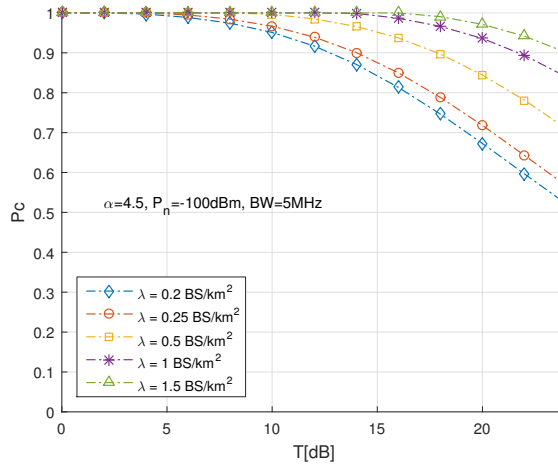


Figure 5.3 – Probability of coverage versus SINR threshold  $T$  for different values of BS density  $\lambda_{BS}$ , with  $\alpha = 4.5$

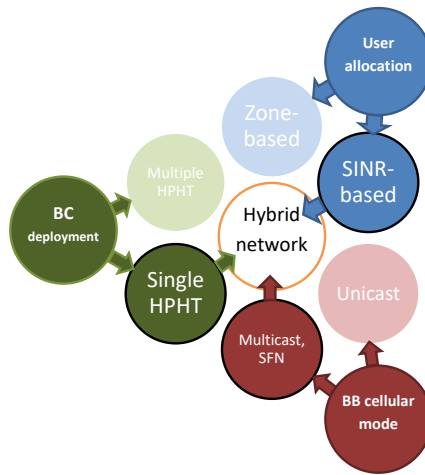


Figure 5.4 – The combination of the fourth studied model: SINR-based single BC/MC hybrid network

transmitted power implies that the transmitted power at each BS is weighted by the BS density.

Eventually, results show that enlarging the density of the BSs will enhance the coverage of the SFN. By raising the density, two changes are in the favor of the network: the serving BS becomes closer, and the delay for the other received signals becomes shorter. These two changes mean that a user will receive more useful power and less interference. This succeeds in compensating the reduction in the transmitted power of each BS (to maintain the total transmitted power of the network) as the density is raised.

## 5.2 Hybrid BC/MC network

Here, in the second part of this chapter, we introduce our fourth hybrid model. The new model is an SINR-based hybrid BC/MC with no frequency coexistence. This is illustrated in Fig. 5.4

We will first present the model details with three proposed scenarios for operation. These three scenarios considers the duality between the power and spectral efficiency in the BB side of the hybrid network. These scenarios show different cases of turning on or

off the transmission over some RBs of part of the BB MC network. Their performance will be compared using some performance metrics, and one will be chosen to continue the analysis.

Then, the chosen scenario will be analyzed to show the gain in power efficiency brought by the hybrid approach compared to full BC or full MC network. Due to the complex form of the resulting hybrid network, the analysis will be limited to numerical simulation. The optimal transmission power will be optimized to minimize the power utilization factor. Some effect of some design parameters like the allocated bandwidth for the MC transmission and the required data rate on the optimal point is investigated.

### 5.2.1 The hybrid model and the proposed scenario

As in the first BC/UC network, this model consists of a single HPHT at the center of the service area resembling the BC sub-network, and a set of BSs resembling the BB sub-network. Both sub-networks are assumed to be transmitting OFDM data to users distributed in the service area. The BCT transmits with isotropic power  $\mathcal{P}_B$  on a frequency band  $f_D$ . The BSs on the other hand transmits with a power  $\mathcal{P}_M$  over a frequency band  $f_M$  where  $\mathcal{P}_B > \mathcal{P}_M$  and  $f_D$  doesn't overlap with  $f_M$ . The BSs are modeled by a PPP  $\Phi$  with density  $\lambda_{BS}$ . The users are modeled by an independent PPP  $\Psi$  with density  $\lambda_U$ .

In contrary to what we've discussed in the previous chapters, here, MC will be the mode of operation to deliver the service in the BB side. In the proposed hybrid BC/MC network, the BC sub-network will have a single HPHT deployment, and the BB network will transmit the service for all interested users within a cell while sharing the same RBs. Moreover, all the cells providing MC will be using the same RBs for the service, thus creating an SFN. The BSs will allocate a number of RBs for the MC users, and use the rest of the available RBs to serve other users requesting other services. These users and services are out of the scope of this study. The accounted transmission in the rest of the analysis is the portion of the power that is used by MC in a BS.

Similar to the case of BC/UC hybrid model, connecting to the BC network is a priority for the users who are assumed to have the capability of connecting to both networks. Since the user allocation is SINR-based, and the BC is the priority, any receiver that attains the threshold SINR from the BC transmission  $T_{BC}$  will be a BC user. All the other users will be labeled as MC users and will be served by the SFN created by the BB network.

Since a considerable number of users will be connected to the BC network, some cells will have a low number of interested MC users, or even no MC users at all. Herein we present three scenarios for operation in such cases:

- Scenario 1: All BSs will always transmit the service in MC even if there are no interested users within the cell. This assures a high SINR to users in other cells.
- Scenario 2: Only BSs with at least  $N_{thr}$  will transmit the service while the rest of the BSs reserve the RBs with no transmission. This reduces interference to neighboring cells without having to transmit the service in all cells.
- Scenario 3: Only BSs with at least  $N_{thr}$  will transmit the service while the rest transmit regular services. This minimizes the needed transmission power in the BB network.

Scenario 1 can provide the highest coverage for the MC network since it has the maximum number of collaborating transmitters and the minimum amount of interference. However, since some of the cells will have idle spectra (transmitting the service with nobody receiving), this scenario might be the least efficient from power and spectral efficiency point of view. Scenario 2, on the other hand, reduces the transmission power by turning off the RBs for some cells. This scales down the average received power for MC users but doesn't add any interference. Nevertheless, by turning off some RBs, the spectral efficiency of the BB network is curtailed. Finally, scenario 3 reduces the needed power for the service by

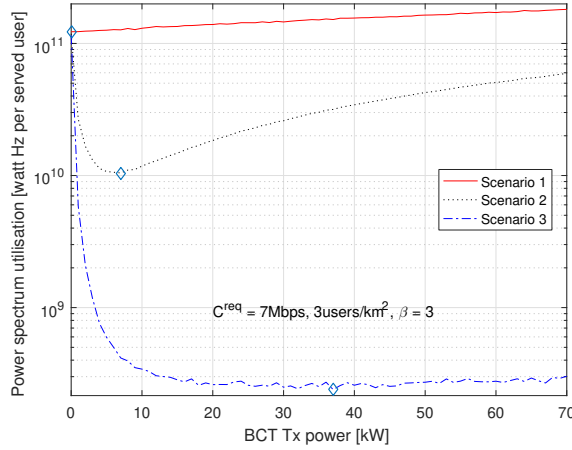


Figure 5.5 – Power utilization versus the BC transmitted power for the three scenarios

allocating the unused RBs to other services (regular UC users that are requesting some other services). This, however, adds interference to the MC receivers, which will weaken the received SINR, consequently the coverage probability.

To get a fair comparison between the scenarios, the total occupied bandwidth is taken into consideration. This is done using the power spectrum utilization. Power spectrum utilization is a measure of how much spectrum and transmitted power are needed to serve one user. It is a modification of the power utilization factor presented in (2.21) and is defined as follows:

$$\mathcal{U}_f := \frac{(\sum_{i \in \Phi'} B_{MC_i})(\mathcal{P}_B + \sum_{i \in \Phi'} \frac{B_{MC}}{B_{BB}} \mathcal{P}_{M_i})}{\sum_{i \in \Psi} \zeta_i} \quad (5.21)$$

where  $\Phi'$  is the subset of BSs transmitting the MC service, and  $B_{MC}$  denotes the bandwidth allocated to MC in the BB cells.  $B_{BB}$  and  $B_{MC}$  are respectively the bandwidth available at a cell and the bandwidth allocated for the MC out of the available bandwidth. So  $\frac{B_{MC}}{B_{BB}} \mathcal{P}_{M_i}$  is the transmission power for the MC in BS  $i$ . As defined before,  $\zeta_i$  is a binary variable indicating that a user is connected ( $\zeta_i = 1$ ) or not ( $\zeta_i = 0$ ), and therefore,  $\sum_{i \in \Psi} \zeta_i$  is the total number of served users by either networks.

The three scenarios are compared in terms of power spectral utilization as a function of BC broadcasted power. The comparison is demonstrated in Fig. 5.5. Scenario 1 has the highest  $\mathcal{U}_f$ , and it grows with the increase of BC transmission power. This is expected for the model where all the BSs are always transmitting. The additional BC power is not reflected in an equal increase in covered users, and therefore the curve always rises with  $\mathcal{P}_B$ . On the other hand, scenario 2 starts with a fast drop in utilization factor following the additional number of served users brought by the increasing BC contribution. Beyond a certain point, the increase in power stops adding more served users, and  $\mathcal{U}_f$  start to grow again. For all values of  $\mathcal{P}_B$ , scenario 2 is more efficient than scenario 1 and less efficient than scenario 3. Finally, scenario 3 starts with a very fast decay in  $\mathcal{U}_f$  following the increasing contribution of the BC network, which reduces significantly the number of MC transmitting BSs. Beyond a certain point, the increase in BC transmission power has a very little impact on the networks power spectral efficiency.

It is clear that the third scenario has the best power and spectrum management and at the same time the most realistic in practice. Therefore, all the following results will then correspond to scenario 3.



Table 5.2 – Simulation setting for the SINR-based hybrid BC/UC model

| Parameter                | Value                |
|--------------------------|----------------------|
| $R_m$                    | 15 km                |
| $\mathcal{P}_U$          | 1.3kW                |
| $W_{BC}, W_{BB}, W_{MC}$ | 8 MHz, 20 MHz, 7 MHz |
| $\mu, \nu$               | 1, 1                 |
| $\alpha, \beta$          | 3.2, 3               |
| $\mathcal{P}_N$          | -141 dBm/Hz          |
| $C^{req}$                | 7 Mbps               |
| $\lambda_{BS}$           | $0.5BS/km^2$         |
| $\lambda_U$              | $2.5user/km^2$       |

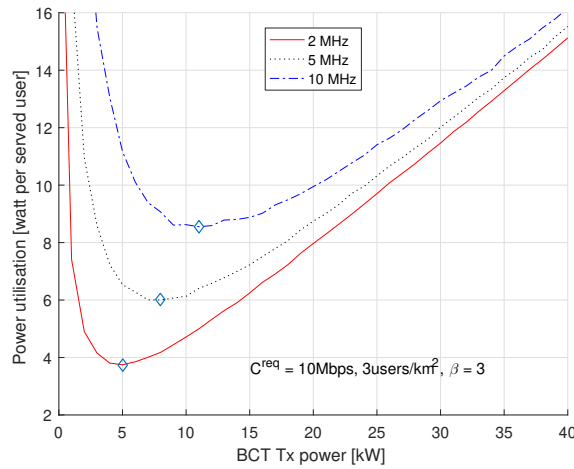


Figure 5.6 – Power utilization versus the BC transmitted power for different MC bandwidth

### 5.2.2 The power efficiency optimization

After we saw that scenario 3 has the best power-spectrum performance, we analyze the optimal operation point of the hybrid network. This includes finding the optimal operating conditions, studying the gain introduced by the hybrid network, and investigating the effect of some design parameters on this optimal point. The simulation settings are summarized in Table. 5.2

The power utilization factor mentioned here complies with the definition stated in (2.21) and is as follows:

$$\mathcal{U} := \frac{\mathcal{P}_B + \sum_{i \in \Phi'} \frac{B_{MC}}{B_{BB}} \mathcal{P}_{M_i}}{\sum_{i \in \Psi} \zeta_i} \quad (5.22)$$

As in the other SINR-based hybrid network presented in Chapter 3, the optimization of the network is done against the BC transmission power  $\mathcal{P}_B$ . When  $\mathcal{P}_B$  is equal to zero, the network is a full BB MC network. As the BC transmission power increases, the contribution of the BC networks increases as well. A high enough  $\mathcal{P}_B$  indicates a full BC network.

Therefore, the power utilization factor was calculated for a range of values of  $\mathcal{P}_B$  (from 0 to 100 kW). Moreover, this was done for a set of MC bandwidth values and a set of required capacity thresholds.

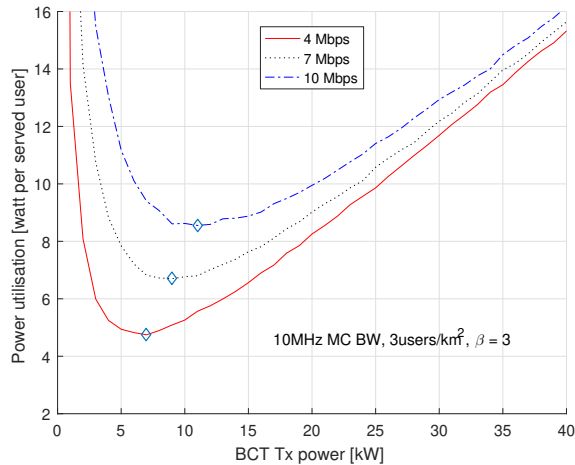


Figure 5.7 – Power utilization versus the BC transmitted power for different required capacity

Fig. 5.6 shows the variation of the power utilization with respect to the BC transmission power for different values of MC bandwidth. First, it is noticeable that for all tested BW, an optimal BC transmission power exists between the two extreme cases of full BC and full MC networks. Increasing  $\mathcal{P}_B$  adds to the total power but at the same time adds a number of served users. Before the optimal point, the rate of the growth of the number of covered users is higher than the increase in the total transmitted power, and so the power utilization factor drops. This is reversed after the optimal point.

Surprisingly, the results also show that when the bandwidth of the MC increases, the power utilization increases as well. Increasing the BW of the MC reduces the SINR threshold for a certain  $C^{req}$ , thus enhancing the coverage probability. It was anticipated that this increase will reduce the power utilization factor. But apparently, the increase in the transmitted power after widening the BW overtakes the increase in the number of served users. This means that even when MC is used in the BB network, the BC transmission remains more efficient from a power point of view.

The same conclusions can be drawn from the variation of the value of the optimal BC power for different MC BW. Due to the reduction in the MC power efficiency with the increase in BW, more contribution of the BC side is needed, and therefore a higher BC power is used to achieve the optimal performance, *i.e.* from 5 kW for 2 MHz MC BW to 12 kW for 10 MHz MC BW.

The effect of the required capacity on the performance of the hybrid network and the optimal point are shown in Fig. 5.7. The results show that for higher quality requirements, the needed transmission power gets higher as well. The optimal  $\mathcal{P}_B$  ranges from 7 kW for 4 Mbps required capacity, to 12 kW for 10 Mbps required capacity. The more power-efficient BC network provides more contribution and hence cover the requesting users.

Note that in all the cases, and both studies, the coverage probability is above 0.98 under the default conditions in Table 5.2. This indicates that both networks are more than capable of handling the users, whatever their density. The question here is limited to which network is more efficient in providing the service.

### 5.3 Summary and conclusion

MC delivery mode as eMBMS is an efficient solution to transmit a common stream to a large number of interested users. MC is usually deployed within SFNs to avoid ICI. In this chapter, we introduced MC as an operating mode of the BB network, and the potential it

has when joined in a hybrid network with BC networks. The work was divided into two parts, one included the analytical study of the SFN deployment, and the other studied the hybridization between the SFN deployed network and the BC network.

In the first part, a new approach based on stochastic geometry is proposed to derive the probability of coverage for an SFN, with a suitable approximation to simplify the analysis. The exact analysis, even if not tractable, represents a base for any further analysis or approximations. The approximation proposed here represents a lower bound for coverage performance of the network. It can be considered as a trade-off between the tractability of the analysis and the accuracy of the estimation.

Numerical evaluations showed that the proposed analytical approximation, being a lower bound, is close to the simulation results. This lower bound gets even more accurate when the path loss exponent increases. Furthermore, the obtained results indicate that the performance of the SFN is enhanced by increasing the network density, even if the total utilized power is maintained.

In the second part of the chapter, a new hybrid model is introduced: SINR-based hybrid BC/MC network with single BCT deployment. After describing the model, three scenarios of operation are proposed. These scenarios deal with turning on or off the RBs on which the MC service is being transmitted. The numerical simulations show that the most efficient scenario is the one where the RBs of MC are used for other UC services when there are no interested users in the cell.

The results show that an optimal point between a full BC and a full MC network can be found when the system is treated from a power efficiency point of view. It was also concluded that even with the resource sharing in the MC SFN, the BC network remains more efficient. This was reflected in the value of the optimal point, which rises with the escalation of quality requirements or even with allocating more resources to the MC transmission.

The done work leaves room for future improvements and deeper studies. For instance, the resulting expressions, especially in Theorem 5.1 open the door for further analysis and suitable approximations to reduce the complexity of the problem. Besides, an analytical analysis can be done to further understand the hybrid BC/MC network.

The work of the first part of the chapter resulted in a conference paper that was accepted and presented in IEEE WiMob 2019. The second part of the chapter is included in a journal paper that is being prepared at the time of writing this thesis.

# Chapter 6

## Practical Issues: Resource management and energy consumption

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### 6.1 Introduction

The work presented in the previous chapters is mostly analytical, and tends toward the theoretical aspects of the network deployment. In this chapter we focus on some of the practical issues regarding the delivery of linear services to users through BB or hybrid networks. Two main issues are chosen to be discussed herein; spectral resource allocation, and energy efficiency of the hybrid model.

In the first section, we tackle the problem of resource allocation. After a short introduction on the general goals of resource allocation schemes, we state some of the most well known algorithms in this context, reviewing each one's advantages and drawbacks. These algorithms, being designed for general services, are not optimized for linear services delivery. So, we then turn the problem into an optimization problem, and propose an algorithm that targets linear services. The performance of the algorithm is compared into those of other existing algorithms in addition to the optimal result provided by branch and cut.

In the second part of this chapter, we use the resource allocation scheme proposed in the first part, and introduce it to the zone-based hybrid BC/UC network model presented in Chapter 3. This time, the hybrid model is treated from energy consumption point of

view. The energy efficiency of the hybrid network is numerically optimized, and the effect of the design parameters on the optimal operation point is analyzed.

The aim of this chapter is to give more insight on the practical problems that faces the delivery of the service. Such issues might be overlooked in the analytical studies as the ones presented in this thesis.

## 6.2 Resource allocation

In a broadband network, like LTE or 5G-NR, certain spectrum is available at each cell to allocate to users in the downlink. However, different users have different channel conditions and different requirements. So, a network needs to efficiently distribute the available resources to the requesting users.

The distribution scheme usually sets some criteria for the allocation of time-frequency resources to users. These criteria are obtained from a goal which is maximizing one of the important metrics for a network, like the system throughput, fairness, and end to end delay. These goals are often contradictory, and some algorithms were proposed as a compromise between them. Round-Robin (RR), Maximum Throughput (MT), and Proportional Fairness (PF) are some of the proposed algorithms in the literature. However, these algorithms are designed for general services, so they are not optimal for linear services.

In contrary to regular services where increasing a user's capacity would enhance the QoE, the allocation of larger number of resource blocks to the linear-service end-users will not be reflected in QoE. Indeed, a user receiving linear service needs a minimum capacity level to properly receive the content, making it inefficient to allocate resources beyond this level. As a result, system capacity enhancement would be a secondary objective when compared to enhancing the percentage of users receiving a linear service. Another important factor resides in the utilization rate. Indeed, in non-linear services, existing methods exploit all the available RBs, while in linear services case, other services might need resources to be allocated. This affects different resource allocation outcomes, such as power reduction, new arrivals, congestion, etc. Hence, it is very important to propose fair allocation approaches when dealing with linear services.

In this part, we firstly derive and model the resource allocation problem of a linear service as a Mixed Integer Programming (MIP) problem. Then, we present a new Linear Service Oriented Resource Allocation Strategy (LSORAS), that aims to maximize the percentage of users receiving the linear service while maintaining a minimum required capacity for each user, with decent fairness level. This guarantees that each user will be allocated the required number of RBs hence, granting resources to other services, or idling unused RBs. The proposed algorithm is compared to RR, PF, MT methods, and more importantly to the optimal allocation provided by the Branch and Cut (BaC) optimization technique usually adopted for MIP problems. Average Success Rate (SR) has been mainly used to assess the two algorithms performance. Moreover, the effect of user density and required capacity on the SR was analyzed.

### 6.2.1 Some existing resource allocation algorithms

We start by presenting some of the important existing algorithms.

- Round Robin: In literature, RR algorithm, among others, is exhibited as the fairness approach. In RR, RBs are iteratively distributed to the different users until all are allocated, or the user's constraints are met [249]. This guarantees that all users are relegated with RBs. However, RR doesn't consider the channel conditions for every client, so it fails to accomplish high rates coverage.

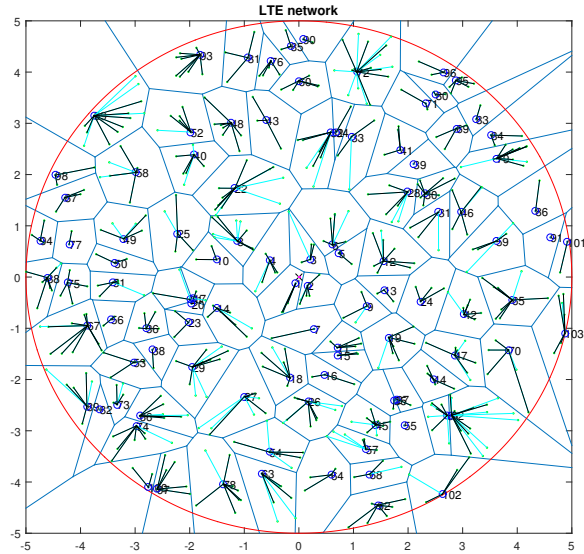


Figure 6.1 – Modeled broadband network with a PPP describing the position of BSs, users and cells. Connections between a BS with its served and unserved users is represented with black and cyan lines respectively.

- Maximum throughput: Conversely, the MT approach allocates the first RB to the user with the best channel conditions, then moves to the second RB, and reruns the distribution until all RBs are designated or the user’s limitations are fulfilled. This strategy guarantees the best achievable rate of the network at the expense of fairness. With such an algorithm, a user with the best channel conditions could acquire the majority of the RBs, leaving several users with limited or even no RBs. Nonetheless, this technique could be utilized as a benchmark for system capacity.
- Proportional fair: As a compromise between the two above methods, PF [250] allocates resources according to a formula that considers not only channel conditions of a user, but also the number of resource blocks already allocated to that user.

As one can notice, neither one of the algorithms is directed towards linear services, in a sense where a certain threshold throughput should be achieved for a user, and any additional resources might be useless.

## 6.2.2 Model description and problem formulation

We consider in this part a BB cellular network like LTE, transmitting linear services to a number of users in the service area.

### 6.2.2.1 Deployment and modeling

The service is assumed to be always available to any user at any time. A minimum capacity  $C^{req}$  is required for a user to properly receive the service, i.e.  $C^{user} \geq C^{req}$ . In the broadband network, UC is used to separately deliver the linear service to each connected user. It is also assumed that the user is connected to the nearest BS, and the transmission power  $\mathcal{P}_U$  is considered to be identical in every cell. The BS are considered to have complete information about the channel to each user within the cell borders.

The BSs are considered to be uniformly distributed over the service area, so they are modeled with a PPP  $\Phi$  with density  $\lambda_{BS}$ . Voronoi tessellation is employed to draw the cell borders. The users are also modeled with an independent PPP  $\Psi$  with density  $\lambda_U$ . An example of the service area, including base stations and users, is shown in Fig.6.1.

### 6.2.2.2 Broadband model and definitions

Out of the available pool of RBs, the BS allocates a number of RBs to each user. The available number of RBs,  $RB^{max}$ , is determined by the bandwidth available for each cell. The selection of which RB gets allocated to which users is done according to a resource allocation scheme.

In this part of the thesis, we will assume that each user has a different channel with the BS for each RB. This is based on the assumption that the fading is flat over the RB, and not flat within the BW of the network transmission. Starting from the path loss model as presented in (2.10), the SINR for user  $m$  at RB  $i$  is given by:

$$S_{m,i} = \frac{\mathcal{P}_U h_{m,i} r_m^{-\alpha}}{\mathcal{P}_N + I_{m,i}} \quad (6.1)$$

where  $\mathcal{P}_U$  is the transmitted power,  $h_{m,i}$  is a random variable representing the channel for user  $m$  and RB  $i$ , with exponential distribution of rate  $\mu$  i.e.  $h \sim \exp(\mu)$ .  $\alpha$  represents the path loss exponent, and  $r_m$  is the distance between the user  $m$  and its serving BS. The noise power at the receiver is considered to be a constant and is denoted by  $\mathcal{P}_N$ , while the interference power at user  $m$  for RB  $i$  expressed as:

$$I_{m,i} = \sum_{j \in \Phi/u_m} \mathcal{P}_U h_{m,i,j} d_{m,j}^{-\alpha} \quad (6.2)$$

where  $\Phi/u_m$  is the set of all BSs excluding the serving BS for user  $m$ ,  $d_{m,j}$  is the distance between the receiver  $m$  and the interfering transmitter  $j$  and  $h_{m,i,j}$  denotes a random variable that represents the channel between user  $m$  and the  $j^{th}$  transmitter, for RB  $i$ . (6.1) could then be reduced to:

$$S_{m,i} = \frac{h_{m,i} r^{-\alpha}}{\mathcal{P}'_N + \sum_{j \in \Phi/b_0} h_{m,i,j} d_{m,j}^{-\alpha}} \quad (6.3)$$

where  $\mathcal{P}'_N$  is the noise power normalized to the transmitted power.

Consequently, the capacity of a single RB  $i$  for a user  $m$  will then be as following:

$$C_{m,i}^{RB} = B^{RB} \log_2(1 + S_{m,i}) \quad (6.4)$$

where  $B^{RB}$  is the bandwidth of a single RB. In LTE for example,  $B^{RB}$  is usually equal to 180 KHz.

The capacity of user  $m$  is defined to be the sum of capacities of the RBs assigned to this user. It is given by:

$$C_m^{user} = \sum_{i=1}^{RB^{max}} C_{m,i}^{RB} a_{i,m} \quad (6.5)$$

where  $a_{i,m}$  is a binary variable that is equal to 1 if RB  $i$  is assigned to user  $m$ , and equal to 0 otherwise.

Similarly, the capacity of a cell is defined as the total capacities of all users attached to this cell and will be defined as follows:

$$C_n^{cell} = \sum_{m \in \mathcal{M}_n^{cell}} C_m^{user} b_m \quad (6.6)$$

where  $\mathcal{M}_n^{cell}$  represents the set of all users in a cell  $n$ , and  $b_m$  represents a binary variable indicating whether user  $m$  is properly receiving the linear service ( $b_m = 1$ ) or not ( $b_m = 0$ ), i.e. whether the transmitter succeeds or fails to assign enough RBs so that  $C_m^{user}$  exceeds  $C^{req}$ .

### 6.2.2.3 Performance metrics

In order to evaluate the different approaches of a linear service, we introduce the average service success rate. The service SR  $\sigma^s$  is defined as the ratio between the number of users that have the access to the service to the total number of users in the service area. In the case of overload, the network will deny the service access. In a cell, the success rate can then be stated as:

$$\sigma_n^{cell} = \frac{\text{Number of served users}}{\text{Number of users in the cell}}$$

which can be also expressed as

$$\sigma_n^{cell} = \frac{\sum_{m \in \mathcal{M}_n^{cell}} b_m}{M_n^{cell}} \quad (6.7)$$

where  $M_n^{cell}$  is the number of users in cell  $n$ . Hence, the success rate of the system is given by:

$$\sigma^s = \frac{\sum_{n=1}^N \sum_{m \in \mathcal{M}_n^{cell}} b_m}{M} \quad (6.8)$$

where  $M$  denotes the total number of users, and  $N$  denotes the total number of cells in the service area.

It should be noted that other metrics are often used to evaluate a resource allocation scheme, like system capacity and fairness index, or Jain's fairness index [251] in precise. However, system capacity has no significant importance in linear services compared to SR. In addition, Jain's fairness index is highly correlated with the served (non-zero) users, i.e. SR, and its information would be redundant.

### 6.2.3 Optimal solution

### 6.2.4 Problem formulation

For a linear service delivery system, fairness and system capacity become secondary objectives behind the primary target, which is serving as much users as possible. Thus, the problem in hand aims at maximizing the success rate defined in Eq. (6.8), with a constraint on the minimum allowed capacity for a served user, and another constraint on a maximum number of users allocated with the same RB, limiting it to only one user at a single time slot (UC transmission). The optimum success rate of the system is achieved when all the cells are also at the optimum success rate. For a realization where the number of BSs is  $N^{BS}$ , we define the following optimization problem for each cell:

$$\begin{aligned} \max_{\mathbf{a}} \quad & \left[ \sum_{n=1}^{N^{BS}} \sum_{m \in \mathcal{M}_n^{cell}} b_m \right] \\ \text{subject to} \quad & \sum_i a_{i,m} \leq RB_{max} \\ & C_m^{user} = \sum_{i=1}^{RB_{max}} C_{m,i}^{RB} a_{i,m} \\ & \forall n \sum_{m \in \mathcal{M}_n^{cell}} a_{i,m} \leq 1. \\ & b_m = \begin{cases} 1, & \sum_{i=1}^{RB_{max}} a_{i,m} C_i^{RB}, m \geq C^{req} \\ 0, & \text{Otherwise.} \end{cases} \end{aligned}$$



where  $\mathbf{a}$  denotes the matrix holding all  $a_{i,m}$ . Recall that  $b_m$  represents a binary variable that is equal to 1 if user  $m$  is connected to its corresponding BS and properly receiving the linear service, and equal to zero otherwise. Also recall that  $a_{i,m}$  represents a binary variable that is equal to 1 if the RB  $i$  is allocated to user  $m$  in its corresponding cell,  $C_m^{user}$  represents the achieved capacity of user  $m$ ,  $C^{req}$  is the minimum required capacity for a user to be connected,  $RB_{max}$  represents the maximum number of resource blocks available in a cell, and  $\mathcal{M}_n^{cell}$  is the set of all users in cell  $n$ .

In the problem described above,  $b_m$  depends on several other variables in the system, so it holds information on SINR, and consequently on the random distance from base station  $r$ , the channel and the interference. It also depends on the set of allocated RBs to the corresponding user, since each RB has different SINR even for the same user and same base station. The limited number of RBs in a cell increases the complexity of the problem. Indeed, whenever a RB is assigned to a user, it won't be available for allocation to other users, hence to the RB pool for the next users. Consequently, options and diversity are reduced. This correlation between users capacities and variable dependencies indicates that the complexity of the above problem makes its analytical solution, without losing generality, prohibitive. We should mention that this algorithm is by nature integer binary problem, hence MIP solutions could be proposed. However, again due to its nature, it is very difficult to propose an adequate analytical solution.

#### 6.2.4.1 Optimal Solution By Branch and Cut

Before proposing a resource allocation algorithm, we start by presenting the optimal solution provided by BaC. Since our problem is an mixed integer (binary) programming problem, BaC algorithm was chosen. Branch and cut [252] is a combinatorial optimization method that solves MIP problems. It is based on two main techniques:

1. Branch and bound [253]: a tree traverses all possible solutions for each variable while calculating lower and upper bound of the possible solutions. The latter are used to eliminate some branches of the tree which cannot produce an optimal solution, hence reducing complexity [254].
2. Cutting planes [255]: used to narrow the linear Programming relaxation. Once a solution is found, it is checked if its an integer. If it is not the case, it is guaranteed to have a separation inequality that separates the optimum from the convex hull.

The MIP problem is solved using a regular simplex algorithm while relaxing the integer constrains, which will result in obtaining a non-integer solution as a first step. The second step is to find an additional linear constraints (by cutting plane algorithm) that is violated by the non-linear solution found in first step, but are satisfied by all integer points. Adding those constrains will lead to a different less fractional solution. The same procedure is repeated until an integer solution is found, or until no more cutting constraints could be found. In this case, branching is done for possible integer solution for an element of the vector. After branching, smaller problems are created, and the same procedure is repeated, until the complete integer vector is found. Fig.6.2 illustrates the mechanism of the algorithm. The BaC algorithm is out of the scope of this thesis, and it is left to interested readers. For more information, the reader can refer to [256, 257].

Solving the resource allocation problem with BaC, especially when the service area is large and crowded is very complicated. Moreover, respecting the real time requirements using this algorithm makes the usage of BaC prohibitive. However, BaC is guaranteed to reach an optimal solution if it is implemented correctly and given enough time. For this reason, it will be used as a benchmark for our proposed algorithm in terms of performance.

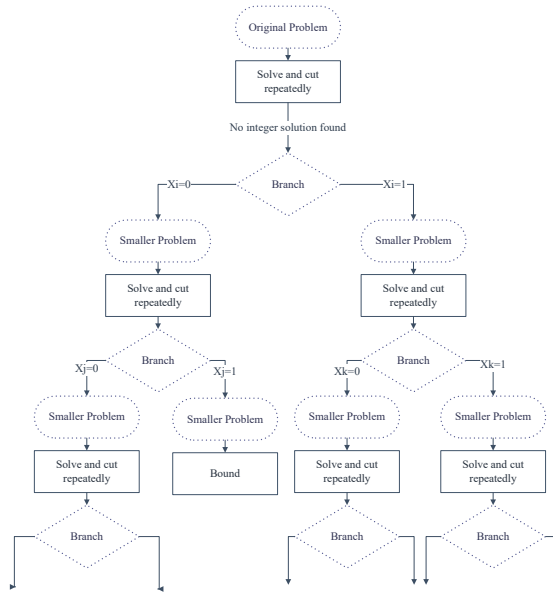


Figure 6.2 – BaC procedure example

### 6.2.5 Linear Services Oriented Resource Allocation Strategy

The linear nature of the services is the fundamental motivation for this algorithm. In non-linear services, enhancing the link capacity improves the QoS. This is why most of the work in this domain aimed at maximizing the system’s overall capacity. Rather when linear service is delivered, a certain level of throughput for a user is enough for a proper reception. Therefore, the main idea of our proposed algorithm is to fix a minimum threshold for the user capacity and try to maximize the success rate while increasing the index of fairness. The proposed algorithm restrains the usage of unnecessary or not gainful RBs.

Due to the finite number of RBs, maximizing the number of connected users could be achieved by allocating the minimum number of RBs for a user just to reach the required capacity  $C^{req}$ . The proposed algorithm relies on assigning the RBs to the users having the best conditions hence, increasing the expected number of served users. The opposite, *i.e.* assigning the RBs to users with worst condition first, will drain the available RBs very fast, since such users could be resource hungry. This greedy strategy reduces the required number to reach  $C^{req}$  by assigning the RBs with best channel coefficients to users that can receive them the best. This will eventually increase the number of connected users by expanding the pool available RBs for next users.

The proposed LSORAS algorithm for each cell is described in Algorithm 2.

Such algorithm satisfies all the points mentioned earlier and consequently leads to the best use of the RBs available in a given distribution. In addition, this algorithm will not assign useless RBs for a user in two cases: the case when the capacity achieved by a user exceeds  $C^{req}$ , and the case when assigning the available number of RBs will not satisfy the given user constraint. This property will save RBs to other services within the same cell, *i.e.* implicitly turn off the unused RBs for power saving.

**Algorithm 2** LSORAS aiming at maximize SR

---

```

for  $n = 1 : N_{cell}$  do
  Select users in cell  $n$ 
  Sort users in descending order according to  $\max(\text{SINR})$ 
  Create a RB pool with all RBs
  Set  $M_{user,n}$  as the number of users in current cell  $n$ 
  for  $m = 1 : M_{user,n}$  do
    Sort available RB of user  $m$  in descending order according to SINR
    Select the RB of best SINR
    Eliminate the RB assigned to  $m$  from the RB pool
    Calculate the new  $C_m^{user}$ 
    if The RB are exhausted and  $C_m^{user} < C^{req}$  then
      Assign no RB to user  $m$ 
      Put back the assigned RB to the pool
      break
    end if
    if  $C_m^{user} \geq C^{req}$  then
      break
    end if
  end for
end for

```

---

Table 6.1 – Simulation parameters for LSORAS testing

| simulation parameters       |                    |
|-----------------------------|--------------------|
| $\lambda_{BS}$              | $1/\pi$ to $4/\pi$ |
| EIRP                        | 1200 Watt          |
| $RB_{max}$ (available RB)   | 100                |
| LTE BW                      | 20 MHz             |
| RB BW $B_{RB}$              | 180 kHz            |
| Path loss exponent $\alpha$ | 3                  |
| operating frequency $f$     | 2110 MHz           |
| Radius of service area      | 5 km               |

**6.2.6 Numerical validation and comparison**

Herein, numerical simulations of the proposed algorithm are presented. The performance is compared to that of MT, RR and PF algorithms, and most importantly to the optimal results provided by BaC. Moreover, the algorithms robustness is tested when the performance is studied against operation conditions such as user density and required quality. Finally, the frequency reuse is briefly studied.

**6.2.6.1 Simulation setting**

A dense BB network model was created, with a PPP of density ranging from  $\lambda = 1/\pi$  to  $\lambda = 4/\pi$ , in a service area of 5 km radius. This will result in an average number of BSs between 25 and 100, and average cell radius of 1 km to 500 m respectively.

The parameters of the simulations are given in Table 6.1. Moreover, a different frequency band and higher required capacity are chosen.

In order to implement the BaC optimal solution, AIMMS<sup>®</sup> [258] software has been used. AIMMS is designed for modeling and solving large-scale optimization and scheduling problems, particularly MIP using BaC.

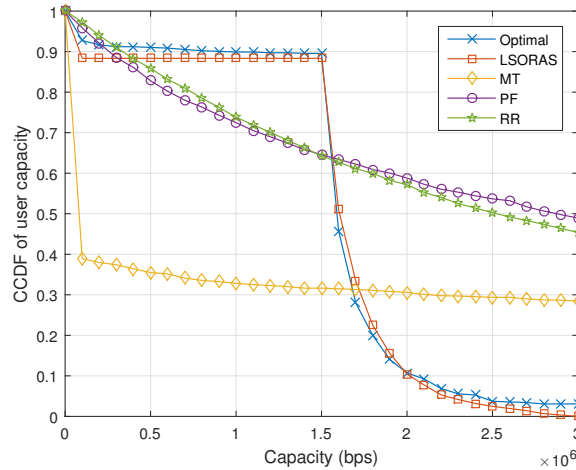


Figure 6.3 – CCDF of user capacity for 5:1 user to base station ratio,  $C^{req} = 1.5 \text{ Mbps}$

### 6.2.6.2 Algorithm verification

Fig. 6.3 exhibits a comparison among the proposed LSORAS algorithm, MT, PF, RR, and the optimal solution provided by BaC algorithm, in terms of CCDF. The CCDF is seen as the average success rate, i.e. the probability of a user to have a capacity that exceeds a certain value. Clearly, LSORAS outperforms MT, PF, and RR. For a user capacity threshold at 1.5 Mbps, 89% of the users receive the service properly, compared to around 64% with RR and PF, and around 31 % for Max Throughput. LSORAS curve has a plane shape below 1.5 Mbps because, as per the proposed allocation, no user will have a capacity within zero and  $C^{req}$ ; it is either zero,  $C^{req}$ , or some value slightly higher. Results also show that LSORAS is inferior to the optimal solution by just 1.8%, which is not a significant value compared to the reduction in computation, and the number of resource blocks employed.

Compared to the computationally expensive branch and cut, particularly at a high number of users, LSORAS is a much less costly method which accomplishes comparable results. From a different perspective, LSORAS uses only a portion of the available RBs, compared to the complete utilization of resources in MT, RR, PF solutions. For  $C^{req} = 1.5 \text{ Mbps}$ , and 5:1 user to BS ratio, only 47% of the available 100 RBs were employed, compared to 100% in MT, PF, RR and branch and cut. This means that the system saves around 53% of the resources, which could be allocated to other services or turned off to reduce energy consumption.

### 6.2.6.3 Effect of operating conditions

LSORAS showed a very good performance comparable to the optimal solution when tested on certain conditions. To test the effectiveness of the proposed algorithm in general situations, its performance was studied on a range of user densities and required user capacities.

Fig. 6.4 shows the variation of success rate with respect to the density in a service area of around 100 base stations. The results show that the success rate with MT, PF and RR methods dramatically decays with the increase in the number of requesting users. On the other hand, LSORAS maintains higher success rates even with a load ratio of 30:1 (users to BSs), while the decline is not as severe as with the other methods. The optimal solution produced by BaC keeps a miniature advantage over LSORAS. Nevertheless, for a large user density, the BaC computation becomes very expensive in terms of memory, power and time compared to LSORAS.

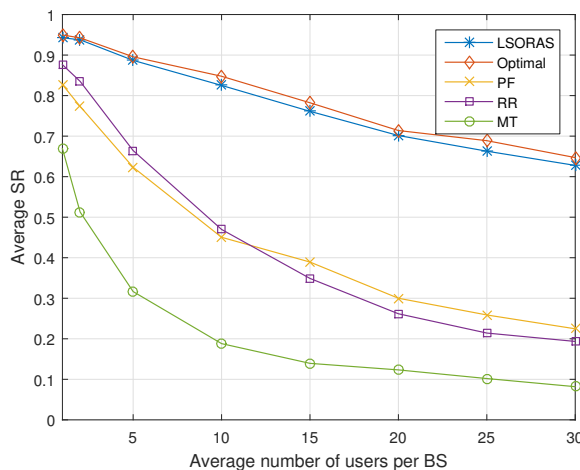


Figure 6.4 – Average SR vs the number of users per BS in the service area, with  $C^{req} = 1.5 \text{ Mbps}$

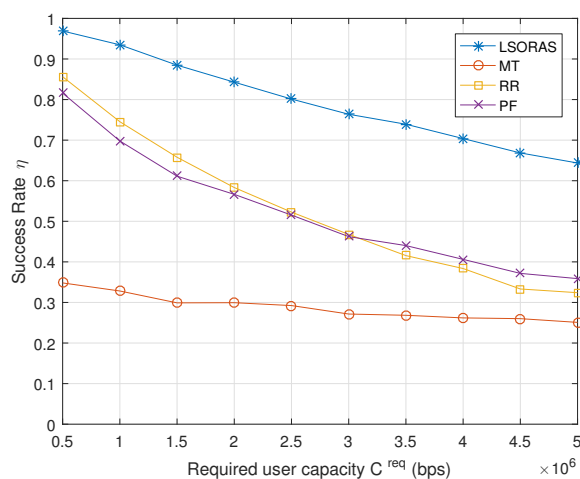


Figure 6.5 – Average SR vs the required capacity  $C^{req}$ , 5:1 users to BS ratio

In another context, to study the effect of the targeted quality, Fig. 6.5 presents the variation of the success rate as a function of the required capacity. The results indicate that LSORAS shows superiority over MT, PF, and RR, even for required capacities as high as 5 Mbps. Results show a smooth slow decline in SR, almost linearly from values slightly lower than 100% at 0.5 Mbps, to around 65% at 5 Mbps, compared to steeper decay in PF and RR. The obtained curves demonstrate how robust LSORAS can be even at higher QoS requirements.

#### 6.2.6.4 Frequency reuse

ICI has been a major limitation for modern BB cellular networks. Measures like frequency reuse approaches were exerted in an attempt to diminish interference, and consequently, enhance the average user throughput.

It is known that to improve the system capacity in a cellular network, the frequency bands are reused in several cells. The frequency reuse factor is equivalent to the number of cells that are not allowed to use the same band. A frequency reuse factor of  $n$  means that the available band of the network is divided into  $n$  sub-bands, and each cell in a network uses one of these  $n$  sub-bands. The allocation of the sub-bands to users is often done in a manner that minimizes the ICI. Note that a frequency reuse factor of 1 means that all the

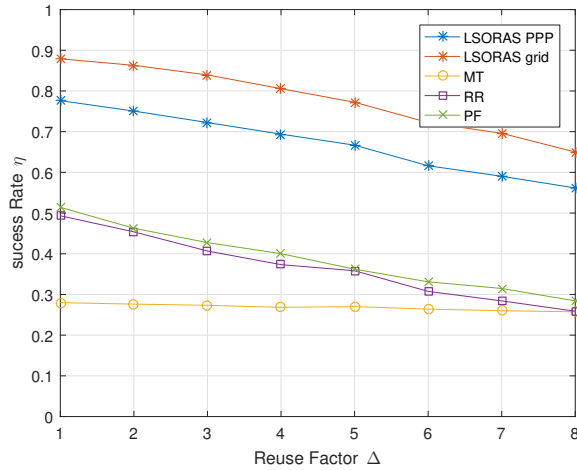


Figure 6.6 – Average success rate as a function of reuse factor with  $C^{req} = 2 \text{ Mbps}$  and 5:1 user to BS ratio

cells in the network use the same (whole) band.

Nevertheless, the effect of frequency reuse can be narrow considering that the capacity has a logarithmic relation with SINR which frequency reuse offers to improve. On the other hand, frequency reuse cuts the available frequency available at a cell by an amount equal to the reuse factor.

The simulation results so far were obtained with a reuse factor of 1. To study the effect of employing a frequency reuse scheme with the LSORAS algorithm on the performance, the conventional frequency reuse method was applied, where each cell selects randomly one of the sub-bands to operate on. The results for the success rate are presented in Fig. 6.6.

The advantage of an efficient resource allocation scheme is brought by the fact that the algorithm has a big pool of RBs to allocate to different users. Yet, when frequency reuse is used, and although the average SINR and capacity of the RBs are improved due to the decline of interference presented in (6.2), the size of the RB pool will narrow, and consequently, the algorithm will lose its maneuverability.

In addition to the comparison between the proposed and the conventional schemes, the results of a PPP modeling and the conventional grid model is also shown. In general, the grid model provides an optimistic view on the performance, indicated here by approximately 10% increase in success rate compared to the case of PPP model, which offers a more pessimistic, yet more realistic evaluation.

### 6.3 Energy Considerations

Modern BB networks are witnessing an exploding increase in provided data rates and QoS, especially with the emergence of 5G networks. However, this growth comes with a larger energy bill. A few years ago, the energy consumption in mobile BB networks was 120 TWh, with 70 million tons global carbon dioxide footprint (CO<sub>2</sub>), and 13 trillion dollars energy cost [259].

In any future approach, it is important to take the energy consumption into consideration when designing the system. This is critical for the environment as well as for the economical profitability of the network. In this section we focus on the energy consumption of the hybrid network for the delivery of linear services.

Herein, we apply LSORAS which was presented in the previous section into the zone-based hybrid BC/UC network model presented in Chapter 3. We use small cells for the BB sub-network deployment, and a single HPHT for the BC sub-network deployment.

The goal is set to minimize the power consumption per served user by tuning the key design parameters like the size of the BC zone and the density of the BB network. Numerical simulations are then conducted to find the optimal values for these parameters. The impact of operation conditions like the user density on the gain the hybrid approach provides is also analyzed.

### 6.3.1 Model description and definitions

The model used is similar to the one presented in the first part of Chapter 3. See Fig. 3.1. We restate briefly here the model description for completeness. The aim is to serve a number of users distributed uniformly over the service area. Those users are modeled by a PPP  $\Psi$  with density  $\lambda_U$ . The users are served by one of two networks, BC and BB, both transmitting using OFDM. The BC network is made out of a single HPHT located at the center of the service area. The BB network on the other hand is modeled with a dense PPP  $\Phi$  with density  $\lambda_{BS}$ . The HPHT transmits with an isotropic power  $\mathcal{P}_B$ , and the BSs transmit with isotropic power  $\mathcal{P}_U$ . The BB network uses UC in the downlink. Besides, the users are assumed to have the equipment compatible with both network types. The BC network covers a circular zone, in which all users are labeled as BC users and receive the service from the BCT. All the other users are labeled as UC users, and they are served by the nearest BS. The BSs within the BC zone are not transmitting the service and operate at a different frequency band, so they do not interfere with our study.

As in the mentioned model, the BC network and the UC BSs (outside the BC zone) uses the same frequency for transmission, *i.e.* they coexist in the time and frequency domains. This was proven earlier to be more efficient from power and spectral perspectives. This will create mutual interference between the two sub-networks. Therefore, the definitions of the SINR and the interference power is the same as in Chapter 3.

The SINR for a BC user is expressed as follows:

$$S_{BC} = \frac{\mathcal{P}_B g r_v^{-\beta}}{\mathcal{P}_N + I_{U/B}} \quad (6.9)$$

where  $I_{U/B}$  is the sum of all received interference power from UC BSs by a BC user, and it can be defined by:

$$I_{U/B} = \sum_{j \in \Phi} \mathcal{P}_U h r_{s_j}^{-\alpha} \quad (6.10)$$

On the other hand the SINR for a resource block allocated to a UC user is as follows:

$$S_{UC_{m,i}} = \frac{\mathcal{P}_U h_{m,i} r_l^{-\alpha}}{\mathcal{P}_N + I_{U/U_{m,i}} + I_{B/U_{m,i}}} \quad (6.11)$$

In addition, where  $I_{U/U_{m,i}}$  and  $I_{B/U_{m,i}}$  are the total interference power received by a UC user (over a single RB) respectively from other UC BSs and the BCT, and they are defined as:

$$I_{U/U_{m,i}} = \sum_{j \in \Phi/b_0} h_{m,i,j} \mathcal{P}_U r_{q_{i,j}}^{-\alpha} \quad (6.12)$$

$$I_{B/U_{m,i}} = \mathcal{P}_B g r_{d_i}^{-\beta} \quad (6.13)$$

For the definition of the distances, please refer to Fig. 3.4 in Chapter 3.

Now the capacity for a BC user will simply be:

$$C_{BC}^{user} = B^{BC} \log_2(1 + S_{BC}) \quad (6.14)$$

while for the UC user in a cell  $m$  it will be:

$$C_{UC_m}^{user} = \sum_{i=1}^{RB^{max}} B^{RB} \log_2(1 + S_{UC_m,i}) a_{i,m} \quad (6.15)$$

All the variables and constants here have the same definitions as in the first part of the chapter.

### 6.3.2 Energy Consumption of the network

Here, the power consumption model is presented, and the power efficiency metric is then examined.

#### 6.3.2.1 Power consumption model

The power consumption model for the BB network is the one that was stated in (2.29), and that was presented in [260]. According to this model, the power consumption of an LTE BS is as follows:

$$\mathcal{E} = N_{TRX}(\mathcal{P}_0 + \Delta_p \mathcal{P}_{out}) \quad (6.16)$$

where  $\mathcal{P}_{out}$  denotes the amplifier's output power,  $\mathcal{P}_0$  is the power consumption when no power is transmitted, and  $\Delta_p$  represents the load dependent power consumption slope.  $N_{TRX}$  is the number of transmit/receive chains. [260] also provides a table of values for the constants based on the size of the BS being a macro cell, micro cell, femto cell...

In this work, we utilized the micro cell case for UC BSs. In such a model, and according to [260],  $N_{TRX} = 2$ ,  $P_0 = 56 W$ , and  $\Delta_p = 2.6$ . Unfortunately, modeling for the power consumption of a HPHT was not similarly reported. Therefore, we used the same model, but with the macro cell set of constants, *i.e.*  $N_{TRX} = 6$ ,  $P_0 = 130 W$ , and  $\Delta_p = 4.7$ .

#### 6.3.2.2 Performance metric: energy efficiency

The main goal in linear services delivery is to serve the maximum possible number of users. The network capacity is a minor goal, since the data rate is controlled by the transmitter, and any extra throughput a user might have will not enhance the QoS. A user is considered to be connected if the allocated resources are enough for the capacity to exceed a certain threshold,  $C^{req}$ . So, a power-efficient network is the one that succeeds in serving a high number of users with low power consumption. This can be measured by the consumed power per served user factor, which is the ratio between the total consumed power by the network, and the total number of served users. Following the definition in (2.20), it can be expressed as follows:

$$\mathcal{U}_E = \frac{\mathcal{E}^{BC} + \sum_i \mathcal{E}_i^{BC}}{\sigma^{BC} N^{BC} + \sigma^{UC} N^{UC}} \quad (6.17)$$

where  $\mathcal{E}^{BC}$  is the power consumed by the HPHT,  $\mathcal{E}_i^{BC}$  is the power consumed by each UC BS,  $\sigma^{BC}$  and  $\sigma^{UC}$  are the SRs of BC and UC networks respectively.  $N^{BC}$  and  $N^{UC}$  are respectively the number of users in the BC and UC zones at a realization of the model. Based on the assumption that all BSs are transmitting the same power, and following the uniform distribution of the users and BSs in the service area, substituting the number of users and BSs by their respective average values gives:

$$\mathcal{U}_E = \frac{\mathcal{E}^{BC} + \pi \lambda_{BS} (R_m^2 - r_b^2) \mathcal{E}^{UC}}{\pi \lambda_U (r_b^2 \sigma^{BC} + (R_m^2 - r_b^2) \sigma^{UC})} \quad (6.18)$$



Table 6.2 – Simulation setting for energy consumption study

| Parameter                      | Value          |
|--------------------------------|----------------|
| $R_m$                          | 40 km          |
| $r_b$                          | 20 km          |
| $\mathcal{P}_B, \mathcal{P}_U$ | 60 dBm, 38 dbm |
| $B_{BC}, B_{UC}$               | 8 MHz, 20 MHz  |
| $\alpha, \beta$                | 3.4, 3.2       |
| $\mathcal{P}_N$                | -141 dBm/Hz    |
| Antenna Gain                   | 14.77 dB       |

In this expression, the BC users' success rate,  $\sigma^{BC}$ , is equivalent to their probability of coverage. The required capacity can be translated into a threshold SINR. This probability was derived in the previous chapters. Besides, the UC users' success rate,  $\sigma^{UC}$ , which is delivered by LSORAS, doesn't have a closed-form expression. It was shown that the two success rates are functions of the design parameters and the environment of operation. However, the complexity makes it difficult to use them in the optimization analytically.

The main goal here is to employ and optimize the hybrid network from the energy consumption perspective. It can be presumed from (6.18) that the BC radius  $r_b$  and the UC BS density  $\lambda_{BS}$  are the two main design parameters that control the power efficiency. These two variables affect the numerator and the denominator of the energy efficiency factor with different rates. These rates are not easy to conclude since both variables are embedded in the success rates as well. Because of the complexity of an analytical optimization of (6.18), Numerical optimization, and interpretation are done next.

### 6.3.3 Optimal Network deployment

In this section, numerical evaluation is done to find a set of design parameters that minimize the power consumption per user, and to study the effect of system parameters on the effectiveness of the hybrid network.

#### 6.3.3.1 Simulation setting

An area of 40 km radius is considered for the numerical evaluation. Both UC and BC networks uses 800 MHz band for transmission, with 10 MHz BW for BC and 20 MHz total BW for UC, with total number of 100 RBs per BS. This transmitted power is 60 dBm for BC and 38 dBm for UC. The default simulation setting are summarized in Table 4.1.

#### 6.3.3.2 Optimization of the hybrid network

The design parameters which are the subject of the optimization are the broadcast radius  $r_b$  and the BS density  $\lambda_{BS}$ .

**a) Broadcast radius** To find the optimal values for  $r_b$ , the power consumption per user is calculated for several values of user density and BS density. The results are shown in Fig. 6.7 for 6.7a: 5 users per BS, 6.7b: 20 users per BS, and 6.7c: 50 users per BS.

The results indicate that for the three shown cases, *i.e.* low, medium and high user density, an optimal broadcast radius can be found that minimizes the energy efficiency. This confirms that a hybrid approach introduces a level of gain to the system.

The other main implication is that the effect of the BSs density on the optimal point depends on the users' density. For a low number of users like in 6.7a, the impact of

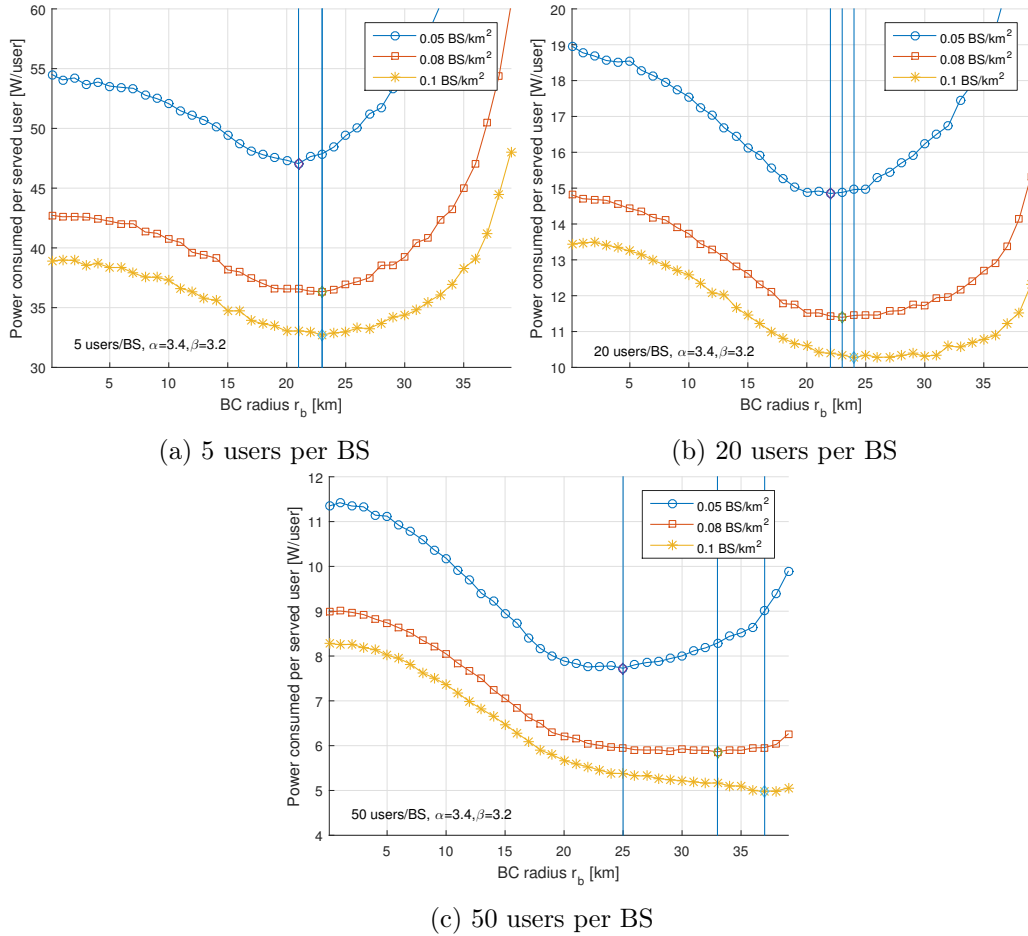


Figure 6.7 – Power consumed per served user vs  $r_b$

changing the BS density on the optimal radius is limited. This impact becomes notable with a medium-density like in 6.7b, and even more significant with high user density like in 6.7c. Generally, adding more BSs to the system increases the optimal radius, and the rate of this increase depends directly on the user density. This follows from the phenomena that we already witnessed in the previous chapters: the BC network is more efficient than the BB network. Adding more BSs requires more contribution from the BC side, so the optimal size becomes bigger.

**b) BS density** To facilitate more the effect of UC BS's density, the energy efficiency is evaluated for various values of  $\lambda_{BS}$  for a set of user density cases. The results are shown in Fig. 6.8.

If the average number of users per BS is fixed, results in Fig. 6.8 indicate that increasing the number of BS enhances energy efficiency by reducing the power consumption per user. However, after a certain point, the increase in  $\lambda_{BS}$  will not be as effective. This is consistent with the conclusions drawn from the previous figure.

### 6.3.3.3 Effect of user density

As can be seen from the results, the user density is a very important factor in the efficiency of the hybrid approach. Precisely, user density controls the success rate of the UC network, and consequently the number of connected users. It is worth mentioning that the resource allocation scheme contributed in reducing the effect of the huge increase in

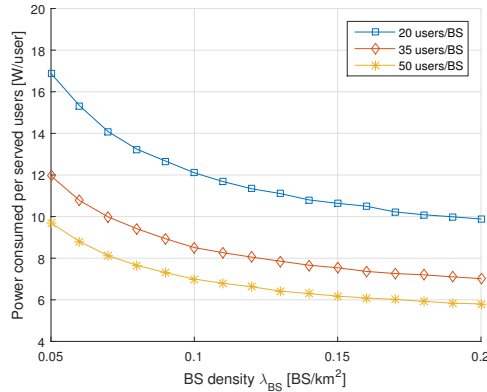
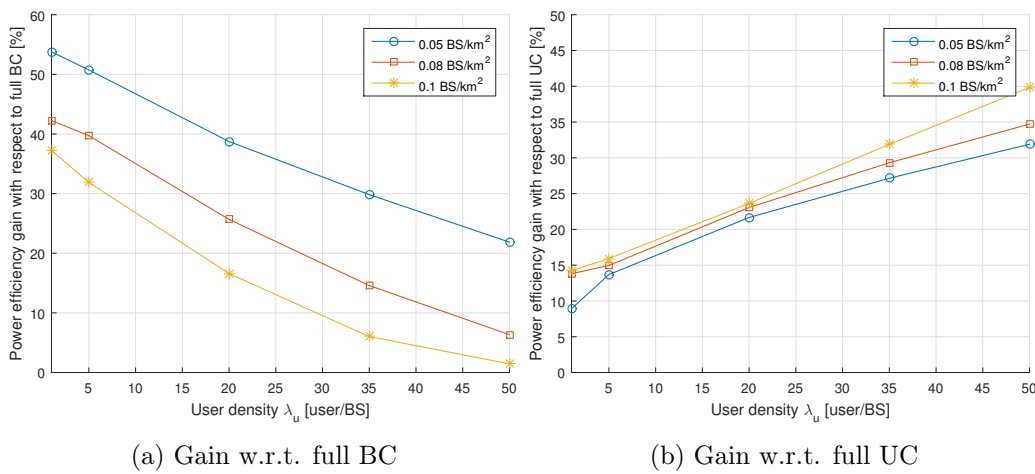


Figure 6.8 – Power efficiency for fixed user/BS ratio



(a) Gain w.r.t. full BC

(b) Gain w.r.t. full UC

Figure 6.9 – Gain provided by hybrid network

users by smartly allocating the available RB, and also reduced the power consumption by utilizing only a portion of the available RB.

To highlight the enhancement of the power efficiency provided by the hybrid approach for the different values of BS density and user density, the gain of the hybrid approach is studied. There exist two gain values, which are the power consumption drop caused by the hybrid approach compared to full BC network and full UC network. The results are shown in Fig.6.9.

Results show that, compared to a full BC network, *i.e.* the case when  $r_b = R_m$ , the highest gain a hybrid network can provide is when the user density is low. Under such conditions, a BC network has a relatively low efficiency, due to high transmission power, without having additional value due to the low number of users. Therefore, a contribution from the BB network will be more valuable than the case where the user density is higher.

On the other hand, compared to a full UC network, *i.e.* the case when the HPHT is removed, the maximum gain provided by the hybrid network is when the user density is the highest. This is mainly because UC BSs have limited number of RBs to allocate, and thus a limited number of served users. Therefore, the contribution from the BC provides the highest gain.

## 6.4 Summary and conclusion

In this chapter, we focused on two of the main practical issues that resemble a challenge for the delivery of linear services and the concept of hybrid networks. These two challenges

are resource management in the BB UC network and the energy efficiency of the hybrid network.

In the first part, the resource management in a modern BB network operating in UC, and delivering linear services to users, was studied. In this context, we presented a new algorithm which, unlike other existing algorithms, is optimized for the linear services delivery. The proposed algorithm, namely LSORAS, aims at maximizing the number of served users who are guaranteed a minimum required throughput that allows a proper reception of the service.

The effectiveness of the proposed algorithm was verified by numerical analysis in different operating conditions. The performance was found to be very close to the optimal solution presented by the computational expensive BaC. The results have shown a significant increase in the success rate compared to other algorithms. The results also showed the robustness of the algorithm against user density and higher QoS requirement. It also showed that unlike the different algorithms, LSORAS saves a significant portion of RBs for other services. Besides, it was concluded that the frequency reuse factor of 1 is the optimal solution.

In the second part, while applying LSORAS, the energy efficiency of the zone-based hybrid BC/UC network is considered. The aim was to test the effectiveness of the hybrid approach in terms of power efficiency and to find the set of parameters that minimize the power consumption per served user. Results indicate that an optimal broadcast zone size can be found and that the effect of the BS's density on that size is related to the user density. Results also show that densifying the network enhances the efficiency of the system up to a certain level beyond which the efficiency is saturated. Moreover, It was shown that under the same network setting, the network with larger users densities is more efficient than the one with lower user densities. The results also show that the denser a network is, the highest the gain of a hybrid network will be compared to a full UC network while reducing the density will increase the gain compared to a full BC network.



# Conclusions and perspectives

## Conclusion

Multimedia streaming services like mobile TV are gaining interest around the world, and they represent a great opportunity for industry parties and service providers. Conventional methods like TBC, SBC, cellular BB, and wireless access networks are generally used to deliver these services. It was shown that each has its own pitfalls and faces some challenges. The hybrid approach can be a suitable approach to overcome these challenges by exploiting the capabilities of two or more networks that cooperate to serve the users. In this thesis, we have investigated the hybrid TBC/BB for the delivery of linear services. The study was conducted through deep analytical analysis using stochastic geometry tools. The tools and the models used are presented in Chapter 2.

In Chapter 3, we studied the BC/BB hybrid model. This model has a single BCT deployment and UC operation for the BB network. Two user allocation criteria were used in this chapter, one is position-based, and the other is signal-quality-based.

As for the zone-based model, two scenarios for network coexistence were proposed, the first implies that both networks share the same band for linear service delivery, and the second assumes the opposite, *i.e.* each network operates at a different frequency band. For both scenarios, a deep analysis was conducted, where key performance metrics like the coverage probability and achievable throughput were derived. The resulting expressions are proven to be highly accurate when compared to simulation results. These expressions were used to study the performance of the hybrid network, and gain introduced by the approach. It was concluded first that an optimal state between a complete BC and a complete UC network exists. This is measured by the size of the BC zone and can be translated into the portion of users that are served by the BC network. The optimal point is different for different targeted metrics, and it is controlled by the design parameters and the environment. The results have shown that as the requirement from the hybrid network, like the required SINR for reception, increases, more contribution from the BC side is needed, and the optimal zone is therefore bigger. Besides, When the two scenarios were compared, it was shown that the coexistence scenario (sharing a frequency band) is more efficient, even though the BC-UC boundary users suffer more.

The second part of Chapter 3 discussed the signal quality based hybrid BC/BB network model. The users in this model are allocated to either network based on the received SINR. Consequently, there will be no hard edges between the BC users' subset and the UC users' subset. This model is more tractable but makes the coexistence scenario problematic. The coverage probability of the network was derived. The expressions matched perfectly the numerical simulation results under different conditions. Since the allocation is SINR-based, the BC transmission power controls the size of each network's users' subset. However, since the coverage probability can be almost perfect for huge transmission power, power efficiency was used to evaluate the network instead. The results show that an optimal transmission power that minimizes the average needed power to serve a user can be found. The optimal point is affected by the nature of the area, the design of the BB network, and the load on

the hybrid network. For instance, having a dense network means that it transmits more power to serve users. Therefore, a higher optimal point is needed so more users are served by the more efficient BC network.

The zone-based model was generalized in Chapter 4, where the BC network consists of multiple BCTs in a much larger area. From the conclusions of Chapter 3, the frequency sharing scenario was deployed here. The presented model was analyzed using stochastic geometry. Because of the complicated shape of the studied network, tight upper and lower bounds were derived for the coverage and capacity. This was done using two approaches for approximation. The tightness of the bounds was verified by numerical simulations. The derived expressions were employed to find the optimal BC zone sizes that maximize coverage and power efficiency. It was shown that the existence of an optimal point in the first place depends on user density. When the service area is too crowded, the UC network suffers from overload, and a full BC network is needed. Contrarily, when the user density is very low, the BC network is not efficient, and a full UC network is a better choice. In between these extreme cases, the optimal point will vary depending on other system parameters. The user density can also control the effect of other design parameters on the result. For example, increasing the number of BCTs has a positive effect when the user density is low, and vice versa.

In Chapter 5, we turned our attention to the other operation mode of the BB network: MC. Since MC is usually operated with an SFN deployment, we started by studying this kind of deployment. In contrary to previous work, we analyzed the SFN from a stochastic geometry perspective. The exact derivations of the coverage probability, however, resulted in very complicated expressions. This was solved by introducing an approximation that reduces the number of serving BSs to the nearest few, which produced a lower bound for the probability of coverage. This lower bound was shown to be accurate in a range of conditions, especially when urban and suburban environments where the path loss is high.

In the second part of Chapter 5, the SFN deployment of the BB network was merged with the single BCT deployment of the BC network to form an SINR-based hybrid BC/MC network model. Three scenarios were proposed for the operation of the MC BSs when all the users within their cells are served by BC. The simulation results showed that the third scenario, where the MC RBs are used by other services, is the most efficient from power and spectral perspectives. The results also indicated that for higher QoS requirements, the optimal transmission power that maximizes the power efficiency is higher. The users' density doesn't affect the results here. The results showed that the power efficiency is better when the number of resource blocks allocated for the MC in the BB network is smaller. This proposes that even with frequency sharing in the BB network, the BC network remains more efficient.

Finally, in Chapter 6, some practical issues were tackled. In the first part of the chapter, a resource allocation algorithm targeting linear service as a min objective was proposed, namely LSORAS. The proposed scheme is a greedy algorithm that assigns the RBs to the users with best channel conditions first. It also assigns only the amount of resource blocks needed for the user to reach the required capacity. The performance of the proposed scheme was compared through simulation with the optimal solution provided by BaC after turning the problem into a mixed integer optimization problem. The results show that the performance of LSORAS is very close to the optimal, and exceeds the conventional resource allocation algorithms in terms of success rate. The proposed algorithm has shown robustness against the load in terms of user density and required throughput. This was achieved while utilizing only a part of the available spectral resources (often less than half), compared to full utilization with other schemes.

In the second part of the chapter, another practical issue was tackled: the energy consumption of the network. Using existing power consumption models for the BSs, the

energy efficiency of the hybrid network was studied. A similar BB model to the one in the first part of the chapter was used, *i.e.* using UC with LSORAS for resource management. A BCT was added to form a zone-based hybrid BC/UC network. The model was analyzed through numerical simulations, which indicate that the energy efficiency of the hybrid network can be optimized for a range of operating conditions. The results have shown that the maximum gain compared to a full BC network is achieved when the user density is low. On the contrary, the maximum gain compared to a full BB network is achieved when the user density is high.

The work presented in this thesis allows operators and researchers to expect the performance of different hybrid network models. It also can be extended to other models by simple modifications of the analysis. The resulting expressions can be calculated easily with modern computers, eliminating the need for extensive simulations. The obtained results give insight into the performance of the hybrid approach and how it can be optimized. This work opens the door for future research which will be discussed next.

## Perspectives

As was shown in Chapter 1, the domain of mobile TV and linear services is very wide and provides numerous opportunities for research. Based on this thesis, many interesting areas and prospects can be further investigated.

First, the rest of the combinations of the hybrid BC/BB network can be studied. As indicated in Fig. 2.6, we introduced to BCT deployments, two BB operation modes, and two user allocation criteria. This creates 8 possible combinations. In the thesis, we studied 4 of these combinations, leaving the other 4 for future research. This include the zone based hybrid BC/MC models with both single and multiple BCT deployment, and the SINR-based hybrid BC/BB models with multiple BCTs and with both UC and MC modes.

Besides, the work on SFN deployments is open to more research. The reached expression from the exact derivations can be further developed. This can be done either by deeper mathematical analysis, by finding a solution to the Lagrange polynomial in the needed integration over the  $\mathbb{R}^2$  plane, or by another approximation that can work in a wider range of conditions. Moreover, the analytic derivations to obtain expressions that can estimate the performance of the hybrid BC/MC network is open for future contributions.

In addition, the work on resource allocation introduces other challenges. For instance, closed-form expressions that estimate the performance of the BB network when LSORAS is applied can help in getting more accurate information on how the hybrid network will perform under various conditions. This is especially important for studying the impact of varying users' density. Furthermore, power allocation can be considered as an additional scope for further optimizing the efficiency of the BB part of the hybrid models.

Other practical issues can be the subject of future studies, as the energy consumption modeling of the BCTs, or handover between networks for the hybrid approach to maintain an acceptable QoE.

In this thesis, we used homogeneous PPPs solely for the modeling of the BB network. More generally, other types of point processes can be used like non-stationary PPP to model areas with variable densities. Moreover, other propagation models can be used to deal with millimeter waves transmission in 5G and even 6G networks. The hybrid approach can be useful to offload traffic from this kind of networks. In addition, MIMO transmission schemes can be considered in future work instead of SISO.

Besides, this work considered linear services as a main target for the hybrid network. The problem can be extended to include non-linear services as well. This kind of applications is growing exponentially. However, they need different modeling approaches and



different considerations like device memory and service provisioning delay. In such cases, monitoring the dynamic load over time and establishing a queuing method is an essential part of the system. Moreover, there will be a need to elaborate complex switching criteria to deal with the varying demand.

Under such conditions, conducting conventional analysis will be too complex. Alternatively, machine learning can provide a simpler and more direct solution. Machine learning techniques can help in aspects like turning on or off the MC services in a cell, selecting the BC zone or BC transmission power, allocating power and spectral resources, and allocating users to networks. Moreover, it can control the service delivery switching and queuing systems. This opens the door of a much wider study in this field.

# Appendix A

## Useful integrations

In the following derivations an integration on a plane for a function over a disk will be needed.

### A.1 Integration over a distinct disk

For a disk  $C$  with radius  $R$ , and with distance  $D$  from the origin, where  $D > R$ , the integration of function  $f$  over the plane, by moving from Cartesian coordinates to polar coordinates can be expressed as:

$$\int_{C/D} f(r) = \int_{D-R}^{D+R} 2\theta r f(r) dr \quad (\text{A.1})$$

By taking an arc strip with length as  $2\theta r$  as shown in Fig. A.1a. According to cosine law:

$$\theta = \arccos\left(\frac{r^2 + D^2 - R^2}{2rD}\right) \quad (\text{A.2})$$

then the integration will finally be given by:

$$\int_{C/D} f(r) = \int_{D-R}^{D+R} 2 \arccos\left(\frac{r^2 + D^2 - R^2}{2rD}\right) r f(r) dr \quad (\text{A.3})$$

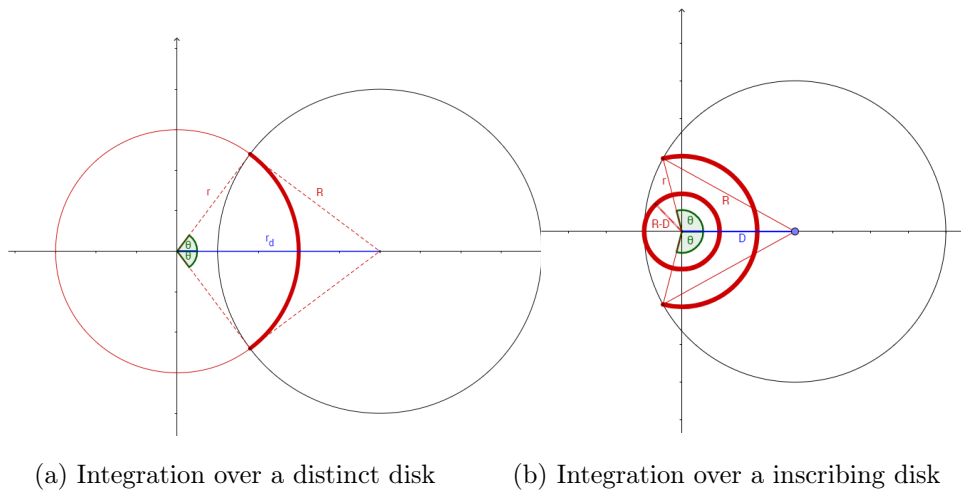
### A.2 Integration over an inscribing disk

For a disk  $C$  with radius  $R$ , and with distance  $D$  from the origin, where  $D < R$ , the integration of function  $f$  over the plane can be done by moving from Cartesian to polar coordinates, and is given by:

$$\int_{C/D} f(r) = \int_0^{R-D} 2\pi r f(r) dr + \int_{R-D}^{R+D} 2\theta r f(r) dr \quad (\text{A.4})$$

where the first term corresponds to the integration of a circular strip from the origin until the strip hits the disk boundaries, and the second term corresponds to a strip starting from the end of first limit, to the end of the disk. This is shown in Fig. A.1b. Similar to the section above, the final integration will be:

$$\int_{C/D} f(r) = \int_0^{R-D} 2\pi r f(r) dr + \int_{R-D}^{R+D} 2 \arccos\left(\frac{r^2 + D^2 - R^2}{2rD}\right) r f(r) dr \quad (\text{A.5})$$



(a) Integration over a distinct disk

(b) Integration over a inscribing disk

Figure A.1 – The two used integrations

## Appendix B

# Coverage probability derivation for BC users

The probability of coverage for a given distance from the HPHT is given by:

$$\begin{aligned}
P_{c_{BC}|r_v} &= \mathbb{P}[S_{BC} > T_{BC}|r_v] \\
&= \mathbb{P}\left[\frac{\mathcal{P}_B g r_v^{-\beta}}{\mathcal{P}_N + I_{U/B}} > T_{BC}|r_v\right] \\
&= \mathbb{P}\left[g > \frac{T_{BC} r_v^\beta (\mathcal{P}_N + I_{U/B})}{\mathcal{P}_B} | r_v\right] \\
&\stackrel{(a)}{=} \mathbb{E}_{I_{U/B}} \left[ \exp\left(\frac{-v T_{BC} r_v^\beta (\mathcal{P}_N + I_{U/B})}{\mathcal{P}_B}\right) \right] \\
&\stackrel{(b)}{=} \exp\left(\frac{-v T_{BC} r_v^\beta \mathcal{P}_N}{\mathcal{P}_B}\right) \mathbb{E}_{I_{U/B}} \left[ \exp\left(\frac{-v T_{BC} r_v^\beta I_{U/B}}{\mathcal{P}_B}\right) \right] \\
&= \exp\left(\frac{-v T_{BC} r_v^\beta \mathcal{P}_N}{\mathcal{P}_B}\right) \mathcal{L}_{I_{U/B}} \left[ \frac{-v T_{BC} r_v^\beta}{\mathcal{P}_B} \right]
\end{aligned} \tag{B.1}$$

where (a) follows the exponential distribution of  $g$ , and (b) follows the Independence of the noise and the interference. The final step follows the definition of the LT as stated in (2.11)

The above expression is a function of the users' distance from the HPHT. To get the general coverage probability for any position, we average over this distance:

$$P_{c_{BC}} = \int_0^{r_b} f_{r_v}(r_v) \exp\left(\frac{-v T_{BC} r_v^\beta \mathcal{P}_N}{\mathcal{P}_B}\right) \mathcal{L}_{I_{U/B}} \left(\frac{v T_{BC} r_v^\beta}{\mathcal{P}_B}\right) dr_v \tag{B.2}$$

Substituting  $f_{r_v}(r_v)$  by its expression in (3.11) produces the final expression.

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## Appendix C

# LT derivation for $I_{U/B}$

Starting from the definition of the LT stated in (2.11), the LT of the interference of UC BSs on the BC users is derived as follows:

$$\begin{aligned}
\mathcal{L}_{I_{U/B}}(s) &= \mathbb{E}[\exp(-sI_{U/B})] \\
&= \mathbb{E}_{\Phi, h} \left[ \exp\left(-s \sum_{j \in \Phi'} \mathcal{P}_U h r_{s_j}^{-\alpha}\right) \right] \\
&\stackrel{(a)}{=} \mathbb{E}_{\Phi} \left[ \prod_j \mathbb{E}_h \left[ \exp(-s \mathcal{P}_U h r_{s_j}^{-\alpha}) \right] \right] \\
&\stackrel{(b)}{=} \mathbb{E}_{\Phi} \left[ \prod_j \frac{1}{1 + \frac{s \mathcal{P}_U}{\mu r_s^\alpha}} \right] \\
&\stackrel{(c)}{=} \exp \left( -\lambda_{BS} \int_{\mathcal{O} \setminus \mathcal{G}} \left( 1 - \frac{1}{1 + \frac{s \mathcal{P}_U}{\mu r_s^\alpha}} \right) \right) \\
&\stackrel{(d)}{=} \exp \left( -\lambda_{BS} \int_{\mathcal{O} \setminus \mathcal{G}} \frac{1}{1 + \frac{\mu r_s^\alpha}{s \mathcal{P}_U}} \right) \\
&= \exp \left( \underbrace{-\lambda_{BS} \int_{\mathcal{O}} \frac{1}{1 + \frac{\mu r_s^\alpha}{s \mathcal{P}_U}}}_{term1} + \underbrace{\lambda_{BS} \int_{\mathcal{G}} \frac{1}{1 + \frac{\mu r_s^\alpha}{s \mathcal{P}_U}}}_{term2} \right)
\end{aligned} \tag{C.1}$$

where (a) follows the independence of the channel  $h$  from the point process  $\Phi$ . (b) follows the assumed exponential distribution of  $h$ :  $h \sim \exp(\mu)$ , and that if  $x$  is exponentially distributed random variable with parameter  $\iota$  then  $\mathbb{E}_x[\exp(-ax)] = \frac{1}{1+(a/\iota)}$ , and (c) follows the PGFL of the PPP. The integration at (c) is done over the UC area, *i.e.* over the whole service area  $\mathcal{O}$ , excluding the broadcast area, or the gap  $\mathcal{G}$ .

*term1* corresponds to interference hypothetically produced by BSs distributed over the whole service area. However, since BSs inside the BC area operate at different frequency, thus not interfering with the users received signal, a gap in the uniformly distributed interferes appears, and this is managed by *term2*. The latter corresponds to this gap in interfering BSs' distribution. Since the integration in both terms are on an inscribing disk the method described in appendix A, part B, could be used to calculate *terms1* and *term2* as following:

$$term1 = -2\lambda_{BS} \left( \int_0^{R_m - r_v} \frac{\pi r_s}{1 + \frac{\mu r_s^\alpha}{s \mathcal{P}_U}} dr_s + \int_{R_m - r_v}^{R_m + r_v} \frac{\arccos\left(\frac{r_v^2 + r_s^2 - R_m^2}{2r_v r_s}\right)}{1 + \frac{\mu r_s^\alpha}{s \mathcal{P}_U}} r_s dr_s \right) \tag{C.2}$$

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$$term2 = 2\lambda_{BS} \left( \int_0^{r_b-r_v} \frac{\pi r_s}{1 + \frac{\mu r_s^\alpha}{s\mathcal{P}U}} dr_s + \int_{r_b-r_v}^{r_b+r_v} \frac{\arccos\left(\frac{r_v^2+r_s^2-r_b^2}{2r_v r_s}\right)}{1 + \frac{\mu r_s^\alpha}{s\mathcal{P}U}} r_s dr_s \right) \quad (C.3)$$

Plugging *term1* and *term2* into (C.1) gives the final expression.

## Appendix D

# Capacity derivation for BC users

The average capacity for the inside users served by broadcast can be evaluated as:

$$\begin{aligned}
C_{BC} &= \mathbb{E}[\log_2[1 + S_{BC}]] = \mathbb{E}_{\Phi, g} \left[ \log_2 \left( 1 + \frac{\mathcal{P}_B g r_v^{-\beta}}{\mathcal{P}_N + I_{U/B}} \right) \right] \\
&= \int_0^{r_b} f_{r_v}(r_v) \mathbb{E} \left[ \log_2 \left( 1 + \frac{\mathcal{P}_B g r_v^{-\beta}}{\mathcal{P}_N + I_{U/B}} \right) | r_v \right] dr_v \\
&\stackrel{(a)}{=} \int_0^{r_b} f_{r_v}(r_v) \int_0^{\infty} \mathbb{P} \left[ \log_2 \left( 1 + \frac{\mathcal{P}_B g r_v^{-\beta}}{\mathcal{P}_N + I_{U/B}} \right) > t | r_v \right] dt dr_v \\
&= \int_0^{r_b} f_{r_v}(r_v) \int_0^{\infty} \mathbb{P} \left[ g > \frac{(2^t - 1) r_v^\beta}{\mathcal{P}_B} (\mathcal{P}_N + I_{U/B}) | r_v \right] dt dr_v \\
&= \int_0^{r_b} f_{r_v}(r_v) \int_0^{\infty} \mathbb{E}_{I_{U/B}} \left[ \exp \left( \frac{-v(2^t - 1) r_v^\beta}{\mathcal{P}_B} (\mathcal{P}_N + I_{U/B}) \right) \right] dt dr_v
\end{aligned} \tag{D.1}$$

The step (a) follows from

$$\mathbb{E}[X] = \int_0^{\infty} \mathbb{P}(X > x) dx \tag{D.2}$$

Substituting the PDF of  $r_v$  by its value from (3.11), and distributing the expectation while applying the definition of the LT gives the final expression.



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## AVIS DU JURY SUR LA REPRODUCTION DE LA THESE SOUTENUE

**Titre de la thèse:**

Optimization of hybrid broadcast/broadband networks for the delivery of linear services using stochastic geometry

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**Membres du jury :**

- Monsieur TONELLO Andrea
- Madame REKAYA Ghaya
- Monsieur DUHAMEL Pierre
- Monsieur NASSER Youssef
- Monsieur BAZZI Oussama
- Monsieur HELARD Jean-François
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M'hamed DRISSI



A handwritten signature in black ink, appearing to be "Dri Y", written over a horizontal line.







**Titre :** Optimisation des réseaux hybrides Broadcast/Broadband pour la fourniture de services linéaires à l'aide de la géométrie stochastique

**Mots clés :** Réseaux hybrides, Réseaux optimisation, Géométrie stochastique

**Résumé :** Les appareils mobiles modernes peuvent se connecter à différents types de réseaux pour recevoir des services tels que la télévision mobile et la diffusion multimédia en continu. Cela inclut les réseaux cellulaires à large bande (BB) tels que les réseaux 4G (LTE) et 5G (5G-NR), ainsi que les réseaux de diffusion terrestre (BC) tels que la diffusion vidéo numérique (DVB). Pourtant, chaque type de réseaux souffre de limitations telles que l'efficacité énergétique pour les réseaux BC et les ressources spectrales limitées pour les réseaux BB. Le concept de réseau hybride, la collaboration de deux réseaux ou plus, a émergé pour tenter de surmonter ces inconvénients. Dans ce contexte, nous visons à explorer les possibilités de fourniture de services modernes exigeants en ressources, tels que le flux multimédia et la télévision mobile, via des réseaux conventionnels et hybrides. La première partie de la thèse présente le système de télévision mobile, les opportunités et les défis

Les moyens classiques et hybrides de diffusion de flux multimédia et les contributions de la communauté scientifique à cet égard y sont également présentés. S'en suit une brève introduction à la géométrie stochastique et aux modèles utilisés dans la thèse. La deuxième partie présente un réseau hybride BC / BB dans lequel le mode Unicast (UC) est utilisée pour le réseau BB et un seul émetteur BC (BCT) pour le réseau BC. Le modèle est ensuite généralisé pour inclure plusieurs BCT. Dans les deux cas, des expressions de couverture et d'efficacité sont dérivées puis utilisées pour optimiser les paramètres du réseau. La troisième partie présente le multicast (MC) pour les réseaux BB et dérive des expressions de couverture pour un déploiement de réseau monofréquence (SFN). Ensuite, un modèle de réseau BC / MC est analysé. Enfin, la quatrième partie aborde des questions pratiques telles que la gestion des ressources et la consommation d'énergie, ainsi que l'optimisation d'un système d'allocation de ressources dédié.

**Title :** Optimization of Hybrid Broadcast/Broadband Networks for the Delivery of Linear Services Using Stochastic Geometry

**Keywords :** Hybrid Networks, Networks optimization, Stochastic Geometry

**Abstract:** Modern mobile devices are able to connect to different types of networks to receive services such as mobile TV and multimedia streaming. This includes cellular Broadband (BB) networks like Long Term Evolution (LTE) and 5GNew Radio (5G-NR), and terrestrial Broadcast (BC) networks like Digital Video Broadcast (DVB). Yet each type suffers from limitations like the power efficiency in BC and limited spectral resources in BB. The hybrid network concept, the collaboration of two or more networks, emerged to overcome such drawbacks. In this context, we aim to explore the possibilities for delivering modern resource demanding services like the multimedia stream and mobile TV through conventional and hybrid networks. The first part of the thesis introduces the mobile TV system, opportunities, and challenges.

It surveys the conventional and hybrid means of the delivery of multimedia streams and the contributions of the scientific community in this aspect. This is followed by a brief introduction to stochastic geometry and the models used in the thesis. The second part introduces a hybrid BC/BB network where Unicast (UC) is used for the BB network and a single BC transmitter (BCT) is used for the BC network. The model is then generalized to include multiple BCTs. In both cases, expressions for coverage and efficiency are derived, and then used to optimize the network settings. The third part introduces Multicast (MC) for BB networks, and derives expressions for coverage for a Single Frequency Network (SFN) deployment. Then, a BC/MC network model is analyzed. Finally, the fourth part introduces some practical issues like resource management and energy consumption, and solutions such as a dedicated resource allocation scheme.