HAL
open science

Radio Resource Management in LTE Networks : Load Balancing in Heterogeneous Cellular Networks

Hana Jouini

To cite this version:

Hana Jouini. Radio Resource Management in LTE Networks : Load Balancing in Heterogeneous Cellular Networks. Networking and Internet Architecture [cs.NI]. Conservatoire national des arts et metiers - CNAM; École nationale d'ingénieurs de Tunis (Tunisie), 2017. English. NNT : 2017CNAM1153 . tel-01878355

HAL Id: tel-01878355

https://theses.hal.science/tel-01878355v1

Submitted on 21 Sep 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

École doctorale Informatique, Télécommunications et Électronique (Paris), Laboratoire Centre d'Etudes et De Recherche en Informatique et Communications

École doctorale Sciences et Techniques de l'Ingénieur, Systèmes de Communications, Laboratoire Systèmes de Communications

THÈSE DE DOCTORAT

présentée par : **Hana JOUINI**

soutenue le : **20 décembre 2017**

Pour obtenir le grade de ***DOCTEUR*** *conjointement du* **Conservatoire National des Arts et Métiers et l'École Nationale d'Ingénieurs de Tunis**

Spécialité : **Informatique**

Radio Resource Management in LTE Networks

Load Balancing in Heterogeneous Cellular Networks

THÈSE dirigée par

M. BARKAOUI Kamel	*Professeur des Universités, Conservatoire National des Arts et Métiers*
M. EZZEDINE Tahar	*Professeur, École Nationale d'Ingénieurs de Tunis*

RAPPORTEURS

M. BOUALLEGUE Ammar	*Professeur, École Nationale d'Ingénieurs de Tunis*
M. MELLOUK Abdelhamid	*Professeur des Universités, Université Paris 12*

PRÉSIDENT

M. ARNAUD Jean-Pierre	*Professeur titulaire de la chaire de réseaux du Conservatoire National des Arts et Métiers*

EXAMINATEURS

Mme. BOUZEFRANE Samia	*Maître de Conférences (HDR), Conservatoire National des Arts et Métiers*
M. CHAHED Tijani	*Professeur, Telecom SudParis*

Abstract

High demands on mobile networks provide a fresh opportunity to migrate towards multi-tier deployments, denoted as heterogeneous network (HetNet), involving a mix of cell types and radio access technologies working together seamlessly. In this context, network optimisation functionalities such as load balancing have to be properly engineered so that HetNet benefits are fully exploited. This dissertation aims to develop tractable frameworks to model and analyze load balancing dynamics while incorporating the heterogeneous nature of cellular networks. In this context we investigate and analyze a class of load balancing strategies, namely adaptive handover based load balancing strategies. These latter were firstly studied under the general heading of stochastic networks using independent and homogeneous Poisson point processes based network model. We propose a baseline model to characterize rate coverage and handover signalling in K-tier HetNet with a general maximum power based cell association and adaptive handover strategies. Tiers differ in terms of deployment density and cells characteristics (i.e. transmit power, bandwidth, and path loss exponent).

One of the main outcomes is demonstrating the impact of offloading traffic from macro- to small-tier. This impact was studied in terms of rate coverage and HO signalling. Results show that enhancement in rate coverage is penalized by HO signalling overhead. Then appropriate algorithms of LB based adaptive HO are designed and their performance is evaluated by means of extensive system level simulations. These latter are conducted in 3GPP defined scenarios, including representation of mobility procedures in both connected state. Simulation results show that the proposed LB algorithms ensure performance enhancement in terms of network throughput, packet loss ratio, fairness and HO signalling.

Keywords : HetNet, LTE, Radio resource management, Load balancing, Stochastic geometry, Poisson point process.

Résumé

Poussés par la demande croissante de services à haut débit sans fil, les réseaux LTE HetNet auto-organisés basés sur les spécifications 3GPP ont émergé comme une solution prometteuse pour les communications mobiles. Dans ce nouveau contexte, le problème de l'optimisation de l'équilibrage de charge entre cellules appartenant à différentes couches (macro, pico, femto cells) composant un même HetNet est crucial.

Cette thèse a pour objectif l'étude et le développement de solutions à ce problème notamment par l'adaptation dynamique des paramètres du handover. Dans une première partie, nous avons développé un modèle analytique basé sur les concepts de la géométrie stochastique capturant la nature hétérogène des réseaux HetNets. Nous avons pu exploiter ce modèle pour proposer et implémenter des algorithmes d'adaptation dynamique des paramètres de handover considérant différents niveaux de granularité et basés sur la maximisation de la puissance reçue et l'ajustement de la valeur de l'hystérésis du handover. Dans une seconde proposition, nous avons implémenté par simulation à événements discrets des algorithmes d'équilibrage de charge pour ces réseaux LTE HetNet auto-organisés basés sur les spécifications 3GPP et en y intégrant le mécanisme d'ajustement dynamique des paramètres de handover proposé dans la partie précédente.

Ces travaux sur l'optimisation de l'équilibrage de charge dans les réseaux HetNets nous ont permis d'aboutir à un bon compromis entre la maximisation du taux de couverture et la minimisation de la fréquence de handover.

Mots clés : HetNet, LTE, Gestion des resources radio, Equilibrage de charge, Géometrie stochastique, Processus de Poisson ponctuel.

Résumé substantiel

Les réseaux cellulaires nouvelles générations, notamment les réseaux LTE et LTE-Advanced, soulèvent des questions d'optimisation avec plusieurs éléments dont on doit tenir compte simultanément. En effet, ils visent à améliorer l'efficacité spectrale et à augmenter la capacité du réseau tout en prenant en considération les exigences des applications en termes de qualité de service et le besoin de garantir un minimum d'équité entre utilisateurs dont le nombre est en constante augmentation. Les réseaux hétérogènes, également appelés HetNet, sont des réseaux mobiles composés de plusieurs sous-réseaux qui se chevauchent avec des caractéristiques différentes en termes de bandes de fréquences, technologies d'accès radio (RAT), tailles de cellules déployées,...etc. Alors que les réseaux HeNet semblent être un moyen attrayant pour remédier aux limites de capacité/couverture du système, les opérateurs ont commencé à intégrer des cellules de petite couverture dans leurs réseaux de macro-cellules, formant ainsi une nouvelle topologie de réseaux LTE.

En outre, les mécanismes d'équilibrage de charge (load balancing-LB) jouent un rôle fondamental dans la gestion des ressources radio des réseaux cellulaires dans la mesure où ils visent à optimiser, selon des critères spécifiques, la répartition des mobiles (user equipment-UE) entre les cellules. Ces mécanismes permettent la répartition des UEs en prenant en considération certains paramètres relatifs à l'état de charge dans le réseau et aux exigences des utilisateurs en termes de qualité de service (QoS).

Poussés par la demande croissante de services à haut débit sans fil, les réseaux LTE HetNet auto-organisés basés sur les spécifications 3GPP ont émergé comme une solution prometteuse pour les communications mobiles. Dans ce nouveau contexte, le problème de

l'optimisation de l'équilibrage de charge entre cellules appartenant à différentes couches (macro, pico, femto cells) composant un même HetNet est crucial. Le défi consiste à fournir un gain de performance supplémentaire en améliorant l'efficacité du réseau. Dans cette thèse, nous proposons d'étudier l'équilibrage de charge basé sur des techniques d'optimisation des paramètres de handover (HO) dans les réseaux auto-organisés LTE HetNet. Nous proposons dans cette thèse de:

- Développer un modèle analytique basé sur les concepts de la géométrie stochastique et capturant la nature hétérogène des réseaux HetNets. Nous avons pu exploiter ce modèle pour proposer et implémenter des algorithmes d'adaptation dynamique des paramètres de HO considérant différents niveaux de granularité et basés sur la maximisation de la puissance reçue et l'ajustement de la valeur de l'hystérésis du handover.

- Implémenter par simulation à événements discrets des algorithmes d'équilibrage de charge pour les réseaux LTE HetNet auto-organisés basés sur les spécifications 3GPP et en utilisant le mécanisme d'ajustement dynamique des paramètres de handover proposé dans la partie précédente.

Équilibrage de charge dans les réseaux cellulaires hétérogènes: état de l'art et classification

Lorsqu'on traite des déploiements HetNet, l'état de l'art est principalement confronté à trois axes principaux:

- Efficacité énergétique: Avec la demande croissante en termes de services de réseaux mobiles, des défis cruciaux en matière d'efficacité énergétique sont attendus à l'avenir. Les opérateurs sont donc intéressés par la réduction de la consommation d'énergie. De nombreuses contributions considèrent l'efficacité énergétique pour les réseaux HetNet [19, 20, 21, 22, 23, 24]

- Gestion de l'interférence : La gestion des interférences est un facteur clé pour améliorer les performances des réseaux HetNet. Des contributions significatives ont jeté des

bases solides pour comprendre les divers aspects de la gestion et de l'atténuation des interférences dans les HetNet [18, 26, 28, 29, 30]

- Contrôle d'admission et équilibrage de charge : Une gestion efficace des ressources radio ne peut être assurée que par un mécanisme de contrôle d'admission efficace qui empêche le réseau d'atteindre un état de saturation importante et par la même garantit les besoins de QoS des applications utilisateurs. Le contrôle d'admission a été excessivement étudiée dans [31] où les auteurs élaborent une taxonomie des principales techniques de contrôle d'admission dans les réseaux mobiles.
  Dans le contexte des réseaux HetNet, l'équilibrage de charge signifie généralement le transfert de trafic supplémentaire du macro-tier vers le small-tier pour améliorer la capacité des macro-cellules. Étant donné qu'une grande partie du trafic intérieur peut être déchargée des macro- et small-tier, moins de macro-cellules seront nécessaires pour la couverture intérieure.

Nous avons focalisé dans cet état de l'art sur une composante clé des technologies SON à savoir l'équilibrage de charge dans les réseaux radio cellulaires LTE HetNet. Plusieurs travaux de recherche ont été proposés dans la littérature pour traiter le problème d'équilibrage de charge entre les cellules LTE et montre que la technique de LB dépend de l'état de connexion de l'UE au réseau (UE en état Idle ou en état Connecté). Ainsi On peut classifier les algorithmes de LB selon deux catégories (Fig. 1); état Idle et état connecté. Afin de mieux étudier les techniques de LB proposées dans la littérature, nous avons fournis

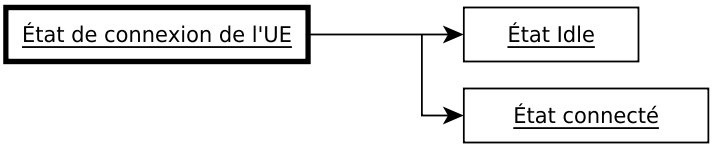

Figure 1: Classification des stratégies d'équilibrage de charge selon l'état de connexion de l'UE

en plus de la classification basée sur l'état de connexion de l'UE, cinq autres sous-catégories et chaque sous-catégories est subdivisée en différentes classes (Fig. 2). Dans cette partie nous avons établi, dans un premier temps, une classification des algorithmes d'équilibrage

de charge en se basant sur les critères les plus utilisés dans la littérature. Nous avons décrit ensuite des principes de fonctionnement de certains des algorithmes d'équilibrage de charge appartenant chacun à l'une des catégories de la classification établie.

Proposition de stratégies de HO adaptatives pour les HetNet basées sur une modélisation stochastique

L'une des solutions les plus adoptées dans la littérature pour résoudre la problématique de l'équilibrage de charge est de prendre en considération l'état de distribution des UEs lors de la configuration des paramètres des procédures de gestion de la mobilité. On parle ainsi de l'équilibrage de charge par ajustement dynamique des paramètres de mobilité. Comme les procédures de mobilité sont liées à l'état de connexion de l'UE, on peut parler de deux types d'équilibrage de charge par ajustement dynamique des paramètres de mobilité. Ainsi pour les UEs en état Idle, l'équilibrage de charge sera lié aux procédures de sélection/resélection et sera basé sur un ajustement dynamique des paramètres de sélection. Lorsque l'UE est en état connecté, l'équilibrage de charge sera lié à la procédure de HO et sera basé sur un ajustement dynamique des paramètres de HO (Stratégies adaptatives de HO). Ainsi nous avons étudier l'équilibrage de charge dans ces deux cas à travers l'étude de deux stratégies d'adaptation des paramètres de mobilité:

- La stratégie de contrôle adaptative de HO « coarse grained HO » (CHO): cette stratégie est basée sur la maximisation de la puissance reçue des cellules les moins chargées pour les rendre plus attractives aux UEs. Dans une telle stratégie, la probabilité de HO est calculée en se basant sur la probabilité d'interruption de service dans la cellule d'attachement (outage probability) et la probabilité que l'UE sélectionne avec succès une nouvelle cellule d'attachement qui lui offre la qualité de service exigée.

- La stratégie de contrôle adaptative de HO « fine grained HO » (FHO): cette stratégie est basée sur l'ajustement de la valeur de l'hystérésis de HO. Dans ce cas, l'UE compare périodiquement la qualité du signal reçu (SINR) de sa cellule d'attachement d'une part et ceux de toutes les cellules voisines d'autre part. Sur la base de cette

comparaison et des mesures de puissances reçues, une nouvelle cellule d'attachement est sélectionnée. Dans une telle stratégie, la probabilité de HO est calculée en se basant sur la probabilité que l'UE sélectionne avec succès une nouvelle cellule d'attachement avec une meilleure puissance reçue parmi tous les tiers composant le HetNet.

Nous avons étudié ces deux stratégies en exploitant les résultats présentés dans [1, 2] pour élaborer un modèle basé sur les concepts de la géométrie stochastique et capturant la nature hétérogène des réseaux HetNets. Ce modèle est basé sur une représentation en processus de Poisson ponctuels des différents nœuds composants les réseaux HetNet. Nous avons adopté les hypothèses de modélisation suivantes (voir Fig. 2.1):

- Les cellules de même type forment un tier (couche).
- Le modèle comporte K tiers.
- Un tier k ($k \in K$) est modélisé par un processus de Poisson ponctuel (PPP) Φ_k de densité λ_k.
- Les cellules du tier k sont caractérisées par une même puissance de transmission P_k et un même modèle d'affaiblissement de propagation (α_k).
- Les UEs sont modélisés par un PPP Φ^u de densité λ^u.
- On assume que les PPP formant le modèle sont tous indépendants.
- Les analyses sont faites pour un UE typique (typical UE) localisé à l'origine de l'espace 2-D.
- La puissance reçue par un UE localisé à une distance x d'une cellule du tier k est:

$$P_k(x) = P_k h x^{-\alpha_k} \tag{1}$$

- Le SINR reçue par un UE localisé à une distance x d'une cellule du tier k est:

$$SINR_k(x) = \frac{P_k(x)}{\sum_{j=1}^{K} I_j + \sigma_k} \tag{2}$$

- Débit reçu par un UE connecté à une cellule du tier k:

$$R_k(x) = \frac{W_k}{N_k} log_2(1 + SINR_k(x)) \tag{3}$$

En se basant sur ce modèle, nous avons investigué l'impact des stratégies CHO et FHO sur la performance des réseaux HetNet en termes d'indicateurs de performance clés:

- Taux de couverture (Rate coverage): Probabilité qu'un UE reçoit un débit supérieur à un seuil prédéfini.

$$R_C = \sum_{j=1}^{K} (A_k + P_k^{HO}) R_{C_k} \tag{4}$$

- Probabilité de HO: Probabilité qu'un UE exécute un HO.

$$P^{HO} = \sum_{k=1}^{K} P_k^{HO} \tag{5}$$

L'objectif est de trouver un compromis entre le débit offert et la signalisation dans le réseau. En fait, parmi les principaux objectifs des algorithmes d'équilibrage de charge c'est l'amélioration du débit reçu par les UEs en redistribuant la charge entre les différentes cellules d'une façon plus adéquate. En plus, la redistributions des UEs implique que le taux de déclenchement de la procédure de HO dans les réseaux qui implémentent l'équilibrage de charge sera plus élevé ce qui génère plus de signalisation dans le réseau. Donc un algorithme d'équilibrage de charge doit trouver une sorte de compromis entre augmenter le débit offert et ne pas trop augmenter la probabilité de HO.

Pour pouvoir calculer les valeurs de ces deux indicateurs il fallait calculer trois autres quantités à savoir:

- Probabilité d'association à un tier (A_k): c'est la probabilité qu'un UE sélectionne une cellule d'un tier donné:

$$A_k = 2\pi\lambda_k \int_0^{\infty} x exp(-\pi \sum_{j=1}^{K} G_{jk} x^{2\frac{\alpha_k}{\alpha_j}}) dx \tag{6}$$

  Ce calcul est basé sur les travaux de Han-Shin Jo dans [60].

- Taux de couverture d'un tier (R_{C_k}): c'est la probabilité qu'un UE attaché à une cellule du tier k, reçoit un débit supérieur à un seuil prédéfinit.:

$$R_{C_k} = P[R_k(X_k) > \rho_k] \tag{7}$$

avec ρ_k = Seuil du taux de couverture.

- Probabilité de HO d'un tier i vers un tier k ($P_{i\to k}^{HO}$): c'est la probabilité qu'un UE exécute un HO d'une cellule d'un tier i vers une cellule d'un tier k. Ce calcul a été fait dans deux cas:en utilisant la stratégie CHO ensuite en utilisant la stratégie FHO.

Calcul de la probabilité de HO en utilisant la stratégie CHO

Pour la stratégie CHO nous avons considéré une mesure biaisée de la puissance reçue:

$$P_k^{BRP}(X_k) = P_k h X_k^{-\alpha_k} B_k \tag{8}$$

et les conditions de déclenchement d'un HO lors de l'utilisation de la stratégie CHO sont traduites comme suit:

- $condition_1^{CHO}$: Le SINR de la cellule courante chute sous un seuil donné: $SINR_i(X_i) \leq \tau_i$.

et

- $condition_2^{CHO}$: Le SINR de la cellule destination est supérieur à un certain seuil et sa puissance est la meilleure par comparaison aux puissances reçues des cellules voisines: $SINR_k(X_k) \geq \tau_k$ et $P_k^{BRP}(X_k) > \underset{j\neq k}{argmax} P_j^{BRP}(X_j)$.

avec τ_k = Seuil du SINR coverage. Ainsi nous avons pu calculer les quantités suivantes:

- Probabilité de $P[condition_1^{CHO}]$:

$$P_1^{CHO} = P[(SINR_i(X_i) \leq \tau_i)|(S = i)] \tag{9}$$

- Probabilité de $P[condition_2^{CHO}]$:

$$P_2^{CHO} = P[(SINR_k(X_k) > \tau_k, P_k^{BRP}(X_k) > \underset{j\neq k}{max}(P_j^{BRP}(X_j)))|(S = i)] \tag{10}$$

- Probabilité de HO du tier i au tier k:

$$P_{i\to k}^{CHO} = P_1^{CHO}.P_2^{CHO} \tag{11}$$

Ainsi la probabilité totale de HO au tier k sera estimée comme suit:

$$P_k^{CHO} = \sum_{i=1, i\neq k}^{K} P_{i\to k}^{CHO} \tag{12}$$

et l'expression de la probabilité totale de HO sera estimée comme suit:

$$P^{CHO} = \sum_{k=1}^{K} P_k^{CHO} \tag{13}$$

Calcul de la probabilité de HO en utilisant la stratégie FHO

les conditions de déclenchement d'un HO lors de l'utilisation de la stratégie FHO sont traduites comme suit:

- $condition_1^{FHO}$: Le RSRP de la cellule destination est supérieur à celui de la cellule source: $RSRP_k(X_k) > RSRP_i(X_i) + Hys_{i\to k}$.

et

- $condition_2^{FHO}$: Le RSRP de la cellule destination est le meilleur par comparaison aux RSRP reçus des cellules voisines: $RSRP_k(X_k) - Hys_{i\to k} > \underset{j\neq k}{argmax}(RSRP_j(X_j) + CSOff_j - Hys_{i\to j})$.

Nous avons pu calculer les quantités suivantes:

- Probabilité de $P[condition_1^{FHO}]$:

$$P_1^{FHO} = P[RSRP_k(X_k) + CSOff_k - Hys_{i\to k} > RSRP_i(X_i)|S = i] \tag{14}$$

- Probabilité de $P[condition_2^{FHO}]$:

$$P_2^{FHO} = P[RSRP_k(X_k) + CSOff_k - Hys_{i\to k} > \underset{j\neq k}{argmax}(RSRP_j(X_j) + CSOff_j - Hys_{i\to j})|S = i] \tag{15}$$

- Probabilité de HO du tier i au tier k:

$$P_{i\to k}^{FHO} = P_1^{FHO}.P_2^{FHO} \tag{16}$$

Ainsi la probabilité totale de HO au tier k sera estimée comme suit:

- Probabilité totale de HO au tier k:

$$P_k^{FHO} = \sum_{i=1, i \neq k}^{K} P_{i \to k}^{FHO} \tag{17}$$

- Expression de la probabilité totale de HO:

$$P^{FHO} = \sum_{k=1}^{K} P_k^{FHO} \tag{18}$$

La principale conclusion de l'analyse ci-dessus est que l'amélioration de la couverture de débit est pénalisée par une augmentation de la signalisation dû au HO. Dans la section suivante, nous avons exploité les résultats de la stratégie FHO pour implémenter une stratégie d'équilibrage de charge pour les réseaux LTE HetNet. Nous avons mis en œuvre des algorithmes de LB basés sur le l'adaptation du seuil d'hystérésis de HO en fonction de la charge cellulaire.

Évaluation par simulation d'algorithme d'équilibrage de charge intégrant des stratégies de HO adaptatives

Dans cette partie nous avons proposé une implémentation dans ns-3 [67] de trois variantes d'une technique d'équilibrage de charge pour les réseaux LTE HetNet. Ces implémentations sont basées sur la stratégie de HO adaptatives FHO étudiée dans la partie précédente. Pour améliorer la capacité globale du système, 3GPP intègre dans les réseaux LTE l'équilibrage de charge à l'aide d'une fonction d'auto-optimisation, à savoir la MLB (mobility load balancing). MLB permet aux cellules souffrant de congestion de transférer le surplus de charge vers d'autres cellules voisines [64]. La MLB est régie par des mécanismes d'échange d'informations relatives à l'état de charge et à la capacité disponible entre les eNBs (sur l'interface X2). Une solution pour introduire la fonction de MLB dans un système LTE est d'orienter le trafic supplémentaire vers les cellules voisines en optimisant dynamiquement les paramètres de HO de la cellule, tels que l'hystérésis, lors de la détection d'un déséquilibre [70]. En effet, les techniques SON permettent d'ajuster automatiquement la configuration de la mobilité en fonction de plusieurs facteurs tels que les informations

de charge. La MLB basée sur des techniques de HO adaptatives permet de déclencher un HO pour des fins d'équilibrage de charge. Pour appliquer ce mécanisme, chaque cellule doit être consciente de ses propres conditions de charge ainsi que des conditions de charge de ses voisines. Ceci permet respectivement de détecter une situation de surcharge et de sélectionner la meilleure cellule voisine pour remettre des UE. À cette fin, les eNB surveillent périodiquement leurs propres conditions de charge et échangent ces informations via l'interface X2. Le protocole X2AP prend en charge les fonctions de signalisation au niveau du plan de contrôle de l'interface radio entre les eNBs. 3GPP définit X2AP comme une collection d'EPs [10]. Un EP X2AP est une unité d'interaction entre deux eNB. Comme X2AP est responsable de la signalisation entre deux eNB voisins, il assure la fonction d'échange d'informations relatives à l'état de charge des eNBs. Ns-3 est un simulateur de réseau à événements discrets, développé en langage C ++. Ns-3 prend en charge la simulation des réseaux cellulaires 3GPP LTE. Baldo et al. proposent dans [71] un modèle de simulation pour les scénarios de HO dans les réseaux LTE en utilisant ns-3. Afin d'intégrer les fonctionnalités d'équilibrage de charge, le modèle proposé implémente l'interface X2 supportant l'EP "RESOURCE STATUS UPDATE". Une telle implémentation n'offre qu'un prototype de cet EP et les détails concernant les variables associées ne sont pas spécifiés. Nous avons implémenté sous ns-3 de nouvelles fonctionnalités de l'interface X2AP afin d'assurer l'échange d'informations relatives à l'état de la charge entre les eNBs (voir Annexe 3.9). Ceci est réalisé à travers deux étapes de mise en œuvre. Le premier concerne les EPs "RESOURCE STATUS REQUEST" et "RESOURCE STATUS RESPONSE" qui sont nécessaires pour l'initiation d'un UE "RESOURCE STATUS UPDATE". Alors que le second se concentre sur l'EP "RESOURCE STATUS UPDATE". L'EP "RESOURCE STATUS UPDATE" inclut un attribut spécial appelé CAC (composite available capacity). CAC représente le niveau global de ressources disponibles qui peut être offert par un eNB afin d'équilibrer la charge sur la liaison descendante (CACD) ou montante (CACU).

MLB basé sur la technique FHO

L'algorithme d'équilibrage de charge que nous avons développé repose sur les principes décrits dans [72]. Cet algorithme est basé sur le calcul de nouveaux seuils de HO en se

basant sur la charge de chaque cellule comme illustré dans Fig. 3.5. Nous avons introduit trois seuils, avec des valeurs comprises entre 0 et 1. Ces seuils ont comme objectif d'estimer l'état de la charge de la cellule:

- $ThPre$: Si CACD diminue en dessous de ce seuil, la cellule correspondante est déclarée comme une cellule surchargée et doit exécuter l'algorithme d'équilibrage de charge en mettant à jour les valeurs de seuil de HO.
- $ThTarget$: Si CACD d'une cellule surchargée qui a activé l'algorithme d'équilibrage de charge dépasse ce seuil, la cellule doit désactiver l'algorithme d'équilibrage de charge et restaurer les valeurs par défaut des seuils de HO.
- $ThAvail$: Ce seuil sert à estimer le degré de capacité des cellules voisines à recevoir du trafic (Tab. 3.1).

Ces seuils sont des paramètres configurables par l'opérateur et sont transmis en input à l'algorithme d'équilibrage de charge. La nouvelle valeur de l'hystérésis est calculée comme suit:

1. variante 1: slow MLB

$$\alpha_{i\to j} = \begin{cases} 1 & si \quad CACD_j \leq ThTarget \\ 0 & si \quad CACD_j > ThTarget \end{cases} \tag{19}$$

2. variante 2: fast MLB

$$\alpha_{i\to j} = \begin{cases} 1 & si \quad CACD_j \leq ThAvail \\ 0 & si \quad CACD_j > ThAvail \end{cases} \tag{20}$$

3. variante 3: smooth MLB

$$\alpha_{i\to j} = \begin{cases} 1 & si \quad CACD_j \leq ThAvail \\ 1 - \frac{ThAvail - CACD_j}{ThAvail - ThTarget} & si \quad ThAvail < CACD_j \leq ThTarget \\ 0 & si \quad CACD_j > ThTarget \end{cases} \tag{21}$$

La nouvelle valeur d'hystérésis entre C_i et $C_{i,j}$ est ajustée comme suit:

$$NewHys_{i\to j} = \alpha_{i\to j} \times Hys_{i\to j} \tag{22}$$

Dans cette partie nous avons abordé la problématique d'équilibrage de charge dans le contexte des réseaux 3GPP LTE SON HetNet. Tout d'abord, nous avons implémenté dans

ns-3 des fonctionnalités 3GPP liées à la procédure de gestion de la charge du protocole X2AP comme spécifié dans TS 136.423. Deuxièmement, des algorithmes d'équilibrage de charge basés sur la technique FHO ont été mis en œuvre pour étudier l'impact de tels mécanismes sur les performances du réseau en termes de débit de réseau, de taux de perte de paquets, d'équité et de signalisation dû au HO.

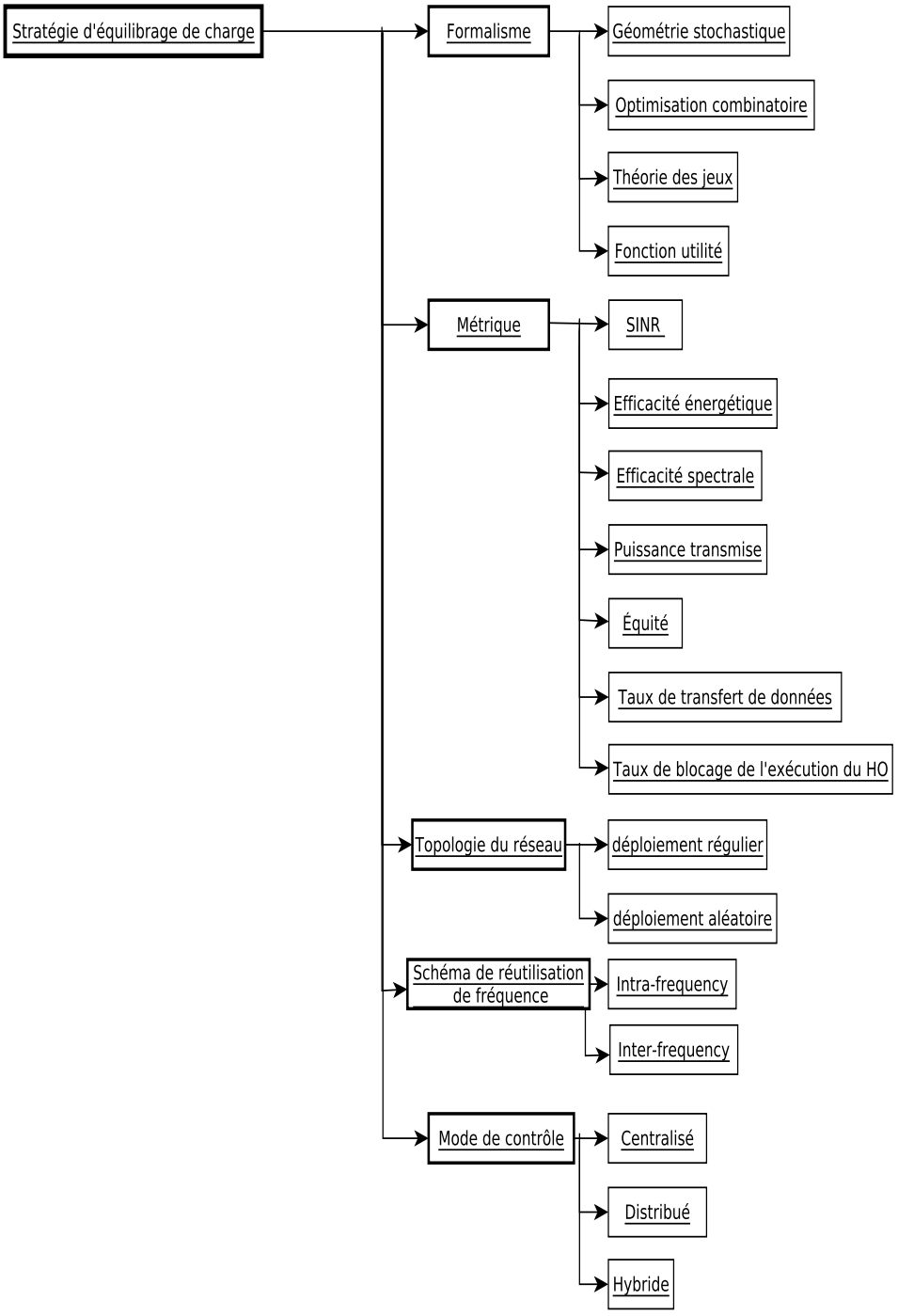

Figure 2: Classification des stratégies d'équilibrage de charge

Acknowledgements

This PhD dissertation is the result of a three-year research project carried out at the laboratories CEDRIC, CNAM Paris, France and SYS'COM, University of Tunis-El Manar, Tunis, Tunisia.

The first debt of gratitude is due to my dissertation supervisors Professor Kamel Barkaoui (CEDRIC, CNAM Paris, France) and Professor Tahar Ezzedine (SYS'COM, University of Tunis-El Manar, Tunis, Tunisia) for their flexibility and freedom provided in formulating my research problems while providing both insightful technical and high-level inputs helped me grow as a scholar. Their guidance together with the trust they showed in my skills are highly appreciated.

I would like to express my sincere gratitude to my advisor Professor Mohamed Escheikh for the continuous support and the countless discussions we had throughout my PhD study and research.

Words fail me in expressing my gratitude towards my family. My parents, Hassan Jouni and Bachira Jouini, inculcated in me the values responsible for making me the person I am today.

I would like to specially thank Ali for being a great friend and husband.

I thank my sister Jihene constant support and encouragement throughout my graduate studies.

Every graduate student needs friends who can keep his sanity in check through this long journey, and I was fortunate to make some. I would cherish the time spent with Zeineb and Fida.

Hana Jouini

Tunis, November 2017

Contents

Abstract **3**

Introduction **31**

0.1 Towards heterogeneous cellular networks: What is driving the evolution? . . 32

0.2 Motivations for wireless HetNets in 4G systems 32

0.3 Small-cells deployment in heterogeneous networks 33

0.4 Self organizing networks 34

0.5 Thesis Scope and Contributions 35

0.6 Thesis Outline 36

1 Heterogeneous Cellular Networks: State-of-The-Art and Load Balancing Classification **39**

1.1 Introduction 40

1.2 Heterogeneous wireless networks in literature 40

1.2.1 Energy efficiency in heterogeneous cellular networks 41

1.2.2 Interference management in heterogeneous cellular networks 42

1.2.3 User association and traffic offloading in heterogeneous cellular networks 44

1.3 Load balancing in heterogeneous cellular networks 45

1.4 Load balancing in idle mode: load-aware based user association 47

1.5 Load balancing in connected mode: load-aware based adaptive handover . . 51

1.6 Summary 53

2 Analytical Modelling of Adaptive Handover Strategies in Heterogeneous Cellular Networks 55

2.1 Motivations and related work 56

2.2 HetNet downlink system model and assumptions 58

2.3 Non adaptive cell association strategy 61

2.4 Adaptive handover strategies 63

2.4.1 Coarse grained HO control strategy 64

2.4.2 Fine grained HO control strategy 70

2.5 Rate coverage analysis 73

2.6 Results and discussion 73

2.6.1 Performance analysis of coarse grained HO control strategy 75

2.6.2 Performance analysis of fine grained HO control strategy 79

2.7 Summary 83

3 Mobility Load Balancing Based Fine Grained Adaptive Handover in Heterogeneous Cellular Networks 87

3.1 Motivations and related work 88

3.2 HO and MLB signalling functions of X2AP in 3GPP specifications 89

3.2.1 HO functions 90

3.2.2 MM function 91

3.2.3 MPM function 92

3.2.4 MRO function 92

3.2.5 LM function 93

3.3 MLB based adaptive HO in DL LTE SON networks 94

3.4 X2AP EPs extension 95

3.5 Problem formulation and DL LTE HetNet system model 96

3.6 MLB based fine grained adaptive handover 98

3.7 Simulations: assumptions and results 100

3.8 Summary 107

Conclusion **109**

Acronyms **111**

Bibliographie **115**

Annexes **127**

3.9 Appendix 127

List of Tables

1.1 Comparison of LB algorithms in UE idle mode for HetNet 49

1.2 Comparison of LB algorithms in UE connected mode for HetNet 52

2.1 Analytical model notations 60

2.2 Analytical model parameters' values 75

3.1 Neighbouring cells classification 99

3.2 Simulation model parameters 102

List of Figures

1 Classification des stratégies d'équilibrage de charge selon l'état de connexion de l'UE 9

2 Classification des stratégies d'équilibrage de charge 19

3 HetNet model 33

1.1 Energy efficiency based LB techniques 41

1.2 Classification of LB strategies according to UE state 46

1.3 Classification of LB strategies 54

2.1 3-tier HetNet (macro-, pico- and femto-tier) 59

2.2 Rate coverage (R_c) versus tier-3 density/tier-1 density (λ_3/λ_1) 76

2.3 HO probability (P_{HO}^{CHO}) versus tier-3 density/tier-1 density (λ_3/λ_1) 77

2.4 Rate coverage (R_c) versus SINR threshold (τ) 77

2.5 HO probability (P_{HO}^{CHO}) versus SINR threshold (τ) 78

2.6 Rate coverage (R_c) versus rate coverage threshold (ρ) 78

2.7 Rate coverage (R_c) versus UEs density (λ^u) 79

2.8 Rate coverage versus tier-3 biasing factor (B_3) 80

2.9 HO probability versus tier-3 biasing factor (B_3) 80

2.10 Rate coverage versus $Hys_{1\to3}$ and $Hys_{2\to3}$ 82

2.11 HO probability versus $Hys_{1\to3}$ and $Hys_{2\to3}$ 82

2.12 Rate coverage versus tier-3 density/tier-1 density (λ_3/λ_1) 83

2.13 HO probability versus tier-3 density/tier-1 density (λ_3/λ_1) 84

2.14 Rate coverage (R_c) versus rate coverage threshold (ρ) 84

2.15 Rate coverage (R_c) versus UEs density (λ^u) 85

3.1 Protocol stack of the X2 interface 90

3.2 Measurement event A3 with $Freq = SOff = 0$ 91

3.3 Resource Status Reporting EP 93

3.4 Sample of dynamic hysteresis adaptation effect on HO triggering when using A3 event with $Freq = SOff = 0$ 94

3.5 Illustration of the proposed MLB algorithm 98

3.6 Network topology 101

3.7 Femto-cell block 101

3.8 Global network throughput vs UEs density 104

3.9 Macro-cells throughput vs macro-cell's identifier 104

3.10 Packet loss ratio vs UEs density 105

3.11 Jain's fairness index vs UEs density 106

3.12 Number of successful HOs vs UEs density 106

3.13 X2AP added procedures 128

Introduction

"As mobile broadband demand continues to grow dramatically, significant increases in capacity can be achieved by adding small cells to complement macro networks, forming heterogeneous networks, also known as HetNets."

Nokia networks [1]

0.1 Towards heterogeneous cellular networks: What is driving the evolution?

Long term evolution (LTE) is the current deployed cellular technology in mobile connectivity domain. It's considered as part of the third generation partnership project (3GPP) release 8 standardization [2] and introduces multiple access schemes for radio transmission and reception [3] in order to fulfil 4G networks fixed targets. During 2016, the number of Voice over LTE (VoLTE) subscriptions has grown strongly and had already surpassed 200 million and estimated to reach 3.3 billion by 2022 [4]. In the other hand, 5G systems have a long way to go before being commercialized. Tests and plans are underway to set the terms for such an upgrade and even if some new technologies are emerging, 5G doesn't signify yet any particular type of technology. However the main target of 5G networks seems to be wireless capacity enhancement. As avowed by the european 5G public private partnership (5G PPP) project, one of the key challenges for 5G systems infrastructure will be to *"provide 1000 times higher wireless area capacity with more varied service capabilities compared to 2010 and to facilitate very dense deployments of wireless communication links"* [5]. Therefore to cope with this exponential growth of mobile broadband demand whether in current or future wireless systems, operators have to upgrade their networks in order to meet the forthcoming capacity demand. This requires progressive migration to hierarchical deployments, also denoted as heterogeneous hetworks (HetNet). This latter are mobile cellular networks composed by several overlapping subnetworks with different characteristics such as different frequency bands, radio access technologies (RAT), cell sizes and backhaul support.

0.2 Motivations for wireless HetNets in 4G systems

Operators deploying 4G wireless broadband had recourse to advanced physical layer technologies (such as orthogonal frequency-division multiple access (OFDMA), multi-antenna techniques or more efficient modulation/coding schemes) to face the exponentially increasing number of mobile subscribers and highly bandwidth demanding applications. However, it seems that capacity demand increasing is faster than spectral efficiency

improvement and then these solutions alone are insufficient in particular at hotspot areas and cell edges where network performance can significantly degrade. One solution maybe to add more macro-cells or multiplying the number of sectors/antennas per macro-cell. Such a solution is hardly difficult to consider since the high cost of macro-cells deployment especially in urban zones [6]. While HeNet seems to be an attractive way to deal with system capacity/coverage limitations, operators started integrating small cells with their macro-cell networks. A new topology for 4G networks had arisen and will strongly influence next generations of cellular networks. A HeNet in 3GPP definition is a network containing cellular cells with different characteristics such as different transmission power (Tx power) levels and radio frequency (RF) coverage areas. In this paradigm, small-cells (low power nodes) and macro-cells (high power nodes) can share a same frequency carrier and a same mobile network provider. The result is a HeNet with large coverage macro-cells network combined with small-cell deployments producing increased bitrates per unit area (Fig. 2.1).

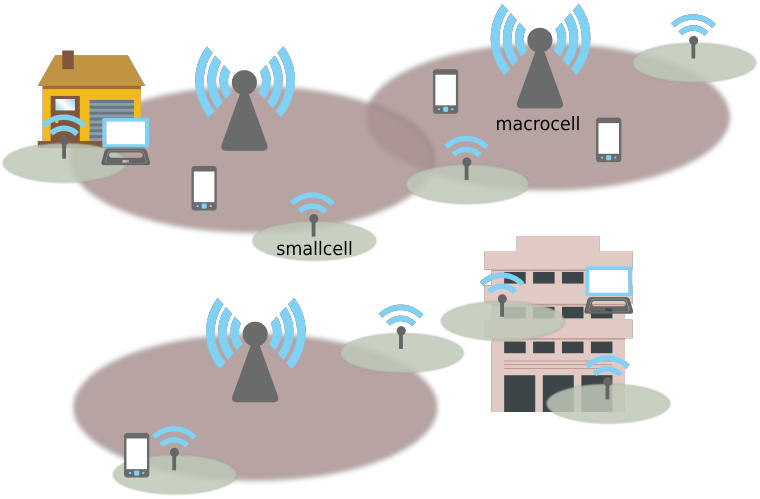

Figure 3: HetNet model

0.3 Small-cells deployment in heterogeneous networks

According to CommScope, leader in infrastructure solutions for communications networks, network densification can be defined as *"adding more cell sites to increase the*

amount of available capacity" [7]. Hence network densification is considered as a key factor to improve capacity and performance of wireless cellular networks. Thus, small-cell deployments proliferation is essential for improving capacity and quality of service (QoS) and reducing cellular networks power consumption in HetNet. There are two key differences between deploying small- and macro-cells. First, small-cells are deployed in much larger numbers into cellular networks. Then, manual processes for configuration and optimization are no longer feasible and must be self-organized. Second, small-cells are deployed dynamically and without an elaborate planning phase, while macro-cell deployments are fully planned. This means that small-cells feature more adaptation and reconfiguration operations per cell. As a consequence self-organizing network (SON) technologies seem to be indispensable for small-cells deployments.

0.4 Self organizing networks

Zero-touch network management and, as a consequence, operational expenditures saving are the principle drivers for bring up SON concept in cellular networks especially for HetNet where diversity of technologies is the principle characterization. Minimizing human factor impact aims to boost the overall network performance by allowing fast re-configuration of network parameters. Three SON categories of functionalities are identified [8]:

- Self-Configuration: consists on giving cells the ability to be self-installed/configured automatically once deployed.
- Self-Healing: aims to automatic detect and remove failures of functionalities related to cells configuration.
- Self-Optimisation: involves both user equipment (UE) and cell and aims to optimise network performance by auto-tuning network configuration parameters basic on UE and cell measurements. This concerns [9]: *(i)* Coverage and capacity optimization. *(ii)* Energy saving and Interference reduction. *(iii)* Mobility robustness optimisation (MRO). *(iv)* Random Access Channel (RACH) Optimisation. *(v)* Automatic Neighbour Relation Function. *(vi)* Mobility Load balancing (MLB) optimisation.

This latter (i.e. Mobility load balancing optimisation) also known as load balancing (LB) is done by dynamically tuning RAN parameters to minimize network disparity between different tiers forming the HetNet. The challenge is to deliver additional performance gain by improving network efficiency. In this dissertation we propose to study LB based adaptive handover (HO) parameter optimization in LTE self-optimizing network networks.

0.5 Thesis Scope and Contributions

The general scope of this dissertation is to investigate SON functionalities related to dynamic load balancing in multi-tier HetNet deployments. We study tier specific biasing as a promising approach for realizing load balancing gains. We propose tu study distributed traffic steering solutions based on redistributing connected UEs between different tiers by using adaptive HO techniques to achieve better load handling. The contributions are twofold.

Modelling and analysis of handover strategies in stochastic HetNets. In chapter 2 we develop general and tractable stochastic model that capture heterogeneity in network infrastructure. A general K-tier HetNet model is proposed with cells of each tier randomly located in a 2-D space and possibly differing in deployment densities, transmit powers, available bandwidths and pathloss exponents. We propose to associate UEs to different tiers according to a stationary based maximum received power association strategy. UEs may execute HO from the serving cell tier to any other tier. We propose to investigate the impact of introducing adaptive HO strategies on network performance in terms of HO probability and rate coverage. We adopt two HO strategies:

- Coarse grained HO strategy based on power biasing: the UE attempts to select a new serving cell based on maximum biased received power. In such strategy HO probability is calculated based on outage probability of current cell and the probability that the UE successfully selects a new serving cell from a specific tier among all HetNet tiers.

- Fine grained HO strategy based on hysteresis adjustment: the UE triggers HO based

on LTE A3 event. By tuning hysteresis thresholds, we steer the traffic to a specific tier. In such strategy HO probability is calculated based on probability that the UE successfully selects a new serving cell that offers better received power.

Based on association and HO probabilities calculation the rate distribution over the network is derived to investigate how adaptive HO strategies may affect network performance.

Developing schemes for load balancing in LTE HetNet deployments. To further investigate the impact of adaptive HO strategies on network performance, in chapter 3 we propose to implement load balancing schemes under realistic network scenarios (using network simulator 3) of a two-tier LTE SON HetNet deployment. The developed self-optimizing schemes aim to boost network capacity by reacting autonomously to cell load variations. To that end two implementation steps are followed:

- In a first step two LM EPs of the of X2AP protocol namely 'Resource Status Reporting Initiation Procedure' and 'Resource Status Reporting Procedure' are implemented as specified in TS 136.423 [10].
- We exploit next these EPs to implement in a second step LB schemes based on adjusting adaptively HO hysteresis threshold according to cell load information. We specifically focus on A3 HO triggering event based on measurements of the reference signal received power (RSRP) [11].

0.6 Thesis Outline

The thesis is divided into 3 chapters and 1 appendix. A brief overview of the following chapters is provided below:

- Chapter 1: *Heterogeneous wireless networks: state-of-the-art and classification of LB techniques* - This chapter sets a detailed literature review giving some background to previous works investigating HetNet. Material from prior studies is reviewed and the major findings are summarized. We next present extensive review of LB in HetNets. We propose then a taxonomy as a framework for studying the existing LB algorithms.

- Chapter 2: *Analytical modelling of adaptive handover strategies in heterogeneous cellular networks* - This chapter describes a baseline downlink model for the analysis of adaptive HO techniques in multi-tier HetNets. The rate coverage across the network is derived as a function of stationary association and adaptive HO probabilities.

- Chapter 3: *Load balancing in heterogeneous cellular networks* - This chapter is dedicated to present performance analysis of LB algorithms for LTE SON HetNet deployments based on ns-3 simulations. A joint LB framework is developed to adjust HO thresholds with respect to cell load.

Chapter 1

Heterogeneous Cellular Networks: State-of-The-Art and Load Balancing Classification

"The ongoing evolution of cellular communication networks into dense, organic and irregular heterogeneous networks ("HetNets") has elevated load-awareness to a central problem, and introduces many new subtleties."

An Overview of Load Balancing in HetNets: Old Myths and Open Problems [12]

1.1 Introduction

Fourth generation mobile networks were envisioned to support the increase of data traffic demand while reducing energy consumption and improving quality of service (QoS). These requirements are still accurate for 5G systems. Authors in [13, 14] identify for 5G networks three principle technologies to satisfy the above mentioned requirements and then enhance network performance (i.e. dense HetNets, massive multiple-input multiple-output (MIMO) and millimeter wave (mmWave) technique). HetNet deployments require the use of innovative functionalities such as enhanced MRO, inter-tier LB and inter-cell interference coordination techniques in order to achieve the promised capacity and coverage gains. This chapter covers the main state-of-the-art with regards to HetNets in cellular networks. Material from prior studies being available in literature is reviewed and the major findings are summarized.

1.2 Heterogeneous wireless networks in literature

Excellent contributions have been provided in [15, 16, 17, 18] to better understand HetNets. In order to investigate the requirements of future HetNet against current cellular topologies, authors in [15] discuss theoretical models including coverage and throughput analysis, signal-to-interference-plus-noise ratio (SINR) distribution, cell association and cellular spatial models. A theoretical framework of two-tier cellular network based on random spatial models using stochastic geometry tools was developed to investigate network performance when using enhanced technologies such as enhanced inter-cell interference coordination (eICIC) and cell range extension (CRE). The work in [16] compares between traditional networks and heterogeneous ones based on performance aspects such as KPI performance metrics, mobility and interference management, cell association and network topology. Authors in [17] review system architecture designs, theoretical performance analysis and key technologies required to improve spectral/energy efficiency in HetNets. They propose a system architecture based on inter- or intra-frequency cells deployment. Also, excessive study of interference coordination, radio resource allocation and SON applications in HetNets is given in [17]. A potential 5G cellular architecture based on HetNet deployment

is proposed in [18] where authors discuss some promising key technologies that can be adopted for 5G systems.

The general proposition suggested by the aforementioned works is that when dealing with HetNet deployments, state-of-the-art mainly faces the problems of energy-efficiency, cell association[1], interference coordination and mitigation as well as traffic offloading from macro- to small-tier. These issues are investigated in next subsections.

1.2.1 Energy efficiency in heterogeneous cellular networks

With the rising demand for mobile network services crucial challenges with respect to energy efficiency are expected to arise in the future. Hence operators are interested in reducing energy consumption and then costs related to this latter. Many contributions consider energy efficiency for HetNet [19, 20, 21, 22, 23, 24]. Feng et al. provide in [19] a comprehensive survey on energy reducing consumption techniques conceived for wireless communication systems. Classification of energy efficient resource management techniques for multicell cellular networks was presented in [20] where authors distinguish between three network domains; homogeneous, heterogeneous, and cooperative networks. It was determined that for the HetNet case, energy efficiency can be improved using three types of based load adaptive techniques (Fig. 1.1):

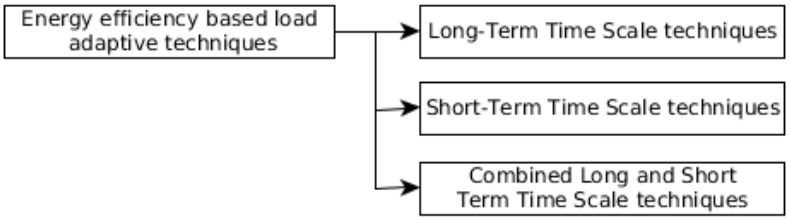

Figure 1.1: Energy efficiency based LB techniques

- **Long-Term Time Scale techniques:** the concept of long-term time scale consists in involving redistribution of UEs to a minimal number of cells and powering off lightly loaded ones when their load level is low for prolonged periods.

[1] Also known as cell selection or user association

- **Short-Term Time Scale techniques:** short-term time scale consists in translate some cells into low power sleep modes to reduce the power consumption over shorter durations. When a peak load situation is sensed, these cells are expected to be fully restored with high agility.

- **Combined Long and Short Term Time Scale techniques:** in this case both long and short-term time scale solutions are considered and combined to optimize energy consumption in HetNets. The problem of optimal on-off cell switching and resource utilization based on the long- and short-term fluctuating load is investigated in [25] for a centralized multi-RAT network consisting of cellular and WiMAX cells with overlapping coverage area.

Many other works in literature propose frameworks aiming to optimise energy efficiency in HetNet. Zhuang et al. propose in [21] a Traffic-driven framework based radio resource management (RRM) to optimize energy efficiency in HetNet. An interference-aware framework based on power coordination is proposed in [22] where a new adjustable utility function is employed to jointly optimise spectral efficiency and energy efficiency issues in HetNet deployments where spectrum efficiency concerns the maximum data rate that can be transmitted over a given bandwidth. Authors in [23] anticipate 5G systems by designing a cooperative green HetNet framework to find compromise between optimizing spectral and energy efficiency. [24] provides a framework for investigating the design of energy efficient cellular networks through the employment of cell sleep mode strategies. Using a stochastic geometry based model, authors in [24] investigate the impact of random sleeping/strategic sleeping on power consumption and energy efficiency in both homogeneous and heterogeneous networks.

1.2.2 Interference management in heterogeneous cellular networks

Interference management is a key factor for improving HetNet RAT performance. Significant contributions have laid a solid foundation for understanding the diverse aspects of interference management and mitigation in HetNet. Interesting surveys of existing interference management techniques developed for HetNet systems are presented in [18, 26].

Ahmed et al. highlight in [26] particularities of interference management with femtocell deployments in HetNets. Most important literature works dealing with this issue were provided to show how interference can be mitigated based on many mechanisms:

- **Interference management based on spectral usage:** by blocking access to DL channels that experience greater co- and cross-tier interferences, resource allocation schemes may play a significant role in avoiding high interference levels.
- **Access control:** performance of femtocell in terms of interference greatly depends on UEs access control mode (i.e. closed, open or hybrid access).
- **Load balancing:** adequate distribution and sharing of traffic between macro- and small tiers yields to effective co-tier interference mitigation with less complexity.

Hossain et al. provide in [27] outlooks and insights on interference management challenges for 5G HetNets. Four new features and potential issues that can arise from future 5G systems and which affect the interference dynamics in UL/DL transmissions are:

- **Heterogeneity and cells' dense deployment:** with massive deployment of small-cells, the aggregate inter- and intra-flow interference management is more complicated to model, especially for cell edge users. Therefore, communication techniques performance evaluation in presence of such interference is challenging and new techniques for interference management should be considered.
- **Coverage and traffic load imbalance due to cells varying Tx powers:** the co-existing of both low and high Tx power cells will generates an imbalanced situation where UEs are more likely to camp in macro-cells with higher Tx power which will further complicate the dynamic of inter-flow interference.
- **Public/private access restrictions in different tiers:** Femtocells can be deployed in whether open, closed (CSG) or hybrid modes. In the case of full frequency reuse deployment, non CSG UEs may experience strong interference from a CSG cell when they are in close proximity. The interference experienced by non CSG UEs could then be severe.

- **Scheduling strategies:** QoS and QoE features which require sophisticated resource allocation techniques generally based on prioritizing some UEs based on metrics such as spectral efficiency, traffic nature, ...etc, are often likely to lead to diverse interference levels.

According to [27] designing efficient power control and cell association techniques are one of the key factors that may deal with the above mentioned issues. A review of existing power control and cell association techniques is also provided to demonstrate their limitations for interference mitigation and guidelines are provided to optimize existing techniques in order to overcome these limitations in the emerging 5G systems. Novel techniques for interference management are proposed in [28, 29, 30]. Authors in [28] propose a combined framework for both interference mitigation and low complexity HO management in heterogeneous cloud small-cell networks. In particular, an effective coordinated multi-point (CoMP) clustering scheme using affinity propagation was presented to mitigate cell edge users' interference. A hybrid model for determining the impact of interference in cellular systems using Poisson point processes (PPP) is proposed in [29]. An interference control based beamforming technique for HetNet was investigated in [30] where authors propose to perform joint beamforming and UE selection in order to mitigate interference.

1.2.3 User association and traffic offloading in heterogeneous cellular networks

User association[2] was excessively investigated in [31] where authors elaborate a taxonomy of principle user association techniques. A detailed reviewing of user association based LB is provided in section 1.4.

In the context of HetNet, traffic offloading generally means the transfer (i.e. offload) of extra traffic from macro- to small-tiers to improve macro-cells capacity. As a large amount of indoor traffic can be offloaded from macro- to small-tiers, fewer macro-cells will be needed for indoor coverage. The reduction of macro-cell sites will result in a huge CAPEX (i.e. significant saving in macro-cell deployments) and OPEX (i.e. significant saving in backhauling) reductions for operators. Since LB refers to techniques enabling

[2]Throughout this dissertation, we use the terms user association, cell association and cell selection interchangeably.

traffic balancing between hot spot cells (i.e. overloaded cells) suffering from a high call blocking rate (CBR) and/or call dropping rate (CDR) and light loaded cells (i.e. low loaded cells) where a large amount of resources remains in idle state causing resource wastes, offloading may be studied under the general heading of LB. In the next section we present a comprehensive review on recent advances in LB algorithms designed for HetNet.

1.3 Load balancing in heterogeneous cellular networks

In this section, we focus on the extensive review of LB in HetNets and provide detailed classification of the main LB algorithms proposed in literature. Notice that the adopted LB technique depends on UE states (i.e. idle or connected). Indeed, LB may be performed at any instance of the radio resource control (RRC) UE state machine (Fig. 1.2). This includes offloading UEs while being in idle or connected states and even when switching from one RRC state to another. LB in idle state is performed by means of cell selections and cell reselections procedures and involves UEs that do not have any radio bearer established and who attempt to join the cellular network or to re-select a new cell to camp in. The main motivation for offloading idle UEs is to mitigate signalling overhead from potential load driven HO executions. Nonetheless, cell reselections should be economically utilized as they cost in terms of UE power consumption; hence, they may jeopardize the battery life of the UE device. After switching to the connected state, a situation where the camping cell does not have enough resources to serve the newly arrived UE may occur. To resolve such a situation, implementing a connected mode LB scheme seems to be the most effective solution. In this context, it can quickly react to inter-layer load variations in HetNets and take the proper offloading decisions either by updating mobility parameters or executing forced HOs. The challenge for connected LB schemes is to maintain HOs executions at an accepted level, as they cost in terms of signalling overhead together with causing service interruption whenever executed since LTE systems support only hard HO. Hence we start by classifying LB strategies into two categories (i.e. LB in idle state and LB in connected state). In order to review proposed LB schemes in literature we provide besides of the UE connection state, five other classes and each class is subdivided into different categories (Fig. 1.3).

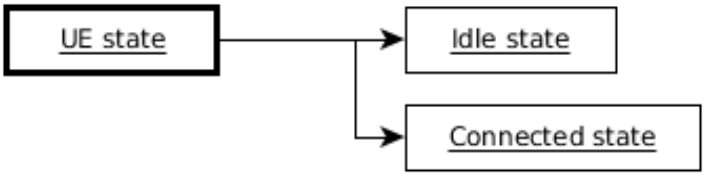

Figure 1.2: Classification of LB strategies according to UE state

1. *Metric:* The choice of a specific metric plays a pivotal role for balancing the traffic among the different layers of a HetNet. Different metrics have been adopted for determining which cell should serve which UE. We selected six categories of metrics that are being used in literature: spectrum efficiency, energy efficiency, SINR, fairness, total transmitted/received power and call blocking/HO failure rates. In the related research literature, either one of the specified metrics or a combination of several of them is used.

2. *Formalism:* There are many interesting mathematical tools that are adopted for modelling and solving the LB issue in HetNets. Notably we distinguish four categories of modelling tools (i.e. stochastic geometry, combinatorial optimization, game theory and utility function).

3. *Network layout:* By network layout we mean the physical placement of different cells among a spatial area. Two basic categories of network layout exist; regular deployment where all cells are placed on a regular grid, (e.g., the traditional hexagonal grid model) and random deployment which is an emerging approach of modelling the topology of wireless networks and consists on a non regular deployment where cells are located arbitrary among the spatial area. In the context of HetNets, small-cells deployment is not planned especially in the case of femtocells. Then a heterogeneous cellular network layout couldn't be regular. For HetNets, when we describe about network topology we mean the topology of macro-cell layer.

4. *Control:* the control approach may be: *(i)* centralized in case where the LB scheme is implemented in a single entity which collects information from all the network

components and performs the LB decision, *(ii)* distributed in case where cells and UEs are allowed to make LB decisions through the interaction between them, *(iii)* hybrid in case where a part of the LB technique is implemented in a centralized manner and another part is implemented in a distributed manner. Such a technique combines the advantages of both centralized and distributed control. The adopted control approach affects essentially the complexity, the signalling overhead, and the optimality of LB algorithms.

5. *Frequency reuse:* Deploying small cells in full frequency reuse with the macro overlay (i.e. intra-frequency or co-channel deployment) poses a handful of challenges. As intra-frequency deployments naturally suffer from strong interference between the two layers, it is not a trivial task to maintain an inter-layer balanced load. Instead of intra-frequency deployments and as mobile broadband traffic continues to grow, operators are compelled to deploy more carriers and to add more spectrum in existing site locations (i.e. inter-frequency deployments). Likewise load balancing across the deployed frequency layers is a key prerequisite for boosting network performance; however, it has to be performed in an efficient manner.

1.4 Load balancing in idle mode: load-aware based user association

The problem of user association for network LB has attracted much attention in recent years. In fact, an efficient method to balance the traffic between macro- and small-tiers seems to be optimizing the cell selection scheme. RAT selection has been extensively studied in earlier works (see [31] for a survey). It has been shown that an efficient cell association scheme for HetNet should jointly consider two objectives; balancing the load among different layers while minimizing the inter-cell interference [32]. From that point of view many recent works cope with LB issue by proposing user association schemes, which are generally considered as a binary NP-hard matching problem [33], that aim to minimize inter- and intra-layer load disparity in HetNets [34, 35, 36, 37, 38, 39, 40, 41, 42, 43]. In this context a classical cell selection approach where UEs camp in the cell with the best

DL signal strength is unsuitable for HetNets combining both macro-cells with high Tx power and small-cells with low Tx power. The concept of CRE (see chapter 2 section 1.2 (cell range expand)) proposed by 3GPP [25] is a popular solution that has been studied in many works. Authors in [34] propose an inter-RAT offloading technique using biased received power based association, where the optimal bias resulting in the highest SINR and the highest rate coverage were determined using numerical evaluation techniques. A weighted pathloss based user association strategy is defined to associate users while optimizing SINR/rate coverage. It has observed that the optimum point of traffic offloading to maximize SINR coverage is not in general the same as the one that maximizes rate coverage, defined as the fraction of users achieving a given rate. In [36] a based effective rate user association scheme formulated as a maximization of the sum of effective rates problem is presented. An enhanced version of the proposed user association scheme is also proposed aiming to mitigate interference and reduce power consumption while performing user association. Authors in [39] propose to perform cell selection based on a hybrid scheme where a centralized entity sends load information to idle UEs which perform cell selection based on a global utility to maximize UEs QoS by achieving optimum values of throughput and call blocking probability. Ye et al. propose in [37] a distributed load-aware cell association scheme aiming to maximize UE data rate which was defined as a logarithmic maximisation problem. First, authors relax the deterministic user association to a fractional association by allowing UEs to associate more than one cell at the same time (i.e. fractional user association). Then the primal combinatorial optimization problem is converted into a convex optimization problem. By exploiting the convexity of the problem, a distributed user association algorithm was developed with the assistance of dual decomposition and gradient descent method. A similar approach was adopted in [40] where authors aim to optimize user association decision by utilizing a logarithmic utility function based on weighted proportional fairness as objective but without relaxing the deterministic user association constraint in order to approach a realistic system modelling. A belief propagation (BP) algorithm is proposed to solve the optimization problem and a stochastic geometry method is used to analyse average sparsity and distribution degree. Similarly, authors in [41] address the user association problem for HetNets from an optimization perspective under

proportional fairness criterion. Based on pricing strategy, users are associated with a cell according to an utility minus a price. Authors in [38] propose a CRE based approach for user association and almost blank subframe (ABS) for interference coordination. The approach consists on minimising a α-fairness objective function using distributed learning algorithms in near-potential games with load and outage constraints. Authors in [42] propose to utilize the concept of topology potential for measuring UEs desirability of different cells in user association issue. Then the problem is resolute as a utility proportional fairness optimization function. A virtually distributed user association algorithm is proposed in [35] for software-defined RAN architecture where the user association scheme is implemented in a centralized manner (i.e. RAN controller (RANC)). While classical user association techniques delegate cell selection task to the UE, authors in [43] propose to implicate cells in the decision by implementing a distributed cell-guided association method. Authors in [44] consider cells' limited backhaul capacity while dealing with the LB issue in HetNets. LB is investigated jointly with interference mitigation in [45] where authors identify and exploit massive MIMO technology as one of the key factors of 5G systems. Since LB is closely related to the manner how we schedule UEs among different cells, authors in [45] design a DL macro-cell scheduler aiming to offload macro UEs to small-cell layer. A network utility maximization problem subject to dynamic wireless backhaul constraints, traffic load, and imperfect channel state information was developed. A comparison of LB based user association algorithms based on the above-mentioned classification is provided in Tab. 1.1.

Table 1.1: Comparison of LB algorithms in UE idle mode for HetNet

Ref.	**Principle**	**Topology**	**Model**	**Metric**	**Control**	**Freq. reuse**
[34]	CRE, Biasing, Weighted association strategy	Random	Stochastic geometry	data rate Energy efficiency Total transmitted/received power	—	Inter-frequency

[39]	Maximizing a global utility function based on data rate (maximize) and call blocking probability (minimize)	—	Game theory	data rate, call blocking probability	Hybrid	—
[36]	Maximizing effective rate sum	Regular	Combinatorial optimization	data rate, Energy efficiency, Total transmitted/received power	Distributed	—
[37]	Offload low-rate UEs	Regular	Combinatorial optimization	data rate	Distributed	Intra-frequency
[40]	Offload low-rate UEs, Priority-based user association	Regular	Combinatorial optimization	data rate, fairness	Distributed	—
[41]	Offload low-rate UEs, pricing-based user association	Regular	Combinatorial optimization	data rate, fairness, Total transmitted/received power	Distributed	Intra-frequency
[46]	Biasing CRE	—	Game theory	fairness, SINR (outage probability), data rate	Distributed	Intra-frequency
[42]	Topology potential based user association	—	Combinatorial optimization	data rate, fairness, energy efficiency	Distributed	Intra-frequency
[35]	—	—	Stochastic geometry	data rate, energy efficiency	Centralized	Intra-frequency
[43]	Maximizing SINR	Regular	Combinatorial optimization	SINR (outage probability)	Distributed	Intra-frequency
[47]	—	—	Utility function (linear utility function)	data rate	Centralized	—

[45]	—	—	Combinatorial optimization	Total transmitted/received power, SINR	Distributed	Inter-frequency

1.5 Load balancing in connected mode: load-aware based adaptive handover

Connected mode refers to the state where a connection is established between the cell and the UE according to the radio resource control (RRC) protocol specification. In 3GPP LTE systems, when UEs are in RRC-connected state, the mobility management is implemented by the HO procedure. Many works propose to perform LB by offloading extra-traffic from over-loaded to low-loaded cells. Authors in [48] propose to balance the load by dividing the traffic of each UE among different networks forming the HetNet. In fact, [48] presents the heterogeneity as an overlapping of networks with divergent characteristics in terms of frequency bands, Radio Access Technology (RAT) and backhaul support. The problem is treated as a weighted-base LB where the traffic of an UE is divided into subflows, each of which is transmitted via a different access network. Authors in [49] consider a relaxed problem formulation where each user can be associated with multiple cells and show that these problems can be solved by convex optimization. For a weight-based LB scheme, the performance of this latter is highly depended on the specific weight, which was heuristically obtained in [49]. Based on the concept of auction in game theory [50], authors in [46] propose a two-stage LB scheme for offloading macro-UEs to small-cell layer. The proposed algorithm allow to a small-cell that has received a HO request message from a macro-UE to calculate the received signal strength indicator (RSSI) of its neighbouring small-cells which is used to identify if there are other small-cells that are more suitable for the macro-UE. Authors in [51] propose to improve the energy efficiency of LTE network by interworking with low energy consuming WiFi networks. The basic idea is to try to hand over users with low signal quality in LTE as many as possible to WiFi system which has enough resources to accommodate more users, while providing throughput-promotion guarantee for LTE system and handover users. Authors in [52] apply the technique of design of experiments (DOE) to dynamically optimize small cell range extension according

to the load of neighbouring macro-cells. DOE aims to obtain the maximum information from an experimental apparatus being modelled, by devising experiments that will yield the most informative data, in a statistical sense, for use in parameter estimation and model validation [53]. Authors in [54] propose a LB scheme in which each small-cell locally performs a load balanced scheduling to equalise the performance of its connected UEs that are scheduled in subframes overlapping and non-overlapping with macro-cell ABS. Authors in [55] investigate and analyze the behaviour of a novel distributed LB scheme for 3GPP HetNet LTE deployment where the cell individual offset (CIO) is updated for each cell depending on calculation of its composite available capacity (CAC) [10]. Authors in [56] propose a HO decision mechanism considering a scenario of a WiFi-WiMAX integrated HetNet environment. Authors in [57] propose an adaptive bias configuration strategy for CRE in a macro-Pico environment. A comparison of LB based adaptive HO algorithms based on the above-mentioned classification is provided in Tab. 1.2.

Table 1.2: Comparison of LB algorithms in UE connected mode for HetNet

Ref.	**Principle**	**Topology**	**Model**	**Metric**	**Control**	**Freq. reuse**
[48]	weighted-base LB	Regular	Combinatorial optimization	SINR(Outage-coverage probability)	Distributed	Inter-frequency
[49]	weighted-base LB	—	Utility function (linear utility function)	Energy efficiency, Total transmitted/received power	—	—
[46]	Max-RSSI	—	Game theory	Total transmitted/received power, data rate	Distributed	Inter-frequency
[51]	—	—	Combinatorial optimization	Energy efficiency	Distributed	Inter-frequency
[52]	Biasing	Regular	Combinatorial optimization	fairness	Distributed	Inter-frequency
[54]	Serve worst-SINR UEs	Regular	Utility function (linear utility function)	SINR	Distributed	Inter-frequency
[55]	CRE	Regular	Utility function	data rate	Distributed	Inter-frequency

[57]	CRE	Regular	_	Total transmitted/received power, data rate	_	_

1.6 Summary

In this chapter numerous pertinent LB algorithms designed for HetNets have been surveyed. We have presented a related classification to highlight the inherent features of the studied LB schemes. A range of challenging open issues regarding LB in HetNets have been discussed.

It seems that when designing and optimizing a cellular network, the most influential factor in predetermining the overall performance of the system is the specific choice of the metric to be optimized. Next we propose to study a specific class of LB algorithms namely adaptive HO based LB. In this context LB is performed while UEs are in connected state by adjusting HO parameters to minimise load disparity between different tiers. In chapter two we propose a stochastic model to investigate the impact of two types of adaptive HO algorithms on network performance in terms of HO signalling and rate coverage. In chapter 3 we exploit results from chapter 2 to implement LB algorithms for 3GPP LTE HetNets based on adaptive HO techniques.

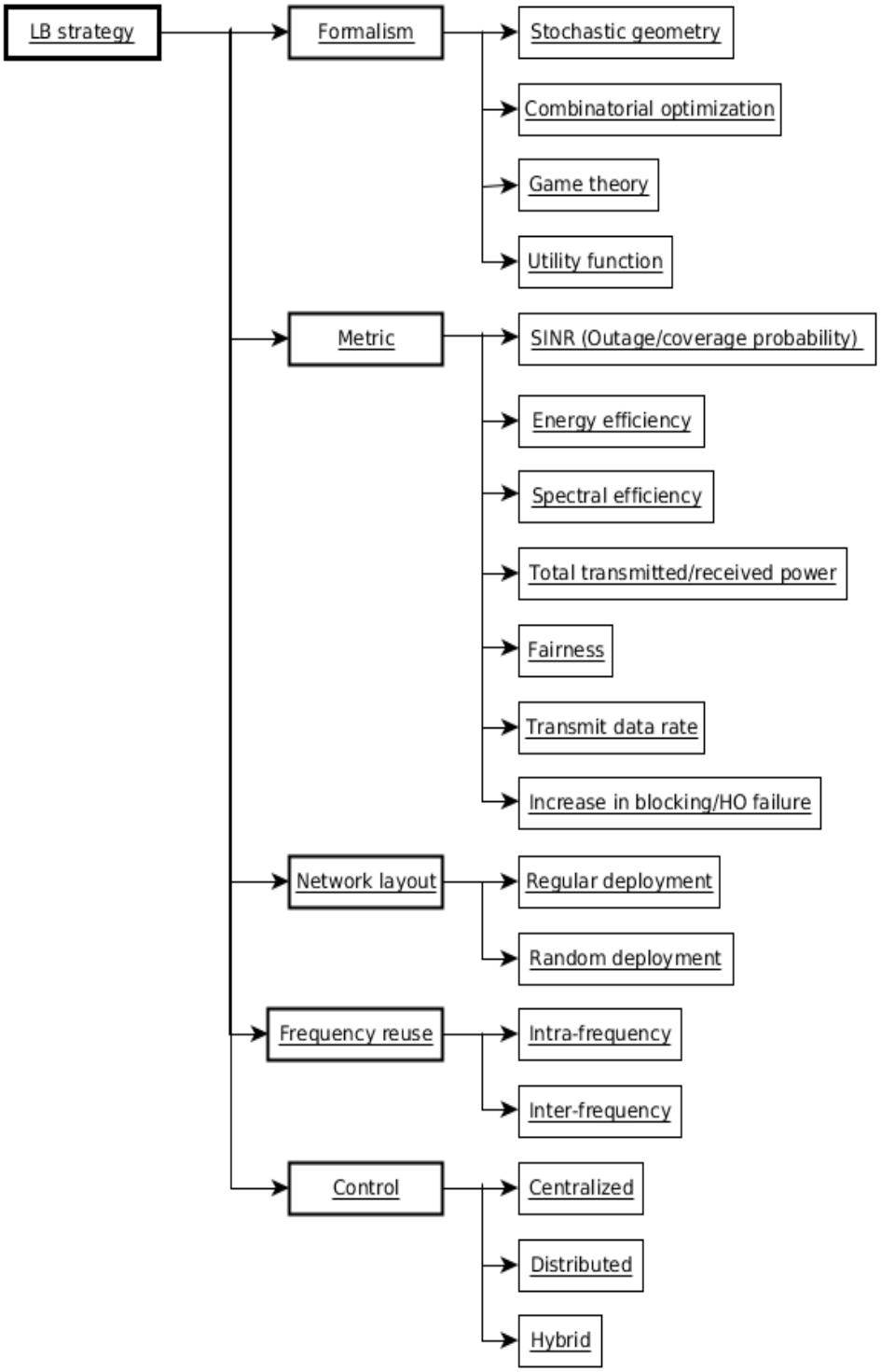

Figure 1.3: Classification of LB strategies

Chapter 2

Analytical Modelling of Adaptive Handover Strategies in Heterogeneous Cellular Networks

"Modeling wireless communication networks in terms of stochastic geometry seems particularly relevant for large scale networks. In the simplest case, it consists in treating such a network as a snapshot of a stationary random model in the whole Euclidean plane or space and analyzing it in a probabilistic way."

Stochastic Geometry and Wireless Networks, Volume I-Theory [58]

2.1 Motivations and related work

Although mixing several heterogeneous tiers in the same network brings significant spatial and spectral network densification, an important challenge for HetNet today is to achieve optimal network planning. This maybe enabled through adopting cutting-edge approaches capturing complex behaviour inherent to random multi-tier topologies. For practical reasons conventional models based on fixed patterns such as hexagonal grid model were widely used both in academia and industry in planning previous cellular networks. The new HetNet context involving a mixture of macro- and small-cells requires more realistic models based on random spatial patterns [59, 60].This is indeed justified by the usually unexpected and unpredictable constraints inherent to HetNet deployment in urban cities. A tractable and efficient deployment modelling approach is to adopt stochastic models based on Poisson point processes (PPP) for describing HetNet topologies. This is mainly justified by the simplicity and versatility of PPP and its capacity to represent planned and unplanned networks usually based on multi-tier random architectures. Several contributions has been proposed in literature to investigate HetNet deployment using PPP [34, 59, 60, 61, 62]. Authors in [61] propose to investigate SINR distribution in Poisson networks by defining a HetNet network model using PPP to describe propagation and SINR processes. They provide a calculation method based on SINR process factorial moments to determine coverage probability. Related results concern single-, two- and three-tier networks and show the impact of SINR threshold and interference cancellation on network performance in terms of coverage probability. Vu *et* al. ([59]) assess HO probability in stochastic HetNet topology based on outage probability. A 2-D homogeneous PPP is firstly defined to model cells' locations. Then HO probability is estimated based on outage probability calculation. The proposed model accounts for two kinds of fading namely static slow Rayleigh fading and time varying Rayleigh fading. Authors in [60] tackle biased cell association issue in HetNet based on SINR analysis. They define the received power from a cell belonging to a specific tier as function of Tx power, pathloss exponent and biasing factor. They evaluate then cell association probability using 2-D Poisson process. They also use cell association probability and SINR to calculate outage probability and average rate. These latter are investigated using analytical and simulation

results for two- and three-tier HetNet. Authors in [34] and [62] exploit results from [60] to study LB in stochastic HetNet. Singh *et* al. propose in [34] a PPP model to represent locations of both cells and mobiles. In this direction rate distribution is derived based on biased cell association strategy proposed in previous work (i.e. [60]). In the same work authors investigate biasing factor optimisation to maximize either rate coverage or coverage probability. In [62] LB in HetNet was inspected with multi-antenna cells (i.e. Multi-Input Single Output -MISO) where SINR distribution is used to derive coverage probability and rate coverage. Results show that cell association in multi-antenna HetNet may differ significantly from the single-antenna case. This could be justified by the possible differences in multi-antenna transmission schemes across tiers.

In this chapter we exploit results given in [34, 60] to present a HetNet stochastic model, based on 2-D homogeneous PPP, to highlight the impact of introducing adaptive HO strategies on network performance in terms of HO probability and rate coverage. We adopt two HO strategies namely:

- *Coarse grained HO adaptive control strategy based on tuning power biasing:* as soon as a mobile becomes in outage, it attempts to select a new serving cell based on maximum biased received power. In such strategy HO probability is calculated based on outage probability of current cell and the probability that the user equipment (UE) successfully selects a new serving cell from a specific tier among all HetNet tiers.

- *Fine grained HO adaptive control strategy based on hysteresis adjustment:* in this case, a UE periodically compares signal received quality between on one hand serving cell and in the other hand all neighbouring cells. Based on this comparison and received power measurements a new serving cell is selected. In such strategy HO probability is calculated based on probability that the UE successfully selects a new serving cell from a specific tier with better received power among all HetNet tiers.

The contributions in this chapter can be summarized under two main headings:

- Modelling and analysis of cell selection and HO rules for HetNets: We first introduce a general HetNet stochastic model based in 2-D homogeneous PPP. The proposed model is similar to [34, 60, 62] with a key difference being the consideration of HO

rules. In fact the rate coverage of a cell did not depend only on the number of idle UEs attaching the cell when accessing the network, but also on the number of users executing HO to that cell. Then an interesting factor to consider when calculating the load of a cell is HO probability.

- HO analysis: Two basic HO strategies are considered:
  - Adaptive HO through power biasing: coarse grained control
  - Adaptive HO through hysteresis adjustment: fine grained control
- System design insights: We derive HO and rate coverage probabilities and introduce inter-tier offloading as function of HO adaptation and show that the bias factor can be tuned to suit a network wide objective.

2.2 HetNet downlink system model and assumptions

Consider a K-tier HetNet where cells of tier k ($1 \leq k \leq K$) are located according to a 2-D homogeneous PPP Φ_k with spatial density λ_k. Cells belonging to the same tier k are assumed having the same pathloss propagation model (i.e. standard power-law path loss propagation model) with pathloss exponent α_k. They are assumed transmitting with fixed Tx power P_k. We assume also that UEs are sensitive to interference from all cells in the network except their serving cell. Another assumption is considered and consists in using a 2-D homogeneous PPP Φ^u to represent UEs' locations. In this model open access network is considered then UEs are allowed to connect to any cell without any admission control restrictions. For simplicity reasons we consider a typical UE located at the origin of the 2-D space (Fig. 2.1). This last assumption is enabled based on Slivnyak's theorem [63]. This latter specifies that properties observed by a typical point of a point process (PP) are the same as those observed by the origin. Tab. 2.1 summarizes the main notations used in this chapter.

In order to characterize the kth tier SINR as perceived by a typical UE located at distance X_k from a kth tier cell, we use the following SINR expression:

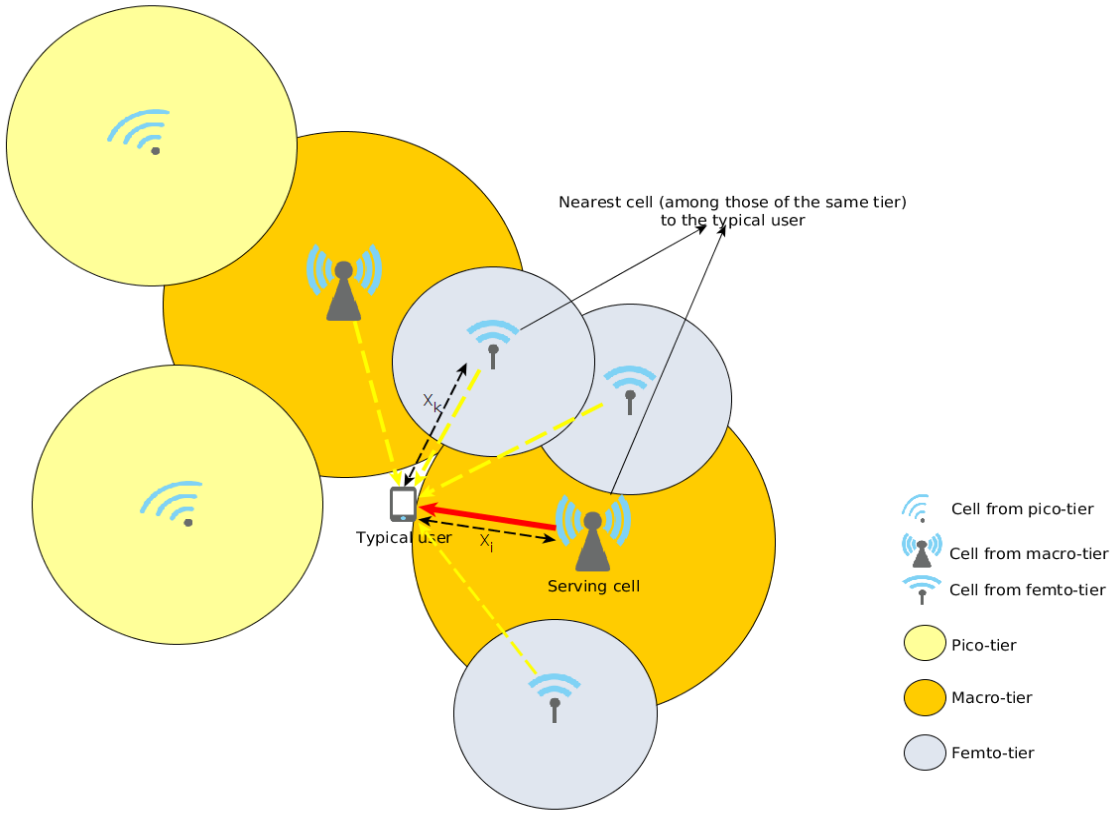

Figure 2.1: 3-tier HetNet (macro-, pico- and femto-tier)

Notation	**Description**
Φ_k	PPP representing tier k cells locations
Φ^u	PPP representing UEs locations
λ_k	Density of kth tier
λ^u	density of UEs
α_k	Pathloss exponent for kth
$SINR_k(x)$	$SINR$ received from a kth tier cell and perceived by a UE located at distance x from that cell
$M_k(x)$	Measurement value received from a kth tier cell and perceived by a UE located at distance x from that cell
$RSRP_k(x)$	RSRP received from kth tier cell and perceived by a UE located at distance x from that cell
$P_k(x)$	Power transmitted by kth tier cell and perceived by a UE located at distance x from that cell
$P_k^{BRP}(x)$	Biased power received from kth tier cell and perceived by a UE located at distance x from that cell
σ_k	Additive noise power for kth
h	channel gain
X_k	Distance between the typical UE and the nearest cell from tier k
N_k	Number of UE served by a cell from tier k
N_k^{RB}	total number of resource blocks (RB) of kth tier cell
$R_k(x)$	Rate of UE associated with tier k and located at distance x from its serving cell
W_k	Bandwidth of a kth tier cell.
$Hys_{i\rightarrow k}$	Hysteresis value from tier i to tier k
$CSOff_k$	offset of tier k
B_k	Power biasing factor of tier k
τ_k	SINR threshold for tier k
ρ_k	Rate threshold for tier k

Table 2.1: Analytical model notations

$$SINR_k(X_k) = \frac{P_k(X_k)}{\sum_{j=1}^{K} I_j + \sigma_k} \tag{2.1}$$

where

$$I_j = \sum_{(p \in \Phi_j \setminus serving_cell)} P_j(p) \tag{2.2}$$

represents the interference caused by all cells of each tier except the serving cell whereas σ_k corresponds to noise power. $P_k(X_k)$ is the received power at distance X_k from a kth cell and is derived according to the standard power-law pathloss propagation model with

independent and identically distributed (i.i.d.) Rayleigh fading channels. Then for a mobile at distance x from a given kth tier cell the received power is:

$$P_k(x) = P_k h x^{-\alpha_k} \tag{2.3}$$

where h is the channel gain following an exponential distribution with mean 1.
We adopt a resource allocation strategy based on weighted round-robin scheduler with saturated resource allocation model. Such model enables to determine load condition of each tier. Therefore the overall radio resources W_k of a kth tier cell (i.e. bandwidth) will be shared between all mobiles served by the cell (i.e. N_k). The bandwidth sharing accounts for link spectral efficiency expressed as a multiplicative weight (i.e. $log_2(1 + SINR_k(x))$):

$$R_k(x) = \frac{W_k}{N_k} log_2(1 + SINR_k(x)) \tag{2.4}$$

The above described assumptions and approximations will be fully used in the next sections to investigate cell association and handover probabilities in HetNets. These probabilities are needful to deduce rate coverage analytical expression.

2.3 Non adaptive cell association strategy

Cell association probability of kth tier (i.e. per tier association probability) is the probability that the typical UE is associated to a kth tier cell. As discussed in the previous chapter, there are many criteria that can be considered when dealing with cell association. For our study we will exploit results from [60] to calculate per tier association probability. Authors in [60] use a power-based cell association criteria for which a UE will camp in the cell having maximum received power. As mentioned above (section 2), for cells belonging to the same tier, typical user will select the closest cell.
According to eq. (2.3), the received power is attenuated with distance. Therefore for homogeneous networks that could be seen as a 1-tier HetNet, cell association is relatively simple since the typical UE attempts to join the cell having the best received power which is in this case the closest cell. For HetNet composed by K tiers ($K > 1$), cell association is more complicated since there are several tiers with different characteristics. In such case the associated cell (the one providing the best received power) is not always the closest cell.

This latter will be chosen among a set of K cells each of them corresponds to the closest cell of its tier to the typical UE: a UE connects to a kth tier cell if:

$$P_k(X_k) > \underset{j \neq k}{max}(P_j(X_j)) \tag{2.5}$$

For illustrative explanation, let's consider a 2-tier HetNet composed by macro- and femto-tier. In such case a UE may join a macrocell (providing the best received power) as a serving cell although a femtocell is the closest one.

To calculate association probability we use the same demonstration given in Lemma 1 of [60] with a minor modification in power expression (i.e. we use the unbiased power expression given by eq. (2.3)). Let S be the serving cell's tier. Then the association probability of the typical UE to kth tier ($k \in [1, K]$) is given by:

$$A_k = P[S = k] = E_{X_k}[P[S = k|X_k = x]] = \int_0^\infty P[S = k|X_k = x] f_{X_k}(x) dx$$

Where $P[S = k|X_k = x]$ is the probability that the typical UE is connected to tier k conditioned on $X_k = x$ given by:

$$\begin{aligned}
P[S = k|X_k = x] &= P[P_k(x) > \underset{j \neq k}{max}(P_j(X_j))] \\
&= \prod_{j=1, j \neq k}^{K} P[P_k(x) > P_j(X_j)] \\
&= \prod_{j=1, j \neq k}^{K} P[P_k h x^{-\alpha_k} > P_j h X_j^{-\alpha_j}] \\
&= \prod_{j=1, j \neq k}^{K} P[X_j > (\frac{P_j}{P_k})^{\frac{1}{\alpha_j}} x^{\frac{\alpha_k}{\alpha_j}}] \\
&= \prod_{j=1, j \neq k}^{K} exp(-\pi \lambda_j (\frac{P_j}{P_k})^{\frac{2}{\alpha_j}} x^{2\frac{\alpha_k}{\alpha_j}})
\end{aligned}$$

and $f_{X_k}(x)$ is the probability density function (PDF) given by:

$$f_{X_k}(x) = \frac{dP[X_k > x]}{dx} = 2\pi \lambda_k x exp(-\pi \lambda_k x^2) \tag{2.6}$$

Then A_k is expressed as follows:

$$\begin{aligned} A_k &= 2\pi\lambda_k \int_0^\infty x.exp(-\pi\lambda_k x^2) \prod_{j=1, j\neq k}^{K} exp(-\pi\lambda_j (\frac{P_j}{P_k})^{\frac{2}{\alpha_j}} x^{2\frac{\alpha_k}{\alpha_j}})dx \\ &= 2\pi\lambda_k \int_0^\infty x \prod_{j=1}^{K} exp(-\pi\lambda_j (\frac{P_j}{P_k})^{\frac{2}{\alpha_j}} x^{2\frac{\alpha_k}{\alpha_j}})dx \\ &= 2\pi\lambda_k \int_0^\infty xexp(-\pi \sum_{j=1}^{K} \lambda_j (\frac{P_j}{P_k})^{\frac{2}{\alpha_j}} x^{2\frac{\alpha_k}{\alpha_j}})dx \end{aligned}$$

Then

$$A_k = 2\pi\lambda_k \int_0^\infty xexp(-\pi \sum_{j=1}^{K} G_{jk} x^{2\frac{\alpha_k}{\alpha_j}})dx \tag{2.7}$$

Where $G_{jk} = \lambda_j (\frac{P_j}{P_k})^{\frac{2}{\alpha_j}}$.

In the above analysis we characterized the association of a UE to a specific tier based on received power. In the next section, we present two adaptive HO strategies and calculate HO probabilities based on specific characteristics of each strategy.

2.4 Adaptive handover strategies

We propose two adaptive control HO strategies based on HO tuning to select a new serving cell. HO tuning is achieved in the first strategy through power biasing tuning whereas in the second one it's achieved by adjusting hysteresis (i.e. LTE A3 event). In what follows the first strategy is referred to as *Coarse grained HO (CHO) control strategy* and the second one is referred to as *Fine grained HO (FHO) control strategy*. We will calculate in a first step HO probabilities for each kind of the above HO strategies. We will jointly use in a next step these HO probabilities with association probability (see section 2.3) to determine rate coverage. It's worth mentioning that in order to calculate HO probability we adopt similar approach to that of the association model given in [60] with some specific modifications. These modifications are mainly introduced to customize cell association approach to HO context. In the first strategy the HO procedure is triggered whenever the UE is out of coverage in the serving cell. Whereas in the second strategy the HO procedure is initiated based on LTE A3 event. HO of a UE between different tiers is tributary of conditions related to the chosen HO strategy.

2.4.1 Coarse grained HO control strategy

2.4.1.1 General principle

A HO decision is made whenever the UE suffers an outage. This means that when the SINR value received from the serving cell falls below a given threshold, the UE attempts to execute HO to camp in another cell. We consider a HO based on choosing the highest biased received power (i.e. BRP) from all cells regardless to the tier they belong to. The BRP is expressed as follows:

$$P_k^{BRP}(X_k) = P_k h X_k^{-\alpha_k} B_k \tag{2.8}$$

Where B_k is the power biasing factor ($B_k \geq 1$) of tier k.

HO between different tiers is assumed tributary of two main conditions related to both current and destination cells (in what follows current tier is referred to as tier i while target tier is referred to as tier k):

- $condition_1^{CHO}$: $SINR_i(X_i) \leq \tau_i$: This condition means that current cell SINR is enough deteriorated to request a HO.

and

- $condition_2^{CHO}$: $SINR_k(X_k) \geq \tau_k$ and $P_k^{BRP}(X_k) > \underset{j \neq k}{argmax} P_j^{BRP}(X_j)$: This condition concerns the choice of the HO destination tier (including the target cell having the best BRP). It is formulated to satisfy simultaneously two sub-conditions. The first one concerns an acceptable SINR (beyond a given threshold τ_k) of the closest cell of the kth tier whereas the second sub-condition requires having the best BRP among all other tiers ($j \neq k, \forall j \in [1..K]$).

Notice that the first condition (i.e. $condition_1^{CHO}$) accounts only for current cell SINR measurement, while the second condition (i.e. $condition_2^{CHO}$) depends on both target cell SINR and neighbouring cells biased received powers measurements. Based on $condition_1^{CHO}$ and $condition_2^{CHO}$ a detailed and illustrative algorithmic description of the CHO strategy is given by:

Algorithm 1 CHO strategy

```
L ← list of tiers to which the UE may execute HO
i ← index of tier including the serving cell (ith tier)
j ← jth neighbouring tier
k ← index of HO target tier (kth tier)
Initial condition: the UE is associated to cell i
UE periodically measures SINR_i(X_i) and tests if condition_1^CHO is verified
if SINR_i(X_i) ≤ τ_i then
    {
    for every tier j ≠ i do
        {
        UE measures SINR_j(X_j)
        UE verifies first sub-condition of condition_1^CHO (i.e. P_j(X_j) > τ_j) for tier j
        if (P_j(X_j) > τ_j) then
            {
            Tier j is added to L
            }
        }
    UE selects tier k from the list L where the second sub-condition of condition_1^CHO
    (i.e. P_k^BRP(X_k) > argmax_{j≠k} P_j^BRP(X_j) ) holds
    UE requests to execute HO from tier i to tier k
    }
```

2.4.1.2 HO probability analysis

HO probability from tier i to tier k using CHO strategy based on power biasing (PB) can be expressed as follows:

$$P_{i\to k}^{CHO} = \underbrace{P[(SINR_i(X_i) \leq \tau_i)|(S=i)]}_{P_1^{CHO}=P[condition_1^{CHO}]}.\underbrace{P[(SINR_k(X_k) > \tau_k, P_k^{BRP}(X_k) > \max_{j\neq k}(P_j^{BRP}(X_j)))|(S=i)]}_{P_2^{CHO}=P[condition_2^{CHO}]}$$

The probability of HO to tier k is:

$$P_k^{CHO} = \sum_{i=1, i\neq k}^{K} P_{i\to k}^{CHO} \tag{2.9}$$

and the expression of total HO probability when using CHO strategy is given by:

$$P_{HO}^{CHO} = \sum_{k=1}^{K} P_k^{CHO} \tag{2.10}$$

In order to determine HO probability based on CHO strategy we provide in next subsections detailed expressions of probabilities P_1^{CHO} and P_2^{CHO}.

1. Probability of $condition_1^{CHO}$: UE outage probability in serving cell (P_1^{CHO})

P_1^{CHO} analytical formula is defined as follows:

$$P_1^{CHO} = P[(SINR_i(X_i) \leq \tau_i)|(S=i)] = E_{X_i}[P[SINR_i(X_i) \leq \tau_i|X_i = x, S=i]]$$
$$= \int_0^{\infty} P[SINR_i(x) \leq \tau_i|X_i = x, S=i] f_{X_i}(x|S=i)dx$$

Where $f_{X_i}(x|S=i)$ is the PDF describing the distribution of distance between typical UE and its serving cell given that i is the serving tier. P_1^{CHO} maybe explicitly expressed by detailing the calculation of the terms involved in.

1.a) Detailed expression of $f_{X_i}(x|S=i)$

$f_{X_i}(x|S=i)$ is defined as follows:

$$f_{X_i}(x|S=i) = \frac{dP[X_i > x|S=i]}{dx}$$

using (2.7) we get

$$P[X_i > x|S=i] = \frac{P[X_i > x, S=i]}{P[S=i]} = \frac{2\pi\lambda_i \int_x^{\infty} xexp(-\pi \sum_{j=1}^{K} G_{ji} x^{2\frac{\alpha_i}{\alpha_j}})dx}{A_i}$$

then

$$f_{X_i}(x|S=i) = \frac{2\pi\lambda_i}{A_i} xexp(-\pi \sum_{j=1}^{K} G_{ji} x^{2\frac{\alpha_i}{\alpha_j}}) \tag{2.11}$$

1.b) Detailed expression of $P[SINR_i(x) \leq \tau_i|X_i = x, S=i]$

Let's now calculate $P[SINR_i(x) \leq \tau_i|X_i = x, S=i]$
Using SINR expression given by (2.1) the above probability can be calculated as:

$$P[SINR_i(x) \leq \tau_i|X_i = x, S=i] = 1 - P[SINR_i(x) > \tau_i|X_i = x, S=i]$$

where

$$
\begin{aligned}
P[SINR_i(x) > \tau_i | X_i = x, S = i] &= P[\frac{P_i h x^{-\alpha_i} B_i}{\sum_{j=1}^{K} I_j + \sigma_i} > \tau_i | X_i = x, S = i] \\
&= P[h > P_i^{-1} B_i^{-1} \tau_i x^{\alpha_i} (\sum_{j=1}^{K} I_j + \sigma_i) | X_i = x, S = i] \\
&= exp(-\frac{\tau_i}{SNR_i(x)}).E_{I_j}[exp(-\frac{\tau_i}{P_i B_i} x^{\alpha_i} \sum_{j=1}^{K} I_j)] \\
&= exp(-\frac{\tau_i}{SNR_i(x)}). \prod_{j=1}^{K} E_{I_j}[exp(-\frac{\tau_i}{P_i B_i} x^{\alpha_i} I_j)] \\
&= exp(-\frac{\tau_i}{SNR_i(x)}). \prod_{j=1}^{K} M_{I_j}(\frac{\tau_i}{P_i B_i} x^{\alpha_i})
\end{aligned}
$$

where $SNR_i(x) = \frac{P_i B_i x^{-\alpha_i}}{\sigma_i}$ and $M_{I_j}(\frac{\tau_i}{P_i B_i} x^{\alpha_i})$ is the Moment Generating Function (MGF) of the interference received by the typical UE. Let $Q = \frac{\tau_i}{P_i B_i} x^{\alpha_i}$, by expanding the interference and biased power terms (i.e.$\sum_{p \in \Phi_j} P_j^{BRP}(p)$ and $P_j^{BRP}(p) = P_j B_j h X_j^{-\alpha_k}$), interference MGF is given by:

$$
\begin{aligned}
M_{I_j}(Q) &= E_{I_j}[exp(-QI_j)] \\
&= E_{I_j}[exp(-Q \sum_{p \in \Phi_j} P_j^{BRP}(p))] \\
&= E_{I_j}[\prod_{p \in \Phi_j} exp(-QP_j B_j h p^{-\alpha_j})] \\
&= E_{I_j}[\prod_{p \in \Phi_j} M_h(QP_j B_j p^{-\alpha_j})] \\
&\overset{(a)}{=} exp(-2\pi\lambda_j \int_{z_j}^{\infty} (1 - M_h(QP_j B_j p^{-\alpha_j})) p dp) \\
&\overset{(b)}{=} exp(-2\pi\lambda_j \int_{z_j}^{\infty} \frac{p}{1 + (QP_j B_j)^{-1} p^{\alpha_j}} dp)
\end{aligned}
$$

The above expressions are further explained as follows: (a) is derived from the probability generating functional (PGFL) of a PPP. Campbell's theorem:

If Φ is a homogeneous PPP with intensity λ, and f is a nonnegative function for which the expectation exists then:

$$
PGFL_{\Phi}(f) = E[\prod_{j=1}^{N} f(X_j)] = exp(\int_{\mathbb{R}} (f(x) - 1)\lambda dx)
$$

and (b) follows from the moment generating function (MGF) of an exponential random variable h with mean 1 (i.e.$h \sim exp(1)$).

The integration range excludes a ball centred at 0 and radius z_j since the interference from each tier is assumed a PPP outside a region of radius z_j centred at the origin. This means that there is an exclusion region of radius

$$z_j = (\frac{P_j}{P_i}\frac{B_j}{B_i})^{\frac{1}{\alpha_j}} x^{\frac{\alpha_i}{\alpha_j}}$$

using change of variables with $t = (QP_jB_j)^{\frac{-2}{\alpha_j}} p^2, M_{I_j}(Q)$ can be simplified as:

$$M_{I_j}(Q) = exp(-\pi\lambda_j(QP_jB_j)^{\frac{-2}{\alpha_j}} \int_{(QP_jB_j)^{\frac{-2}{\alpha_j}} z_j^2}^{\infty} \frac{1}{1+t^{\frac{\alpha_j}{2}}} dt) = exp(-\pi\lambda_j Z(QP_jB_j, \alpha_j, z_j^{\alpha_j}))$$
$$= exp(-\pi\lambda_j(QP_jB_j)^{\frac{-2}{\alpha_j}} Z(1, \alpha_j, \frac{z_j^{\alpha_j}}{QP_jB_j}))$$

with $Z(a,b,c) = a^{\frac{2}{b}} \int_{(\frac{c}{a})^{\frac{2}{b}}}^{\infty} \frac{1}{1+u^{\frac{b}{2}}} du$
Let's $\hat{T}_{ji} = \frac{P_jB_j}{P_iB_i}$ and . Using $Q = \frac{\tau_i}{P_iB_i} x^{\alpha_i}$ and $(\dots)$ we get:

$$P[SINR_i(x) > \tau_i | X_i = x, S = i] = exp(-\frac{\tau_i}{SNR_i(x)}) \prod_{j=1}^{K} exp(-\pi\lambda_j(\hat{T}_{ji})^{\frac{2}{\alpha_j}} x^{2\frac{\alpha_i}{\alpha_j}} Z(\tau_i, \alpha_j, \frac{1}{\alpha_j}))$$
$$= exp(-\frac{\tau_i}{SNR_i(x)}) exp(-\pi \sum_{j=1}^{K} \lambda_j(\hat{T}_{ji})^{\frac{2}{\alpha_j}} x^{2\frac{\alpha_i}{\alpha_j}} Z(\tau_i, \alpha_j, \frac{1}{\alpha_j}))$$
$$= exp(-\frac{\tau_i}{SNR_i(x)} - \pi \sum_{j=1}^{K} \lambda_j(\hat{T}_{ji})^{\frac{2}{\alpha_j}} x^{2\frac{\alpha_i}{\alpha_j}} Z(\tau_i, \alpha_j, \frac{1}{\alpha_j}))$$

$$P_1^{CHO} = P[(SINR_i(x_i) \leq \tau_i)|(S = i)] = \int_0^{\infty} P[SINR_i(x) \leq \tau_i | X_i = x, S = i] f_{X_i}(x|S = i) dx$$
$$= 1 - \frac{2\pi\lambda_i}{A_i} \int_0^{\infty} x exp(-\frac{\tau_i}{SNR_i(x)} - \pi(\sum_{j=1}^{K} \lambda_j \hat{T}_{ji}^{\frac{2}{\alpha_j}} x^{2\frac{\alpha_i}{\alpha_j}} Z(\tau_i, \alpha_j, \frac{1}{\alpha_j}) + \sum_{j=1}^{K} G_{ji} x^{2\frac{\alpha_i}{\alpha_j}})) dx$$

then

$$P_1^{CHO} = 1 - \frac{2\pi\lambda_i}{A_i} \int_0^{\infty} x exp(-\frac{\tau_i}{SNR_i(x)} - \pi \sum_{j=1}^{K} (\lambda_j \hat{T}_{ji}^{\frac{2}{\alpha_j}} x^{2\frac{\alpha_i}{\alpha_j}} Z(\tau_i, \alpha_j, \frac{1}{\alpha_j}) + G_{ji}^{BP} x^{2\frac{\alpha_i}{\alpha_j}})) dx \tag{2.12}$$

2. Probability of $condition_2^{CHO}$: Coverage probability of target cell (P_2^{CHO})

By taking into consideration independence between all tiers, probability P_2^{CHO} can be expressed as follows:

$$P_2^{CHO} P[SINR_k(X_k) > \tau_k, P_k(X_k) > \underset{j \neq k}{argmax} P_j(X_j) | S = i]$$
$$= \underbrace{P[SINR_k(X_k) > \tau_k | S = i]}_{P21} \underbrace{P[P_k(X_k) > \underset{j \neq k}{argmax} P_j(X_j) | S = i]}_{P22}$$

2.a) Detailed expression of P21 (Coverage probability of tier k)

$$P21 = 2\pi\lambda_k \int_0^\infty x exp(-\frac{\tau_k}{SNR_k(x)} - \pi \sum_{j=1}^{K} (\lambda_j \hat{T}_{jk}^{\frac{2}{\alpha_j}} x^{2\frac{\alpha_k}{\alpha_j}} Z(\tau_k, \alpha_j, \frac{1}{\alpha_j})) + \lambda_k x^2) dx$$

Proof:

$$\begin{aligned} P21 &= P[SINR_k(X_k) > \tau_k | S = i] \\ &= 1 - P[SINR_k(X_k) \leq \tau_k] \\ &= E_{X_k}[P[SINR_k(X_k) > \tau_k | X_k = x]] \\ &= 2\pi\lambda_k \int_0^\infty x exp(-\frac{\tau_k}{SNR_k(x)} - \pi \sum_{j=1}^{K} (\lambda_j \hat{T}_{jk}^{\frac{2}{\alpha_j}} x^{2\frac{\alpha_k}{\alpha_j}} Z(\tau_k, \alpha_j, \frac{1}{\alpha_j})) + \lambda_k x^2) dx \end{aligned}$$

The result is obtained by a minor modification of P_1^{CHO} calculation proof.

2.b) Detailed expression of P22

$$\begin{aligned} P22 &= P[P_k^{BRP}(X_k) > \underset{j \neq k}{argmax}(P_j^{BRP}(X_j)) | S = i] \\ &= E_{X_k}[P[P_k^{BRP}(x) > \underset{j \neq k}{argmax} P_j^{BRP}(X_j) | X_k = x]] \\ &= \int_0^\infty P[P_k^{BRP}(x) > \underset{j \neq k}{argmax} P_j^{BRP}(X_j) | X_k = x] f_{X_k}(x) dx \end{aligned}$$

where:

$$f_{X_k}(x) = 2\pi\lambda_k x.exp(-\pi\lambda_k x^2)$$

and

$$P[P_k^{BRP}(x) > \underset{j \neq k}{argmax} P_j^{BRP}(X_j) | X_k = x] = \prod_{j=1, j \neq k}^{K} P[X_j > \hat{T}_{jk}^{\frac{1}{\alpha_j}} X_k^{\frac{\alpha_k}{\alpha_j}} | X_k = x]$$

then :

$$\begin{aligned} P22 &= 2\pi\lambda_k \int_0^\infty x exp(-\pi\lambda_k x^2) \prod_{j=1,j\neq k}^{K} exp(-\pi\lambda_j \hat{T}_{jk}^{\frac{2}{\alpha_j}} X_k^{2\frac{\alpha_k}{\alpha_j}})dx \\ &= 2\pi\lambda_k \int_0^\infty x exp(-\pi\lambda_k x^2) exp(-\pi \sum_{j=1,j\neq k}^{K} \lambda_j \hat{T}_{jk}^{\frac{2}{\alpha_j}} X_k^{2\frac{\alpha_k}{\alpha_j}})dx \\ &= 2\pi\lambda_k \int_0^\infty x exp(-\pi(\lambda_k x^2 + \sum_{j=1,j\neq k}^{K} \lambda_j \hat{T}_{jk}^{\frac{2}{\alpha_j}} X_k^{2\frac{\alpha_k}{\alpha_j}}))dx \end{aligned}$$

$P_{i\to k}^{HO_PB}$ can be derived by $P_{i\to k}^{HO_PB} = P_1^{CHO}.P_2^{CHO} = P_1^{CHO}.P21.P22$

2.4.2 Fine grained HO control strategy

2.4.2.1 General principle

The UE attempts to execute HO to camp in another cell whenever detecting cells satisfying LTE A3 event (see section 3.2.1) which might be triggered if a neighbouring cell signal quality becomes offset better than the serving cell signal quality (i.e. entering condition). We consider a HO based on choosing cell offering best reference signal received power (RSRP). HO between different tiers is conditioned by satisfaction of $condition_1^{FHO}$ and $condition_2^{FHO}$ related to both current and destination cells.

- $condition_1^{FHO}$: $RSRP_k(X_k) + CSOff_k - Hys_{i\to k} > RSRP_i(X_i)$: Test if event A3 entering condition is verified. This means that closest cell from kth tier to typical mobile becomes offset better than serving cell from ith tier.

and

- $condition_2^{FHO}$: $RSRP_k(X_k)+CSOff_k-Hys_{i\to k} > \underset{j\neq k}{argmax}(RSRP_j(X_j)+CSOff_j-Hys_{i\to j})$: test if tier k has the highest value of $RSRP_k(X_k) + CSOff_k - Hys_{i\to k}$ among all other tiers.

where

$$RSRP_k(X_k) = \frac{\sum_r P_k^r(X_k)}{N_k^{RB}}$$

Notice that the first condition (i.e. $condition_1^{FHO}$) depends on RSRP values of both current and target cells, while the second condition (i.e. $condition_2^{FHO}$) depends on neighbouring

cells' RSRP values. Based on $condition_1^{FHO}$ and $condition_2^{FHO}$ expressions a detailed and illustrative algorithmic description of the FHO strategy is given:

Algorithm 2 FHO strategy

```
L ← list of tiers to which the UE may execute HO
i ← index of tier including the serving cell (ith tier)
j ← jth neighbouring tier
k ← index of HO target tier (kth tier)
Initial condition: the UE is associated to cell i
UE periodically measures RSRP_j(X_j) for all tiers
for every tier j ≠ i do
    {
    UE verifies condition_1^FHO for tier j
    if (RSRP_j(X_j) + CSOff_j > RSRP_i(X_i) + Hys_{i→j}) then
        {
        tier j is added to L
        }
    }
UE selects tier k from L for which condition_2^FHO is verified
UE requests to execute HO from tier i to tier k
```

2.4.2.2 HO probability analysis

HO probability from tier i to tier k using FHO strategy based on hysteresis adjustment can be expressed as follows:

$$P_{i\to k}^{FHO} = \underbrace{P[RSRP_k(X_k) + CSOff_k - Hys_{i\to k} > RSRP_i(X_i)|S = i]}_{P_1^{FHO}=P[condition_1^{FHO}]}.$$

$$\underbrace{P[RSRP_k(X_k) + CSOff_k - Hys_{i\to k} > \underset{j\neq k}{argmax}(RSRP_j(X_j) + CSOff_j - Hys_{i\to j})|S = i]}_{P_2^{FHO}=P[condition_2^{FHO}]}$$

The probability of HO to tier k is:

$$P_k^{FHO} = \sum_{i=1, i\neq k}^{K} P_{i\to k}^{FHO} \tag{2.13}$$

and the expression of total HO probability when using CHO strategy is given by:

$$P_{HO}^{FHO} = \sum_{k=1}^{K} P_k^{FHO} \tag{2.14}$$

Hypothesis:

- $SOff_K = 0$
- $RSRP_k(X_k) = \frac{\sum_r P_k^r(X_k)}{N_k^{RB}} \simeq P_k(X_k)$

1. Probability of $condition_1^{FHO}$ **(**P_1^{FHO}**)**

$$\begin{aligned}
P_1^{FHO} &= P[RSRP_k(X_k) + CSOff_k - Hys_{i\to k} > RSRP_i(X_i)|S=i] \\
&= P[P_k(X_k) - Hys_{i\to k} > P_i(X_i)|S=i] \\
&= P[P_k h X_k^{-\alpha_k} - Hys_{i\to k} > P_i h X_i^{-\alpha_i}|S=i] \\
&= P[\frac{P_k h X_k^{-\alpha_k} - Hys_{i\to k}}{P_i h} > X_i^{-\alpha_i}|S=i] \\
&= P[X_i > (\frac{P_k h X_k^{-\alpha_k} - Hys_{i\to k}}{P_i h})^{-\frac{1}{\alpha_i}}|S=i] \\
&= \int_0^\infty P[X_i > (\frac{P_k h X_k^{-\alpha_k} - Hys_{i\to k}}{P_i h})^{-\frac{1}{\alpha_i}}|X_k = x, S=i].f_{X_k}(x|S=i)dx
\end{aligned}$$

then

$$P_1^{FHO} = \int_0^\infty exp(-\pi\lambda_i(\frac{P_k h X_k^{-\alpha_k} - Hys_{i\to k}}{P_i h})^{-\frac{2}{\alpha_i}}).f_{X_k}(x|S=i)dx \tag{2.15}$$

2. Probability of $condition_2^{FHO}$ **(**P_2^{FHO}**)**

$$\begin{aligned}
P_2^{FHO} &= P[RSRP_k(X_k) + CSOff_k - Hys_{i\to k} > \underset{j\neq k}{argmax}(RSRP_j(X_j) + CSOff_j - Hys_{i\to j})|S=i] \\
&= \int_0^\infty \prod_{j=1,j\neq k}^{K} P[P_k(X_k) - Hys_{i\to k} > P_j(X_j) - Hys_{i\to j}|X_k = x, S=i].f_{X_k}(x|S=i)dx \\
&= \int_0^\infty \prod_{j=1,j\neq k}^{K} P[P_k h X_k^{-\alpha_k} - Hys_{i\to k} > P_j h X_j^{-\alpha_j} - Hys_{i\to j}|X_k = x, S=i].f_{X_k}(x|S=i)dx \\
&= \int_0^\infty \prod_{j=1,j\neq k}^{K} P[P_k h X_k^{-\alpha_k} - (Hys_{i\to k} - Hys_{i\to j}) > P_j h X_j^{-\alpha_j}|X_k = x, S=i].f_{X_k}(x|S=i)dx
\end{aligned}$$

Let's $\Delta Hys_{kj}^i = Hys_{i\to k} - Hys_{i\to j}$, then

$$\begin{aligned}
P_2^{FHO} &= \int_0^\infty \prod_{j=1,j\neq k}^{K} P[P_k h X_k^{-\alpha_k} - \Delta Hys_{kj}^i > P_j h X_j^{-\alpha_j}|X_k = x, S=i].f_{X_k}(x|S=i)dx \\
&= \int_0^\infty \prod_{j=1,j\neq k}^{K} exp(-\pi\lambda_j(\frac{P_k h X_k^{-\alpha_k} - \Delta Hys_{kj}^i}{P_j h})^{-\frac{2}{\alpha_j}}).f_{X_k}(x|S=i)dx
\end{aligned}$$

then

$$P_2^{FHO} = \int_0^{\infty} exp(-\pi \sum_{j=1, j\neq k}^{K} \lambda_j (\frac{P_k h X_k^{-\alpha_k} - \Delta Hys_{kj}^i}{P_j h})^{-\frac{2}{\alpha_j}}).f_{X_k}(x|S=i)dx \tag{2.16}$$

2.5 Rate coverage analysis

The rate coverage of a UE associated with kth tier can be defined as:

$$R_{C_k} = P[R_k(X_k) > \rho_k]$$

where ρ_k is the rate threshold corresponding to tier k. Using (2.4) gives

$$\begin{aligned}
R_{C_k} &= E_{X_k}[P[R_k(X_k) > \rho_k|S=k]] \\
&= E_{X_k}[P[\frac{W_k}{N_k} log_2(1 + SINR_k(X_k)) > \rho_k|S=k]] \\
&= E_{X_k}[P[SINR_k(X_k) > 2^{(\frac{N_k}{W_k}\rho_k)} - 1|S=k]] \\
&= \int_0^{\infty} P[SINR_k(x) > 2^{(\frac{N_k}{W_k}\rho_k)} - 1|X_k = x].f_{X_k}(x|S=k)dx \\
&\overset{(a)}{=} \int_0^{\infty} exp(-\frac{2^{(\frac{N_k}{W_k}\rho_k)} - 1}{SNR_k(x)} - \pi \sum_{j=1}^{K} \lambda_j (\frac{P_j}{P_k})^{\frac{2}{\alpha_j}} x^{2\frac{\alpha_k}{\alpha_j}} Z(2^{(\frac{N_k}{W_k}\rho_k)} - 1, \alpha_j, \frac{1}{\alpha_j}))f_{X_k}(x|S=k)dx
\end{aligned}$$

where (a) is obtained by replacing τ_i by $2^{(\frac{N_k}{W_k}\rho_k)} - 1$ in P21 (see subsection 2.4.1.2) and by using unbiased power expression.

The rate coverage is given by:

$$R_C = \sum_{j=1}^{K} (A_k + P_k^{HO}) R_{C_k} \tag{2.17}$$

where P_k^{HO} is equal to P_k^{CHO} (resp. P_k^{FHO}) when using the CHO strategy (resp. FHO strategy).

2.6 Results and discussion

In this section we consider a special case for general results provided in the above analysis. We assume neglected thermal noise ($\sigma_k = 0, \forall k \in [1..K]$) and equal pathloss

exponents ($\alpha_k = 0, \forall k \in [1..K]$). Therefore rate coverage probability of kth tier is simplified as follows:

$$\begin{aligned} R_{C_k} &= \frac{2\pi\lambda_k}{A_k}\int_0^\infty xexp(-\pi x^2 \sum_{j=1}^{K}(\lambda_j(\frac{P_j}{P_k})^{\frac{2}{\alpha}} Z(2^{(\frac{N_k}{W_k}\rho_k)}-1,\alpha,\frac{1}{\alpha})+G_{jk}))dx \\ &= \frac{\lambda_k}{A_k(\sum_{j=1}^{K}(G_{jk}Z(2^{(\frac{N_k}{W_k}\rho_k)}-1,\alpha,\frac{1}{\alpha})+G_{jk}))} \\ &= \frac{\lambda_k}{A_k(Z(2^{(\frac{N_k}{W_k}\rho_k)}-1,\alpha,\frac{1}{\alpha})+1)\sum_{j=1}^{K}G_{jk}} \\ &= \frac{1}{Z(2^{(\frac{N_k}{W_k}\rho_k)}-1,\alpha,\frac{1}{\alpha})+1} \end{aligned}$$

where

$$A_k = 2\pi\lambda_k\int_0^\infty xexp(-\pi\sum_{j=1}^{K}G_{jk}x^2)dx = \frac{\lambda_k}{\sum_{j=1}^{K}G_{jk}}$$

For numerical investigation of rate coverage we consider the approximation proposed in [34] to estimate the mean number of users served by a kth tier cell:

$$N_k = 1 + (1.28\frac{\lambda^u}{\lambda_k}A_k) \tag{2.18}$$

We validate our analytical model for three-tier HetNet (i.e. macro-, pico and femto-tier) scenario where:

- Φ_1 is the PPP modelling macro-tier cells locations with density λ_1.
- Φ_2 is the PPP modelling pico-tier cells locations with density $\lambda_2 = a\lambda_1, a \geq 1$.
- Φ_3 is the PPP modelling femto-tier cells locations with density $\lambda_3 = b\lambda_2, b \geq 1$.

In the above analysis we set $\tau_k = \tau$ and $\rho_k = \rho$ for all $k \in [1..K]$. Tab.2.2 summarizes principle model parameters default values.

Parameter	**Numerical value**
Bandwidth	5Mhz
Tx power	• $P_1 = 46dbm$ • $P_2 = 33dbm$ • $P_3 = 23dbm$
Pathloss exponent	$\alpha = 4$

Table 2.2: Analytical model parameters' values

2.6.1 Performance analysis of coarse grained HO control strategy

Consider HO probability from tier i to tier k using coarse grained HO control strategy. For the above mentioned case of study P_1^{CHO}, P21, and P22 have the following expressions:

$$\begin{aligned} P_1^{CHO} &= 1 - \frac{\lambda_i}{A_i(\sum_{j=1}^{K}(\lambda_j(\hat{T}_{ji})^{\frac{2}{\alpha}} Z(\tau_i, \alpha, \frac{1}{\alpha}) + G_{ji}^{BP}))} \\ &= 1 - \frac{\lambda_i}{A_i(\sum_{j=1}^{K} G_{ji}^{BP}(Z(\tau_i, \alpha, \frac{1}{\alpha}) + 1))} \end{aligned}$$

$$P21 = \frac{\lambda_k}{\lambda_k + \sum_{j=1}^{K} \lambda_j(\hat{T}_{jk})^{\frac{2}{\alpha}} Z(\tau_i, \alpha, \frac{1}{\alpha})}$$

$$P22 = \frac{\lambda_k}{\lambda_k + \sum_{j=1, j\neq k}^{K} \lambda_j(\hat{T}_{jk})^{\frac{2}{\alpha}}}$$

In the rest of this subsection we investigate both rate coverage (2.17) and HO probability (2.10) when using CHO strategy with respect to tier-3 density, rate coverage/SINR thresholds, tier-3 biasing factor and UEs density. The objective here is to study the effect of offloading UEs from macro-tier (tier-1) and pico-tier (tier-2) to small-tier (tier-3) by tuning tier-3 biasing factor to virtually stretch small-cells coverage. Plots in Fig. 2.2 (resp. Fig. 2.3) represent coverage probability R_c (resp. HO probability P_{HO}^{CHO}) versus tier-3 density (λ_3) for different tier-3 biasing factor B_3 values (i.e. 1, 10 and 20). A first general observation is that increasing B_3 leads to an increase of both rate coverage and HO probability. The increase of rate coverage confirms the common trends offloading more UEs to small-tier to enhance network rate coverage. For a given B_3 value, as λ_3 increases rate coverage

and HO probability also increase to attempt a maximum value. This latter depends on biasing factor B_3. As shown in Fig. 2.2 increasing λ_3 beyond the optimal density (i.e. λ_3 value corresponding to the maximum rate coverage value) leads to a decrease of R_c. This is explained by the increase in interference due to deploying more tier-3 cells (since interference is an increasing function of cells' density). Fig. 2.4 and Fig. 2.5 respectively

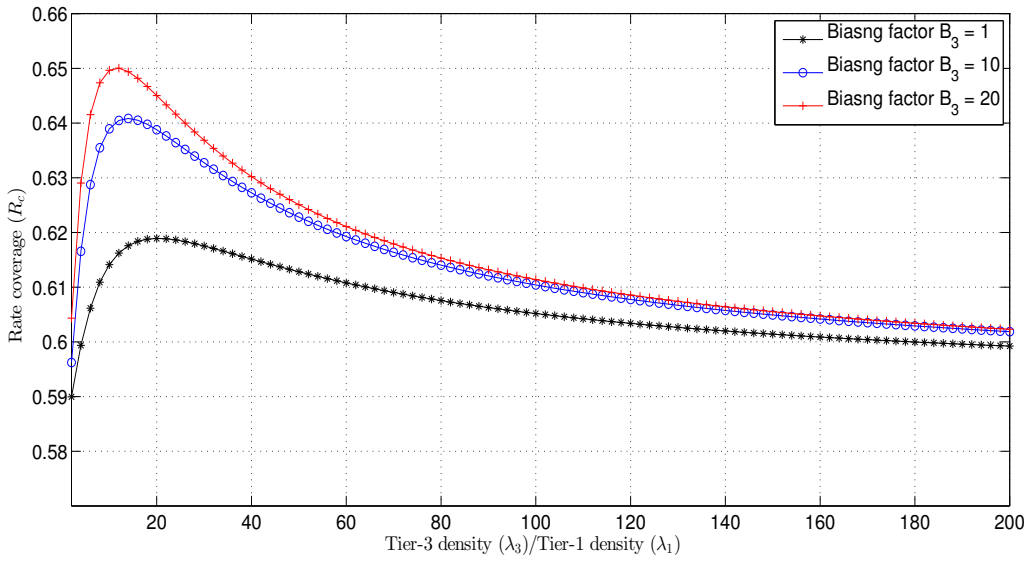

Figure 2.2: Rate coverage (R_c) versus tier-3 density/tier-1 density (λ_3/λ_1)

depict rate coverage and HO probability with respect to SINR threshold τ. In order to interpret numerical results given in Fig. 2.4 and Fig. 2.5, let us make some preliminary observations. Note that when τ increases, the probability that a UE becomes in outage in his current cell (probability of $condition_1^{CHO}$-P_1^{CHO}) also increases. This means that as well as τ increases P_1^{CHO} increases. Conversely, as τ increases probability of $condition_2^{CHO}$, and particularly P21 (i.e. probability to select an adequate cell to camp in) decreases. hence even if the UE attempts to trigger HO, it will be more difficult to find a target cell offering an acceptable SINR coverage. Therefore as τ increases HO probability (Fig. 2.5) decreases. This affects R_c and generate rate coverage degradation (Fig. 2.4). The variation of rate coverage with rate coverage threshold (ρ) is shown in Fig. 2.6 and with UEs density (λ^u) is shown in Fig. 2.7. As expected R_c decreases with increasing ρ (i.e. the probability that the

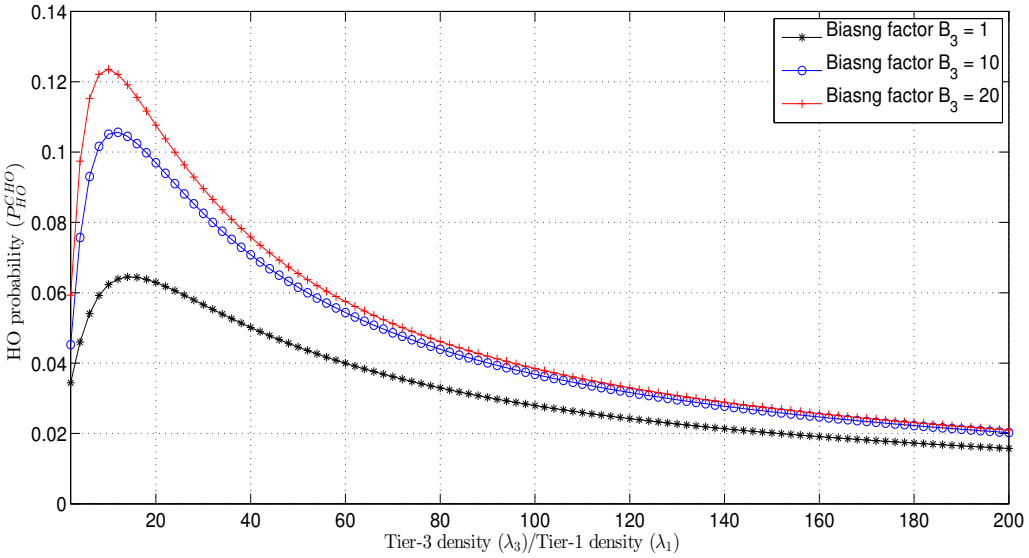

Figure 2.3: HO probability (P_{HO}^{CHO}) versus tier-3 density/tier-1 density (λ_3/λ_1)

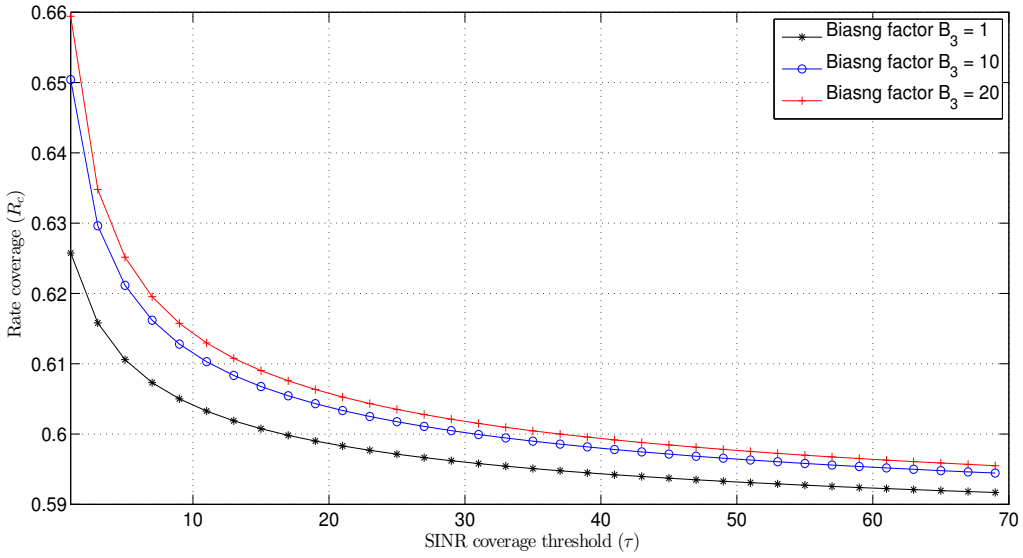

Figure 2.4: Rate coverage (R_c) versus SINR threshold (τ)

typical UE received rate is above a given threshold ρ). Also we notice that R_c decreases with increasing UEs density. This is due to the increase in load at each cell. A common observation in Fig. 2.62.7 is the increase of R_c with the increase of B_3. Fig. 2.8 and

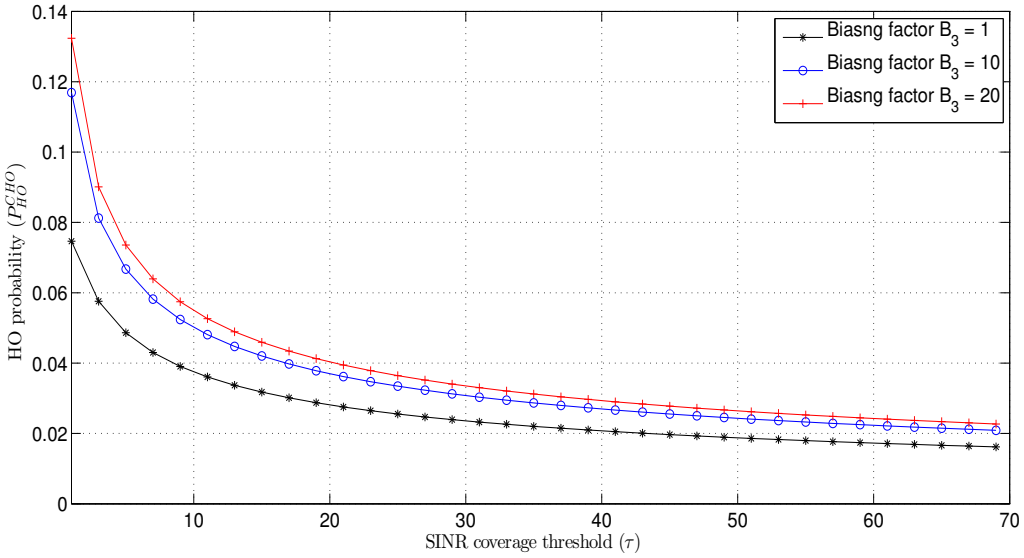

Figure 2.5: HO probability (P_{HO}^{CHO}) versus SINR threshold (τ)

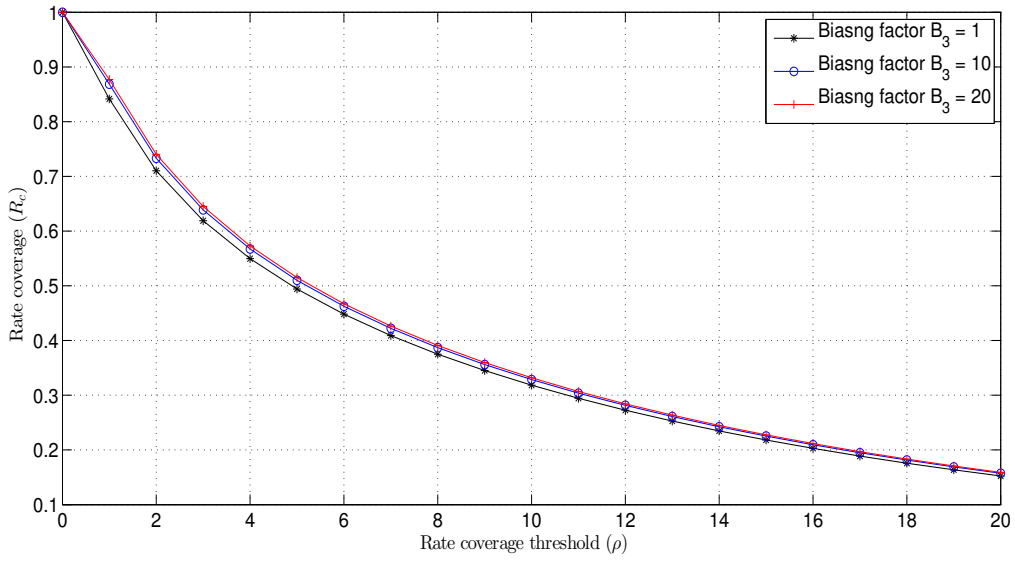

Figure 2.6: Rate coverage (R_c) versus rate coverage threshold (ρ)

Fig. 2.9 respectively show rate coverage and HO probability versus tier-3 biasing factor. As mentioned before B_3 increase leads to R_c increase. This phenomenon is more prominent for $R_c \in [1..20]$ (Fig. 2.8). In the other hand P_{HO}^{CHO} also increases with B_3 increase (Fig. 2.9).

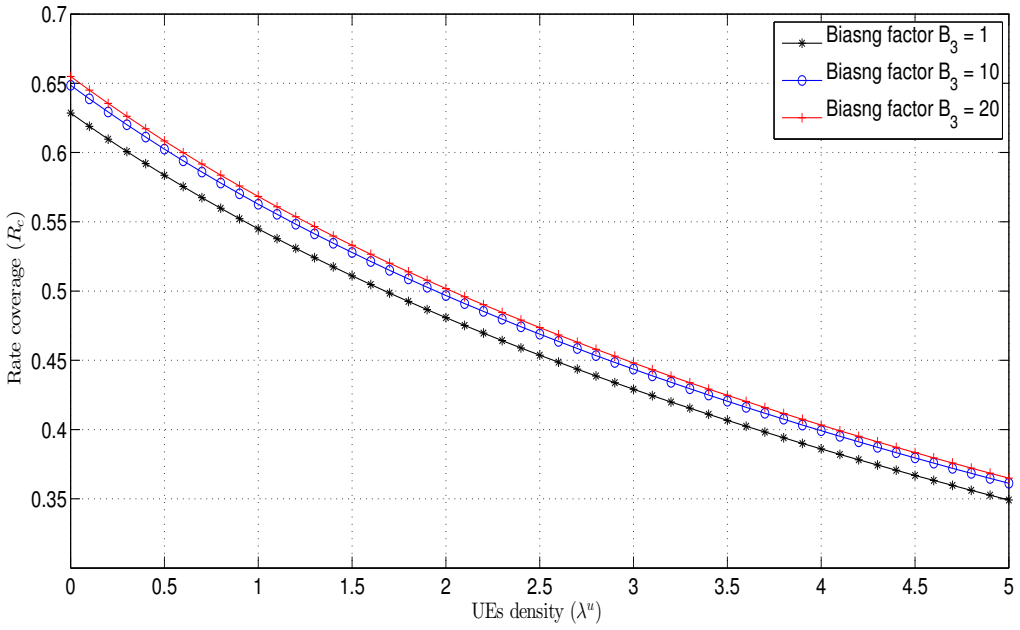

Figure 2.7: Rate coverage (R_c) versus UEs density (λ^u)

In real HetNet network deployments an increase of HO probability leads to an increase in rate of intra- and inter-tier HO signalling. Therefore a convenient trade-off between improve network rate coverage and decreasing the rate of HO signalling should be made when tuning small-cells coverage. In next subsection we study rate coverage and HO probability under FHO strategy hypothesis.

2.6.2 Performance analysis of fine grained HO control strategy

Now we consider HO probability from tier i to tier k using FHO strategy. For the above mentioned case of study P_1^{FHO} and P_2^{FHO} have the following expressions:

$$\begin{aligned}
P_1^{FHO} &= 2\pi\lambda_k \int_0^\infty x.exp(-\pi\lambda_i(\frac{P_k h x^{-\alpha} - Hys_{i\to k}}{P_i h})^{-\frac{2}{\alpha}}).exp(-\pi\lambda_k x^2)dx \\
&= 2\pi\lambda_k \int_0^\infty x.exp(-\pi(\lambda_i(\frac{P_k h x^{-\alpha} - Hys_{i\to k}}{P_i h})^{-\frac{2}{\alpha}} + \lambda_k x^2))dx \\
&= 2\pi\lambda_k \int_0^\infty x.exp(-\pi x^2(\lambda_i(\frac{P_k h - x^\alpha Hys_{i\to k}}{P_i h})^{-\frac{2}{\alpha}} + \lambda_k))dx
\end{aligned}$$

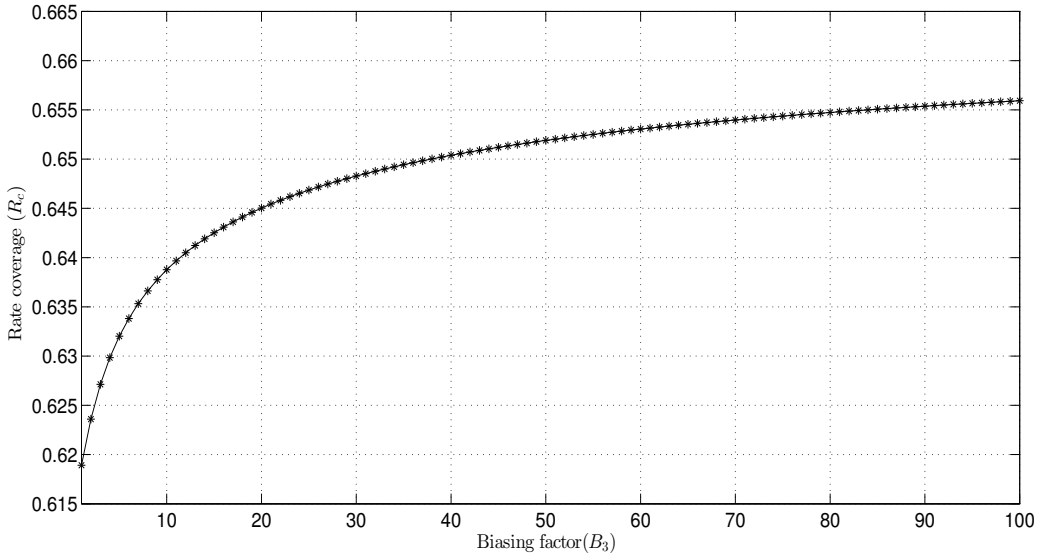

Figure 2.8: Rate coverage versus tier-3 biasing factor (B_3)

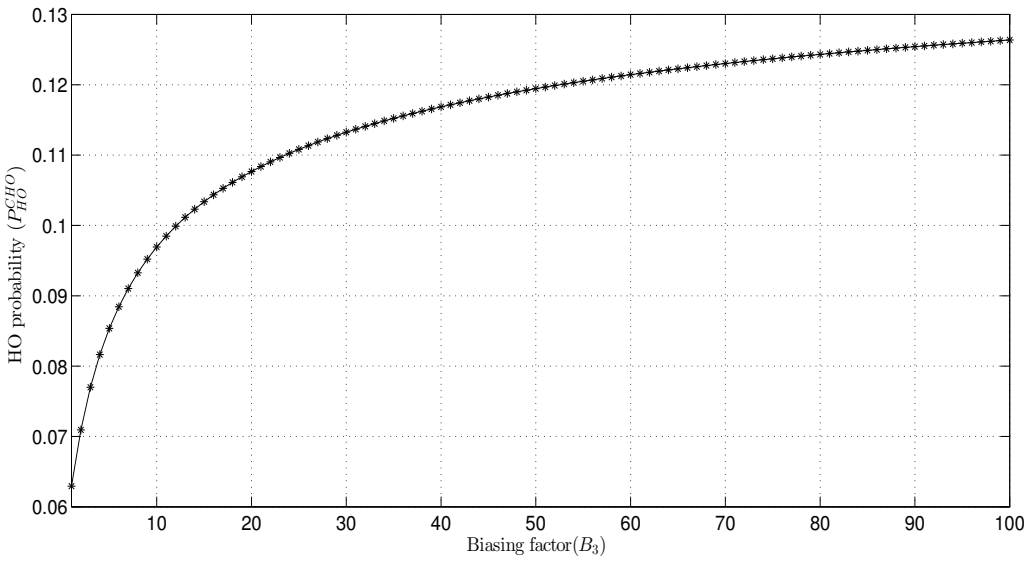

Figure 2.9: HO probability versus tier-3 biasing factor (B_3)

$$P_2^{FHO} = \int_0^{\infty} exp(-\pi \sum_{j=1, j\neq\{i,k\}}^{K} \lambda_j (\frac{P_k h x^{-\alpha} - \Delta H y s_{kj}^i}{P_j h})^{-\frac{2}{\alpha_j}}).f_{X_k}(x|S=i)dx$$

$$= 2\pi\lambda_k \int_0^{\infty} x.exp(-\pi \sum_{j=1, j\neq\{i,k\}}^{K} \lambda_j (\frac{P_k h x^{-\alpha} - \Delta H y s_{kj}^i}{P_j h})^{-\frac{2}{\alpha}} + \lambda_k x^2))dx$$

Notice that $f_{X_k}(x|S=i) = f_{X_k}(x) = 2\pi\lambda_k x.exp(-\pi\lambda_k x^2)$.

We consider now both rate coverage (2.17) and HO probability (2.14) when using FHO strategy with respect to tier-3 density, rate coverage threshold, tier-3 hysteresis Hys_3 thresholds (i.e. Hys_3 is equivalent to $Hys_{1\to3}$ when executing HO from tier-1 to tier-3 and to $Hys_{2\to3}$ when executing HO from tier-2 to tier-3) and UEs density. As in previous subsection we investigate the effect of offloading UEs to small-tier (tier-3). In this case we offload traffic to small-tier by tuning Hys_3 thresholds to facilitate HO triggering from all tiers toward tier-3. We first investigate the effect of simultaneously tuning $Hys_{1\to3}$ and $Hys_{2\to3}$ on R_c (Fig. 2.10) and P_{HO}^{FHO} (Fig. 2.11). We notice two observations from these plots:

- As well as Hys_3 increase R_c and P_{HO}^{CHO} decrease continually. This observation is in coherence with CHO strategy results demonstrating that offloading more UEs to small-tier leads to enhancing network rate coverage.

- The two plots present a periodic trend with progressive attenuation in periodicity as well as Hys_3 decreases. In order to interpret this phenomenon, we refer to probability of $condition_1^{FHO}$ (P_1^{FHO}) and $condition_2^{FHO}$ (P_2^{FHO}) expressions (see expressions of P_1^{FHO} and P_2^{FHO} in 2.6.2) showing that HO probability is dependent on two factors: *(i)* $\underline{Hys_k \text{ value}}$ (i.e. $Hys_{i\to k}$): as well as Hys_3 increases P_1^{FHO} increases. *(ii)* $\underline{\Delta Hys_{kj}^i \text{ value}}$: as well as Hys_k increases $-\Delta Hys_{kj}^i$ decreases and P_2^{FHO} as well. Therefore P_{HO}^{FHO} alternates depending on whether P_1^{FHO} or P_2^{FHO} has the more effect on the overall probability expression. Periodicity attenuation is due to the increase of Hys_3 leading to neglect the effect of $-\Delta Hys_{kj}^i$.

Notice also that best R_c value is given for $Hys_3 = 0$. We choose to investigate tier-3 density, rate coverage threshold and UEs density effects on R_c and P_{HO}^{FHO} in two cases: $Hys_{1\to3} = Hys_{2\to3} = 0$ and $Hys_{1\to3} = Hys_{2\to3} = 3$. Fig. 2.12 (resp. Fig. 2.13) represent coverage probability R_c (resp. HO probability P_{HO}^{FHO}) versus λ_3. Decreasing Hys_3 from 3 to 0 leads to a little increase of both rate coverage and HO probability. For a given Hys_3 value, as λ_3 increases rate coverage and HO probability also increase to attempt a maximum value. As shown in Fig. 2.2 increasing λ_3 beyond the optimal density (i.e. λ_3

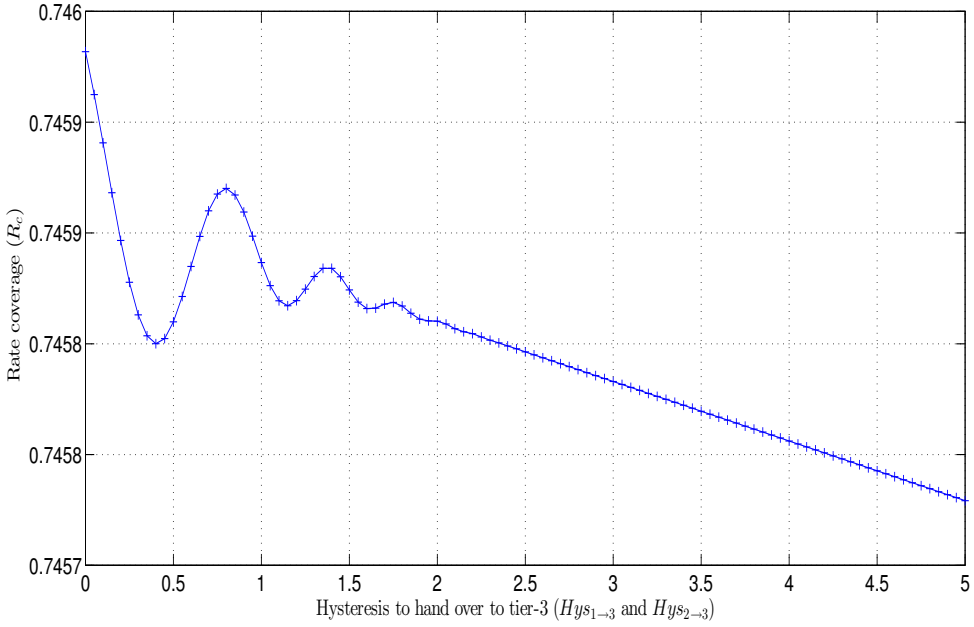

Figure 2.10: Rate coverage versus $Hys_{1\to3}$ and $Hys_{2\to3}$

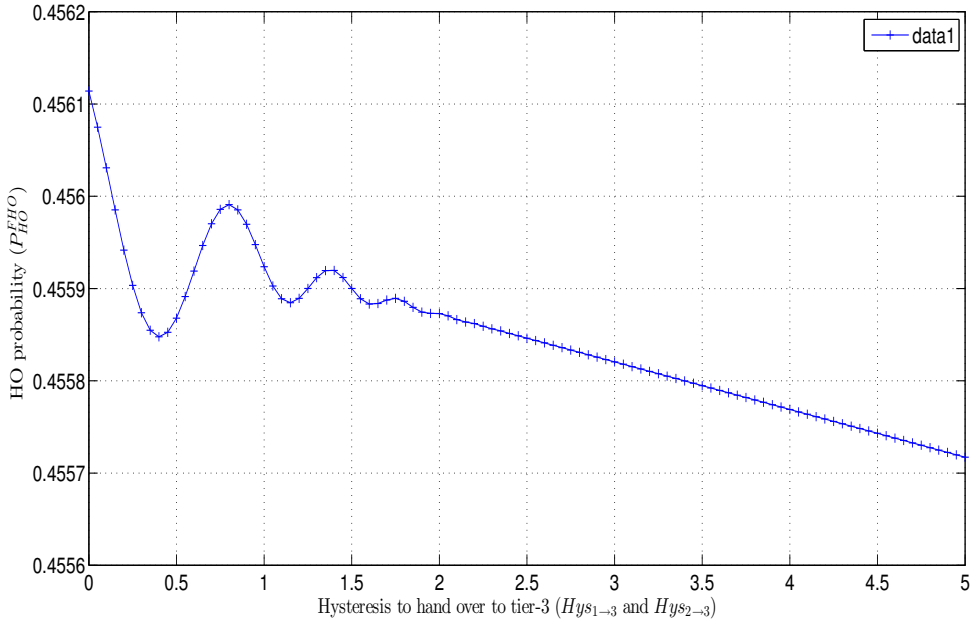

Figure 2.11: HO probability versus $Hys_{1\to3}$ and $Hys_{2\to3}$

value corresponding to the maximum rate coverage value) leads to a decrease of R_c. This is explained by interference effect on rate coverage. Notice that P_{HO}^{FHO} (Fig. 2.13) plot presents some periodic transitions. It seems that HO probability behaviour depends on hysteresis values combined with tier density. Therefore for a given Hys_3 value, HO probability decrease/increase is function of λ_3. Hence we can exploit curves in Fig. 2.122.13 to set convenient Hys_3 value depending on real network small-tier density so that satisfactory trade-off between rate coverage and HO signalling can be achieved. Fig. 2.14 and Fig. 2.15

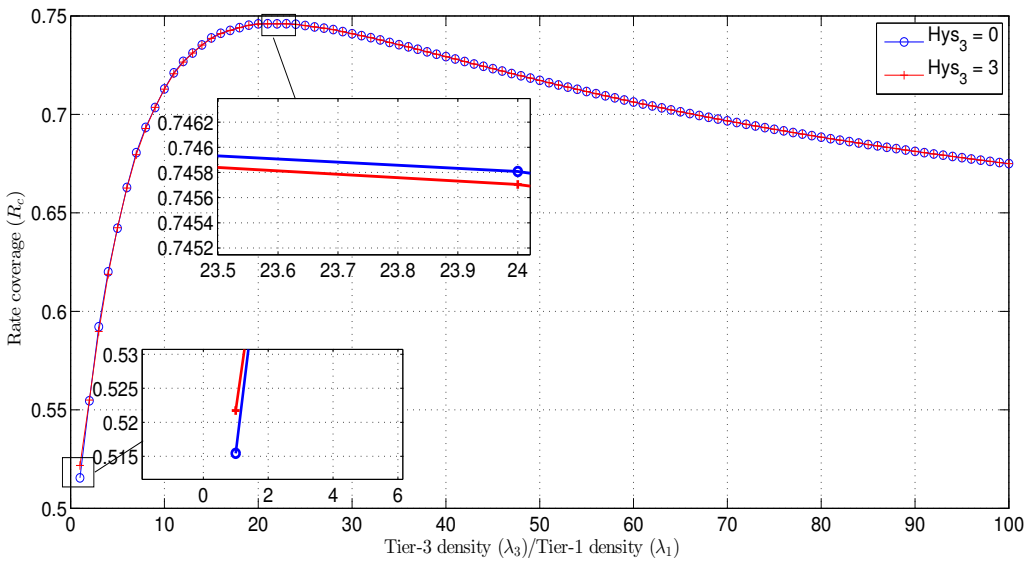

Figure 2.12: Rate coverage versus tier-3 density/tier-1 density (λ_3/λ_1)

show R_c evolution respectively with respect to rate coverage threshold ρ and UEs density λ^u. Rate coverage is decreasing function of these latter metrics and as observed before the case where $Hys_3 = 0$ leads to a little increase in rate coverage compared to the case where $Hys_3 = 3$.

2.7 Summary

In this chapter, we proposed and developed an analytical model based on PPP for the downlink of cellular HetNet. The model takes into account different transmit powers, path loss exponents, SINR/rate coverage thresholds, and cells densities in each tier. The rate

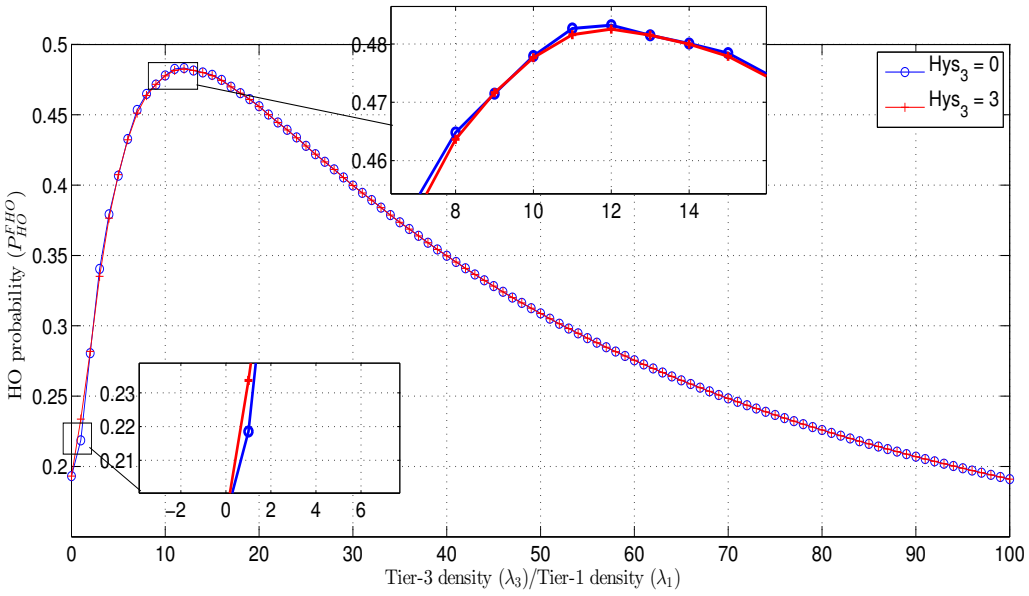

Figure 2.13: HO probability versus tier-3 density/tier-1 density (λ_3/λ_1)

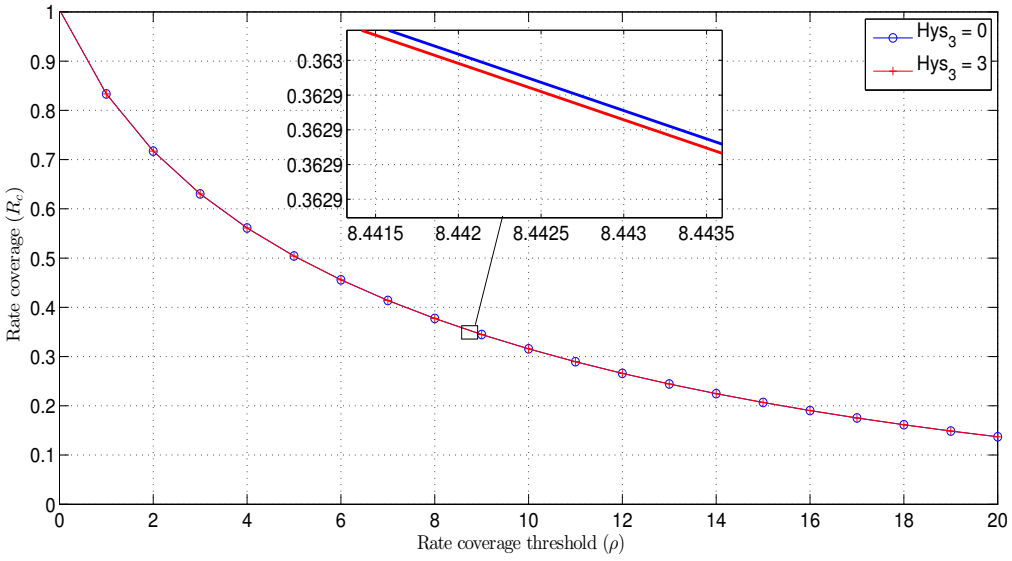

Figure 2.14: Rate coverage (R_c) versus rate coverage threshold (ρ)

distribution is derived assuming a max-power based association strategy combined with adaptive HO strategy. We proposed two adaptive HO strategies:

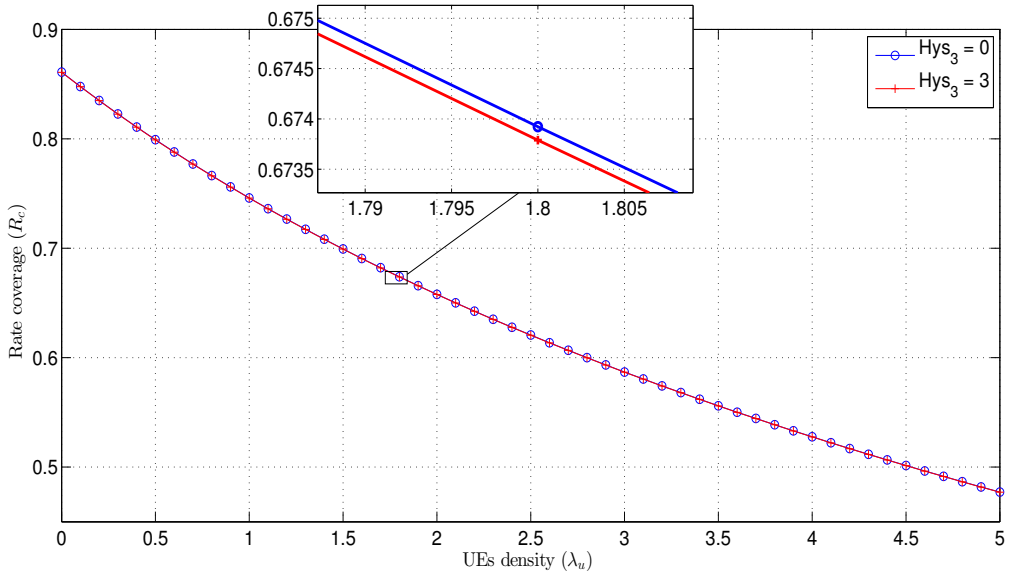

Figure 2.15: Rate coverage (R_c) versus UEs density (λ^u)

- Coarse grained adaptive HO strategy (CHO): in this strategy power biasing factor are used to tune the rate distribution across the network. It is observed that HO and rate coverage are proportional to the biasing factor of small-tier.

- Fine grained adaptive HO strategy (FHO): we proposed to use LTE A3 event to trigger HO between different tiers. Adaptive hysteresis based HO strategy was investigated and shows that decreasing hysteresis thresholds to facilitate offloading of traffic to small-tier enhance network rate coverage. This enhancement is related simultaneously to both hysteresis threshold and small-tier density.

The main finding from the above analysis is that enhancement in rate coverage is penalized by HO signalling overhead. In next chapter we propose to exploit FHO strategy to investigate LB in LTE HetNet. We propose to implement LB algorithms based on adjusting adaptively HO hysteresis threshold according to cell load. We specifically focus on A3 HO triggering event based on measurements of the reference signal received power. Intensive simulations for LB algorithms under realistic network scenarios of a two-tier LTE HetNet deployment are considered in chapter 3.

Chapter 3

Mobility Load Balancing Based Fine Grained Adaptive Handover in Heterogeneous Cellular Networks

"Mobility load balancing (MLB) is a function where cells suffering congestion can transfer load to other cells, which have spare resources. MLB includes load reporting between eNBs to exchange information about load level and available capacity."

3GPP, Self Organizing Networks [64]

3.1 Motivations and related work

In HetNets, loads in different cells are frequently unequal. This leads to critical situation where overloaded cells suffer from a high call blocking rate (CBR) and/or call dropping rate (CDR). In contrast, a large part of resources in low-loaded cells remains in idle state causing resource wastes. Therefore, load imbalance between neighbouring cells seriously deteriorates network performance. In this regard, the concept mobility load balancing (MLB[1]) was introduced in 3GPP LTE SON systems aiming to give dynamic and adaptive techniques to enhance fairness and availability of LTE networks. In this chapter we investigate adaptive FHO based MLB through discrete event simulations, using network simulator 3 (ns-3), of 3GPP LTE network for DL data transmissions. MLB is introduced by 3GPP as a key target of LTE SON networks [65]. Our contribution in this chapter is twofold. First, we implement elementary procedures (EPs) related to load management (LM) function of the X2-application protocol (X2AP) as specified in 3GPP specification TS 136.423 [10]. We particularly focus on EPs namely 'Resource Status Reporting Initiation Procedure' and 'Resource Status Reporting Procedure'. Second, we implement adaptive FHO based MLB algorithms enabling to configure adaptively HO hysteresis threshold for each neighbouring cell, of an overloaded cell, according to its current load information.

Yang et al. propose in [66] an auto-configuration technique of handover hysteresis threshold according to load information of current overloaded cell and its neighbours. The proposed technique leads to significant reduction of CBR, HO dropping/blocking rate and ping-pong HO rate. However, the paper neglects the proposed MLB mechanism impact on some key performance metrics such as network global throughput and LB index. The proposed model in the above paper is implemented using a formal description technique based on a description language (SDL). Thereby algorithm efficiency in [66] needs to be improved for more realistic conditions and in this regard a more realistic implementation with respect to 3GPP specifications could be established. In this chapter we propose a MLB algorithm implementation based on discrete-event network simulator ns-3 [67]. To that end two implementation steps are followed. In a first step two LM EPs of the of X2AP protocol namely 'Resource Status Reporting Initiation Procedure' and 'Resource Status Reporting

[1]Tackling LB is referred to as mobility load balancing (MLB) in 3GGP specifications.

Procedure' are implemented as specified in TS 136.423 [10]. We exploit next these EPs to implement in a second step the MLB algorithm proposed in [66] based on adjusting adaptively HO hysteresis threshold according to cell load information. We specifically focus on A3 HO triggering event based on measurements of the reference signal received power (RSRP)[11]. Numerical results show how MLB enhances network performance without incurring significant overhead. We particularly show for DL how performance metrics such as network throughput, PLR, number of successful HO and LB fairness index evolve for different UE densities.

3.2 HO and MLB signalling functions of X2AP in 3GPP specifications

In LTE architecture, the core network (CN) includes mobility management entity (MME), serving gateway (SGW) and packet data network gateway (PDN-GW), whereas E-UTRAN includes eNodeBs (eNBs) [10]. The X2 interface is defined between two neighbouring eNBs at two planes (Fig. 3.1) [68]:

- X2-UP (User-plane): is the user-plane interface between two neighbouring eNBs. X2-UP protocol tunnels end-user packets between eNBs. The transport network layer is built on IP transport, and GTP-U is used on top of the UDP to carry the user-plane PDUs.
- X2-CP (Control-plane): is the control plane interface between two neighbouring eNBs. X2-CP has stream control transmission protocol (SCTP) as transport layer protocol and X2AP as application layer signalling protocol.

X2AP supports radio network layer signalling functions of the control plane between eNBs. 3GPP defines X2AP as a collection of EPs [10]. A X2AP EP is a unit of interaction between two eNBs. Since X2AP is responsible of signalling between two neighbouring eNBs, it ensures two major SON functions namely HO signalling functions (i.e. mobility management (MM), mobility robustness optimization (MRO), mobility parameters management (MPM) and load information exchanges function (i.e. LM)). The HO enables one eNB to hand over an user equipment (UE) to another eNB and requires the transfer of useful information to

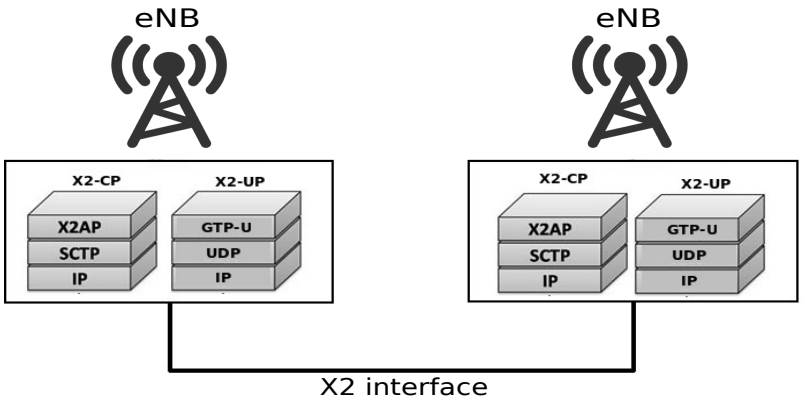

Figure 3.1: Protocol stack of the X2 interface

maintain the LTE radio access network (RAN) services at the new eNB. The LM function allows to exchange traffic load and its related signalling between neighbouring eNBs. In what follows we give more details about HO and LM functions.

3.2.1 HO functions

In LTE the HO procedure is based on UE's measurements; A serving eNB sends a connection reconfiguration message through the radio resource control (RRC) layer to inform an UE of its related measurement configuration. If the UE detects any event related to measurement configuration, a measurement event is triggered and the serving eNB is informed. The decision of triggering a HO is based on the detection of a special event. 3GPP specifies several reporting events to trigger HO [11] depending on the measurements' values. The serving eNB should indicate to UEs the event to use in the connection reconfiguration message. In order to trigger a HO within LTE several kind of events may be adopted. Our choice is directed toward A3 event, which might be triggered if a neighbouring cell measurement becomes offset better than the serving cell. The entering condition to be satisfied for A3 event can be simplified as follows:

$$Mn > Ms + Hys_{s \to n} + Off + Freq + SOff \tag{3.1}$$

where Ms is the UE measurement corresponding to the serving cell and Mn is the UE measurement corresponding to the neighbouring cells. As part of the reporting configuration,

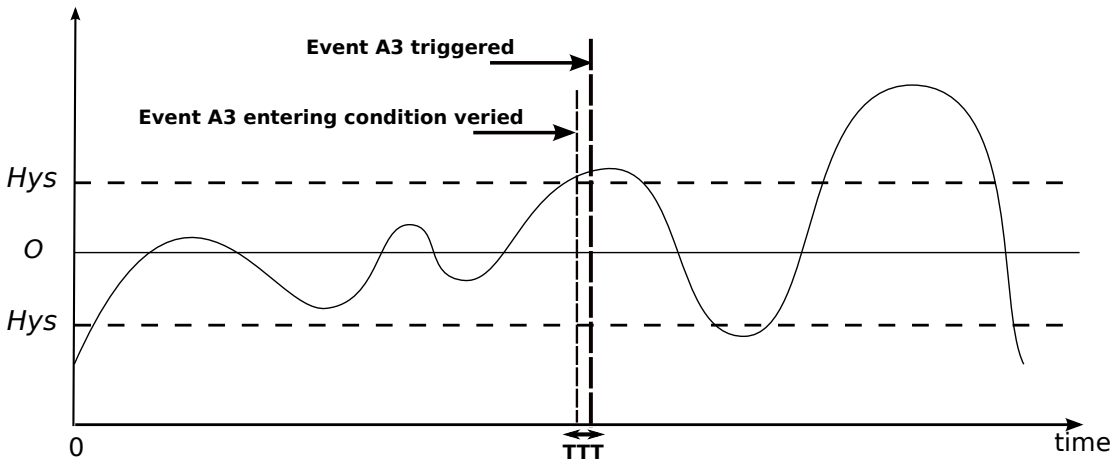

Figure 3.2: Measurement event A3 with $Freq = SOff = 0$

the eNB can tell the UEs to measure either their cells RSRP, or their reference signal received quality (RSRQ) [69]. Hys is a hysteresis parameter for measurement reporting. If the UE sends a measurement report to its serving cell, then Hys prevents any more reports until the signal level changes by (Fig. 3.2). Similarly, Off is a hysteresis parameter for HOs. If the measurement report triggers HO, then Off prevents the UE from moving back to the original cell until the signal level changes by . Freq (resp. SOff) is the difference between frequency specific offsets (resp. cell specific-offsets) of the serving and neighbouring cells [11]. The time to trigger (TTT) parameter is the time during which the condition of triggering A3 event needs to be maintained in order to trigger a measurement report (Fig. 3.2). If a measurement report is sent to the serving cell with a triggered A3 event, this latter may trigger a HO procedure by starting a MM function with the neighbouring cell. In what follows we describe the MM function of the X2AP protocol.

3.2.2 MM function

The MM function covers four EPs:

- Handover Preparation EP: during this procedure the serving cell initiates the HO with the HANDOVER REQUEST message and includes necessary information for neighbouring cell preparation to an incoming HO. The neighbouring cell responds back to the serving cell with a HO REQUEST ACKNOWLEDGE message (successful

operation) or a HANDOVER PREPARATION FAILURE message (unsuccessful operation);

- SN Status Transfer EP: along this procedure the SN Status Transfer is sent from the serving cell to its neighbours to transmit uplink (UL) and DL packet data convergence protocol sequence number (PDCP SN) and hyper frame number (HFN) receiver status and transmitter status from the source eNB to the target eNB during an X2 handover. This is achieved for each evolved radio access bearer (E-RAB) for which PDCP SN and HFN status preservation applies;
- UE Context Release EP: By sending an UE CONTEXT RELEASE message, the target eNB informs the source eNB of HO success and a release of resources by the eNB source is triggered. The target eNB sends this message after receiving the PATH SWITCH ACKNOWLEDGE message from the MME. Upon reception of the UE CONTEXT RELEASE message, the source eNB can release data and C-plane related resources associated to the UE context. Therefore, any ongoing data forwarding may continue;
- Handover Cancel EP: is used by a source eNB to cancel an ongoing HO preparation or an already prepared HO.

3.2.3 MPM function

MPM function covers one EP: the mobility settings change (MSC) EP. This latter enables an eNB to negotiate the HO trigger settings with a peer eNB controlling neighbouring cells.

3.2.4 MRO function

MRO function detects and corrects automatically errors in the mobility configuration. It covers two EPs:

- Radio link failure (RLF) indication EP: The purpose of this EP is to transfer information regarding RRC re-establishment attempts or received RLF reports, between eNBs;

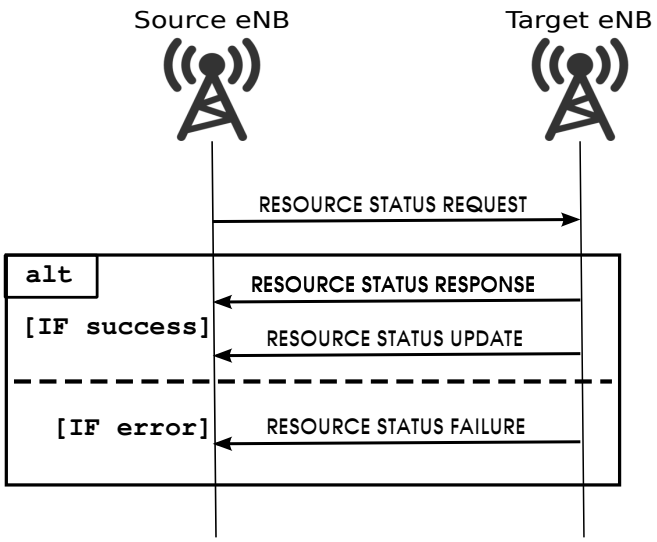

Figure 3.3: Resource Status Reporting EP

- Handover report EP: This EP enables to transfer mobility related information between eNBs.

3.2.5 LM function

In order to detect a load imbalance between eNBs in the network, it is necessary to compare cells' load information and exchange them between neighbouring eNBs [70]. Three separate EPs are used to exchange load information via the X2 interface:

- Load Indication EP: The load indication procedure is used over the X2 interface for load and interference management information exchange. An eNB initiates this EP by sending LOAD INFORMATION message to a neighbouring eNB;

- Resource Status Reporting Initiation EP and Resource Status Reporting EP (Fig. 3.3): These EPs are used to initiate and report load measurements result between eNBs. A source eNB sends a RESOURCE STATUS REQUEST message to a target eNB. If this latter is able to provide requested resource status information, it responds with the RESOURCE STATUS RESPONSE message and then Resource Status Reporting EP could be initiated. The target eNB will report measurement results in RESOURCE STATUS UPDATE message.

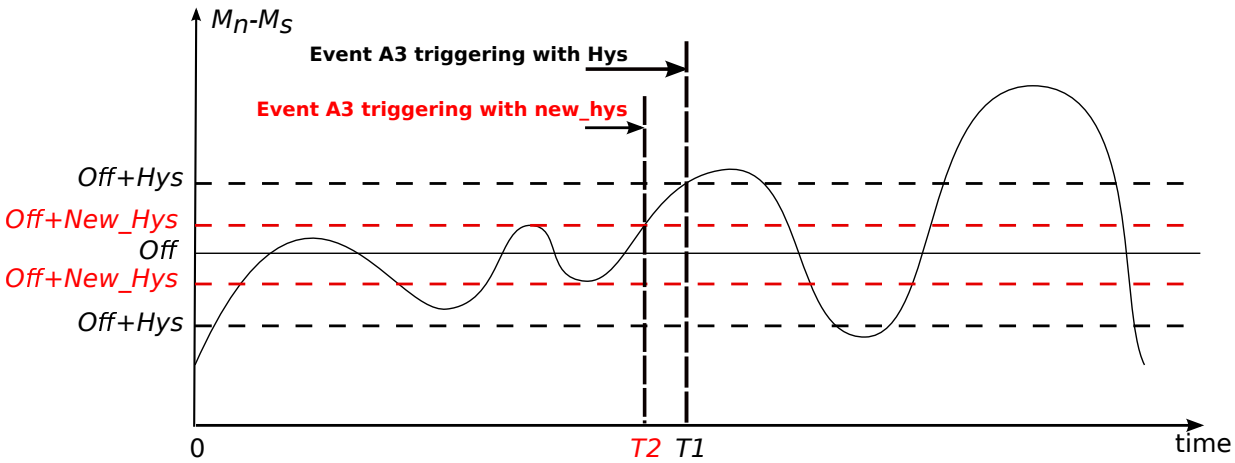

Figure 3.4: Sample of dynamic hysteresis adaptation effect on HO triggering when using A3 event with $Freq = SOff = 0$

3.3 MLB based adaptive HO in DL LTE SON networks

To improve the overall system capacity 3GPP defines a self-optimizing function namely MLB. MLB enables cells suffering from congestion to transfer extra-load to other neighbouring cells willing to cooperate toward their spare resources [65]. The MLB is governed by load reporting mechanisms activated between eNBs (over the X2 interface) to exchange information about load level and available capacity. One solution to introduce MLB in a LTE system is to steer extra-traffic toward neighbouring cells by optimizing dynamically the cell HO parameters, such as hysteresis, upon detection of an imbalance [70]. In fact, SON techniques allow to automatically adjust mobility configuration based on several factors such as received load information. In order to describe MLB principle let's consider event A3 (Fig. 3.2) described above and assume that it is triggered between an overloaded cell and its neighbour at time T1. The decreasing of the Hys value fosters the triggering of A3 event ($T2 < T1$) and consequently facilitates the HO triggering from the overloaded cell to its neighbouring cell (Fig. 3.4) (To simplify the figure, TTT is not represented). By adjusting Hys value, the hot spot cell forces UEs to hand over to its neighbouring cell. Then MLB based adaptive HO may be defined as an explicit triggering of a forced HO for load balancing purposes. To apply this mechanism, each cell should be aware of its own load conditions as well as the load of its neighbours. This enables respectively to

detect an overload situation and to select the best neighbouring cell to hand over UEs. For that purpose, eNBs periodically monitor their own load conditions and exchange load information over the X2 interface (Fig. 3.3). The RESOURCE STATUS UPDATE message includes a special attribute called composite available capacity (CAC). CAC represents the overall available resource level that can be offered for MLB purposes in either DL (CACD) or UL (CACU). CAC can be represented as a data structure including two information elements (IE):

- Cell Capacity Class Value IE: classifies the cell capacity with regards to the other cells. The Cell Capacity Class Value IE indicates resources that may be reserved for data traffic;
- Capacity Value IE: Indicates the ratio between the amount of available resources and the amount of total E-UTRAN resources. The Capacity Value IE is measured and reported so that suitable E-UTRAN resources of the existing services are reserved. The Capacity Value IE can be weighted according to the ratio of cell capacity class values.

In this chapter we turn our interest only to CACD which is not supported by the eNB model in given in current version of ns-3 (i.e. ns-3.24). In this regard we will define and develop the calculation of CACD. In the next section we will describe the system model and explain basic set notation we used for the formulation of the treated problem.

3.4 X2AP EPs extension

Ns-3 [67] is an open-source discrete event network simulator, developed using C++ programming language. Ns-3 supports the simulation of 3GPP LTE cellular networks. Baldo et al. propose in [71] a simulation model for LTE HO scenarios using ns-3. In order to integrate MLB SON functionalities, the proposed model implements X2 interface supporting RESOURCE STATUS UPDATE message. Such implementation offers only a prototype of this message and details regarding associated variables are not specified. In this chapter we implement new added methods illustrated in appendix 3.9. This is achieved through

two implementation steps. The first one concerns RESOURCE STATUS REQUEST and RESOURCE STATUS RESPONSE messages (i.e. Resource Status Reporting Initiation EP), which are necessary for the initiation of a RESOURCE STATUS UPDATE message (RESOURCE STATUS FAILURE message is not considered). Whereas the second focuses on RESOURCE STATUS UPDATE message (i.e. Resource Status Reporting EP).

3.5 Problem formulation and DL LTE HetNet system model

The HO procedure enables one cell to hand over an UE to another cell while maintaining the RAN services at the new cell. In 3GPP LTE systems intra-frequency HO is triggered based on A3 event [11]. The entering condition to be satisfied for A3 event can be formulated as follows:

$$M_j + CSOff > M_i + Hys_{i \to j} \tag{3.2}$$

where M_i and M_j are the UE measurement corresponding to the serving cell i and the neighbouring cell j respectively. $CSOff$ is a parameter depending on the measurement biasing (i.e. $CSOff$ calculation depends on whether we have intra- or inter-layer HO) and $Hys_{i \to j}$ is the HO offset from cell i to j (a.k.a. hysteresis). If the serving cell i is overloaded, one way to offload the excess traffic to its neighbours is by decreasing $Hys_{i \to j}$ value. To alleviate the traffic in the congested cell, we adopt two scenarios:

- Inter-tier HO threshold adjustment: a principle issue in HetNet is the traffic balancing between the macro-layer, more sensitive to overloaded situations, and the small-layer. Inter-layer HO biasing concerns the biasing of HO threshold between a congested macro-cell and its neighbouring from the small-tier (i.e. small-cells).

- Intra-tier HO threshold adjustment: since loads in different cells from the same macro-layer are frequently unequal [72], a scenario to consider when balancing the network traffic concerns the biasing of HO threshold between a congested macro-cell and its neighbours from the same tier (i.e. macro-cells).

The proposed MLB scheme relies on the performing of intra- and inter-layer HO biasing to guarantee a best interoperability, scalability and reliability of the traffic offloading. In this

chapter we consider the DL transmission of a two-tier 3GPP LTE HetNet with multiple macro-cells and small-cells as shown in Fig. 3.6. Each eNB consists of three macro-cells (i.e. sectors) and a small-cell represents a femtocell configured in open access mode. Femtocells are composed by one small-cell. In HetNet, the total bandwidth in a cell is determined by the network's frequency planning. To facilitate the implementation of intra-frequency MLB algorithm, a full frequency reuse scheme is considered (we assume a frequency reuse of one). This means that no frequency partitioning is performed between cells which is considered as a realistic scenario for LTE systems. We adopt a regular deployment for modelling the macro-cell layer where eNBs are deployed in an hexagonal layout. All UEs and small-cells are scattered into each macro-cell in a random manner. We denote C the set of cells including macro-cells and small-cells, and represent the set of scheduled UEs as U. We assume that the number of connected UEs in the network is constant along the simulation duration. C_i represents the cell i. $C_{i,j}$ denotes a neighbouring cell C_j of a cell C_i. The amount of Physical Resource Blocks (PRBs) quantifying time-frequency resources of a cell is denoted R (We assume that all cells have the same amount of PRBs). $U_i(t)$ is the set of UEs scheduled in C_i at time t and $U_{i,k}(t)$ indicates an UE k scheduled in C_i at time t. $R_{i,k}(t)$ is the amount of consumed PRBs by $U_{i,k}(t)$ at time t. The load $\rho_i(t)$ of C_i at time t can be calculated as follows:

$$\rho_i(t) = \frac{\sum_{k \in U_i(t)} R_{i,k}(t)}{R} \tag{3.3}$$

To detect an overloaded situation, each cell periodically monitors information about its own load conditions and exchange load information with its neighbouring cells. LTE systems define the X2 interface between neighbouring eNBs which allows cells to be aware about network load condition [10]. Load information is transmitted over the X2 interface in the form of Composite Available Capacity (CAC) parameter. Formally, CAC expresses the amount of load that a particular cell is willing to accept subject to several factors such as resource utilization, QoS requirements, backhaul capacity and the load of control channels. We define CACD as the CAC in DL. Let $CACD_i$ be the overall available resource level that a cell i can offer for MLB purposes in DL. Then it can be expressed as:

$$CACD_i(t) = 1 - \rho_i(t) \tag{3.4}$$

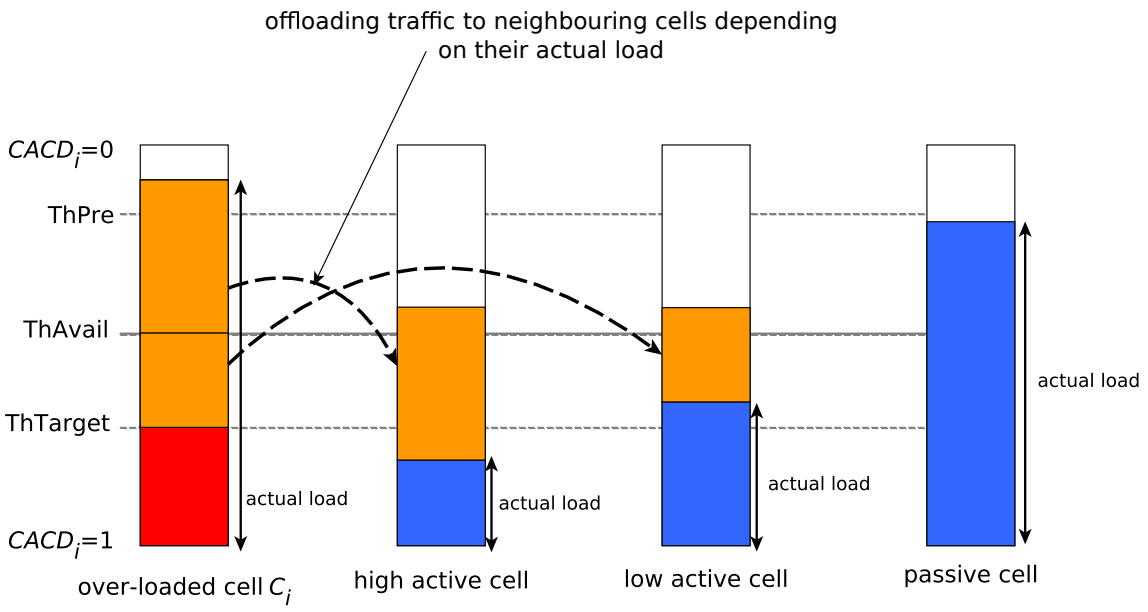

Figure 3.5: Illustration of the proposed MLB algorithm

Depending on $CACD$ value, each cell may estimate its load condition and decide whether to enable the MLB algorithm if it experiences an overloaded situation or to keep it disabled.

3.6 MLB based fine grained adaptive handover

The MLB algorithm developed to balance the load among neighbouring cells relies on the principles described in [72]. The proposed MLB scheme is based on calculating new HO thresholds based on the load of each cell as illustrated in Fig. 3.5. We introduce three thresholds, with values between 0 to 1, that would serve to estimate cell load status:

- $ThPre$: If $CACD_i$ decreases below this threshold, C_i is declared as an overloaded cell and should enable the MLB algorithm to balance its load by updating HO threshold values according to the MLB scheme.

- $ThTarget$: If $CACD_i$ of an overloaded cell C_i that activated the MLB algorithm increases over this threshold, C_i should deactivate the MLB algorithm and restore default HO threshold values.

Neighbouring cell load condition	**Neighbouring cell status**
$CACD_j > ThTarget$	High active
$ThAvail < CACD_j \leqslant ThTarget$	Low active
$CACD_j \leqslant ThAvail$	passive

Table 3.1: Neighbouring cells classification

- $ThAvail$: it serves to estimate the degree of neighbouring cells' capability to receive offloaded traffic.

These thresholds are operator-configurable parameters and are transmitted as an input to the MLB algorithm. E.g. if we set $ThPre$ to 0 the MLB scheme is only executed when the concerned cell is fully-loaded and has zero available resources. If $ThTarget$ is set to 1, the MLB scheme will be disabled only if the cell is totally empty. Operators may tune thresholds according to their specific objectives. Low $ThAvail$ values mean that more cells will participate to MLB if it's enabled by a neighbouring cell. To maximize the number of active cells, $ThAvail$ should be set to 0. High $ThPre$ values may be chosen if operators want to promote network performance in terms of QoS. This means that the network will be very sensitive to overloaded situations and will aim to avoid call blocking/dropping situations by optimising load distribution among different network tiers. Low $ThTarget$ values mean that the operator aims to minimise signalling traffic between cells by minimising HO executions due to LB, while high values will reduce the risk of ping-pong HO.

Cells periodically perform load measurements and estimate their own CACD. If a cell C_i is overloaded (i.e. $CACD_i \leqslant ThPre$) it should offload some of its attached UEs to neighbouring cells. As shown in Fig. 3.5 and Tab. 3.1, neighbouring cells are classified into three categories given their own load conditions and based on the aforementioned thresholds; High active cells correspond to nodes whose available capacity is higher than $ThTarget$ threshold and are willing to accept more traffic. On the contrary, those with a $CACD$ value equal or under $ThAvail$ are denoted as passive and constitute cells declared incapable to participate to MLB procedure. Ultimately, cells operating within the $]ThAvail, ThTarget]$ $CACD$ range are characterized as low active ones as they may participate in MLB procedures with little rate of resources. Formally, all MLB procedures

are triggered by overloaded macro-cells. Therefore, upon overload declaration, the cell has to estimate an hysteresis decrement so that excess traffic is offloaded to adjacent cells. In addition, it informs its active neighbours over the X2 interface to the new hysteresis modification subject to their own cell load conditions. Both active and passive cells need to estimate their $CACD$. Once $CACD_j(t)$ is estimated, it is basically mapped to an $\alpha-$modification. We propose three variants of the MLB algorithm depending on how we calculate new hysteresis values:

1. variant 1: slow MLB

$$\alpha_{i\to j} = \begin{cases} 1 & if \quad CACD_j \leq ThTarget \\ 0 & if \quad CACD_j > ThTarget \end{cases} \tag{3.5}$$

2. variant 2: fast MLB

$$\alpha_{i\to j} = \begin{cases} 1 & if \quad CACD_j \leq ThAvail \\ 0 & if \quad CACD_j > ThAvail \end{cases} \tag{3.6}$$

3. variant 3: smooth MLB

$$\alpha_{i\to j} = \begin{cases} 1 & if \quad CACD_j \leq ThAvail \\ 1 - \frac{ThAvail - CACD_j}{ThAvail - ThTarget} & if \quad ThAvail < CACD_j \leq ThTarget \\ 0 & if \quad CACD_j > ThTarget \end{cases} \tag{3.7}$$

The new hysteresis value between C_i and $C_{i,j}$ (i.e. $NewHys_{i\to j}$) is adjusted as follows:

$$NewHys_{i\to j} = \alpha_{i\to j} \times Hys_{i\to j} \tag{3.8}$$

3.7 Simulations: assumptions and results

System level simulations using the discrete-event network simulator ns-3 [67] are considered. We consider the dual stripe model proposed by 3GPP to illustrate realistic scenarios of dense-urban Home eNBs (HeNB[2]) deployment [73]. Simulations implement an intra-frequency network where both macro-cells and small-cells are deployed at 2 GHz sharing 5 MHz of bandwidth. Fig. 3.6 illustrates the multi-cell network considered in the 3GPP dual stripe model. The simulated network is composed by 7 eNBs (21 cells) regularly

[2]Also known as femtocell.

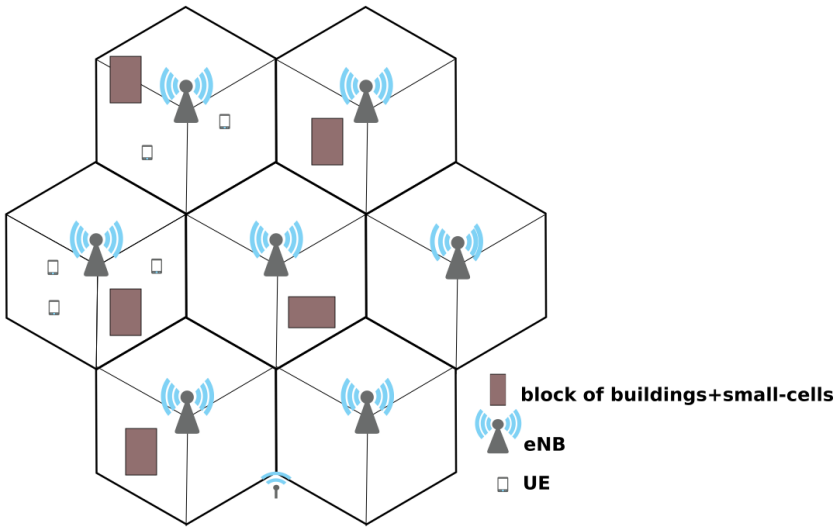

Figure 3.6: Network topology

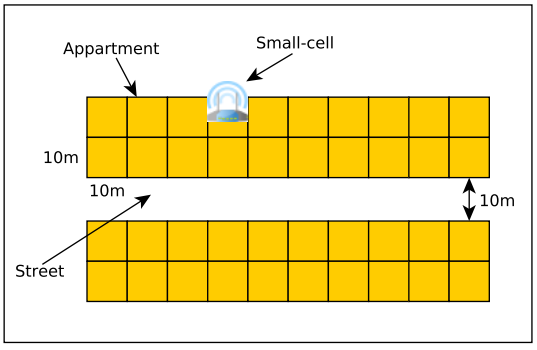

Figure 3.7: Femto-cell block

deployed in hexagonal layout where the distance between two eNBs is assumed equals to 500 meters. 4 blocks (apartment buildings) are randomly dropped among the network. Each block represents two stripes of apartments, each stripe has 2 by 10 apartments (Fig. 3.7). We simulate a street between the two stripes of apartments with width of 10m. Each small-cell block has one floor. Each block has 1 small-cell. The number of connected macro-UEs is gradually increased to show the effect of high traffic generation areas (hotspots) on the network performance.

A fixed number of home UEs is considered (i.e. $nbHomeUE = 16$). Tab. 3.2 summarizes the main parameters of the simulated scenarios. Thresholds values are fixed as follows:

Parameter	**Value**
Macro-tier cellular layout	7 eNBs (21 cells) in hexagonal layout
Number of smallcells	16
Inter-eNBs distance	500m
Macro-cell Tx power	46dbm
small-cell Tx power	20dbm
Path loss model	both outdoor and indoor communication are considered in pathloss calculation
Carrier frequency	2 Ghz
System bandwidth	5 Mhz
Traffic model	Guaranteed Bit Rate (GBR) conversational voice over IP
UE distribution	random
Macro UE densities	$\{0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1\} \times 10^{-4}$
UE measurement reporting interval	50 ms
Simulation duration	50 s
MLB parameters tuning	
Hysteresis default value	3.0 db
Hysteresis margin with MLB	[0..3db]
$ThPre$	0.2
$ThTarget$	0.8
$ThAvail$	0.5

Table 3.2: Simulation model parameters

- $ThPre = 0.2$: In fact $ThPre$ refers to the point from which a cell may enable the MLB scheme. $ThPre = 0.2$ means that when 80% of the cell resources are occupied and only 20% are still available the cell is considered as overloaded, which may be a realistic assumption if no QoS is required.

- $ThTarget = 0.8$: It refers to the point that, when reached, the cell may disable the MLB scheme. A reason to set $ThTarget$ to such a high value is to avoid ping-pong HO due to MLB while offloading UEs to neighbouring cells.

- $ThAvail = 0.5$: operators can control the number of neighbouring cells that may participate to LB by tuning $ThAvail$.

To evaluate the trade-off between capacity enhancements provided by LB and a potential mobility performance degradation, the following cases are considered:

- No LB (i.e. Fixed hysteresis): No hysteresis adjustments are performed. A fixed

handover hysteresis of 3 dB is assumed for all cell pairs; hence, $Hys_{m\to m} = Hys_{m\to s} = 3db$ (i.e. $Hys_{m\to m}$ is the hysteresis value for HO between macro-cells and $Hys_{m\to s}$ is the hysteresis value fro HO from a macro-cell to a neighbouring small-cell)

- Adaptive HO LB (i.e. Hysteresis adjustment):
  - smooth MLB algorithm: in this case $Hys_{m\to m}$ and $Hys_{m\to s}$ are dynamically adjusted based on formula 3.7 and within the range of [0db, 3db] dB.
  - Slow MLB algorithm: in this case hysteresis range is calculated based on formula 3.5 for both $Hys_{m\to m}$ and $Hys_{m\to s}$.
  - Fast MLB algorithm: in this case hysteresis range is calculated based on formula 3.6 for both $Hys_{m\to m}$ and $Hys_{m\to s}$.

Cell load observations are obtained periodically every second. Fig. 3.8 illustrates the global network throughput for all simulated schemes with different UEs densities. When using a MLB algorithm, the global throughput is ameliorates across different network cells, especially for high traffic simulations. As observed, the MLB impact on network performance depends closely on UEs density. For relatively low UEs densities (i.e. $[10^{-5}, 5\times10^{-5}]$) MLB integration has low impact on the network performance. Since in such case a heavy-loaded situation may not occur during the simulation, MLB algorithm will very probably not be enabled. For higher densities (i.e. $[6\times10^{-5}, 10^{-4}]$), some macro-cells will fall under a heavy-loaded situation. Then by offloading extra traffic from those macro-cells to its macro neighbours and to the small-cell layer the network global throughput is significantly ameliorated. To highlight the impact of deploying small-cell layer alongside the macro-cell layer, we present the macro-layer's cells throughput for each simulated scheme and for a UE density of 5×10^{-5} (Fig. 3.9). Notice that throughput disparity between macro-cells is more severe for simulations without MLB; while cells 15 and 18 experience high throughput values which may result in high call blocking/dropping rates, cells 6, 17 and 20 present low throughput leading to a resource waste. Such disparity is mitigated when integrating MLB algorithm, especially for fast and smooth MLB schemes. Fig. 3.10 represents the Packet Loss Ratio (PLR) evolution with respect to UEs density with and without activation of MLB. Results show that smooth MLB scheme presents the lower values of PLR. This

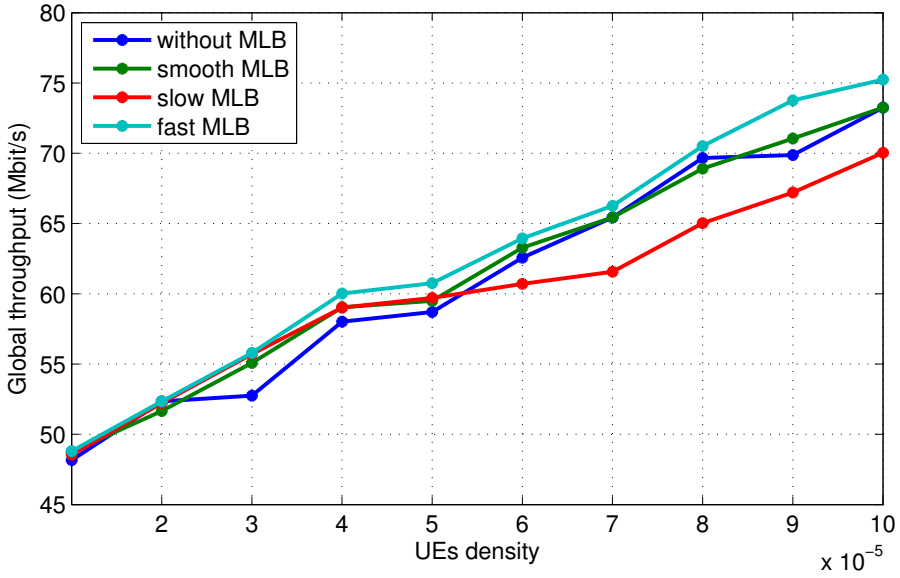

Figure 3.8: Global network throughput vs UEs density

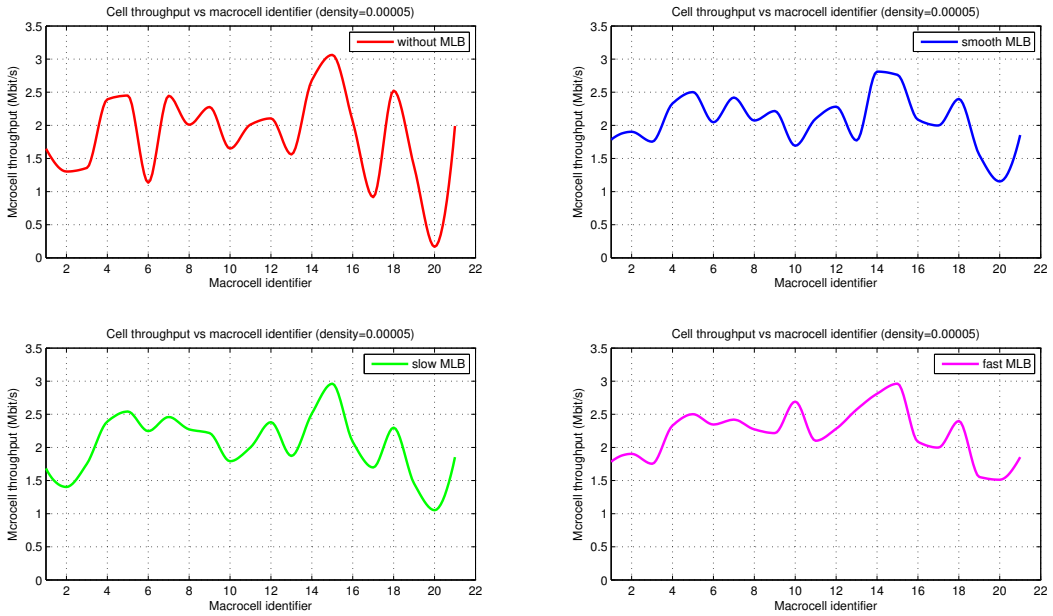

Figure 3.9: Macro-cells throughput vs macro-cell's identifier

phenomenon may be explained by the particularity of smooth MLB scheme that tune hysteresis values in a non-aggressive and progressive manner with a more meticulous respect to neighbours' load conditions comparing to fast and slow MLB schemes (see

eq. 3.7, 3.6, 3.5). Fig. 3.11 highlights Jain's Fairness Index (JFI) versus UEs density. We

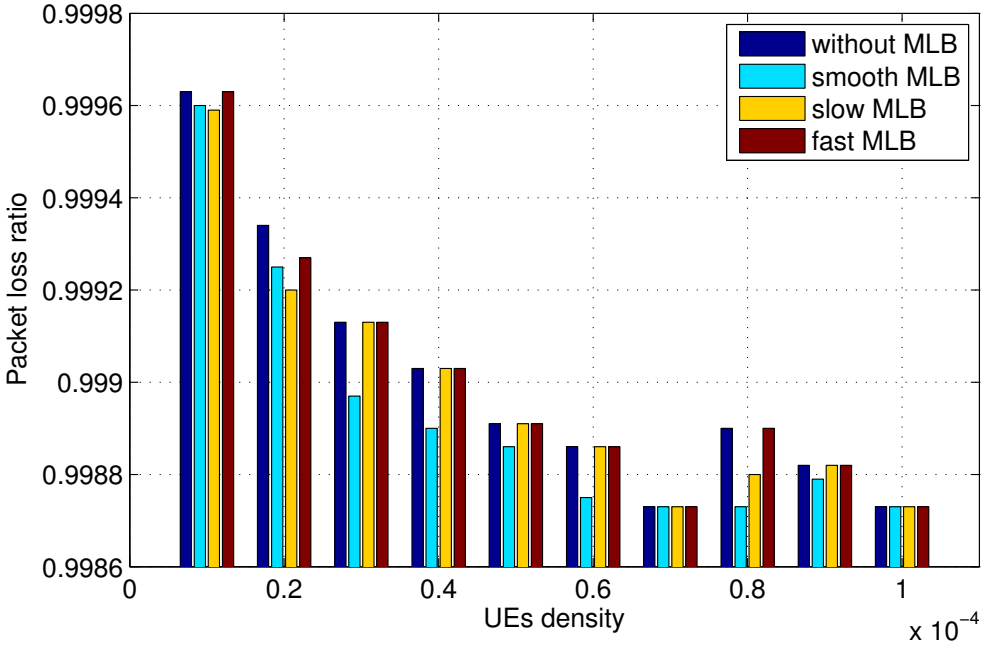

Figure 3.10: Packet loss ratio vs UEs density

observe that JFI values are improved for relatively high densities in a similar manner when activating MLB algorithms. For lower densities, no improvement in the fairness between macro-cells is generated and the simulated MLB schemes present in some cases (i.e. 0.1×10^{-4} and 0.2×10^{-4}) a degradation in JFI values. Fig. 3.12 illustrates the evolution of the number of successful HOs according to UEs density with and without MLB algorithms activation. The number of successful HOs is almost unchanged when activating one of the MLB algorithm or when deactivating MLB schemes. This may be considered as a significant gain, since a MLB scheme promotes enabling more HOs in order to attenuate load disparity between cells. Then the implemented MLB algorithms seem to be able to find convenient trade-off between different investigated network key performance indicators (KPIs) since they improve global network throughput and PLR without strongly increasing the rate of HO signalling.

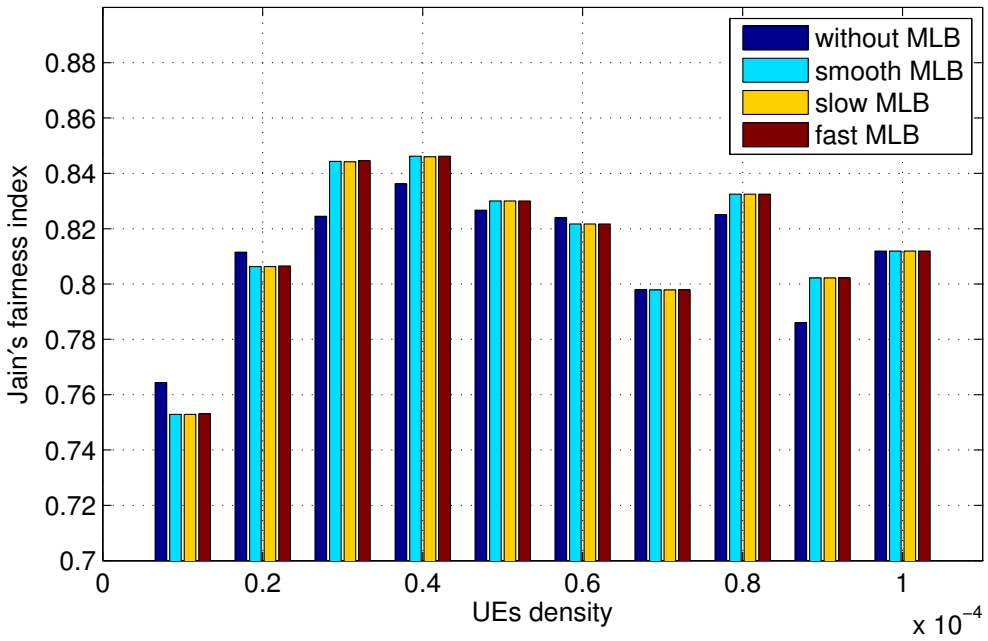

Figure 3.11: Jain's fairness index vs UEs density

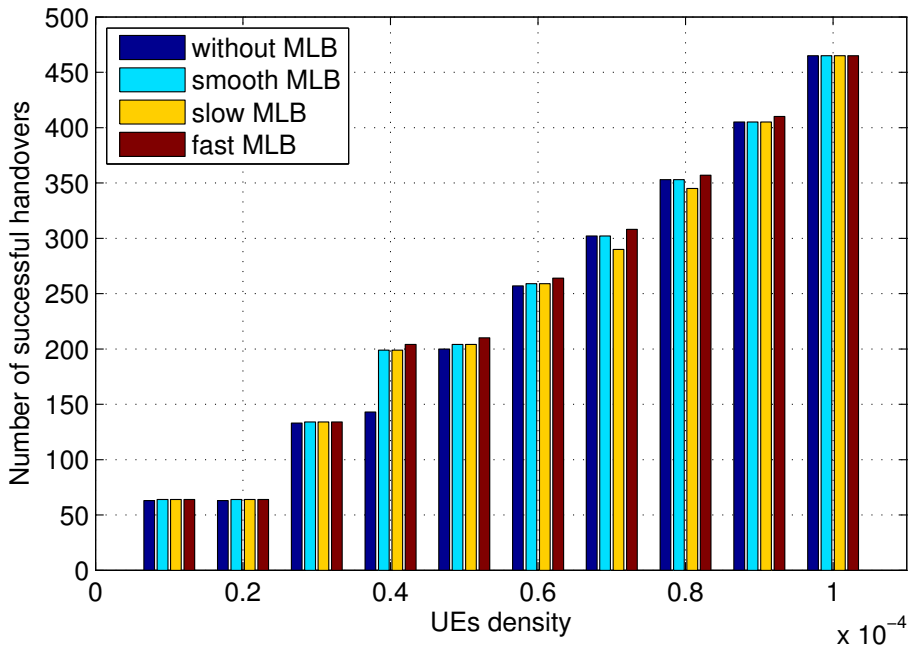

Figure 3.12: Number of successful HOs vs UEs density

3.8 Summary

This chapter has addressed the problem of MLB in the context 3GPP LTE SON HetNet. First, we implemented in ns-3 3GPP functionalities related to load management procedure of the X2AP protocol as specified in TS 136.423. Second, adaptive FHO based MLB algorithms were implemented to investigate the impact of such mechanisms on network performance in terms of network throughput, PLR, fairness and HO signalling.g HO overhead.

Conclusions

The growth of mobile cellular traffic in both rate density and peak rates has led to the migration of cellular network from homogeneous networks composed by carefully placed macro-cells, to HetNet containing overlapping tiers composed by cells differing in transmit power and backhaul capacities. Three primary alternatives to add capacity to HetNet exist: buying more spectrum, making that spectrum more efficient, and densifying the network. When dealing with network densification, SON functionalities and particularly LB techniques seem to be a key factor in realizing the potential capacity of such dense and diversified network. Load balancing is achieved by load aware cell association schemes, or by load aware adaptive HO schemes. For this latter the key objectives is to develop tractable models that capture heterogeneity in network infrastructure and characterize appropriate metrics that measure the end UE QoS. Tackling these two objectives and consequently developing a fundamental understanding of load balancing has been the principle goal of this dissertation. The main results of this dissertation are summarized below.

- We developed general and tractable K-tier stochastic HetNet model where each tier is modelled as a 2-D homogeneous PPP. The K independent tiers are differing in terms of deployment densities, transmit powers, available bandwidths and pathloss exponents. This model was used to provide cell association and HO probabilities. We investigated the impact of introducing two adaptive HO strategies (i.e. CHO and FHO adaptive strategies) on network performance in terms of rate coverage and HO probability. Based on the developed analysis, it was shown that tuning HO parameters (i.e. biasing factor for CHO and hysteresis threshold for FHO) leads to an enhancement in rate coverage. This enhancement is optimal for a given HO parameters configuration and is associated with HO signalling increasing (i.e. increasing in HO probability).

- We exploited results of FHO strategy to implement adaptive HO based LB algorithms under realistic network scenarios using discrete-event simulations of a two-tier LTE HetNet deployment. Numerical results show that enhancements provided by the proposed MLB schemes are closely dependent on network UEs density and are illustrated through different KPIs. These improvements concern particularly PLR reduction, JFI and network global throughput without HO overhead.

Acronyms

3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5GPPP	5G Public Private Partnership
ABS	Almost Blank Subframe
BRP	Biased Received Power
CAC	Composite Available Capacity
CAPEX	CAPital EXpenditure
CBR	Call Blocking Rate
CDR	Call Dropping Rate
CHO	Coarse grained HO
CoMP	Coordinated Multi-Point
CRE	Cell Range Extension
CSG	Closed Subscriber Group
DL	Downlink
DOE	Design Of Experiments
E-RAB	Evolved Radio Access Bearer

eICIC enhanced Inter-Cell Interference Coordination

EPs Elementary Procedures

FHO Fine grained HO

HetNet Heteregeneous Network

HFN Hyper Frame Number

HO Handover

JFI Jain's Fairness Index

KPI Key Performance Indicators

LB Load Balancing

LM Load Management

LTE Long Term Evolution

MGF Moment Generating Function

MIMO Multiple-Input Multiple-Output

MISO Multi-Input Single Output

MLB Mobility Load Balancing

MM Mobility Management

mmWave millimeter Wave

MPM Mobility Parameters Management

MRO Mobility Robustness Optimisation

OFDMA Orthogonal Frequency Division Multiple Access

OPEX OPerational EXpenditure

PDCP Packet Data Convergence Protocol

PDF Probability Density Function

PGFL Probability GEnerating FunctionaL

PLR Packet Loss Ratio

PPP Poisson Point Processes

QoE Quality of user Experience

QoS Quality of Service

RACH Random Access Channel

RAN Radio Access Network

RANC Radio Access Network Controller

RAT Radio Access Technology

RF Radio Frequency

RLF Radio Link Failure

RRC Radio Resource Control

RRM Radio Resource Management

RSRP Reference Signal Received Power

RSRQ Reference Signal Received Quality

RSSI Received Signal Strength Indicator

SAP Service Access Points

SCTP Stream Control Transmission Protocol

SINR Signal-to-Interference plus Noise Ratio

SN Sequence Number

SON Self Organizing Networks

TTT Time To Trigger

Tx power Transmission power

UE User Equipment

UL Uplink

VoLTE Voice over LTE

WiMAX Worldwide Interoperability for Microwave Access

X2AP X2-Application Protocol

Bibliography

[1] Heterogeneous networks, hetnets, let you mix and match for the best. https://networks.nokia.com/solutions/heterogeneous-networks. Accessed: 2017-11-03. 11, 31

[2] European Telecommunications Standards Institute. *Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN): Overall Description*, April 2010. 11, 32

[3] S Srikanth, PA Murugesa Pandian, and Xavier Fernando. Orthogonal frequency division multiple access in wimax and lte: a comparison. *IEEE Communications Magazine*, 50(9), 2012. 32

[4] Future of mobile technology: Voice over lte. `https://www.ericsson.com/mobility-report/future-of-mobile-technology-voice-over-lte`. Accessed: 2017-01-06. 32

[5] The 5g infrastructure public private partnership. `https://5g-ppp.eu/`. Accessed: 2017-01-06. 32

[6] European Telecommunications Standards Institute. *LTE; Feasibility study for Further Advancements for E-UTRA (LTE-Advanced)*, January 2010. 33

[7] Commscope definitions: What is network densification? http://www.commscope.com/Blog/CommScope-Definitions-What-Is-Network-Densification/. Accessed: 2017-11-03. 34

[8] Sujuan Feng and Eiko Seidel. Self-organizing networks (son) in 3gpp long term evolution. *Novel Mobile Radio Research*, 2008. 34

[9] European Telecommunications Standards Institute. *LTE; Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Self-configuring and self-optimizing network (SON) use cases and solutions*, May 2011. 34

[10] European Telecommunications Standards Institute. *LTE; Evolved universal terrestrial radio access network (E-UTRAN); X2 application protocol (X2AP)*, September 2014. 16, 36, 52, 88, 89, 97

[11] European Telecommunications Standards Institute. *LTE ; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification*, November 2012. 36, 89, 90, 91, 96

[12] Jeffrey G Andrews, Sarabjot Singh, Qiaoyang Ye, Xingqin Lin, and Harpreet S Dhillon. An overview of load balancing in hetnets: Old myths and open problems. *IEEE Wireless Communications*, 21(2):18–25, 2014. 39

[13] Ekram Hossain and Monowar Hasan. 5g cellular: key enabling technologies and research challenges. *IEEE Instrumentation & Measurement Magazine*, 18(3):11–21, 2015. 40

[14] Jeffrey G Andrews, Stefano Buzzi, Wan Choi, Stephen V Hanly, Angel Lozano, Anthony CK Soong, and Jianzhong Charlie Zhang. What will 5g be? *IEEE Journal on selected areas in communications*, 32(6):1065–1082, 2014. 40

[15] Amitabha Ghosh, Nitin Mangalvedhe, Rapeepat Ratasuk, Bishwarup Mondal, Mark Cudak, Eugene Visotsky, Timothy A Thomas, Jeffrey G Andrews, Ping Xia, Han Shin Jo, et al. Heterogeneous cellular networks: From theory to practice. *IEEE communications magazine*, 50(6), 2012. 40

[16] Jeffrey G Andrews. Seven ways that hetnets are a cellular paradigm shift. *IEEE Communications Magazine*, 51(3):136–144, 2013. 40

[17] Mugen Peng, Chonggang Wang, Jian Li, Hongyu Xiang, and Vincent Lau. Recent advances in underlay heterogeneous networks: Interference control, resource allocation, and self-organization. *IEEE Communications Surveys & Tutorials*, 17(2):700–729, 2015. 40

[18] Cheng-Xiang Wang, Fourat Haider, Xiqi Gao, Xiao-Hu You, Yang Yang, Dongfeng Yuan, Hadi Aggoune, Harald Haas, Simon Fletcher, and Erol Hepsaydir. Cellular architecture and key technologies for 5g wireless communication networks. *IEEE Communications Magazine*, 52(2):122–130, 2014. 9, 40, 41, 42

[19] Daquan Feng, Chenzi Jiang, Gubong Lim, Leonard J Cimini, Gang Feng, and Geoffrey Ye Li. A survey of energy-efficient wireless communications. *IEEE Communications Surveys & Tutorials*, 15(1):167–178, 2013. 8, 41

[20] Jaya B Rao and Abraham O Fapojuwo. A survey of energy efficient resource management techniques for multicell cellular networks. *IEEE Communications Surveys & Tutorials*, 16(1):154–180, 2014. 8, 41

[21] Binnan Zhuang, Dongning Guo, and Michael L Honig. Energy-efficient cell activation, user association, and spectrum allocation in heterogeneous networks. *IEEE Journal on Selected Areas in Communications*, 34(4):823–831, 2016. 8, 41, 42

[22] Chungang Yang, Jiandong Li, Alagan Anpalagan, and Mohsen Guizani. Joint power coordination for spectral-and-energy efficiency in heterogeneous small cell networks: A bargaining game-theoretic perspective. *IEEE Transactions on Wireless Communications*, 15(2):1364–1376, 2016. 8, 41, 42

[23] Rose Qingyang Hu and Yi Qian. An energy efficient and spectrum efficient wireless heterogeneous network framework for 5g systems. *IEEE Communications Magazine*, 52(5):94–101, 2014. 8, 41, 42

[24] Yong Sheng Soh, Tony QS Quek, Marios Kountouris, and Hyundong Shin. Energy efficient heterogeneous cellular networks. *IEEE Journal on Selected Areas in Communications*, 31(5):840–850, 2013. 8, 41, 42

[25] Muhammad Ismail and Weihua Zhuang. Network cooperation for energy saving in green radio communications. *IEEE Wireless Communications*, 18(5), 2011. 42, 48

[26] Afaz Uddin Ahmed, Mohammad Tariqul Islam, and Mahamod Ismail. A review on femtocell and its diverse interference mitigation techniques in heterogeneous network. *Wireless Personal Communications*, 78(1):85–106, 2014. 9, 42, 43

[27] Ekram Hossain, Mehdi Rasti, Hina Tabassum, and Amr Abdelnasser. Evolution toward 5g multi-tier cellular wireless networks: An interference management perspective. *IEEE Wireless Communications*, 21(3):118–127, 2014. 43, 44

[28] Haijun Zhang, Chunxiao Jiang, Julian Cheng, and Victor CM Leung. Cooperative interference mitigation and handover management for heterogeneous cloud small cell networks. *IEEE Wireless Communications*, 22(3):92–99, 2015. 9, 44

[29] Robert W Heath, Marios Kountouris, and Tianyang Bai. Modeling heterogeneous network interference using poisson point processes. *IEEE Transactions on Signal Processing*, 61(16):4114–4126, 2013. 9, 44

[30] Yongyu Dai, Shi Jin, Leyuan Pan, Xiqi Gao, Lei Jiang, and Ming Lei. Interference control based on beamforming coordination for heterogeneous network with rrh deployment. *IEEE Systems Journal*, 9(1):58–64, 2015. 9, 44

[31] Dantong Liu, Lifeng Wang, Yue Chen, Maged Elkashlan, Kai-Kit Wong, Robert Schober, and Lajos Hanzo. User association in 5g networks: A survey and an outlook. *IEEE Communications Surveys & Tutorials*, 18(2):1018–1044, 2016. 9, 44, 47

[32] Maryam Chinipardaz and Majid Noorhosseini. A study on cell association in heterogeneous networks with joint load balancing and interference management. *Telecommunication Systems*, pages 1–20, 2017. 47

[33] Wen-Hsing Kuo and Wanjiun Liao. Utility-based resource allocation in wireless networks. *IEEE Transactions on Wireless Communications*, 6(10), 2007. 47

[34] Sarabjot Singh, Harpreet S Dhillon, and Jeffrey G Andrews. Offloading in heterogeneous networks: Modeling, analysis, and design insights. *IEEE Transactions on Wireless Communications*, 12(5):2484–2497, 2013. 47, 48, 49, 56, 57, 74

[35] Tao Han and Nirwan Ansari. A traffic load balancing framework for software-defined radio access networks powered by hybrid energy sources. *IEEE/ACM Transactions on Networking (TON)*, 24(2):1038–1051, 2016. 47, 49, 50

[36] Tianqing Zhou. Joint user association and power control for load balancing in downlink heterogeneous cellular networks. *arXiv preprint arXiv:1607.00853*, 2016. 47, 48, 50

[37] Qiaoyang Ye, Beiyu Rong, Yudong Chen, Mazin Al-Shalash, Constantine Caramanis, and Jeffrey G Andrews. User association for load balancing in heterogeneous cellular networks. *IEEE Transactions on Wireless Communications*, 12(6):2706–2716, 2013. 47, 48, 50

[38] Mohd Shabbir Ali, Pierre Coucheney, and Marceau Coupechoux. Load balancing in heterogeneous networks based on distributed learning in near-potential games. *IEEE Transactions on Wireless Communications*, 15(7):5046–5059, 2016. 47, 49

[39] Salah Eddine Elayoubi, Eitan Altman, Majed Haddad, and Zwi Altman. A hybrid decision approach for the association problem in heterogeneous networks. In *INFOCOM, 2010 Proceedings IEEE*, pages 1–5. IEEE, 2010. 47, 48, 50

[40] Youjia Chen, Jun Li, Zihuai Lin, Guoqiang Mao, and Branka Vucetic. User association with unequal user priorities in heterogeneous cellular networks. *IEEE Transactions on Vehicular Technology*, 65(9):7374–7388, 2016. 47, 48, 50

[41] Kaiming Shen and Wei Yu. Distributed pricing-based user association for downlink heterogeneous cellular networks. *IEEE Journal on Selected Areas in Communications*, 32(6):1100–1113, 2014. 47, 48, 50

[42] Tiankui Zhang, Hongzhang Xu, Dantong Liu, Norman C Beaulieu, and Yutao Zhu. User association for energy-load tradeoffs in hetnets with renewable energy supply. *IEEE Communications Letters*, 19(12):2214–2217, 2015. 47, 49, 50

[43] Jaesung Park. Distributed association method assisted by cell for efficiency enhancement of wireless networks. *Mobile Information Systems*, 2017, 2017. 47, 49, 50

[44] Ho Huu Minh Tam, Hoang Duong Tuan, Duy Trong Ngo, Trung Q Duong, and H Vincent Poor. Joint load balancing and interference management for small-cell heterogeneous networks with limited backhaul capacity. *IEEE Transactions on Wireless Communications*, 16(2):872–884, 2017. 49

[45] Trung Kien Vu, Mehdi Bennis, Sumudu Samarakoon, Mérouane Debbah, and Matti Latva-aho. Joint load balancing and interference mitigation in 5g heterogeneous networks. *IEEE Transactions on Wireless Communications*, 16(9):6032–6046, 2017. 49, 51

[46] Chih-Cheng Tseng, Hwang-Cheng Wang, Kuo-Chang Ting, Chih-Chieh Wang, and Fang-Chang Kuo. Fast game-based handoff mechanism with load balancing for lte/lte-a heterogeneous networks. *Journal of Network and Computer Applications*, 85:106–115, 2017. 50, 51, 52

[47] Hongyan Du, Yiqing Zhou, Haihua Chen, Lin Tian, and Jinglin Shi. Load balance for centralized heterogeneous networks with limited fronthaul capacity. In *Communications and Information Technologies (ISCIT), 2016 16th International Symposium on*, pages 17–21. IEEE, 2016. 50

[48] Hyukmin Son, Sanghoon Lee, Soo-Chang Kim, and Yeon-Seung Shin. Soft load balancing over heterogeneous wireless networks. *IEEE Transactions on Vehicular Technology*, 57(4):2632–2638, 2008. 51, 52

[49] Jingya Li, Emil Björnson, Tommy Svensson, Thomas Eriksson, and Mérouane Debbah. Joint precoding and load balancing optimization for energy-efficient heterogeneous networks. *IEEE Transactions on Wireless Communications*, 14(10):5810–5822, 2015. 51, 52

[50] Martin Shubik. The dollar auction game: A paradox in noncooperative behavior and escalation. *Journal of Conflict Resolution*, 15(1):109–111, 1971. 51

[51] Fanqin Zhou, Lei Feng, Peng Yu, and Wenjing Li. Energy-efficiency driven load balancing strategy in lte-wifi interworking heterogeneous networks. In *Wireless Communications and Networking Conference Workshops (WCNCW), 2015 IEEE*, pages 276–281. IEEE, 2015. 51, 52

[52] Iana Siomina and Di Yuan. Load balancing in heterogeneous lte: Range optimization via cell offset and load-coupling characterization. In *Communications (ICC), 2012 IEEE International Conference on*, pages 1357–1361. IEEE, 2012. 51, 52

[53] Gaia Franceschini and Sandro Macchietto. Model-based design of experiments for parameter precision: State of the art. *Chemical Engineering Science*, 63(19):4846–4872, 2008. 52

[54] David Lopez-Perez and Holger Claussen. Duty cycles and load balancing in hetnets with eicic almost blank subframes. In *Personal, Indoor and Mobile Radio Communications (PIMRC Workshops), 2013 IEEE 24th International Symposium on*, pages 173–178. IEEE, 2013. 52

[55] Panagiotis Fotiadis, Michele Polignano, Daniela Laselva, Benny Vejlgaard, Preben Mogensen, Ralf Irmer, and Neil Scully. Multi-layer mobility load balancing in a heterogeneous lte network. In *Vehicular Technology Conference (VTC Fall), 2012 IEEE*, pages 1–5. IEEE, 2012. 52

[56] Abhijit Sarma, Sandip Chakraborty, and Sukumar Nandi. Deciding handover points based on context-aware load balancing in a wifi-wimax heterogeneous network environment. *IEEE Transactions on Vehicular Technology*, 65(1):348–357, 2016. 52

[57] Peng Tian, Hui Tian, Jianchi Zhu, Lan Chen, and Xiaoming She. An adaptive bias configuration strategy for range extension in lte-advanced heterogeneous networks. 2011. 52, 53

[58] B François and B Bartłomiej. Stochastic geometry and wireless networks. volume i. theory. *NoW PublishersBreda*, 2009. 55

[59] Than-Tung Vu, Laurent Decreusefond, and Philippe Martins. An analytical model for evaluating outage and handover probability of cellular wireless networks. *Wireless personal communications*, 74(4):1117–1127, 2014. 56

[60] Han-Shin Jo, Young Jin Sang, Ping Xia, and Jeffrey G Andrews. Heterogeneous cellular networks with flexible cell association: A comprehensive downlink sinr analysis. *IEEE Transactions on Wireless Communications*, 11(10):3484–3495, 2012. 12, 56, 57, 61, 62, 63

[61] Bartłomiej Błaszczyszyn and Holger Paul Keeler. Studying the sinr process of the typical user in poisson networks using its factorial moment measures. *IEEE Transactions on Information Theory*, 61(12):6774–6794, 2015. 56

[62] Abhishek K Gupta, Harpreet S Dhillon, Sriram Vishwanath, and Jeffrey G Andrews. Downlink multi-antenna heterogeneous cellular network with load balancing. *IEEE Transactions on Communications*, 62(11):4052–4067, 2014. 56, 57

[63] Sung Nok Chiu, Dietrich Stoyan, Wilfrid S Kendall, and Joseph Mecke. *Stochastic geometry and its applications*. John Wiley & Sons, 2013. 58

[64] Self-organizing networks. `http://www.3gpp.org/technologies/keywords-acronyms/105-son`. Accessed: 2017-1-04. 15, 87

[65] Self-organizing networks. `http://www.3gpp.org/technologies/keywords-acronyms/105-son`. Accessed: Dec. 2015. 88, 94

[66] Qi-Ping Yang, Jae-Woo Kim, and Tae-Hyong Kim. Mobility prediction and load balancing based adaptive handovers for lte systems. *International Journal on Computer Science and Engineering*, 4(4):638, 2012. 88, 89

[67] Network simulator 3. `https://www.nsnam.org/`. Accessed: 2017-05-07. 15, 88, 95, 100

[68] X2 interface function in lte a connection between two enodebs. http://www.teletopix.org/4g-lte/x2-interface-function-in-lte-a-connection-between-two-enodebs/. Accessed: December 2015. 89

[69] Christopher Cox. *An introduction to LTE: LTE, LTE-advanced, SAE and 4G mobile communications*. John Wiley & Sons, 2012. 91

[70] Alcatel-lucent. *The LTE Network Architecture: A comprehensive tutorial*, 2013. 15, 93, 94

[71] Nicola Baldo, Manuel Requena-Esteso, Marco Miozzo, and Raymond Kwan. An open source model for the simulation of lte handover scenarios and algorithms in ns-3.

In *Proceedings of the 16th ACM international conference on Modeling, analysis & simulation of wireless and mobile systems*, pages 289–298. ACM, 2013. 16, 95

[72] Hana Jouini, Mohamed Escheikh, Kamel Barkaoui, and Tahar Ezzedine. Mobility load balancing based adaptive handover in downlink lte self-organizing. 16, 96, 98

[73] picoChip Designs Alcatel-Lucent and Vodafone. *Simulation assumptions and parameters for FDD HeNB RF requirements*, May 2009. 100

appendices

3.9 Appendix

X2AP implemented procedures:

- LteEnbRrc::DoSendResourceStatusRequest(): An overloaded cell executes this function to interrogate neighbouring cells about their load conditions.
- LteEnbRrc::DoRecvResourceStatusRequest(): This function is executed when a cell receives a RESOURCE STATUS REQUEST message.
- LteEnbRrc::DoSendResourceStatusResponse(): A cell that receives a RESOURCE STATUS REQUEST message will execute this method to send an acknowledgement to its neighbour.
- LteEnbRrc::DoRecvResourceStatusResponse(): This function is executed when a cell receives a RESOURCE STATUS RESPONSE message.
- LteEnbRrc::DoSendResourceStatusUpdate(): A cell calculates its CACD and executes this function to send it to a neighbouring cell.
- LteEnbRrc::DoRecvResourceStatusUpdate(): This function is executed when a cell receives a RESOURCE STATUS UPDATE message.

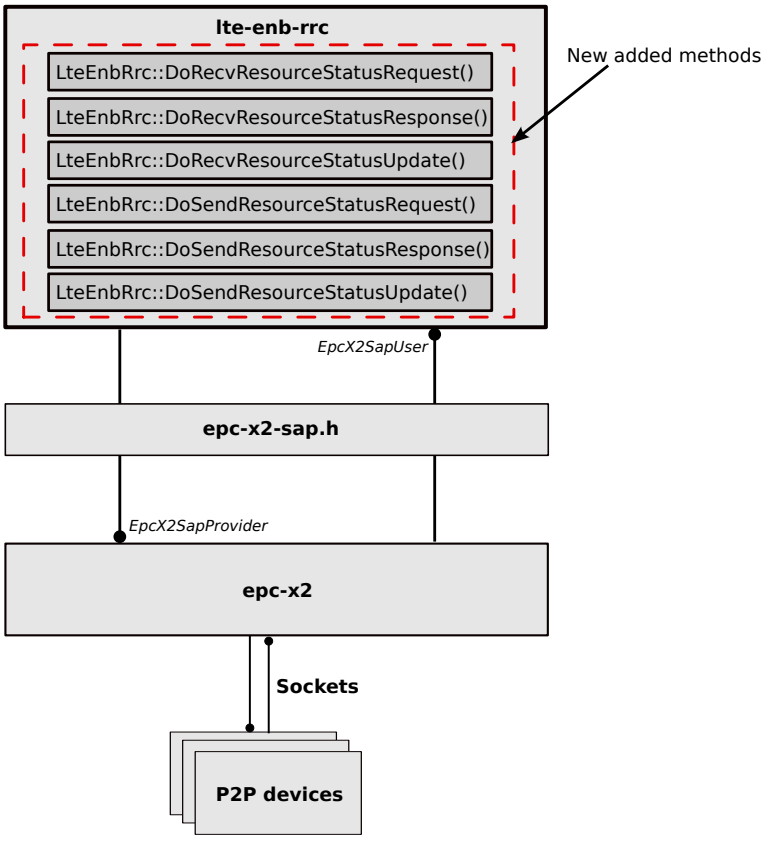

Figure 3.13: X2AP added procedures

Hana JOUINI

Radio Resource Management in LTE Networks: Load Balancing in Heterogeneous Cellular Networks

Abstract :
This dissertation aims to develop tractable frameworks to model and analyze load balancing (LB) dynamics while incorporating the heterogeneous nature of cellular networks. In this context we investigate and analyze a class of LB strategies, namely adaptive handover (HO) based LB strategies. These latter were firstly studied under the general heading of stochastic networks using independent and homogeneous Poisson point processes based network model. We propose a baseline model to characterize rate coverage and HO signalling in K-tier HetNet with a general maximum power based cell association and adaptive HO strategies. Tiers differ in terms of deployment density and cells characteristics (i.e. transmit power, bandwidth, and path loss exponent). One of the main outcomes is demonstrating the impact of offloading traffic from macro- to small-tier. This impact was studied in terms of rate coverage and HO signalling. Results show that enhancement in rate coverage is penalized by HO signalling overhead. Then appropriate algorithms of LB based adaptive HO are designed and their performance is evaluated by means of extensive system level simulations. These latter are conducted in 3GPP defined scenarios, including representation of mobility procedures in both connected state. Simulation results show that the proposed LB algorithms ensure performance enhancement in terms of network throughput, packet loss ratio, fairness and HO signalling.
Keywords :
HetNet, LTE, Radio resource management, Load balancing, Stochastic geometry, Poisson point process.

Résumé :
L'intégration dans les réseaux hétérogènes (HetNet) de fonctionnalités d'auto-configuration automatisant et simplifiant l'exploitation des réseaux deviennent une demande forte des opérateurs. Cette thèse a pour objectif l'étude et le développement de solutions de gestion dynamique de l'équilibrage de charges entre les différentes couches composant un même HetNet, pour une expérience utilisateur (QoE) améliorée. Dans ce contexte, une classe des algorithmes d'équilibrage de charges dite 'équilibrage de charges par adaptation dynamique des paramètres de la procédure de HO' est étudiée. Pour commencer, nous développons un modèle théorique basé sur des solutions et des outils de la géométrie stochastique et incorporant le caractère hétérogène des réseaux cellulaires. Ensuite nous exploitons ce modèle pour introduire des algorithmes d'adaptation des paramètres de HO basés sur la maximisation de la puissance reçue et du rapport signal/brouillage plus bruit (SINR). Nous exploitons ces résultats pour implémenter et étudier, par simulation à évènements discrets, des algorithmes d'équilibrage de charges dans le contexte des réseaux LTE HetNet auto-organisés basés sur les spécifications 3GPP. Ces travaux soulignent l'importance de l'équilibrage de charges afin de booster les performances des réseaux cellulaires en termes de débit global transmis, perte de paquets de données et utilisation optimisée des ressources radio.
Mots clés :
HetNet, LTE, Radio resource management, Load balancing, Stochastic geometry, Poisson point process.