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Optimisation of Radio Techniques and Deployments for Energy Efficient Networks

Luis Alberto Suarez Rivera

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Ecole Doctorale – MATISSE

Optimisation des Techniques et Déploiements Radio pour les Réseaux Efficaces en Energie

(Optimisation of Radio Techniques and Deployments for Energy-Efficient Networks)

Thèse de Doctorat

Mention : Informatique

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Abstract

The objective of this thesis document is to contribute into the set of techniques for energy efficiency in mobile networks, the often so-called Green Radio mechanisms. The work has been done taking as reference framework the current and future trends in mobile and cellular technologies as 3G/W-CDMA, LTE and LTE-Advanced. This has permitted us to classify these methods in a coherent classification framework, as well as establishing the different advantages, drawbacks of each one these techniques and also have an idea of how those approaches could work together by means of integration. Into the set of techniques, we have different mechanisms that work at different scales and abstraction levels: the Base Station (BS) component enhancement approach, the Cognitive Radio (CR), the transmission link level improvements, the Radio Resource Management (RRM) optimisation and at the top level we have the cell layout adaptation mechanisms where we find the heterogeneous network approaches, as well as the switching-off & cell breathing mechanisms. We decide in this thesis, after the previous studies done on the green radio techniques, to contribute specifically on this already discussed top-layer given the important global network savings that could be obtained from this level.

First, we start by concentrating our efforts on the Radio Access Network (RAN) energy consumption problem. In order to have an energy efficient network, we propose a BS distributed and clustered cell-breathing technique that provides a self-organized BS switching-off and network adaptation mechanism that avoids the use of a centralised server and their associated single-point failure issues. Then, we try then to take into account in such an approach, the Mobile Station (MS) side and its individual transmitting power. Due to the increase of cell sizes as consequence of cell breathing, the uplink transmitted power noticeably increases with undesirable consequences as an associated electromagnetic radiation increase and a reduced battery lifetime. Here, we propose means to regulate the cell-breathing behaviour in order to find a trade-off between MS transmission power vs. RAN power consumption.

Afterwards, we enhance the already discussed proposal done in cell-breathing by combining it with a heterogeneous network approach, specifically a Macro/femto-layer network. The proposed approach increases the capabilities of BS switching-off at the Macro-layer by including also the possibility of having a macro-to-femto offloading. In the studied scenario, the potential issue of access blocking due to Closed Subscriber Group (3GPP CSG)[1] access polices is taken into account. Also at this level we study other issues as the mechanisms to handle coverage holes as consequence of relying on

small access devices with non-overlapped cells,(i.e. in our specific case, the femto-layer).

Later on in our discussion, the electromagnetic issues associated to the cell-breathing are studied. Here, we see how the cell size expansion in cell breathing and its associated transmission power increase, could potentially violate the electric field acceptable exposure limits established by ICNIRP [2] as well as the national limits established in some European countries. In our study we also include the cell breathing combined with a macro/femto network and we analyse how such a strategy could reduce the associated electromagnetic radiation originated from the RAN downlink transmission.

Finally, we propose a more general BS offloading and switching-off technique based on a multi-metric decision-making approach. This approach is intended to tackle the issues on networks composed by devices with very heterogeneous characteristics, i.e. different energy sources, different power consumption regimes, different coverage ranges and different level of available resources. In such sense we propose a set of metrics that permits to select the best BSs that receive the offloaded traffic. The study here finishes by giving some directions on how this approach could be enhanced by a learning strategy.

Résumé

Contexte Générale

Le secteur des télécommunications a progressé à un rythme vertigineux. Au jour d'aujourd'hui, les utilisateurs sont en mesure d'utiliser une vaste gamme de services grâce à des technologies telles que l'Internet, le multimédia et les derniers dispositifs de communications sans fil, ce qui permet d'avoir dans un même appareil des capacités de calcul énormes avec un accès presque illimité aux contenus et les informations provenant du world wide web. Ces tendances de progrès dans le secteur mobile arrivent, cependant, avec une croissance exponentielle du trafic qui ajoute de nouveaux défis pour le monde des télécommunications sans fil dans les années à venir. Cela implique de grands investissements à niveau d'infrastructure ainsi qu'une augmentation des coûts de opération. Ces coûts seront influencés par un élément important qui vient ici pour jouer un rôle: l'augmentation de la consommation d'énergie du réseau mobile. Pour donner quelques exemples aux Etats-Unis, le marché résidentiel des TICs (Technologies de l'information et de la communication) utilisa 1% (42 TW-h) de l'énergie totale produite en 2005 [3][4]; Telecom Italia en 2005 consomma environ 2TW-h correspondant à 1% de la production totale d'énergie [4][5][6]; également un chiffre similaire de 2TW-h à été consommé par France Télécom en 2006 correspondante à 0.4% de la production d'énergie du pays [5][6].

Dans les réseaux mobiles, ces augmentations de consommation d'énergie sont surtout remarquables dans la partie du réseau d'accès, dû au fait que plus de la moitié de la consommation vient de cette section réseau [7]. Deux raisons principales expliquent cette importante proportion de la consommation d'énergie dans cette section du réseau: tout d'abord, l'inefficacité des composants internes de la station de base, surtout, la section d'amplificateur de puissance (PA) qui consomme environ un 60-70% de l'énergie totale consommée par le BS [8] qui est d'ailleurs accompagné par la nécessité d'avoir des composants de réfrigération continument actifs pour refroidir le système en raison de la chaleur résultant dissipée. Par ailleurs, en raison des fluctuations continues de trafic, à niveau temporel et géographique, il existe une utilisation inefficace des systèmes de stations de base, ayant partout la totalité de l'infrastructure de radio active de façon continue. Il est mentionné en [6] que pour un déploiement cellulaire typique, autour d'un 10% des stations de base s'occupent d'environ 50% du trafic sur le réseau, pendant qu'environ de la moitié des stations de base se chargent de seulement 5% du trafic.

Cependant, il n'y a pas seulement des enjeux économiques autour de l'énergie. Il existe une véritable préoccupation environnementale basée sur les limites des ressources énergétiques et les émissions de CO_2 associées. Communément ici, la littérature dans ce domaine cite souvent le chiffre fourni par Gartner [9] du 2% contribution du secteur des TICs, ce qui correspond à 0.53Gtonnes de CO_2 . D'ailleurs, comme indiqué par le rapport SMART 2020 [10], le chiffre sera approximativement 3 fois plus élevé pour 2020 (1.43Gtonnes de CO_2). Spécifiquement pour le secteur mobile, ce même rapport présente que pour 2002, les émissions de CO_2 étaient autour de 66Mtonnes de CO_2 et les prévisions affirment que ce chiffre montera à 179Mtonnes de CO_2 d'ici à 2020. Les données estimées dans [11] sont encore plus pessimistes en disant que pour 2007, les émissions étaient de l'ordre de 86Mtonnes de CO_2 pour le secteur mobile, la prévision pour 2012 correspondait à un chiffre de 150 Mtonnes de CO_2 et environ 235 Mtonnes de CO_2 pour le 2020. Plus récemment, le rapport GESI SMARTer 2020 [12] fournit des nouvelles perspectives sur les chiffres d'émissions et les moyens potentiels pour obtenir des réductions. Malgré des réductions de CO_2 sont possibles, le défi se pose encore à nous.

Par ailleurs, en considérant le côté des terminaux mobiles, un utilisateur voudrait une longue autonomie de sa batterie sans perdre de la performance des applications et des services mobiles. Additionnellement, il existe aussi une préoccupation de la communauté internationale de prévenir les préjudices potentiels dus aux niveaux d'émissions électromagnétiques associés à la transmission d'un terminal mobile. Selon [13] pour 3 milliards d'abonnés, l'énergie totale est de 2TW-h par an (correspondante à 2% de l'énergie consommée pour faire fonctionner les réseaux mobiles à travers le monde), ce qui correspond à une puissance moyenne consommée par abonné de approximativement 0.1W. Ces chiffres sont précédentes à 2009, un moment où smartphones n'étaient pas à la mode comme ils le sont maintenant. Selon [11], qui compte avec des sources mises à jour, un dispositif mobile conventionnel consomme chaque année 2kW-h, ce qui rend une puissance moyenne de 0.23 watts. Aussi la même référence mentionne que dans le cas d'un smartphone, l'énergie pourrait atteindre jusqu'à 7 kW-h par an et une puissance moyenne de 0.8 Watts. Selon les dernières données fournies par l'UIT, le nombre d'abonnements actifs a atteint presque les 6 milliards en 2011 [14] et selon IDC environ 16% de ces souscriptions sont des smartphones [15]. Donc, en faisant quelques calculs de la consommation mondiale d'énergie de dispositifs mobiles, nous estimons une nouvelle chiffre de 16,8 TWh par an, quelque chose qui est de loin supérieur au chiffre souvent cité de 2TW-h [13][16].

Pour toutes les raisons décrites, afin de réduire la consommation d'énergie associée et les émissions de CO_2 associées aux secteurs des télécommunications, et plus partic-

ulièrement dans le secteur mobile, des efforts conjoints dans le monde entier essayent de faire face à la problématique. Ces efforts sont le fruit d'alliances de collaboration composées par des organismes gouvernementaux, des instituts de recherche, des universités et des opérateurs de télécommunications afin de résoudre ce problème. Toutes ces initiatives de projets, en cours d'exécution, ou déjà terminés, ont travaillé ou travaillent actuellement à attaquer le problème de l'efficacité énergétique de plusieurs approches différentes regroupées dans ce que la littérature appelle la Green Radio. Les voies de solution proposées démarrent des niveaux les plus bas, les améliorations des composants de la station de base, la couche hardware, en passant par des techniques plus orientées vers l'optimisation des ressources comme la radio cognitive (CR), l'Energy-Aware Radio Resource Management (EA-RRM) et l'amélioration des approches au niveau liaison de transmission, jusqu'à atteindre des techniques de couche supérieure, c'est à dire, le niveau d'adaptation de la topologie cellulaire, où l'architecture active du réseau mobile est adaptée aux besoins dynamiques du trafic afin de générer des économies globales d'énergie, par exemple, les techniques de respiration et désactivation de cellules, les réseaux hétérogènes et les approches associées au relayage.

Description des Travaux

L'objectif de ce document de thèse est de contribuer à l'ensemble de techniques d'économie d'énergie dans les réseaux mobiles, et les bien connus mécanismes en Green Radio. Le travail effectué a été fait en prenant pour cadre de référence les tendances actuelles et futures pour des technologies mobiles cellulaires comme 3G/W-CDMA et LTE. Cela nous a permis de les classer dans un cadre cohérent de classification, ainsi que d'établir les différents avantages, désavantages de chacune de ces techniques et aussi d'avoir une idée de la façon dont ces approches pourraient travailler ensemble et les voies potentielles d'intégration. Nous avons décidé dans cette thèse, après de nos études menées sur les techniques de Green Radio, de contribuer spécifiquement sur la couche d'adaptation de topologie réseau où nous pouvons atteindre des économies à niveau global.

Tout d'abord, nous commençons pour concentrer nos efforts sur la consommation énergétique du réseau d'accès. Pour donner un moyen de solution, nous proposons une technique de respiration cellulaire avec intelligence distribuée et architecture basée en clusters. Ce type de mécanisme a été conçu comme une stratégie d'adaptation du réseau qui évite l'utilisation d'un serveur centralisé et les potentiels problèmes de dépendance de fonctionnement sur ce noeud spécifique. Ensuite, nous essayons alors de prendre en compte dans une telle approche, la station mobile et sa puissance d'émission individu-

elle. A cause de l'augmentation de la taille des cellules en tant que conséquence de la respiration cellulaire, les voies montantes et descendantes augmentent sensiblement la puissance de transmission avec des conséquences indésirables comme une durée de vie réduite de la batterie du dispositif et une augmentation des rayonnements électromagnétiques associés. Ici, nous proposons des moyens pour contrôler le comportement de la respiration de cellules afin de trouver un balance entre la puissance de transmission du terminal mobile vs. la consommation d'énergie du réseau mobile.

Ensuite, nous améliorons la proposition de respiration cellulaire déjà discutée en combinant avec une approche de réseau hétérogène, plus précisément un réseau Macro/femto. L'approche proposée augmente le capacité de éteinte de stations de base au niveau de la couche macro avec l'utilisation de la couche femto pour effectuer un niveau additionnel de déchargement. Dans le scénario étudié le problème potentiel de blocage d'accès en raison des politiques d'accès pour Closed Subscriber Groups (3GPP CSG) [1] est prise en compte. Aussi à ce niveau, nous étudions d'autres questions telles que les mécanismes pour gérer les trous de couverture comme conséquence de se supporter sur des dispositifs d'accès de courte couverture comme c'est le cas des femtocellules.

Plus tard dans la discussion, les questions électromagnétiques associées à la respiration cellulaire sont étudiés. Ici, nous voyons comment l'expansion de la taille des cellules dans la respiration cellulaire et l'augmentation de sa puissance d'émission associée, pourraient violer les limites acceptables d'exposition aux champs électriques établies par l'ICNIRP [2], ainsi que les propres limites établies dans certains pays Européens. Dans notre étude, nous incluons aussi la respiration cellulaire combinée avec un réseau macro/ femto et nous analysons comment une telle stratégie pourrait réduire le rayonnement associé à la transmission en voie descendante.

Finalement, nous proposons une technique plus générale de déchargement et extinction de stations de base sur une approche multi-métrique de prise de décisions. Cette approche vise à être utilisé en réseaux constitués par des dispositifs présentant des caractéristiques très hétérogènes, comme par exemple, des différentes sources d'énergie, des régimes de consommation, ainsi que des différentes portées de couverture et niveau de ressources disponibles. Dans ce sens, nous proposons un ensemble de paramètres qui permet de sélectionner la meilleure station de base pour recevoir le trafic redistribué. L'étude ici finit par donner quelques indications sur la façon comme cette approche pourrait être renforcée par une stratégie d'apprentissage.

Organisation du Manuscrit

Ce document de thèse a été organisé en sept chapitres. Le chapitre 1: “L’introduction”, commence par fournir un bref aperçu du panorama actuel des réseaux mobiles en termes de consommation d’énergie globale et des émissions de CO_2 , exprimant aussi la nécessité de travailler sur les approches existantes dans le Green Radio pour faire face au challenge environnemental et technique. Ce chapitre décrit et présente également des autres éléments importants pour la compréhension du travail effectué dans cette thèse comme les objectifs définis de notre projet, la nouveauté de ce travail et sa contribution, ainsi que la description de la méthodologie suivie .

Ensuite, chapitre 2: “Approches efficaces en énergie pour les réseaux mobiles”, offre un panorama général des approches de état de l’art en efficacité énergétique actuelles, les projets à travers le monde et initiatives sur les réseaux Green et finalise en justifiant notre axe scientifique et l’approche de notre contribution sur le Green Radio. Ce chapitre fournit également un modèle de classification général des différentes approches à haute efficacité énergétique, ce qui permet d’établir le potentiel d’intégration des approches, ainsi que, permet de simplifier le panorama de la littérature en Green Radio.

Dans le chapitre 3: “Un algorithme distribue et clustérisé de respiration de cellules”, nous présentons le Distributed BS based Cell Breathing (DBCB) [17] et le Mobile Aware Distributed BS based Cell Breathing (MA- DBCB) [18], en fournissant une discussion sur les avantages de ces deux algorithmes, qui sont principalement l’architecture clustérisée et de l’intelligence distribuée combiné avec les moyens de réguler l’impact de la respiration cellulaire sur la performance du terminal mobile.

Après, dans le chapitre 4: “La respiration cellulaire améliorée par une approche d’architecture du réseau Hétérogène”, notre discussion va au-delà en présentant une technique de déchargement macro vers femto combinée avec la respiration de cellules. Ce chapitre analyse les performances de déchargement Macro vers femto et respiration de cellules et en comparant avec notre nouvelle proposition. Le scénario de réseau hétérogène est étudié en prenant en plus en compte l’impact de l’utilisation de politiques de controle d’accès pour les 3GPP CSGs.

Le Chapitre 5: “Compatibilité électromagnétique pour la respiration de cellules et les approches combinées avec réseaux hétérogènes” analyse des techniques précédemment étudiées dans le chapitre 4 selon le critère de la conformité électromagnétique, en tenant compte l’augmentation des rayonnements associées aux émissions du réseau d’accès, un phénomène qui pourrait être sensiblement réduit par l’introduction d’une couche d’accès femtocellulaire.

Le Chapitre 6: “Un Algorithme d’extinction de Stations de Base basé sur une approche Multi-métrique pour des environnements réseaux très hétérogènes”, ferme nos contributions effectuées au cours du projet de thèse en présentant un algorithme d’extinction de stations de base appliqué en réseaux avec des caractéristiques très différentes pour le déploiement de dispositifs dans le réseau d’accès. Dans ce chapitre, nous introduisons de possibles travaux futurs avec des perspectives envisageant l’utilisation de stratégies d’apprentissage associées à la Radio Cognitive.

Finalement, le chapitre 7: “Conclusions finales de la thèse”, ferme le document en fournissant des conclusions obtenues à partir de ces travaux, ainsi que les perspectives et les travaux futurs à faire comme une continuation de cet axe de recherche.

List of Acronyms

- 3GPP - 3rd Generation Partnership Project.
- AEE - Area Energy Efficiency.
- BS - Base Station.
- CAPEX - Capital Expenditure.
- CB - Component Baseline layer.
- CCZ - Centralized Cell Zooming.
- CDMA - Code Division Multiple Access.
- CENELEC - European Committee for Electrotechnical Standardization.
- CET - Coverage Extension Technique.
- CLA - Cell Layout Adaptation Layer.
- CoMP - Coordinated Multipoint Transmission
- CR - Cognitive Radio.
- CSG - Closed Subscriber Group.
- CSS - Cell Size Shaping Sublayer.
- DAS - Distributed Antenna System.
- DBCBCB - Distributed BS Based Cell Breathing.
- DCZ - Distributed Cell Zooming.
- DUT - Device Under Test.
- EA-RRM - Energy Aware Radio Resource Management.
- ECG - Energy Consumption Gain.
- ECR - Energy Consumption Rating.
- EE-RRM-OT - Energy Efficient Radio Resource Management and Optimal Transmission layer.
- EL-IE - Environment Learning & Information Exchange layer.
- EM - Electromagnetic.
- FEC/ARQ - Forward Error Correction/Automatic Repeat Request.
- femto-DBCBCB - Macro-to-femto Offloading & Distributed Macro-BS Based Cell Breathing.
- GHG - Green-House Gas.
- HARQ - Hybrid ARQ.
- HHEA-DBCBCB - Highly Heterogeneous Environment Aware Distributed BS Based Cell Breathing.
- ICNIRP - International Commission on Non-Ionizing Radiation Protection.
- ICT - Information and Communications Technologies.
- IFA - Iterative Femto Activation.
- IMPEX - Implementation Expenditure.

LTE - Long Term Evolution.

MA-DCB - Mobile Aware Distributed BS Based Cell Breathing.

MIMO - Multiple Input / Multiple Output.

MIPS - Million of Instructions per Second.

MFLOPS - Million of Floating Point Operations per Second.

MS - Mobile Station.

OFDMA - Orthogonal Frequency Division Multiple Access.

OPEX - Operational Expenditure.

PA - Power Amplifier.

PAPR - Peak to Average Power Ratio.

PCB - Proto-cooperative Cell Breathing.

RAN - Radio Access Network.

RRM - Radio Resource Management.

SDR - Software Defined Radio.

SMPA - Switched Mode Amplifier.

SoC - System on Chip.

SSOCB - Sequential Switch-Off Cell Breathing.

TEG - Thermoelectric Generator.

UAA - User Aware Activity.

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1.1 General Background

In recent years, the telecommunications sector has advanced at a vertiginous pace. Nowadays, the users are able to use a vast range of services thanks to technologies such as the Internet, the multimedia and the latest wireless communication standards and devices, which permits to have in a single mobile device, huge computing capabilities with an almost unlimited access to the useful contents and information coming from the world wide web. These trends of advance in the mobile sector come along, however, with an exponential growth of traffic which carry together some tough challenges for the world of telecommunications in the years to come. According to [19], since year 2006 the data rate of traffic in the mobile sector has grown nearly a 400%. Such an increase of the traffic levels year-by-year bring as consequence an increased need of network capacity and, along with that, the necessary network infrastructure to support it. This implies larger money investments from the operators to provide such an infrastructure as well as the associated operation costs also increase (i.e. Operational Expenditure (OPEX)). These costs are influenced by an important element that enters here to play a role: The increase of the mobile network energy consumption.

Some operator's energy consumption figures are presented here. In USA the residential ICT market required 1% (42 TW-h) of the total energy produced in 2005 [3][4]; Telecom Italia during 2005 consumed around 2TW-h corresponding to 1% of total Italian energy production [4][5][6]; Also a similar figure of 2TW-h was consumed by France Telecom in 2006 corresponding to 0.4% of the energy production of the whole country[5][6]. Specifically, for mobile networks the literature give us figures of how the energy consumption is distributed throughout the different sections of the network. According to [7] approximately 57% of the consumption comes from the Radio Access Network (RAN) as seen in Fig. 1.1. Two main reason explains this large percentage of energy consumption from this network section: Firstly, the inefficiency of internal BS components, above all, the Power Amplifier (PA) section that consumes around a

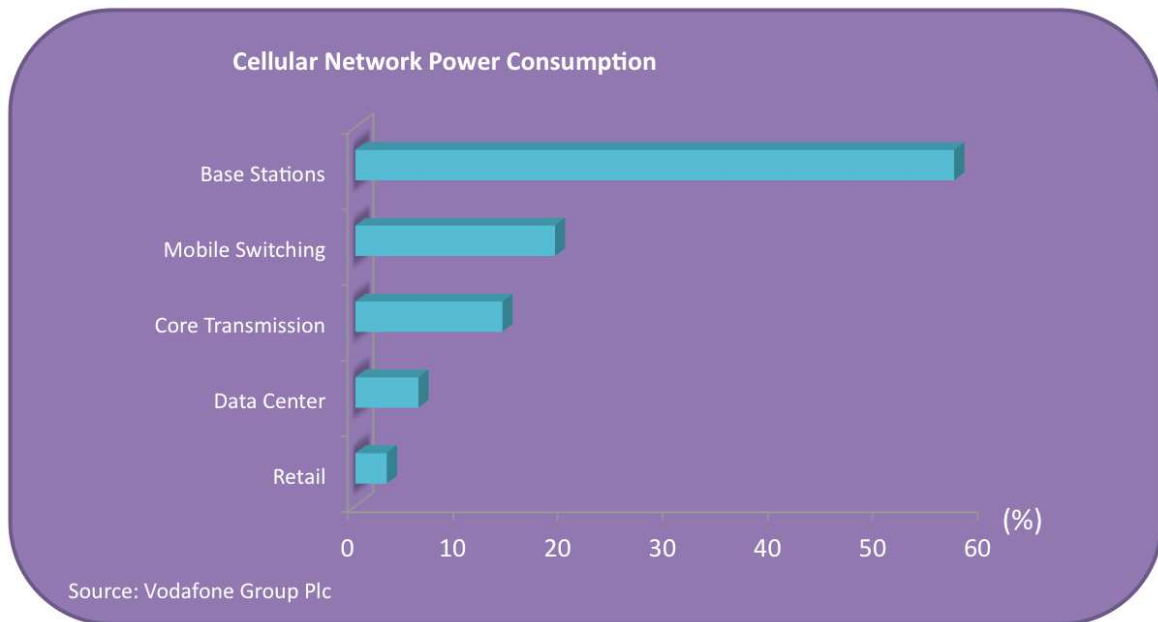


Figure 1.1 – Power consumption percentages for each one of the network sections in a cellular network infrastructure. Source: Vodafone GroupPlc,[7].

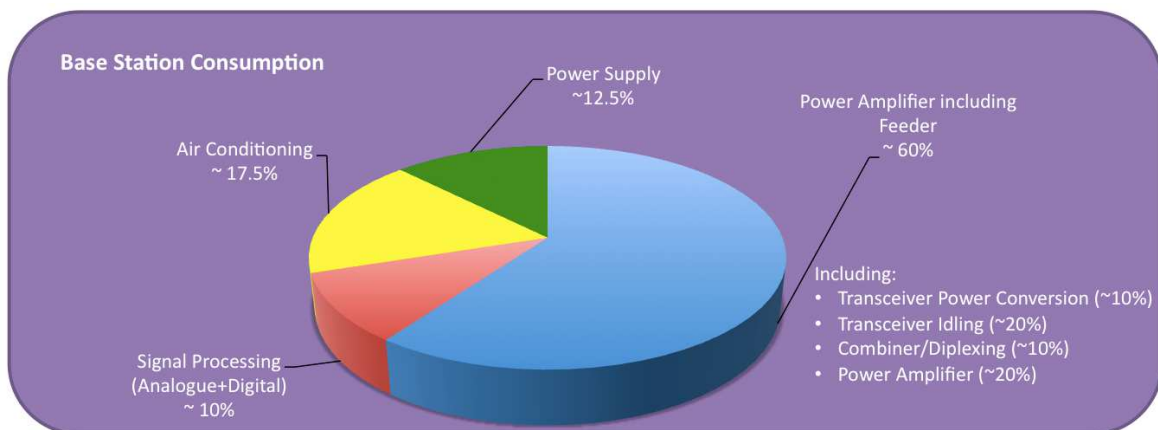


Figure 1.2 – Estimated BS energy consumption for each component section. Synthesis of models from: [7, 20, 21, 22].

60-70 % of the total energy consumed by the BS [8], additionally accompanied by the associated need of having the cooling components kept on running to refrigerate the system due to the resulting heat dissipated (see Fig. 1.2). Second, due to the continuous fluctuations of traffic, temporally and geographically speaking as seen in Fig. 1.3, it exists an inefficient usage of the BS systems, when having everywhere the whole radio infrastructure continuously active. About this discussed issue, it is mentioned in [6] that for typical cellular deployment, around a 10% of the BSs handle approximately a 50% of the network traffic, whereas around a half of the BSs deployed are taking care of only a 5% of the traffic.

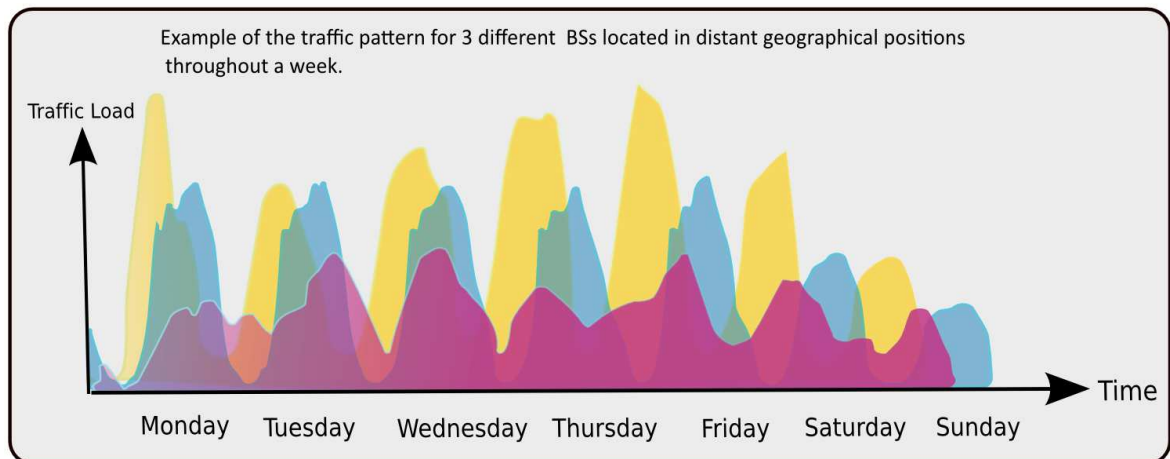


Figure 1.3 – A drawing example of three BSs geographically located in distant positions with different traffic load patterns throughout the week

However, there is more behind of the economic issues around the energy. There exist a genuine environmental preoccupation based on the limitations of the energy resources and the associated carbon-footprint emissions. Commonly here, the literature in this domain often cites the figure provided by Gartner [9] of 2% contribution from the ICT sector to the Green-House Gas (GHG) emissions, which corresponds to 0.53GTons of CO₂. Moreover, as stated by the SMART 2020 report [10], the figure will be about 3 times higher by 2020 (1.43GTons of CO₂). Specifically for the mobile sector (see Fig. 1.4), the same report presents that for 2002 the CO₂ emissions were around 66 MTons of CO₂ and the forecast shows that such a figure will rise up 179 MTons CO₂ by 2020. The data estimated in [11] are even more pessimistic by saying that for 2007 the emissions were around 86 MTons of CO₂ for the mobile sector, forecasting for 2012 a figure of 150 MTons CO₂ and around 235 MTons CO₂ for 2020. More recently, the up-to-date report GESI SMARTer 2020 [12] provides new perspectives on the ICT GHG emissions figures and the potential ways for abatement. Despite the CO₂ reductions are possible the challenge stands still in front of us.

On the other hand for the mobile phone, according to ETSI the MS side corresponds to 2% of the global mobile network energy consumption [16]. Looking at this figure, it can drive us to underestimate the importance of the functioning regime of a MS device. However, there are two basic reasons for being concerned of it. First of all, a mobile user wants long time battery autonomy without losing the performance on applications and mobiles services. Secondly, it is a preoccupation of the international community to prevent the potential harms of high electromagnetic emissions levels associated to the mobile device transmission. We also think this figure of 2% should be revised. According to reference [13] for a number of 3 billion of subscribers the total energy

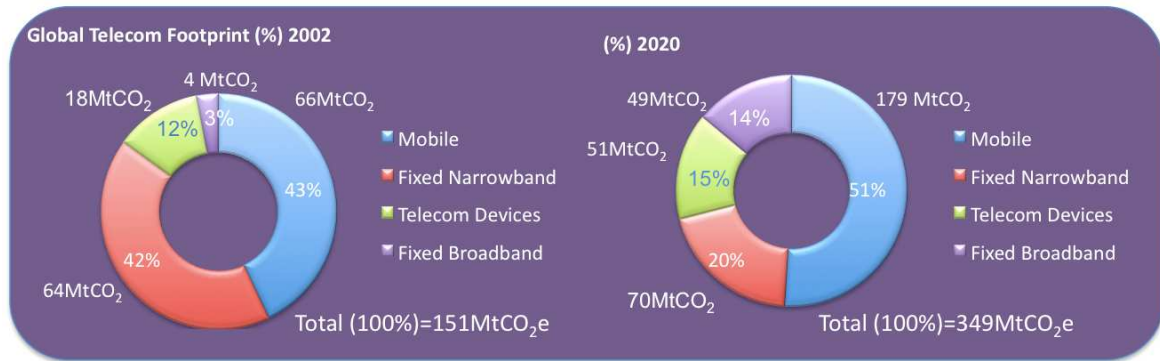


Figure 1.4 – Percentage of the carbon footprint contribution from Telecommunications industry. Values the year 2002 (left) and forecast values for the year 2020 (right). Source:[10].

is 2TW-h per year (i.e. 2% of the energy consumed for running the mobile networks worldwide), which corresponds to an average consumed power per subscriber of around 0.1 W. Those figures are previous to 2009, a moment where smartphones were not in fashion as they are right now. According to [11], that counts with updated sources, a regular mobile device consumes each year 2kW-h, which makes an average power of 0.23 W. Also the same reference mentions that in the case of a smartphone the energy could reach up to 7kW-h per year and an average power of 0.8 W. According to recent data provided by the ITU the number of active subscriptions has reached nearly the 6 billions for 2011 [14] and according to IDC about 16% of such subscriptions are smartphones [15]. So, by doing some calculations of the global energy consumption of MSs we estimate a new figure of 16.8 TW-h per year, which is by far greater than the often cited 2TW-h figure.

For all the described reasons, in order to reduce the associated consumed energy and the carbon-footprint associated to the telecommunications, and more specifically to the mobile sector, joint efforts worldwide are taken place. These efforts are the product of collaborative alliances composed by government organizations, research institutes, the academia and the Telco Operators in order to overcome this issue, e.g., ICT-EARTH [23], Greentouch [24], Opera-Net 1 & 2 [25], Mobile VCE: Green Radio [26], TREND [27] etc. All those project initiatives, some of them currently running, some others already finished or in another stage of development, have been worked or currently work on attacking the energy-efficiency issue from several different approaches grouped in what the literature calls the Green Radio. The ways of solution proposed start from the very bottom level, the Base Station components enhancement, the pure hardware layer, going through techniques more oriented to resource optimisation like the Cognitive Radio (CR), the Energy-Aware Radio Resource Management (EA-RRM) and the improvement on the transmission link level approaches, until reaching higher

layer techniques, i.e. the cell layout adaptation level, where the active architecture and overall mobile network topology are adapted to the dynamic traffic needs in order to yield overall energy savings, e.g. BS Switching-Off & Cell-Breathing techniques, the Heterogeneous Networks and the Relay Devices approaches. A deeper discussion of all these techniques will be given in chapter 2.

1.2 Thesis Objectives

This thesis has the main goal of contributing into the domain of techniques of the Green Radio by proposing a novel set of energy-efficient mechanisms for the current and future mobile cellular network environments by focusing on the radio access network (RAN) attainable energy savings. In order to provide the necessary robustness we want to build our proposal on the basis of a self-organised and distributed mechanism structure, avoiding the use of central management servers, that although are able to bring a very high performance due to its capability of making decisions based on large and complete picture of the network state, could bring drawbacks as the lack of scalability as the network infrastructure grows, or additionally, the risk of network failure due to central server malfunctioning or unavailability.

The work done here has studied the different trends found in the Green Radio literature in order to have a larger panoramic view of what it exists so far and then detect and exploit the potential approaches where improvements provide a larger impact in the energy-efficiency at the overall network level. After an exhaustive study of the state of art, we have chosen two axis of research, that we think could be able to accomplish this objective: i) the BS switching-off & cell-breathing mechanisms [28, 29, 30, 31], a group of techniques that consist of adapting the BS cell sizes to the distribution of traffic in the coverage area by shrinking and deactivating those BSs that count with zero or low load associated, whereas the remaining active BSs go for expanding their cell size in order to guarantee coverage; ii) to apply network architectures based on the combination of large and small cell devices, usually called heterogeneous or hybrid networks. The most common configuration considered today in this type of networks is to use a classic Macro-BS cellular layer accompanied by a second layer of femto-BSs, also called femtocells [32]. These devices are conceived to provide a small coverage in the range of tens of meters, offering on the other hand, a very low power consumption with good QoS levels and dedicated data rates for reduced number of users [32]. An interesting energy-efficient approach is to deactivate the maximum possible number of Macro-BSs by offloading traffic toward the femtocell layer [33]. We will call this approach the Macro-to-femto offloading.

After having chosen those two approaches, we decided to combine the principles of BS switching-off & the cell-breathing with the use of Macro-to-femto offloading in order to provide high energy-savings by switching-off any unnecessary piece of the radio access network equipment (i.e. the BSs), granularly adapting the active network infrastructure to the real traffic needs. We must mention that by having multiple ways of intelligent BS offloading and deactivation, we aim to guarantee the network access availability and QoS levels, without missing from the picture some potential disadvantageous situations like the lack of the necessary radio resources to receive offloaded traffic by the radio access layer; the possibility of blocking due to access policies from the femtolayer as it could occur due to 3GPP Closed Subscriber Groups (CSG) access lists [1]; last but not least, the presence of coverage holes that could be caused whether by the absence of active access devices within range or by the existence of non-overlapped contiguous femtocells deployments.

On the other hand, we also think that the green aspects analysis of a green solution must not be conducted only based on the classic maximization of the energy savings point of view but must also delve deep in other issues related, like its potential environmental impact and undesired side-effects on user perception. In our case we want to open the discussion on the cell-breathing approach and its potential consequences originated by the increase of the transmission power figures due to the cell size adaptation, something that impacts on the electromagnetic radiations levels, an issue that to the best of our knowledge has not been studied before. Also based on this fact, we want also to analyse the implications specifically for the uplink where the increase of such a transmission power needed is going to play a disadvantageous role on the MS energy performance and the battery lifetime. In such sense we think that by proposing to use the cell-breathing as one element of our approach, it is also important to think a way of having control on its BS switch-off aggressiveness behaviour in order to limit the effect on the already described drawbacks.

Last but not least, we want to consider into our proposal the real complexity of the current and future mobile network with highly heterogeneous deployments. In this aspect, we want provide into our set of mechanisms a way to make the best BS switch-off decisions taking into account the heterogeneity of the BS deployment. Here the BSs deployed could count with a variety of different characteristics in terms of consumption power regimes, energy source types, radio resource capacity and coverage size ranges. Following this last axis, we hope it allows us latter opening, in the short term, the possibility of working on decision making mechanisms based on learning strategies.

1.3 Project Methodology

The methodological path followed throughout these three years of PhD work initially started by an exploration of the scientific literature on Green Radio. This permitted us to know each one of the proposed approaches on the domain in order to know the offered features and drawbacks of each technique and mechanism, as well to establish a classification model, which has facilitated the use of the rich existing information on the subject. Moreover, it permitted us to target our axis of research toward the cell breathing and heterogeneous network environments, techniques that will permit to yield important energy saving in the years to come.

Then, our next step of development was conceiving new mechanisms based on the objectives we defined for our solution (see section 1.2). In order to test such proposed mechanisms, our main approach has been to use the computer simulations supported on MATLAB. We have looked for, at each stage of development of our ideas, to find similar techniques or algorithms that could be useful as mean of comparison, but also as a source to extract useful elements in order to provide more complex, robust and efficient mechanisms.

Our computer simulation is based on the Montecarlo method. The main idea here is to take a given RAN deployment and then to introduce, by using hundreds of independent snapshots, different distribution sets of incoming MSs and then different levels of traffic. Here, different algorithms and mechanisms, including ours, are tested by means of taking the results of those multiple snapshots and then perform the averaging of the values. In order to provide valid simulation scenarios we have consulted the different standards and related documentation for mobile networks, more specifically for the 3G/W-CDMA and LTE technologies, as well as establishing and reusing any common parameter, model or methodology provided by the scientific literature and the collaborative projects deliverables in the energy-efficiency for the mobile networks field.

1.4 Novelty and contribution

The study of the state-of-art in energy-efficient techniques has allowed us to establish a pretty wide overview of what is being done so far in such domain worldwide. As product of this study, we achieved to conceive a classification model of the different green radio approaches as presented in [34]. This classification model has permitted us to establish the potential existing interaction between some approaches as well as

to define the target of our contribution into the set of techniques for this domain. As seen in [34], we have established a layered classification model where the bottom techniques are the enablers of the overall savings obtained for some global approaches that impact in the whole mobile network performance. The conclusions obtained, drove us to explore deeper, techniques such as the BS switching-off/cell breathing and the heterogeneous macro/femto approaches.

The main work of this thesis consists of presenting a novel family of energy efficient switching-off & cell breathing mechanisms supported on a clustered architecture and a BS based distributed algorithmic intelligence. The goal of this latter is to avoiding the use of a centralised control approach and its associated drawbacks as it is the lack of scalability and the fact of being prone to single-point failures. Although in the literature some other authors have already previously proposed distributed energy efficient cell breathing algorithms for cellular networks [29][30], those mechanisms normally present a lower performance compared to other centralised approaches [17][29]. Our first proposal, the distributed BS based cell breathing (DBCB), the first stage of our work, has been able to overtake the performance exhibited by other distributed proposals as seen in [17], and what is even better, has been able to match or in some cases outperform the efficiencies presented by some other studied centralised techniques.

In a second stage, we enhance our proposed DBCB algorithm in [18] by introducing a new algorithm called the Mobile Aware Distributed BS Based Cell-breathing (MA-DBCB). The aim of this enhancement was to introduce the possibility of setting the network operation point in order to find a balance between the RAN energy savings and the MS transmission power, something that to the best of our knowledge at that moment was not taken into account so far by other cell breathing proposals. A recent proposal, however, [35] uses distances as decision criterion, in order to take into account the transmission powers in uplink and downlink. Although here, there is not a proposed way to balance the algorithm behaviour between load oriented or distance oriented. In our approach, we achieved a mean to find such a balance by controlling the switching-off aggressiveness by regulating the number of Macro-BS to be switched-off. The change consisted of adding a local BS minimum load threshold, which determined if the execution of the DBCB was performed or not into the BS. Although [31] had already proposed a similar mechanism based on a global load threshold and a centralised switching-off approach, our MA-DBCB proposal presented in [18] is able to exploit its distributed approach by giving the possibility of setting the BS load threshold locally in a cluster basis or BS basis. This latter was conceived with the aim of allowing a fine tuning-up of the cell-breathing behaviour across the network. Moreover, a second major change in the mechanism consisted of including a metric based on a combination of

load and SINR that takes additionally into account the MS-BS transmission distances and associated losses, different to other mechanisms that make the redistribution decisions by focusing on the goal of concentrating the load in few BSs in order to maximize the number of deactivated BSs, however forgetting the impact on the MS side where the transmission power increases as well as its associated battery consumption.

In a later stage, we decide to combine our cell-breathing technique with a heterogeneous network approach based on a macro/femto cellular deployment [36], calling this new technique the femto-DBCBC. This latter, in order to boost the number of Macro-BSs deactivated by the combination of two ways of offloading, additionally adding a more robust network capacity. This enhancement was able to clearly outperform other approaches based on a single technique, whether cell-breathing only or Macro-to-femto offloading only. Additionally, we explored at this level, the potential impact of having closed subscriber groups (CSG) and access policies at the femto-layer for the performance of the macro-to-femto offloading technique. By using a combined technique we tried to tackle this down with a secondary way of offloading by means of the cell-breathing.

Parallel to this initiative, we started a work on electromagnetic compliance for cell-breathing and heterogeneous networks approaches in [37]. This is something that to the best of our knowledge was not studied so far in the related literature. In this work we found how the cell-breathing could potentially violate the acceptable electric field thresholds for RAN downlink transmission established in some country regulations and international recommendations proposed by the International Commission on Non-Ionizing Radiation Protection - ICNIRP, due to the cell sizes changes and its associated re-adaptation of the transmission power levels. We notice how this is alleviated as we introduce the femto-DBCBC due to a part of offloading is achieved by using the femto infrastructure, which transmit by using much more lower levels of power.

Finally, as final contribution of this work we propose a last enhancement for the DBCBC family aimed to improve the mechanism of BS neighbour selection for traffic offloading at highly heterogeneous networks. Our introduced idea, the Highly Heterogeneous Environment Aware-DBCBC (HHEA-DBCBC) counts with a multi-metric approach able to take into account different BS characteristics such as, current BS load, power consumption regime, power source type and the MS-BS distance (i.e. SINR), in order to make a better decision compared to the classic single criterion approaches. The system model for this study includes the use of renewable energy (e.g. solar, wind) for the BS power supply. With this last piece of work, we open the gate to further enhancements in this axis, which is very suitable for learning strategies. In the Fig. 1.5 we provide a synthesis overview of all contributions already described in this section.

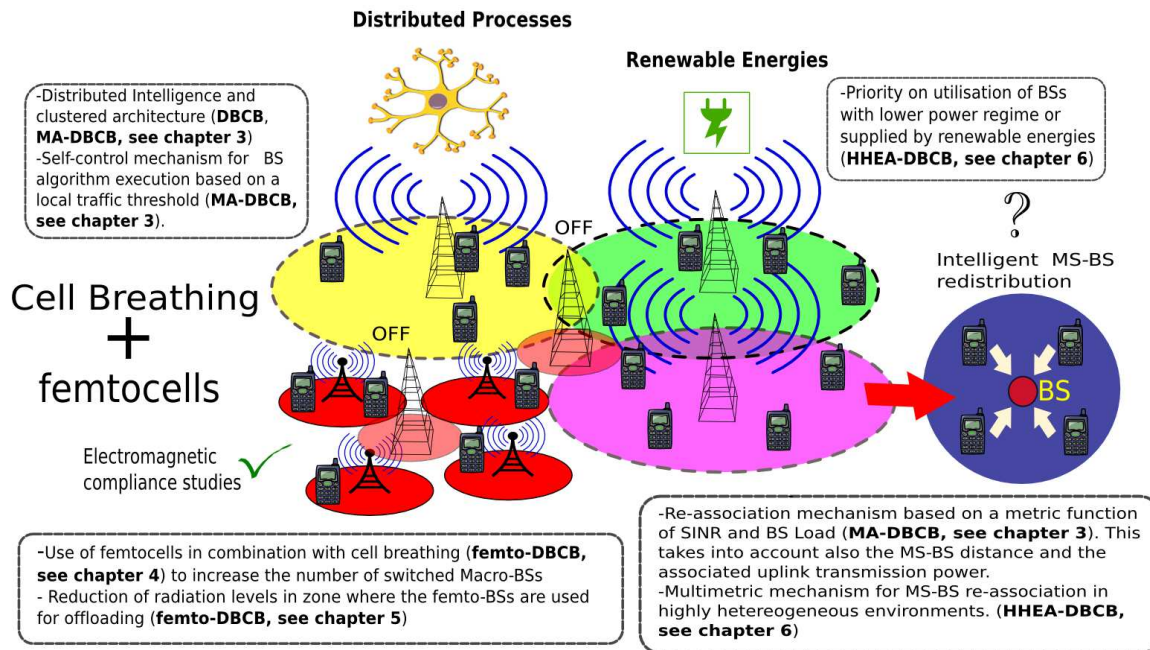


Figure 1.5 – Synthesis of Contributions in this PhD Thesis Project. In this figure, some clipart images are from <http://www.clker.com>.

1.5 Thesis Outline

This thesis document has been organised in a total of seven chapters. The *Chapter 1: The Introduction*, starts by providing a brief background of the current panorama in mobile networks in terms of overall energy consumption and associated carbon-footprint, additionally expressing the necessity of working on green network approaches to overcome the environmental and technical challenge. This chapter also describes and presents other important elements for the understanding of the work done in this thesis like the defined objectives of our project, the novelty of this work and its contribution, as well as the description of the followed methodology.

Then, the *Chapter 2: Energy Efficient Approaches in Mobile Networks*, provides a general panorama of the current state-of-art energy-efficient approaches, the worldwide projects and initiatives on green networks, and ends by introducing our scientific direction and approach for our contribution on Green Radio. This chapter also provides a general classification model of the different energy-efficient approaches, which permits to establish their potential integration, as well as, it permits to simplify the panorama of Green Radio.

In *Chapter 3: A Clustered and Distributed BS Based Cell-Breathing Algorithm*, we present the *Distributed BS Based Cell Breathing (DBC)* [17] and *Mobile Aware Distributed BS Based Cell Breathing (MA-DBC)* [18], providing a discussion on the

advantages of these two algorithms, such as the clustered architecture and distributed intelligence combined with the means to regulate the impact of cell breathing on the MS performance.

Later, in *Chapter 4: The Cell-Breathing in a Heterogeneous Network Environment*, our discussion goes beyond by presenting the *Macro-to-femto Offloading & Distributed Macro-BS Based Cell Breathing (femto-DBC)*. This chapter analyses the performance of Macro-to-femto offloading only and cell breathing only techniques by comparing with our enhanced combined proposal. The heterogeneous network scenario is studied by additionally taking into account the impact of 3GPP CSGs access policies in the femtolayer and the performance of the studied mechanisms.

For *Chapter 5: Electromagnetic Compliance for the Cell-Breathing and the Combined Cell-Breathing/Het-Net Approach*, the analysis of the techniques previously studied in chapter 4 is extended toward the electromagnetic compliance given the increase of the RAN associated radiation produced by the downlink transmission power levels due to cell-breathing, which could be substantially reduced by the introduction of a femtocell access layer.

The *Chapter 6: A Multi-Metric BS Switching-Off Algorithm for a Highly Heterogeneous Cellular Network Environment* closes our contributions done during this thesis project by presenting the *Highly Heterogeneous Environment Aware Distributed BS Based Cell Breathing (HHEA-DBC)*. In this chapter we extend our scenario to the highly heterogeneous networks including renewable energy and open our future work toward the learning strategies.

Finally, *Chapter 7: Thesis Outcome*, closes the document by providing the final conclusions obtained from this work, as well as the perspectives and global future work expected to be continued in the following, right after the finalisation of this PhD project.

Energy Efficient Approaches in Mobile Networks

2.1 Introduction

This chapter is dedicated to the wide spectrum of techniques classified into the domain of the green radio. The basis of this chapter is our first publication entitled *An overview and classification of research approaches in green wireless networks* [34] for the *EURASIP Journal on Wireless Communications and Networking*. The aim of this article was to provide a state-of-art on the green radio domain, additionally providing the added value of a layered classification model that allows to see the interaction and the integration possibilities of the different abstraction levels and approaches: the BS internal component enhancement, the Cognitive Radio, the Transmission Link Optimisation Techniques & Energy Aware Radio Resource Management (RRM), and finally at the top network level, the cell layout adaptation techniques, where we find approaches like the Switching-off/Cell-Breathing mechanisms (i.e. also called cell shaping approaches) and the Coverage Extension Techniques (CET), where we find the heterogeneous network architectures and the relay mechanisms.

The concerns about energy efficiency are something that quickly grows worldwide. In such sense, several overview and survey papers have been written on the topic. We can say that the last decade was a period of progressive awakening and rapid awareness on the subject. To the best of our knowledge, a first survey on the topic was published in the year 2001 [38]. This survey explored the different advances and research approaches for wireless networks following each one of the layers of the wireless protocols stack going beyond the typical approach to physical layer, emphasising at that moment that higher savings could be achieved if also upper layer processes are optimised. Another survey in the domain of energy-efficiency techniques for mobile

systems was proposed in 2004 [21] and it remains today a good entry point for this topic. This reference gives a wide overview of energy-efficiency mechanisms for wireless networks, mainly WLAN and cellular networks, taking into account hardware, architectures and protocols. Some surveys were written in the framework of collaborative projects (see section 2.8) such as [39] from the EARTH project or [40] from Mobile VCE Core 5 giving the future challenges and perspectives. A parallel overview of EARTH and Green Touch projects is presented in [41]. These surveys devote their work to describe what has been done so far within their projects, showing their own present and future steps of development. Some other surveys are dedicated to specific approaches like, for example, MIMO as presented in reference [42]. The authors of [43] focus on energy-efficient transmission, discussing the research on some techniques like MIMO, OFDM/OFDMA, adaptive modulation, scheduling, etc. In this paper the radio resource allocation and transmission mechanisms are viewed from three different perspectives: space, frequency and time domain. The survey presented in [44] studies similar topics with [43] (e.g. MIMO and OFDMA), however it includes a short discussion about relaying. We can also mention the exhaustive work of compilation and synthesis of [45] dedicated to the energy-efficiency of fixed networks with an impressive list of more than 150 references.

2.2 Energy-Efficient Metrics

Several metrics have been defined so far in order to characterise the wireless network energy efficiency and consumption at different levels, i.e. the internal components, the base station or the radio access network, as already summarised in reference [46]. Such metrics may additionally be classified as energy efficiency metrics or energy consumption metrics as briefly mentioned in [47]. An energy efficiency metric corresponds to the ratio of attained utility (e.g. transmission distance reached, area covered, output power, bits transmitted, etc.) to the consumed power or energy used. On the other hand, an energy consumption metric corresponds to the energy or power consumed per unit of attainable utility. In Fig 2.1 we provide a classification of metrics using these already discussed criteria. The purpose of this section is to summarise the main metrics used in the literature to quantify the energy efficiency & consumption of physical devices and techniques aimed to this purpose.

Some relevant metrics concerning the component level are discussed in the following. Important attention is given on the power amplifier efficiency metric (i.e. ratio of PA output power to supplied power) [46], due to the already-mentioned lack of performance of this element. Some other metrics are also considered for power amplifier section

like the peak-to-average power ratio (PAPR). The reduction of the PAPR guarantees better amplifier efficiency [39][48] due to the improvement on the linearity behaviour. However, the interest is not only focused on the power amplifier. Other sections of the RF transmission chain, where any improvement in terms of efficiency counts (e.g. antenna elements), are also considered. Nevertheless, all the efforts are not devoted to the analogue components but also the digital section is taken into account. Some specific metrics have been used so far in order to measure the performance of computing processing associated to energy consumption (e.g. MIPS/W - millions of instructions per second per watt, MFLOPS/W - millions of floating point operations per second per watt) [46]. Also at this layer we can include the energy consumption gain (ECG) [40] that corresponds to the ratio of the consumed energy of a baseline device to the consumed energy of a given device under test (DUT). This metric may be extended from separated components like a new power amplifier prototype to larger devices like base station systems.

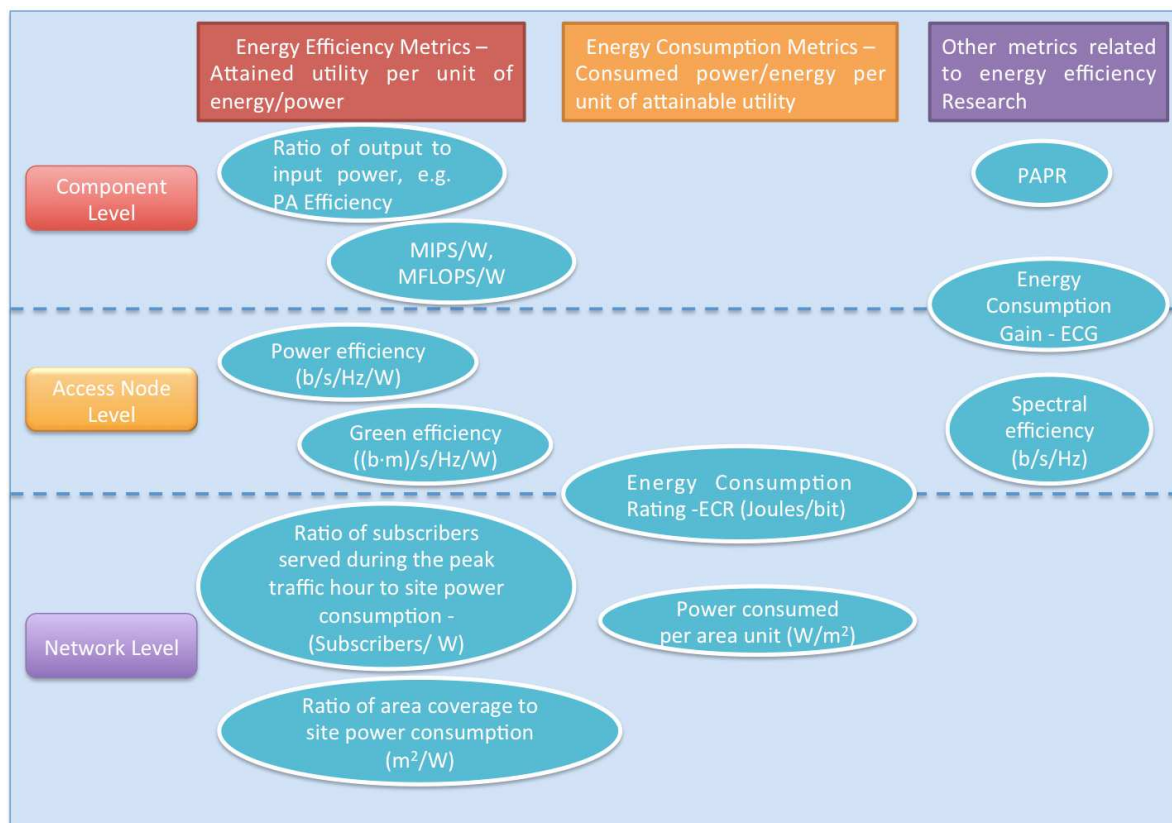


Figure 2.1 – Classification of metrics used in energy efficiency for wireless networks. Synthesis from [39, 40, 46, 47, 48, 49, 50]

At access node level, more precisely the base station (BS), there is also a rich set of metrics. Although some classic metrics are still useful (e.g. average BS consumed power [46]), new metrics have been introduced specifically for this topic. The energy

consumption rating (ECR) [40][46], gives the energy used for transmitting a piece of information (Joules/bit) [40]. Some other metrics aim to observe the attained utility of the different resources regarding there exists trade-offs, such as the spectral efficiency (b/s/Hz) and the power efficiency (b/s/Hz/W) [49]. One metric targeted to cover all the aspects in a more general way is the called by authors green efficiency criterion ((b-m)/s/Hz/W) [49], measuring the data rate transmitted and transmission distance attainable given the respective figures of bandwidth and supplied power resources.

There are some other metrics that address the radio access network performance. The metrics here evaluate the global attained service provision given a consumed power. This level of service provision can be measured as proposed by ETSI for GSM networks [46][50], whether in terms of the ratio of served subscribers or the covered area to site power consumption. The ratio of served subscribers during the peak traffic hour to site power consumption is used for urban environments, whereas the ratio of area coverage attained to site consumption is used for rural areas. In references [39][47] they propose to use as metric the consumed power per area unit (W/m^2). According to [47], in order to avoid misinterpretations it is important to fix the coverage area for having then a point of reference for comparisons.

2.3 Cell Layout Adaptation Mechanisms

In this section we speak of the techniques in the category of cell layout adaptation. This category, as we will see in section 2.7, it is on the top of our classification and integration model. The reason for this, it is the fact that approaches from this category yields the higher energy reductions at a network scale. However, these top layer mechanisms must rely on lower layer approaches to enhance their savings. The techniques from lower layers have a repercussion in a more reduced scale such as the BS transmission performance or the internal component level savings. The techniques into the category of cell layout adaptation allow adapting, customising and extending the infrastructure of the radio access network in function of spatial and temporal traffic distributions, aiming to reduce the network energy consumption. In this category we consider the cell shaping techniques (i.e. BSs switching-off and cell breathing), the heterogeneous networks deployments (e.g. Macro/femto deployments) and last but not least, the relays.

2.3.1 The Cell Shaping: The Switching-Off and Cell-Breathing techniques

A first way to globally reduce the energy consumption in a cellular network is to adapt the cell layout to the traffic distribution by cell shaping. In such a category we introduce the switching-off and cell breathing schemes. Specifically, the cell breathing [51][52] was originally conceived as an alternative to the classic MS-BS association methods (i.e. MS-BS associations in function of SINR) in order to reduce the resulting levels of global interference. Such a mechanism is being exhaustively studied in the recent years for energy-efficient networks due its capability for adapting the cell sizes to the distribution of traffic and the possibility of switching-off any unnecessary BS. In a basic switching-off and cell breathing mechanism, the idea is to turn off, or equivalently send to the sleep mode state, the most number of base stations during the low traffic period, with no compromise of coverage or service availability. Here, a blocking probability threshold must be respected. Additionally, the cells kept active must take charge of the remaining traffic, needing to increase their coverage range constrained by a maximum BS transmission power and therefore the cell is limited to a maximum coverage radius. In order to perform the switching off, it is necessary that the BSs about to be deactivated redistribute the traffic to their closest neighbours. Some BSs are not be able to redistribute their full traffic and then remain active with a lower transmission power. The dynamic of cells has a size adaptation to incoming traffic, that metaphorically speaking can be seen as the cell is breathing (see Fig. 2.2). As we will see there exists a very rich literature in this domain, more taking into account the future challenges of access networks. Several questions are still open in subjects like the use of distributed or centralised approaches for coordination and self-organisation [53] or the optimal deployment characteristics to apply such techniques [54].

The switching-off and cell breathing literature can be classified in two types: switching-off network planning and cell breathing coordination. Firstly for network planning, in reference [28], a switching-off planning method is proposed. This method allows finding the ratio of deactivated BSs to remaining active BSs, as well as the switching-off period, where traffic is considered sufficiently enough low to perform the BS switching-off not violating a blocking probability limit. They call this low traffic period the “night zone”. In reference [55], the same team from [28], presents a generalised method that permits to calculate and optimise the night zone period independently of the existing cell geometry architecture. In reference [56] an analysis of the potential savings using a switching-off technique is done by using real data traffic traces. This article considers after the analysis that the estimated energy savings for mobile operators could be between 8 and 22% by benefiting of the low traffic periods.

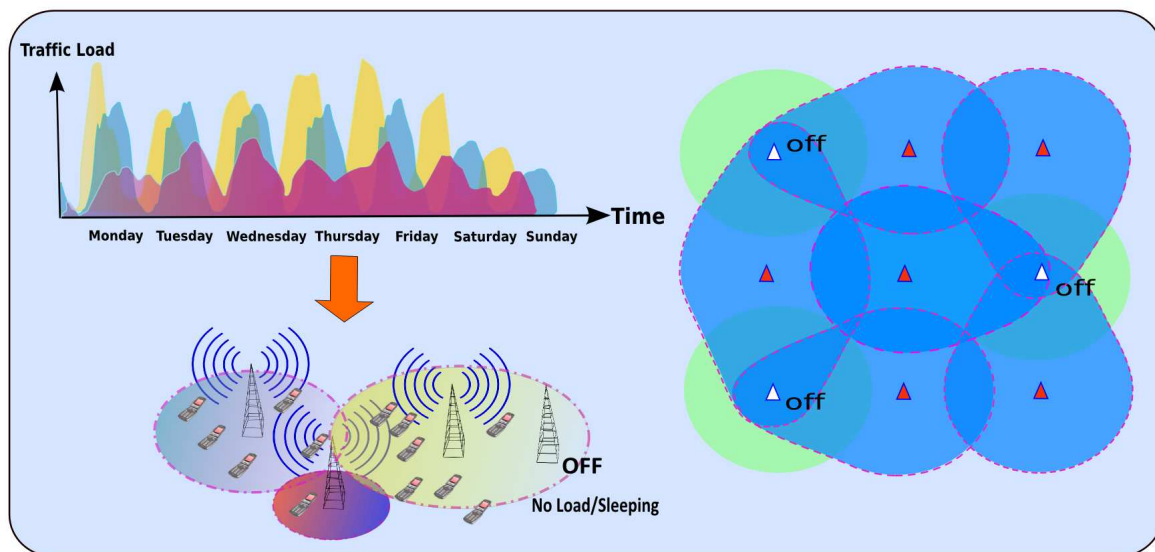


Figure 2.2 – The Cell Breathing Technique as a mean for global energy-efficiency at the RAN: cell sizes and number of BSs switched-off adapted to the traffic load distribution. In this figure, clipart images of antennas from <http://www.clker.com>; cell phone clipart from Microsoft Office 2011 Clipart Database.

Also in this paper many perspectives are opened by the authors for the future network deployments such as the implementations of heterogeneous networks, the introduction of cooperative mechanisms and the use of cognitive schemes.

There are other references that devote their efforts on proposals for dynamic cell breathing coordination. The reference [57] proposes to concentrate the network traffic preferring highly loaded BSs, whereas remaining idle base stations can be switched-off. This reference takes into account also the importance of keeping a balance in the spectrum efficiency vs. energy efficiency trade-off. For this purpose, the BS-MS association algorithm does not neglect the spectrum efficiency importance and gives preference to the associations that yields the best possible spectrum efficiency values. This article presents a distributed and a centralised version (i.e. a central device that provides coordination) of the cell-breathing algorithm. The results presented show that, despite the fact the distributed version exhibits a lower signalling overhead, the centralised version presents higher energy efficiency. The work presented in [57] can be considered as a preliminary version of the cell zooming approach proposed in [29]. For this reference also a centralised (i.e. the coordination role is played by the cell zooming server) and distributed versions of the algorithm are presented. The most remarkable advance compared to [57] appears in the centralised version proposed. Here, the algorithm is executed in two phases: In a first phase the cell zooming server associates all MSs and BSs preferring the associations where the attainable spectrum efficiency is the best among the different association possibilities. Afterwards, any BS whose load

is zero can go to sleep. In a second phase the cell zooming server redistributes traffic from very low loaded BSs to the top highly loaded ones. By doing this, some new BSs may also be switched off. There is a continuation of the work about cell zooming in reference [54]. Here the authors discuss the network planning issues in order to enhance a cellular deployment to better exploit the cell zooming technique. This paper analyses the efficiency improvements due to smaller cell deployments and proposes to continue the work toward coverage extensions techniques such as relays. However the cell zooming proposal is not the unique algorithm of its type. The algorithm presented in [31] combines the cell breathing with a tilt angle optimisation algorithm. In this algorithm each BS decides to become a candidate to be switched off if the BS is below a low traffic threshold. A centralised node is in charge of sequentially deactivating the BS candidates to go to sleep mode. This sequentiality allows evaluating the consequences of switching off a given BS. The algorithm continues till there are not candidates to switch off. Moreover, in [30] a cell breathing style algorithm with a new ingredient known as proto-cooperation is proposed. The proto-cooperation is a term originally used in biology and it refers to an interaction among species where nobody is mutually getting more benefit of such an interaction. The authors of [30] propose the proto-cooperation for mutual collaboration of BSs deployed to reduce energy consumption. This algorithm as well as [31] uses traffic thresholds but with the difference is a fully distributed BS based algorithm. On the other hand, in reference [58] another concern into the domain of cell breathing coordination is analysed. In this paper, soft transitions to pass from active to sleep mode and vice versa are proposed in order to avoid jeopardising the network during the traffic redistributions. It is shown here that such transitions can be achieved in a very short period of time that it is not going to significantly affect the energy efficiency expected from the cell breathing technique. In [59] a cell breathing mechanism is proposed where the switching-off is studied deeper by taking into account the BS sectorisation. Here, a centralised mechanism is defined for controlling the cell expansion and contraction by benefiting of the use of the sector antenna systems, mainly the beam direction and tilting features.

In the last year the number of publications on this subject has been increasing quickly. For instance, a distance aware cell breathing mechanism is proposed in reference [35]. This algorithm takes a totally opposite direction to the classic load concentration approach. Here, they prefer to take into account the transmission distances something that guarantees savings at downlink without forgetting the uplink side. A very recent reference [60] presents cell-breathing based on a genetic algorithm approach. The aim of this technique is to find an optimal switching-off configuration taking into account the global interference and the associated variable load and real network capacity. The article claims that such approach outperforms the classic heuristic approaches

that skip the already cited elements. Also quite recently, the reference [61] presented a cell switching-off mechanisms supported on a pricing approach. The idea here is to maximise the utility that corresponds to serve a larger number of MSs but at the same time reducing the energy expenditure that means deactivate the largest number of BSs.

After this extensive review we notice, there are several things to work in the future for this promising approach. From the literature review we see that a large number of publications propose algorithms for switching-off and cell breathing. However, there is still work to do in the transition of the network states and handover as we saw in reference [58]. Moreover, although there is already some work done into the aspect of joining the cell breathing approach with coverage extension techniques such as femtocells and relays, this work is still in the first stages of development. We will discuss about femtocells and relays in the next subsection.

Future proposals on cell breathing coordination must delve deeper into things like the feasibility of such algorithms to be implementable into a large-scale network. It is known that centralised coordination approaches yield better performance results than distributed proposals. The clear advantage of the centralised approaches lies on the fact that central nodes have a full view of the network and better decisions can be made. However, to depend on centralised nodes can limit the network scalability, as well as introducing single point failure nodes. One clear direction is to find better BS based distributed algorithms based on cooperative approaches where the main objective is the overall savings and not the local benefit into the BS. A halfway solution, between the centralised and distributed approach, could be the utilisation of clusters dividing the network and distributing coordination responsibility as we will see in chapter 3.

2.3.2 The Coverage Extension Techniques

Heterogeneous Networks

Also in the same category of cell layout adaptation we find the heterogeneous or also called hybrid network approaches, a trend that is gaining more and more relevance into the current research and development perspectives. This domain has a crucial importance for us, due to the possibilities of these mechanisms as a way of enhancement of the cell shaping techniques already discussed in subsection 2.3.1. There exist already several proposals and studies in such area, many of them focusing on energy efficient networks, where the classic macrocell layer is extended whether by the use of a second layer of pico or femtocells (i.e. coverage range not greater than 200m [62]). An example of this kind of network deployments is shown in Fig. 2.3.

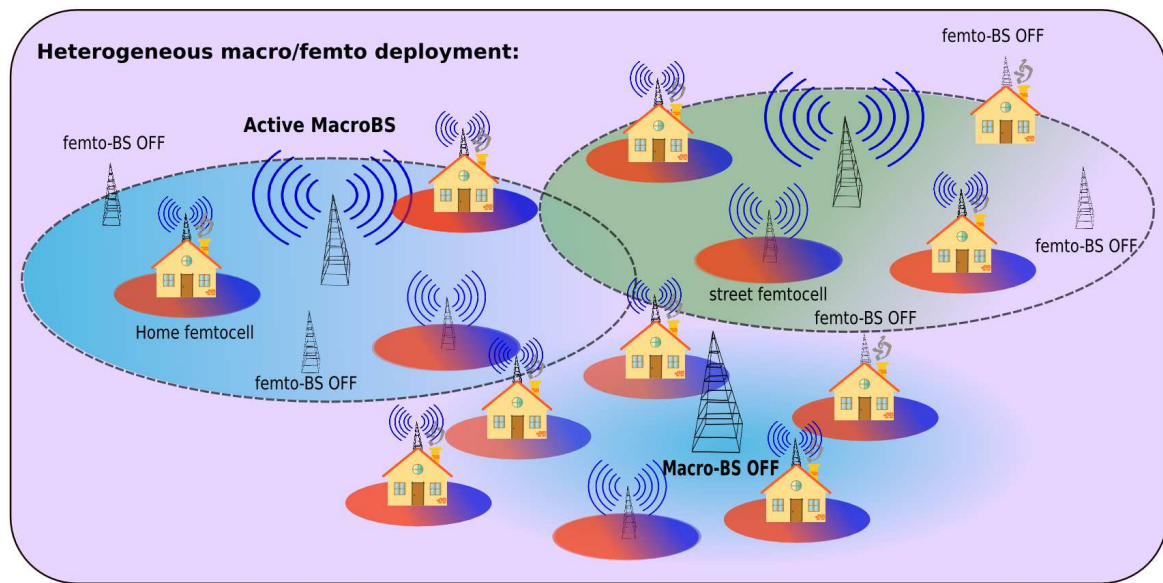


Figure 2.3 – Example of a hybrid deployment: a classic macrolayer is joined by a second layer of home and street installed femto-BSs. In this figure, antenna clipart images used from <http://www.clker.com/>

Specifically, a femtocell consists of a small base station, i.e. the femto-BS, with coverage of tens of metres (see, e.g., [32]). The literature mentions the advantages of these technologies like lower energy consumption and low maintenance costs compared to those of a Macro-BS [32][63], as well as higher dedicated data rates and better QoS for small groups of users, which leads to better user perception [8][32]. The consequences of joint large and small cell deployments are something deeply discussed in references like [8]. In this reference, the authors analyse and propose a solution to the femto/pico over-provisioning, which occurs when a dense deployment of small cells is underutilised driving the network to overconsumption. In order to overcome this issue, the authors propose the introduction of sleep modes for the pico/femto deployment to maintain the very robust capacity while controlling the energy consumption. On the other hand, in [64], an analysis of the optimisation of the macrocell size is performed. The objective here is to find the optimal operation point for capacity and energy, when the deployment is enhanced by the utilisation of small BSs (i.e. pico, femto) in the cell edges. In [65], the authors present how energy-efficiency increases as the cell size is reduced. This is an important result that is studied deeper in other articles for small cell devices. For instance, [66] shows that it exists a certain density of picodevices in a given deployment that provides an energy efficient optimal solution. Additionally, it is shown how smaller cells can be more energy-efficient based on the area energy efficiency (AEE) indicator (bits/joule/km²). In [67] a study is conducted which analyses several aspects of femtocells to show the advantages. First, it is highlighted the good qualities of hybrid

deployments for handling indoor traffic compared to the macro-only architectures where penetrations losses oblige to higher power levels. Then, a discussion is presented on the best strategy to save energy: it is shown that by reducing uniformly the transmission power levels on the entire cell deployment better energy reductions can be achieved than by switching some BSs off. In their model, only the radio front-end is deactivated. In [68] the hybrid access cellular networks are studied from a wider perspective, taking into account the different economic cost related to network lifetime, i.e. IMPEX, OPEX and CAPEX. It is shown how during the growth of a network, the best strategy is to introduce first new pico/femto access points before introducing new Macro-BSs, which consume more energy. However, the density of pico/femtocells introduced must be chosen carefully in order to avoid any unnecessary increase of economical costs.

The heterogeneous network advantages and drawbacks are well known, and one of the hot topics is the study of the intercell interference. In [69] the effect of femtocells on the global interference and the energy efficiency is studied. It is shown in this article how the insertion of low and medium density femto-deployments can increase the energy performance. However, it also can bring other problems like an increased intercell interference, which is more complicated to handle than in classic only macro-deployments. Some articles have discussed algorithms and methods to allocate efficiently the spectrum in femto-macro deployments in order to avoid such intercell interference by means of shared and partitioned spectrum strategies [70][71][72].

In the area of Heterogeneous RAN switching-off and BS offload algorithms we find also some proposals. In [33] an algorithm based on user aware activity (UAA) techniques is proposed. In this algorithm the femto-BSs sniff the radio channel during the sleep mode periods by using a low-power receiver. The idea is to detect any ongoing call served by the Macro-BS within the femtocell range and then decide if the call can be transferred or not to the femto-layer. The detection is done by measuring the intensity of signal strength, which also provides the information to determine the proximity of the MS to the femto-BS. The reference [73] proposes the utilisation of a centralised heuristic algorithm for BS deactivation and BS-MS association. This algorithm exploits the principle of concentration of the load in few spots to maximise the number of deactivated BSs by encouraging the association of MSs with few BS choices toward BSs with many potential MSs to serve. The simulations are performed for two different deployments, one for femtocells-only and another for macrocells-only. It is shown how this algorithm provides very important reductions as the cell sizes are reduced in the deployment. Another centralised algorithm for BS switching-off in macro/femto deployments is proposed in [74]. An objective function is selected with modifiable parameters that allow the choice between a capacity-oriented behaviour or

an energy-efficient behaviour. The goal is to maximise the objective function by using an iterative algorithm respecting the network constraints such as the transmission power. The algorithm finds the best configuration by testing different combinations of ON/OFF states and power levels for the set of BSs in the hybrid deployment in order to maximise the utility.

The utilisation of cell breathing on hybrid networks remains as an open hot topic that we have aimed to study in this project. Although it always exists the possibility of having improvements on femto-BS hardware, an important work remains still on the cell coordination algorithms that permit the interaction of macro/femtoBSs in order to redistribute the network load in order to switch off any unnecessary device off. Those future algorithms must exploit the granularity that femtocells could bring to cover small spots uncovered or the capability of sharply adapting the access device resources to the density of users given in a zone. Thanks to femtocells and cell breathing we will achieve a fine-tuning of network coverage with an energy consumption tailored to the real necessities in the years to come.

The Relay Devices Approach

A third approach in the category of cell layout adaptation is the use of relays. This technique has been considered so far, as an alternative to the use of femtoBSs. Both can be considered as valid coverage extension techniques (CET) to enhance a deployment by increasing its energy efficiency performance. Based on the references used in this section, we can say that relaying can be performed in two ways: i) using repeater stations or ii) using the mobile stations as relays. We can consider reference [75] into this first approach of using dedicated devices as repeaters. Here, the use of relays is proposed in order to reduce the mobile phone transmitted power, which reduces therefore the radiation exposure of the user during the call. A network device named green antenna is presented (see Fig. 2.4). These antennas are connected by a wired link (e.g. optical fibre) to the BS and have only receiver capabilities. With this approach, it is possible to increase the BS receiver range and therefore reduce the power levels needed by mobile phones for uplink transmission. It can be noticed here that by reducing the transmission power for uplink transmission, it implies that the mobile terminal reduces its battery energy consumption, which is also a contribution to overall energy savings.

Some other references propose the use of mobile phones as relays. In [76], a cooperative relaying mechanism is proposed under a modified Vickrey auctioning strategy where a mobile phone serves as a relay for downlink transmission trading the expended

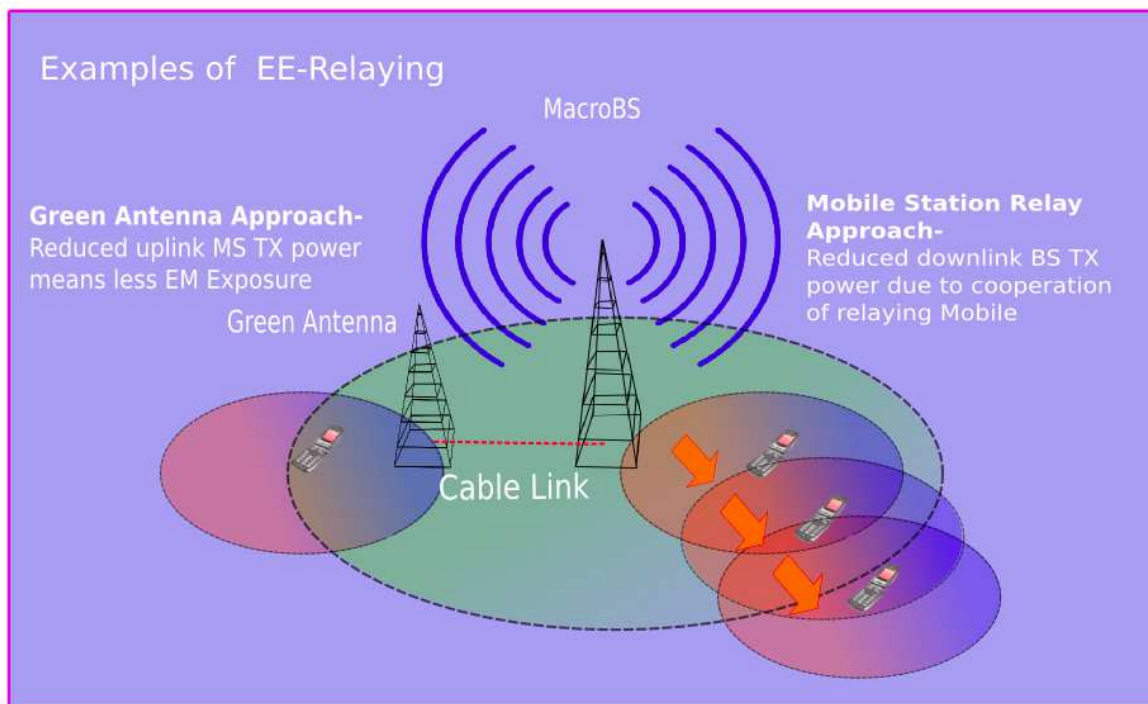


Figure 2.4 – Two examples of relaying in the same figure: (left) a green antenna relay [75]; (right) downlink relaying using MSs as relays nodes [76]. In this figure, clipart images of Antennas from <http://www.clker.com/>; mobile phone clipart from Microsoft Office 2011 Clipart Database.

energy on relaying for an economic reward. The reason for using a Vickrey model as the auctioning model is that the bidders, given the mechanism rules, are obliged to give a real value to the goods they trade [76], which allows a fair exchange. As we can see, this mechanism permits to reduce the transmission energy needed for the BSs systems that as we know is the most critical device into the mobile network in terms of consumption. Other references, on the contrary, give proposals but applied for the uplink. In reference [77] it is proposed to use close terminals to transmit data cooperatively to a common BS. When a given user is transmitting, a close idle terminal may decide to collaborate into transmission, becoming a relay that transmits a second stream increasing the transmission rate of the active user and reducing therefore the energy used per bit transmitted (i.e. ECR, see section 2.2). A Nash bargaining approach is used to achieve the cooperation assuming that mobile terminals behave selfishly and therefore a motivation is needed. The Nash equilibrium here can be reached if an infinite-stage game is performed. Other publications study the inherent energy efficient advantages of relaying compared to direct transmission. For instance, [78] conducts an analysis of wireless relays, Coordinated Multipoint Transmission (CoMP) and the classic BS-MS point-to-point transmission. In the schemes analysed, the BS/relay sleep mode feature is included. From this analysis some conclusions are drawn: i) increasing the BS den-

sity and reducing the cell size leads to better results in terms of energy-efficiency for any of the mechanisms considered, and ii) wireless relays must have a very reduced consumption compared to a BS in order to be an option of being an energy-efficient mechanism. In [79] some transmission mechanisms using direct transmission and relaying are analysed with the additional consideration of having at their disposal the capabilities of average channel state feedback or instantaneous channel state feedback. The results of this paper show that cooperative relaying must be used when outage probability target is very low, in order to enhance energy efficiency. On the contrary, for less exigent outage probabilities it is advised to use direct link transmission. In any case the fact of introducing instantaneous channel knowledge features into a transmission mechanism is a key for reduced energy consumption. This latter, could be implemented by using the sensing capabilities of the cognitive radio, as we will see in section 2.5.

In the relay domain there are still very hot topics still open and a good amount of work to do. The concerns on this area for future research are very well expressed in [44]: in order to coordinate the resource allocation for cooperative relaying some extra power is needed, and therefore minimise this overhead energy expended is a task to do. Additionally, this reference remarks the importance of working in bi-directional relaying systems and multi-cell environments, due to most of the work is done for point to point transmission and moreover only considering whether uplink or downlink, but not both. Additionally, as we said before in subsection 2.3.1, the reference [54] mentions the introduction of relaying devices as a possibility to enhance a cellular deployment for cell breathing. For such an approach, there are open subjects for real life implementation such as the coordination mechanisms and the communications protocols that permit the exchange of information to achieve the cooperation among the different devices [44].

2.4 Transmission Link Level Approaches and the Energy Aware Radio Resource Management

After having studied the cell layout adaptation techniques, that as we already said, constitute the top layer category of energy saving at network scale, we are going to continue with techniques that can also contribute to energy saving but into a more local reach. We speak of the energy efficient transmissions mechanisms and the radio resource management (RRM). A first reference dating from 2003, [21] presents a survey of energy-efficient radio techniques. Several mechanisms are shown, such as the

transmission power control that consists of adapting the system transmission power level in function of variables like channel state or transmission peers locations. Also in this reference, some other general techniques that can also be used for energy efficient packet transmission are also mentioned: packet size adaptation, FEC/ARQ (forward error correction/automatic repeat request) schemes, adaptive modulation, data rate adaptation and collision avoidance.

If we start discussing about energy efficiency on transmission mechanisms, MIMO systems are extensively reviewed by energy-efficiency surveys like [42][43][44]. In [42] is shown the existing relation between data rate, transmission power and energy efficiency for SISO and MIMO systems. The behaviour presented by a SISO system shows that in order to minimise the energy per joule transmitted the system must transmit at very low data rate (i.e. a lower transmission power level is necessary). As said in [42] this can be acceptable for some delay tolerant systems such as a sensor networks, but for some others like mobile telephony this latter cannot be accepted in order to guarantee a certain level of quality. For MIMO in slow fading channels, it is shown by this paper that higher number of antennas, results in a attaining a higher system energy-efficiency optimal value. On the other hand, the review of reference [43] dedicates an important place also to discussing on MIMO, mentioning for instance, how MIMO systems combined with adaptive modulation exhibit better energy-efficiency performance as the transmission distance increases compared to classic SISO systems [80].

For OFDMA, [81] addresses the energy efficiency for this transmission mechanism in uplink. The combination of OFDMA and the adaptive modulation is studied and some conclusions are provided: i) higher the number of sub-channels are assigned to a mobile user, higher the attainable energy-efficiency maximum will be for an OFDMA system functioning at an optimal modulation order, ii) the optimal energy-efficient modulation order decreases with the distance from MS to the BS. Such results are very useful, however, in the survey given by [44] is remarked that research work has been only focused in the uplink transmission. Future proposals according to [44], must exploit the existing trade-off between energy and spectrum seeking to find an optimal balance between these two variables for the system design on OFDMA. A crucial importance is given also in [44] to traffic statistics in order to better allocate resources.

The cooperation in relaying techniques was already discussed in subsection 2.3.2. For this section, we give a brief mention to the cooperation diversity attainable by a scheme of multiple coordinated BSs transmitting to a single user. A comparison of the energy efficiency attainable by CoMP (Cooperative Multipoint Transmission Systems) vs. wireless relays was already cited in the subsection 2.3.2 [78]. It is shown that due to

the spatial diversity introduced by coordinated BSs working cooperatively, the energy efficiency could be enhanced compared to a classic single BS transmission scheme. Similar conclusions can be extracted from [40] where the energy efficiency performance of different Distributed Antenna Systems (DAS) schemes is compared to the classic single BS-MS point-to-point transmission. However, the success of this cooperation and coordination among a group of neighbour BSs relies on backhaul protocols in order to exchange information. Protocols for this purpose are presented in reference [82].

Another important issue found in the energy efficiency schemes into literature is related to the radio resource management (RRM). The main idea is to optimise the allocation or utilisation of transmission resources such as bandwidth or time in order to reduce energy consumption. This optimisation problem must be solved under some constraints given by channel conditions, QoS and transmission/receiver system characteristics. The authors of [83] propose the framework of four fundamental trade-offs to be considered among the main resources of a mobile network: deployment cost- energy, spectrum-energy, bandwidth-power and delay-power. To find a balance point for such variables not compromising the service quality, availability and network coverage is the goal of radio resource management approaches. Reference [84] addresses the subject similarly emphasising the economic factor by bounding infrastructure costs, energy costs and spectrum costs. This reference studies the behaviour patterns and relations among such variables in order to give a generalised model, very useful for wireless network optimisation regarding the resource trade-offs and cost perspective.

Here we present some examples of proposals in RRM. In such ideas presented, researchers work with the resource trade-offs in order to improve the energy efficiency of a communication system. In reference [85], for instance, an energy-aware admission control and bandwidth allocation mechanism is proposed. This mechanism builds on the fact that for a given curve of energy consumption rating (ECR) (i.e. bits transmitted per joule, see section 2.2) vs. transmission rate (i.e. bandwidth allocated), for the operation points of different mobile terminals for a fixed transmission rate variation, the obtained value of ECR (Joules/bits) does not change in a proportional fixed quantity. Taking advantage of this fact, the paper proposes ways for bandwidth allocation/reallocation aiming to optimise energy-efficiency with a minor bandwidth trade-off. Some other references consider the trade-off between transmission time and consumed power. It is shown in [43] that the energy per bit vs. time per bit curve has a convex decreasing behaviour. From this point of view, longer the transmission time per bit, higher the energy-efficiency obtainable. However, in a more realistic implementation it must be considered that it exists behind the circuitry consumed

energy that increases with the transmission time per bit. The combination of both energy components gives a curve where it exists an optimal operation point, which maximises the energy efficiency. Such optimal point should not exceed however the delay constraints that guarantee service quality. We can provide some examples of how the time delay-power trade-off is exploited. In [86] a scheduling algorithm for periodic packets is proposed. As expected, it seeks to optimise the consumed energy by increasing the transmission time. Here, the delay constraint is given by the transmission period of the sequence of periodic packets. Another example is reference [87]. Here, a lazy scheduling mechanism is presented where transmission is buffered respecting delay constraints. It is shown in this paper that small-buffered systems exhibit better energy-performance compared to non-buffered deterministic schedulers. Last but not least, in the same line of transmission time- power trade-off, [88] proposes a variable-length slot TDMA. Here, the length is chosen by an adaptive mechanism, which makes the decisions based on some other parameters such as the transmission distance and the transmission queue length.

The need of continuously improving the RRM and transmission mechanisms is currently concern of mobile communications in order to better exploit and complement the already shown advantages of top layer mechanisms that yield energy efficiency at large scale (i.e. cell breathing, femtocells and relays). In addition, if the transmission techniques and the way in which resources are allocated is improved, a noticeable enhancement is obtained for the access equipment during active mode, that complements the already important reductions product of sleep modes.

2.5 The Cognitive Radio

Joseph Mitola has defined the Cognitive Radio (CR) as: *"a radio frequency transmitter/receiver that is designed to intelligently detect whether a particular segment of the radio spectrum is currently in use, and to jump into (and out of, if necessary) the temporarily-unused spectrum very rapidly, without interfering with the transmission of other authorised users"* [89]. In other words, a CR system must be capable of reconfiguring its transmission parameters in order to adapt and match the channel conditions (see Fig. 2.5) [90], and in the same sense that the CR has been proposed and widely studied for spectrum optimisation, we can use it in order to optimise energy consumption.

On the hardware level, new flexible technologies, capable of working by using different transmission parameters (modulation order, bandwidth, data rate, frequency,

power, etc.) and having a wide operational range are needed. Currently, one viable option is the Software Defined Radio (SDR) that compared to other choices like System-on-Chip (SoC) as mentioned in [90], provides enough flexibility and low cost in a single piece of hardware. The utilisation of cognitive radio is a key for enhancing all the set of techniques already discussed. This technique is strongly related to the RRM and transmission mechanisms we analysed due to its capability of sensing the channel conditions and make decisions on transmission parameters and resources to allocate.

In [91], for instance, a machine-learning mechanism for transmission power assignment in a non-cooperative environment is proposed. A non-cooperative environment is considered given the fact that power strategies among nodes could not be shared in a real scenario (e.g. due to conflict of interests between two operators). Each node chooses the transmission power behaving selfishly, only driven by receiving a reward. Based on the maximisation of this reward, a node can evaluate its strategy without knowing the other nodes strategy. This consideration leads us to an optimal transmission power strategy for all nodes deployed, which converges to Nash equilibrium [91]. In reference [92], a presentation of applications of CR for Green Radio systems is carried out. In the examples given, the capability of CR to be aware of surrounding environment is exploited. For instance, CR can help beam-forming control in a multi-sector BS, establishing the radiation pattern shape and tuning the direction of radiated power of sector antennas reducing the energy losses. Another example from the same reference presents the possibility of using CR to reduce radiation exposure by alerting the user that the body position towards the associated BS increases the cross body exposure.

As we will see later on, the Cognitive Radio should be considered more as an enabler for upper layer techniques than an approach that could bring savings by itself. As we will see in future chapters where we describe our contributions in cell breathing and macro/femto approaches, we will point out how the learning skills associated to Cognitive Radio could be really useful to adapt functioning parameters of those energy efficient algorithms in order to modify the network/component behaviour in function of environment conditions.

2.6 Base Station Components Enhancement Approach

Research on energy-efficient components is another very active research domain. It provides the foundations where benefits of each one of the upper layers techniques to

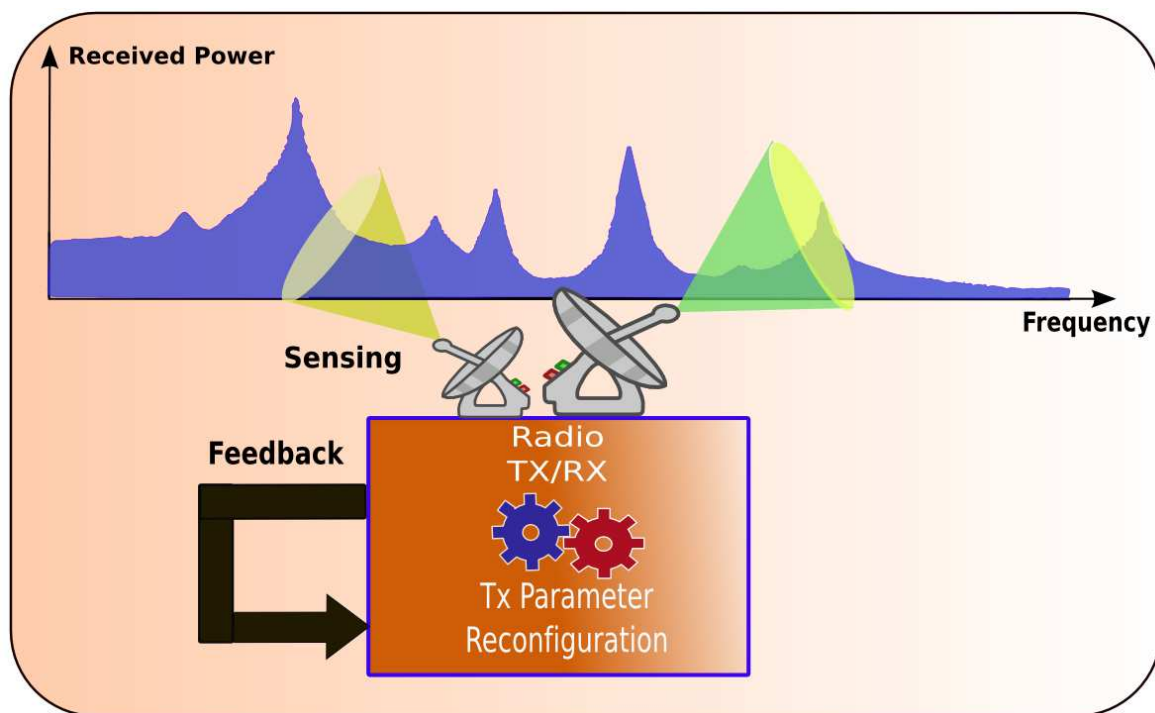


Figure 2.5 – The Cognitive Radio Process. In this figure, dish antenna clipart from <http://www.clker.com/>.

be discussed are supported. This research includes the internal BS architecture, idle components switch-off and component energy-efficiency enhancement. Probably one of the biggest concerns at this level is the RF power amplifier efficiency and, linked to that, the overall RF transmission chain efficiency. Some new internal base station architectures are being studied, like the one discussed in [8][40], where an amplifier goes right behind each antenna element (on the tower-top), located outside the equipment room. With this architecture the insertion losses due to cable connections are diminished. Those so-called top-tower architectures [8][40] connect the digital section to the RF antenna head-end by means of optical fibres to minimise here transmission losses. The obtainable benefits from photonics and optical fibres is a very hot topic nowadays and in the future of network research.

As already mentioned, great efforts are being made for the amplifier section, where different architectures and features have been proposed (Class J amplifier [40], switched mode power amplifier -SMPA [93], drain modulation technique [93], etc.). Such proposals promise higher efficiencies compared to pre-distorted Doherty amplifier [8][48][94], which is currently 45-50%. These approaches have the common objective of reducing amplifier losses and increasing power efficiency, linearity and reducing the PAPR. More details on this approach can be found in the above-cited references and in [39]. On the other hand, some manufacturers claim that their state-of-art amplifiers can

avoid the use of air-cooling as stated by FUJITSU for its Doherty pre-distorted power amplifier in [94]. This is also true for smaller BS equipment like femto or pico-BSs, which do not need an air-cooling component as shown in the models presented by [47]. Therefore, avoiding using air-cooling system in larger base station is a clear direction for fabricants. However it is also possible to take benefit of heat produced by Power Amplifier. The reference [93] shows the work done on benefiting from heating by reutilising the heat generated by means of using a Thermoelectric Generator (TEG). Such a device transforms such heat into electricity allowing some of the dissipated energy to be recovered.

2.7 Energy-Efficiency Classification Framework

In this section we classify all these mechanisms and proposals for energy efficient mobile networks that we have discussed so far. In Table 2.1 and 2.2, we propose a general classification for these proposals. Each technique is assessed in terms of attained energy savings and the consequences of applying such an approach on network planning and operation. Finally, we highlight some of the research challenges for each of these approaches. Then, these mechanisms and proposals can be integrated in the framework model we propose in Fig 2.6.

In our framework model of classification & integration we propose a stacked structure, where upper layers need the lower layers to increase their attainable savings. Firstly, we consider the component enhancement as the base of the energy efficiency for the radio access network (see section 2.6). For this reason, we name it component baseline layer (CB). The enhancement at this layer permits to relax the design constraints in order to facilitate the design in upper levels. This layer has a critical importance and new developments in internal components must be done for reducing the consumption and mitigate the losses into the base station. As we have seen a great amount of work is being done around the power amplifier and the effort should continue toward this direction. The reduction of power amplifier consumption reduces the heat dissipated and additionally avoids the necessity of having air-cooling systems into the Macro-BS, which reduces even more the consumption. Future advances in photonics and optical networks will reduce the losses due to internal components interconnection and at the backhaul level infrastructure.

However, considering the component approach as the solution of all the problems is rather insufficient in order to achieve large-scale savings. A not negligible amount of energy is wasted due to a not fully efficient utilisation of resources, which is even

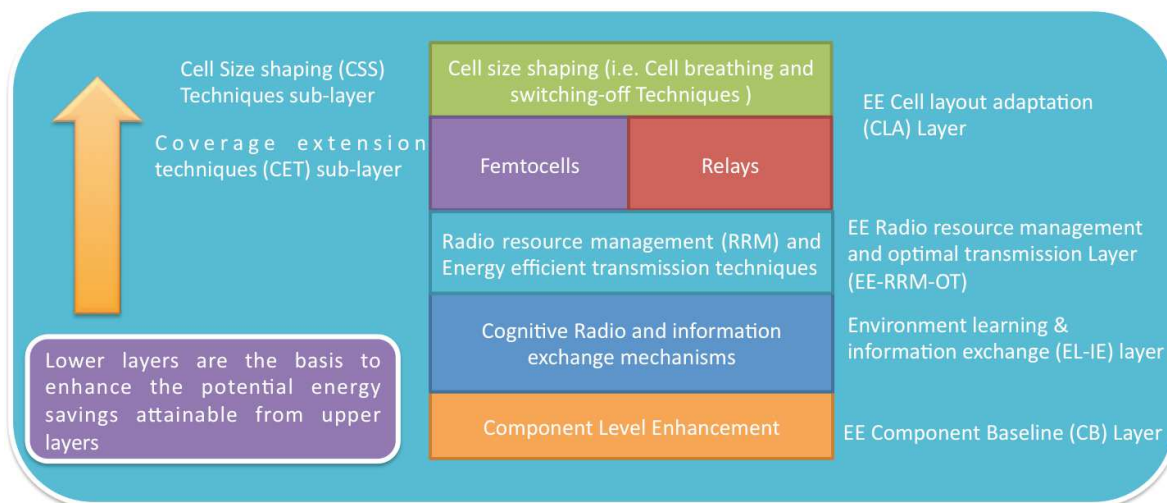


Figure 2.6 – Framework model of energy-efficient approaches

Research Issue	Energy Savings/Enhancements	Consequences on Planning & Operation Stage	Challenge
Cell layout adaptation (1/3): Cell breathing and switching-Off Schemes	Energy saving around (8-50)% according to: [28][29][55][56]	<ul style="list-style-type: none"> Energy efficiency improves with denser deployments and small cells [54]. However, it could increase infrastructure costs. Centralised cell breathing mechanisms could limit scalability and introduce single point failure nodes. 	Further work must be done in the mechanisms for coordination of distributed/clustered mechanisms at large-scale networks. This is important considering that future cell breathing mechanism will work in heterogeneous networks environments.
Cell layout adaptation (2/3): Macro/Femtocells Networks	Energy savings up to 60% combined with sleep modes[8].	<ul style="list-style-type: none"> Provides granularity for service provision by tailoring the network resources to the real traffic needs. Operating costs for a Macro-BS are higher compared to those for a femtoBS [32]. Careful planning needed: too many femtoBSs may imply over-provisioning (if no sleep mode used) [8] and increased OPEX [68]. 	Open aspects to study on coordination/management mechanisms associated to the network heterogeneity: e.g. BSs with different characteristics; interference and spectrum management in different environments.
Cell layout adaptation (3/3): Relays	Results in [78] shows savings of around (5%-20%) compared to classic single BS-MS point-to-point transmission.	The relays are useful as energy efficient mechanism only if the power consumed by relaying is sufficiently low compared to a direct BS-MS transmission [78][79].	The need for protocols and mechanisms in order to have cooperative schemes of relaying is still an open topic to explore. Additionally, further work must be done in bidirectional relaying [44].

Table 2.1 – Comparison Table of the different energy-efficient approaches – part 1.

Research Issue	Energy Savings/Enhancements	Consequences on Planning & Operation Stage	Challenge
RRM, Radio Resource Management, Mechanisms and energy-efficient transmission	There is a diversity of approaches in this domain. Therefore is difficult to give a representative figure.	With RRM algorithms and transmission techniques it exist always the possibility of taking advantage of trade-offs. However, to find the optimal operation point is a complex task.	Develop new mechanisms considering all different trade-offs is not an easy matter. The task becomes more complex if we consider that future networks are going moving forward to co-operative schemes.
Cognitive Radio	Cognitive Radio is a tool that works along with the RRM and the transmission mechanism. It is difficult to give a representative figure.	<ul style="list-style-type: none"> • New technologies like Software defined Radio (SDR) [90], are providing flexibility and low cost for the cognitive radio systems. • The cognitive radio is a very advantageous tool in environments where it exists conflict of interests and information is not shared among nodes. 	<ul style="list-style-type: none"> • Need of further work on flexibility of software and hardware to enhance the features that cognitive radio may bring to the energy-efficient approaches [90]. • There are open topics to study like the combination of backhauled protocols for information exchange with cognitive radio for having more accurate information of the network and surrounding environment.
BS Component Approach	<ul style="list-style-type: none"> • The main concern is the PA, which nowadays (e.g. Doherty-Pre-distorted, Class AB) has PA eff. around 50% [48][94]. • The Class J Amplifier is aimed to achieve PA eff. of 85% to 90% [40] • The SMPA although theoretically could reach 100% according to [48], so far it has reached PA eff. of 55% [93]. 	Having Energy efficient components is the basis before considering the other approaches for energy-efficient wireless networks	<ul style="list-style-type: none"> • Achieve higher components efficiencies is critical. New prototypes like Class J Amplifier [40] and SMPA [93] are candidates for next generation PAs. • Further work must be done in optical networks and photonics to reduce transmission losses at the backhaul and components interconnection.

Table 2.2 – Comparison Table of the different energy-efficient approaches – part 2.

more critical during the idle states of the base station. That is the reason for having upper layers above the components. The next layer is the environment learning & information exchange layer (EL-IE). For the EL-IE layer, we introduce the natural capabilities of cognitive radio (see section 2.5) to adapt the radio devices transmission parameters based on sensing external conditions. This adaptation will permit to find the optimal transmission strategies that optimise energy efficiency at the RRM level. These CR mechanisms however should not work alone taking into account that also information about surroundings can be complemented by the information shared by

BS neighbours. Such an information exchange can be done, whether by using the radio link or the backhaul infrastructure in a cooperative approach. The combination of the cognitive radio with the cooperative exchange of information among neighbours of a same radio access network will permit the base stations systems to have a good picture of environment and channel conditions, even if there are surrounding devices from a different network operator (i.e. non-cooperative neighbours) or any other type of radio devices and services sharing the frequency spectrum. All these efforts are intended to have an instantaneous information feedback that will permit the RRM level to make the best decisions. However, it has a huge importance to have a minimal consumption energy overhead due to these learning and information exchange processes and a lot effort must be done in maintaining here a very low energy regime.

To benefit of the previous layer we propose an energy efficient radio resource management and optimal transmission layer (EE-RRM-OT). This layer deals with the resources trade-offs we already spoke in section 2.4 for energy efficient transmission. The resources for transmission are limited and designers must carefully find a balance among the spectrum, the energy, power and time delays. For the current and future mobile networks, relax the constraints on transmission time delays is something very difficult, due to that such networks are increasing more and more the volume of data traffic for real time applications like video streaming and multimedia phone calls. This latter, makes more exigent the time delay constraints in order to guarantee quality. However, we have seen in the section 2.4 how frequency and space diversity approaches can help in the increase of the energy efficiency of a system. A clear direction to enhance the transmission performance is to continue the research in techniques like OFDMA and MIMO, which will permit to exploit better their capabilities to reduce the energy per bit figures. Moreover, if we consider that the future of mobile radio access networks goes toward the hybrid macro-femto approaches and BS cooperative transmissions (e.g. CoMP and DAS) there is a lot of work to do in coordination mechanisms for resource allocation in such approaches. Such RRM mechanisms should additionally permit the coexistence of a cooperative scheme of femto/macro base stations with other elements such as relays, by sharing efficiently the spectrum, avoiding the interference and allocating in a tailored way the resources (e.g. power and spectrum) to serve the incoming users.

Finally, we have the cell layout adaptation layer (CLA). The main mechanisms at this level are the switching-off and cell breathing schemes that provide savings at a network scale. We put these techniques at the top into the cell size shaping sub-layer (CSS). The granularity on service provision and the coverage extension is given by the (CET) sub-layer, where we find the heterogeneous femto/macro network architectures

and the relay devices. At the CET sub-layer is important to remark the importance of careful planning to avoid femto-BS overprovisioning, as well as, the need of coordination to apply the switching-off and cell breathing not only on the Macro-BS deployment but also extend or combine it with the femto-BS and relay level. Here we can say that the main keys to achieve the network scale savings at the CLA layer come from the lower layer approaches: firstly, a better circuitry and components that permit sleep modes with the lowest consumption and rapid transition from sleep to active and vice versa. During active mode the devices must work under power regimes tailored to real service demands by i) reducing the internal losses and power consumption into the devices, but above all, ii) by proper choices of resource allocated and adapted transmission parameters. Moreover, a critical point to discuss is the way in which the coordination will be performed in such heterogeneous environment. Although centralised approaches permit to obtain an instantaneous network panoramic, as we discussed in section 2.3, is something that limits the scalability and introduce single-point failure nodes into the network. Such coordination mechanisms should be therefore a halfway point that as we also said in 2.3 must be implemented by the utilisation of cooperative clusters of devices. Those devices into a common cluster (e.g. femto-BSs, Macro-BSs, relays, etc.) are responsible of an area of coverage with the collective goal of maximizing a cluster energy-performance indicator. In order to avoid conflicts with surrounding clusters, to manage the cluster resource allocation and coordinate cooperative transmission by means of heterogeneous devices, the combination of information exchange mechanisms and cognitive radio are a clear necessity to obtain an instantaneous information feedback of surroundings, which gives the necessary background information to establish the best actions to take.

2.8 Collaborative Projects on Energy-Efficiency or mobile networks

Due to the importance of this issue, a number of collaborative projects composed of different organisations from different sectors, such as research institutes, universities, and telecommunications providers, are dedicated to the energy-efficiency in wireless networks. In this section, we summarise the main projects on this topic.

The GreenTouch consortium [24] is a worldwide large-scale project led by Alcatel-Lucent/Bell Labs with partners from academia, research institutes, operators and fabricants, starting in January 2010 with a duration of five years finishing in January 2015. The ambitious goal intended by GreenTouch is to develop the whole architecture

needed to reduce by a factor of 1000 the current levels of energy consumptions in ICT networks. The large-scale proposal of this consortium, as stated in its mission [24], includes the necessary specifications and roadmap to achieve this goal. The projects and axis of GreenTouch cover all the network architecture including the core networking (i.e. switching, routing, transmission, etc.) and the wireless and mobile front-end networks. They propose to rethink and reinvent communications systems starting from the principles only constrained by the law of physics [24][41]. Moreover, there exists a great interest of GreenTouch in specific areas like optical networks and photonics, large scale antenna systems, dynamic wavelength mechanisms and distributed services [24]. Into GreenTouch there exists the project GREAT from Huawei [95], specialised in the domain of radio resource management for energy efficient networks. Their work is focused on identifying, analysing and modelling the resource trade-offs in mobile networks as mentioned in section 2.4 for the power, energy, spectrum, bandwidth, latency and deployment cost variables [83][96][97].

In Europe, the ICT-EARTH Project (Energy Aware Radio and Network Technologies) into the European Seventh Framework FP7 is also a very important large-scale initiative [23]. This project, mainly funded by European Commission, started in January 2010 and ended by June 2012. ICT-EARTH had a hollistical approach to the energy-efficiency problem [41], where all aspects and elements, i.e. social impact, energy efficiency metrics, green networks management mechanisms, components and green radio transmission aspects, were joined into a common integrated platform [23]. An important contribution of this project is the often-used E3F framework [47] where the network modelling (traffic Behaviour, BS energy model, deployment structure, etc.), the necessary energy-efficiency performance metrics, the energy-aware RRM techniques which can be applied, the network architecture and extension devices (e.g. femtoBSs and relays) were elements taken into account. For the final results of this project they established as objective new contributions for reducing at least by 50% the energy consumption of mobile networks. The shown final results and hardware prototypes were presented in the Future Network & Mobile Summit 2012 [23]. The attained simulation results outperformed the initial goals by having potential savings up to 70% for the 4G mobile networks technologies [98].

Also in Europe, the OPERA-NET (Optimising Power Efficiency in Mobile Radio Networks) in the framework of CELTIC (Cooperation for a sustained European Leadership in Telecommunications) is another key project in this field. Led by France Telecom, this project has already finished its phase 1 (OPERA-NET 1), which started in June 2008 and finished by May 2011. A second phase, OPERA-NET 2, is currently running since December 2011 with expected ending date in November 2014. In general

lines, the OPERA-NET initiative wants to respond to the concerns of European Union due to climatic change by enhancing the energy efficiency by 20% before 2020 [25]. The approach here is similar to the one already discussed with ICT-EARTH where the problem is studied from a holistic point of view. In OPERA-NET 1, different task forces were considered to cover different vital aspects: mobile radio access network engineering (e.g. key performance indicators, cell size optimisation, sleep modes, etc.), link level optimisation and technology enablers. About the obtained results, it must be remarked the important contribution done in the technology enablers axis, where new power amplifier architectures (e.g. SMPA [48][93]) and other hardware features were proposed (e.g. drain modulation technique and thermoelectric generator [93]). On the other hand, the OPERA-NET 2 is a continuation of the previous project but some other new axis were included. Here, although it is planned to delve deeper into the PA studies as done by OPERA-NET 1, other new subjects are analysed, as it is the studies on heterogeneous networks (macro/femto deployments) or the design and implementations of hybrid (grid/renewable energy) power supplied BS systems.

In United Kingdom, the Mobile VCE is a long-term platform started in 1997, where its last conducted work stage was the Core 5. This phase started in January 2009 and a duration of 3 years (finished by 2012). It was divided in four basic axis: Flexible Networks, User Interaction, Instant Knowledge and Green Radio. The goal in this last work axis was to reduce energy consumption by a factor of 100 in current high-speed data mobile services [26]. A good overview of the work carried out by this project can be seen in references [7][19][40]. The project presented some important contributions [26] like the random network coding as a better energy efficient alternative to the classic Hybrid ARQ (HARQ) [99], or the fibre-to-air concept where the RF signals are transported via optical fibre to the antenna transmitter, reducing therefore the transmission line losses [40][100]. However, the most remarkable contribution could be the introduction of the class J amplifier that promises efficiencies between 85-90% [40][101].

The project FP7-TREND (Towards Real Energy-efficient Network Design) [27] is also another european initiative with a hollistic approach, that as Greentouch is focused on studying all the network sections (i.e. terminal devices, core & access network, servers. etc). This project that started in september 2010 and expected to end in september 2013, supports its approach on four basic perspectives: find the way to measure and evaluate the energy-efficiency at the different network levels; to identify any element (devices, technologies, architectures & protocols) that contribute to the energy-efficiency goal and establish how to include it into the functioning of current networks; define the design basis of energy-aware networks; find experimental means

to test the proposed mechanisms. This project has contributed so far by providing a rich set of literature for the overall network green aspects. For the green radio, we can find examples like references [53] and [67].

On the other hand, in Germany, the Cool Silicon Cluster of Excellence, a project led by Technical University of Dresden, is a research effort mainly devoted to micro-electronics advances on energy-efficient components in the ICT domain [102]. In the specific area of green communications systems, there is an important set of topics being studied by Cool Silicon. There exists, for instance, a great interest from this initiative in developing mobile electronic devices with reduced consumption powered by solar energy. This latter is also considered for femto/Macro-BSs where low regime consumption is expected by optimising not only internal component functioning but also computing resources utilisation. Moreover, the Cool Silicon cluster is doing also research on topics like energy-efficient relays supported on the latest VLSI techniques, software optimisation for vehicular applications, and others like the study of transition from analogue technologies to low-consumption digital radio [102].

There exist others initiatives like the GREENET, a training program to prepare future PhDs in Energy Efficiency for Green mobile networks led by the Polytechnic University of Catalonia and supported by European Commission, the FP7 and the 2010 Marie Curie Programme [103]. The project that started in 2011 with duration of 3 years, studies the energy efficiency at different levels into a collaborative scheme and a structured training platform with teams working on different approaches: physical layer components, energy-aware RRM and MAC mechanisms, network coding and cooperative schemes [103] [104]. So far, this project has contributed with a great number of articles into the Green Networks domain (See, for instance, [35][105][106][107]).

In the area of femtocells, The BeFemto Project, started in January 2010 with a duration of 30 months (finished in July 2012), was fully dedicated to femtocells technology and its real applicability in mobile networks [108]. Within the goals of this project, it was intended to reduce the maximum averaged transmit power under the 10mW for indoor femto-BSs, and reach a system spectral efficiency of at least 8b/s/Hz/cell. Other objectives proposed were to find new ways of use and applications of femtocells in different environments considering additional aspects like mobility (e.g. vehicular applications). Some interesting publications have come out from this project in the domain of femtocell networks, like [109] for power allocation, [110] about interference management, [111] in CoMP for heterogeneous networks or [112] on interference coordination and radio resource sharing in macro-femto networks.

Finally, we mention the project eWIN (Energy-efficient wireless networking) led by KTH in Sweden. The project proposes to provide the fundamental basis that permit

to reduce the energy consumption, as well as to rethink the way as wireless technology architectures are conceived and designed, which so far only takes care of elements like availability, coverage and throughput capacity. The approach of the project studies specifically the radio resource management optimisation, the protocols and mechanisms, in order to deal with the resource trade-offs, which are the key enablers of future energy-efficient architectures. A good example of the work is being performed in this project are the references [64][84][113][114].

2.9 A justification to our chosen axis contribution in Green Radio

In section 2.7 our point of view on how the current energy-efficient approaches should work together, was described. It is clear now, how impossible is to attack all the perspectives and all the abstraction levels by a single proposal. It was rather the purpose of this state of art to detect the good direction to take by choosing an approach where the impact on the overall network savings were the largest. In that sense, after a profound analysis, we decided to explore and contribute into the domain of techniques we already grouped into the cell layout adaptation layer (CLA), due to the expertise of our research team in Radio Resource Management (RRM) and radio access network infrastructure, as well as we consider that the family of techniques at this layer is able to bring a higher impact on the global energy savings for the mobile network.

We noticed the multiple options of research paths to choose by combining one of the already coverage extension approaches (i.e. heterogeneous architectures, relays) with the switching-off scheme and cell breathing approaches. In the literature study, we have seen already work on combining, for example, relaying methods and BS switch-off techniques (see, for instance, ref. [78]), as well as, a large quantity of work on switching-off schemes for heterogeneous networks under configurations macro-femto or macro-pico. However, into that wide spectrum of proposals we did not find any initiative so far aimed to combine elements like the cell-breathing at the Macro-BS layer and the heterogeneous network features in order to boost the savings. That last idea constituted our milestone to lead our research and we decide first going through a distributed cell-breathing basic architecture, for afterwards, enhance it by the use of Macro-to-femto offloading.

We found however that at this level the research initiatives were not going deeply in some aspects. In such sense, we must say that in general most of the approaches and proposals we found in this layer were exclusively targeted to provide energy-savings on

the RAN skipping of the analysis, important elements like the implications of using a given technique on the MS side performance, or other green aspects, like the associated electromagnetic compliance of a determined mechanism implementation. Furthermore, we point out some other weaknesses in this approach like, for example, a clear bias for solving the management problem by relying on centralised mechanisms, instead of going deeper into distributed techniques.

Moreover, it is well-known the fact that mobile networks become more and more heterogeneous. We then noticed i) that current networks are becoming more complex due to having access devices with different regimes of power consumption, energy supply sources, ranges of coverage and resource capacities ii) proposed mechanisms in the literature normally make decisions by relying on a single parameter, e.g., current BS load, SINR, power levels, etc. In such sense we decided to go forward by improving our mechanism with a multi-metric approach that allow us to define a better intelligence behaviour based on the network characteristics, opening the possibility in the future work after this thesis to include a learning mechanism behind, in order to give to our solution a fully self-organised and autonomous way of management. Summing this up, all those described elements entered to count on the way we designed our energy-efficient strategy and how we planned its related analysis.

A Clustered and Distributed BS Based Cell-Breathing Algorithm

3.1 Introduction

In this chapter we present our first contribution in Green Radio, which is the milestone of our further progress presented in this thesis. Here we describe the Distributed BS Based Cell-Breathing (DBCBC) originally presented in our article “*Energy performance of a distributed BS based green cell breathing algorithm*” [17]. As we already mentioned in the previous chapter, the cell breathing is a technique that permits to adapt the network topology and cell sizes to the current traffic conditions. Here, the low-loaded cells reduce their coverage area to zero as well as they redistribute their load toward the surrounding active neighbors, which additionally must extend their coverage. The BS switch-off can be performed by deactivating the BSs and conveniently expanding the cell size of the BSs around to provide coverage, or in a more sharp way, by deactivating the individual BS sectors and extending the coverage of the surrounding adjacent sectors in order to fill the coverage holes left by the switched-off sectors (see for instance, reference [59]). An example of this described type of cell expansion is given in Fig. 3.1.

The first novelty of this cell breathing approach is the use of a clustered architecture, something that we will describe deeper in the subsection 3.3.2. This type of architecture permits to implement a robust distributed algorithmic intelligence into the network. The reason of having chosen a distributed approach is to avoid the single point failures nodes of centralised approaches, as well as, bring a better network scalability to our proposed solution. The algorithm is executed independently in each BS, where each one of the BSs belong to a group of BSs that we call cluster. Each one of these clusters

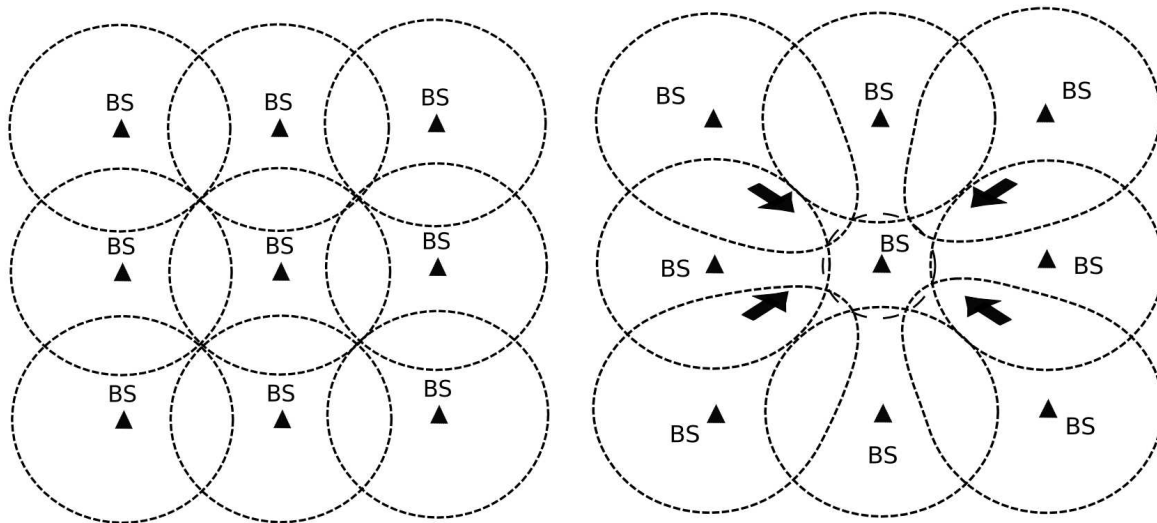


Figure 3.1 – Cell Breathing BS switching-off and coverage holes handling based on individual neighbouring sectors expansion.

is controlled by a cluster head, a delegated BS into the cluster group, with very basic management and signaling functions compared to a real central server that must take charge of the whole organisation. The algorithm presents a very good performance that outperforms other distributed approaches and is able to match, and in some cases improve, the performance of some centralised proposals. Also in this chapter we present the enhancement of the DBCB presented in our article “*Analysis of the overall energy savings achieved by green cell-breathing mechanisms*” [18], a proposal that we called Mobile Aware DBCB (MA-DBCB). The motivation of this new work is the search of a way to balance the RAN savings and the MS individual energy consumption, something that has been not discussed deeply by literature, except by recent references like [35] that proposed a distance aware cell-breathing, more or less in the same period we presented our first results. Despite of that fact, we can say that our proposal is in some sense more complete with respect to [35], due to the possibility of setting the desirable operation point by means of tunable parameters, something that in the approach considered in [35] is lost by relying only in MS-BS distance.

3.2 Macrocellular Network System Model

In this section we describe the system model used for our first two Green Radio Proposals. For this chapter we consider a Macro-Only cellular network based on 3G/CDMA technology in order to test the Macro-Cell Breathing approach proposed and other algorithms found in the literature. Here we give a description of the device mod-

els considered for the BS and the MS respectively; the network model and the cell breathing problem assumptions; finally, we close by describing the transmission channel characteristics.

3.2.1 BS and MS Models

First, we define a power model for each BS j that allows us to study the total consumption of the radio access network as well as the individual BS site consumption. For this first model, we have considered a 3-sectorised BS transmission system and its associated BS antenna gain pattern model. In this first version of the simulator, the BS switch-off is not done individually per sector but we switch off the full BS site instead. The BS power model could be derived from the figures found in sources like [22][39][47][115] (ICT-EARTH Project), which shows the relationships of input power to output power for a BS. The behavior of a BS j in active mode is characterised by, first, a fixed consumption P_j^{fixed} product of the sum of the contributions of different components as it is the baseband signal processing, the cooling system, the power supply and the idle component of the power amplifier, whose consumed power is considered not dependent of the transmission power P_j^{Tx} . On the other hand, the power amplifier consumption during transmission is, on the contrary, directly dependant of transmission power. The BS j consumed power P_j , in active mode may be expressed by the Eq. 3.1 [115]:

$$P_j = P_j^{fixed} + \eta \cdot P_j^{Tx} \quad (3.1)$$

where $\eta \geq 1$ corresponds to a constant that represents the power supply increment needed by the power amplifier per watt transmitted. On the other hand, for the sleep mode we consider a BS consumed power P_j equal to P_j^{sleep} .

For the capacity model of the BSs at this first development stage we made the very basic assumption of considering a fixed maximum capacity for a BS j given by C_j^{max} , a similar approach to the one done in [28][29]. We must mention that in our capacity model we consider a common resource pool for the whole BS site represented in a value of maximum attainable data rate. In our simulations we take similar values to those of [31] for the BS data rate capacity. Then, we provide to each MS i a fixed amount of resources c_i in order to be served by its acceptor BS. Consequently, a BS j can have associated a number of M_j users, which must respect the following condition of normalised load $L_j \leq 1$ as expressed in Eq. 3.2 [29]:

$$L_j = \sum_{i=1}^{M_j} \frac{c_i}{C_j^{max}} \leq 1 \quad (3.2)$$

For the BS transmission model, we considered a 3-sectorised model. All BSs in the deployment share a portion of the spectrum called W_M with multiple access system based on the 3G/W-CDMA technology. Specifically for the BS site antenna gain we shape the radiation pattern by using three associated main lobes, one per sector. In the model we implement only the horizontal radiation pattern is considered [116]:

$$A(\theta) = -\min \left[12 \left(\frac{\theta}{\theta_{3dB}} \right)^2, A_m \right]$$

where, $-180 \leq \theta \leq 180$ (3.3)

where θ corresponds to the angle between the direction of interest and the maximum beam intensity direction (i.e. the boresight direction); θ_{3dB} corresponds to the 3dB beamwidth, and A_m to the maximum attenuation [116]. For the MS antenna model we simply consider an omnidirectional antenna pattern with unitary gain. On the other hand, we consider a MS power consumption model for active (i.e. calling) and idle modes. Each MS i consumes a total power P_i . The numerical values we define here, they are chosen taking approximative figures from the measurements done in [117]. During idle mode the mobile consumes a power of P_i^{fixed} , whereas during a call, a power P_i^{call} is consumed. We consider this power as the sum of the P_i^{fixed} component (i.e. a minimum consumption always present) plus a component associated to transmission, where MS transmitted power corresponds to P_i^{Tx} . The power P_i can be therefore defined as:

$$P_i = \begin{cases} P_i^{fixed} & \text{in idle mode} \\ P_i^{call} = P_i^{fixed} + \frac{1}{\gamma_i} P_i^{Tx} & \text{during a call} \end{cases} \quad (3.4)$$

where, $\gamma_i \leq 1$ corresponds to the PA efficiency (see for instance ref. [118]) of the MS transmitter. The values for γ_i were approximated from figures in references [118][119].

3.2.2 Transmission channel characteristics

For the transmission channel we considered a COST-HATA 231 path loss model [120], which is valid for frequencies between 1.5 and 2GHz. The equation of the path-loss L according to the model is the following:

$$\begin{aligned}
L &= 46.3 + 33.9 \log \left(\frac{f}{\text{MHz}} \right) - 13.82 \log \left(\frac{h_{BS}}{m} \right) - a(h_{MS}) \\
&+ \left[44.9 - 6.55 \log \left(\frac{h_{BS}}{m} \right) \right] \log \left(\frac{d}{\text{km}} \right) + C_m
\end{aligned} \tag{3.5}$$

where $a(h_{MS})$ corresponds to:

$$\begin{aligned}
a(h_{MS}) &= \left[1.1 \log \left(\frac{f}{\text{MHz}} \right) - 0.7 \right] \left(\frac{h_{MS}}{m} \right) \\
&- \left[1.56 \log \left(\frac{f}{\text{MHz}} \right) - 0.8 \right]
\end{aligned} \tag{3.6}$$

and C_m is 0dB for suburban scenarios and 3dB for large metropolitan city scenarios. The model is valid under the following restrictions:

- a range of frequency between 1500 and 2000 MHz
- a BS height h_{BS} between 30 and 200m
- a MS height h_{MS} between 1 and 10m
- a path distance d between 1 and 20km

For this first path-loss approach, we did not consider a shadowing function accompanying the path losses. However, in our link budget constant margins associated to the fast fading and shadow fading were considered [121]. Also in our model of losses some other element were taken into account like the BS cable losses and the MS body losses [121]. All those values are shown later on in the simulation parameters in table 3.1.

3.2.3 Interference Model

Downlink interference

For the downlink we consider a simplified model for the interference. We call $P_{S,i}^{Rx}$ the received power in downlink for a given MS i associated to the BS $S \in \Omega$, where Ω corresponds to the whole set of BSs that compose the macrolayer. The equation that expresses this power $P_{S,i}^{Rx}$ is given by:

$$P_{S,i}^{Rx} = P_{S,i}^{Tx} G_S^{Tx} G_i^{Rx} G_{i,S} \quad (3.7)$$

where, $P_{S,i}^{Tx}$ corresponds to the transmitted power from S ; G_S^{Tx} corresponds to the BS transmitter gain, G_i^{Rx} corresponds to the receiver gain into the MS and $G_{i,S}$ corresponds to the channel gain.

Moreover, we have the associated Signal to Interference and Noise ratio $\gamma_{S,i}$ for the incoming signal given by:

$$\gamma_{S,i} = \frac{P_{S,i}^{Tx} G_S^{Tx} G_i^{Rx} G_{i,S}}{\sum_{j \neq S}^N P_{i,j}^{Rx} + N_0} \quad (3.8)$$

where, $P_{i,j}^{Rx}$ corresponds to the power received from any other BS $j \neq S \in \Omega$, and N_0 corresponds to thermal background noise.

In our model we check that for each MS i associated to the BS S the downlink received power is sufficiently enough to have a minimal $\gamma_{S,i}$ that makes the signal intelligible for the MS receiver. This is a very rough estimation due to the fact the power values of other already associated MSs are not updated after associating a new incoming MS. This approach may be considered valid for low network loads where interference values is small.

Uplink interference

For the interference in uplink, we use the equations for the estimation of capacity for a CDMA system as shown in [122]. According to this reference the number of users per cell M_c can be calculated as:

$$M_c = \frac{G_A \cdot W/R}{(1 + f) \cdot (Eb/N_0)_T} \quad (3.9)$$

where, f corresponds to the ratio of intracell to intercell interference, normally equal to 0.55; G_A corresponds to the sectorisation gain, which for simplicity reasons we consider equal to 1; W/R corresponds to the ratio of spectrum bandwidth W to data rate R , and finally, $(Eb/N_0)_T$, corresponds to the minimal ratio of energy per bit to noise power spectral density for any user. This last parameter corresponds to $(Eb/N_0)_T =$

$(W/R) \frac{P_{th}^{Rx}}{I_0}$, where P_{th}^{Rx} is the threshold power received by the BS receiver and I_0 the total interference for a MS transmission in uplink. By using the Eq 3.9 and replacing the definition of $(Eb/N_0)_T$ and $G_A = 1$ we have that:

$$M_c = \frac{1}{(1+f) \frac{P_{th}^{Rx}}{I_0}} \quad (3.10)$$

From there we can have an estimated value for I_0 as:

$$I_0 = M_c \cdot (1+f) \cdot P_{th}^{Rx} \quad (3.11)$$

Although this is a rough estimation, our interest is more focused on understanding the behaviour of the uplink transmission power rather than having accurate interference values.

3.2.4 Macrocellular network modelling, constraints and the cell breathing problem

In our model we consider a set Ω of N deployed 3 sector BS sites and another set Ψ composed of M MSs located in a given area. For the the set Ω we consider a hexagonal architecture deployment, whereas for Ψ the MSs are randomly deployed by using an uniform distribution. We define the total energy consumed by the RAN $E_{RAN}(\tau)$ from $t = 0$ to $t = \tau$ as:

$$E_{RAN}(\tau) = \int_{\tau} P_{RAN}(t) dt = \sum_{j=1}^N \bar{P}_j \cdot \tau \quad (3.12)$$

where $P_{RAN}(t)$ corresponds to the total power consumed by the RAN and \bar{P}_j the average power consumed by a BS $j \in \Omega$, during a period τ . The purpose of any green cell-breathing algorithm including the one we originally presented in [17] is to minimise E_{RAN} respecting the network service and functioning constraints. This is done by switching-off the greater number of BSs during the longest period of time possible. The network is constrained by three main conditions: firstly, the blocking percentage ρ_b must be below a limit $\rho_{b,max}$ to guarantee service quality and availability; secondly, for the cell breathing the acceptor neighbor cells cannot grow limitless in size

because there exist a finite transmission power $P_i^{Tx_{max}}$ for any MS $i \in \Psi$ and $P_j^{Tx_{max}}$ for any BS $j \in \Omega$; last but not least, each BS j has a limited value of maximum capacity C_j^{max} . Therefore, derived from the previous facts the problem formulation of cell breathing can be summarised then in the following expression:

$$\begin{aligned}
 \min(E_{RAN}(\tau)) &= \int_{\tau} P_{RAN}(t) dt = \sum_{j=1}^N \bar{P}_j \cdot \tau \\
 \text{s.t :} \\
 C_j(t) &\leq C_j^{max}, P^{Tx_j} \leq P_j^{Tx_{max}}, \forall j \in \Omega \\
 P^{Tx_i} &\leq P_i^{Tx_{max}}, \forall i \in \Psi \\
 \rho_b(t) &\leq \rho_{b_{max}}
 \end{aligned} \tag{3.13}$$

This interest of minimise the RAN energy under the network constraints is the classic approach that normally is taken for the cell breathing. However, if we go deeper into the spirit of the green networks, the game should be rather applied on the overall total energy consumed E_{Total} during a period τ , $E_{Total}(\tau)$ i.e. the energy of the MSs and the RAN:

$$E_{Total}(\tau) = \left(\sum_{j=1}^N \bar{P}_j + \sum_{i=1}^M \bar{P}_i \right) \cdot \tau \tag{3.14}$$

The proposed Cell breathing algorithms, so far and to the best of our knowledge, have given only proposals for the RAN side neglecting the importance of mobile phone consumption. We consider that the optimisation problem must address both, the MS and the BS. By reducing the number of active cells we increase the average distance between the MS and BS, increasing therefore the needed transmission power in uplink. Hence, an energy trade-off appears between the RAN and the MS users. What we want to do is to minimise the impact of cell breathing as much as possible in the MS without a major impact on the RAN, where the major savings are obtained.

3.3 A Distributed BS Based Cell Breathing Algorithm (DFCB)

3.3.1 Benchmark proposals on Cell breathing

The proposals detailed in this subsection have the purpose of being the reference benchmark for our cell-breathing algorithms presented in this chapter. As we said in the previous chapter, the cell-breathing is a technique that was conceived in the 90's [51][52] in order to find a way to reduce the global interference. It is just recently that cell-breathing is being used for energy saving purposes. The works to be presented here were chosen because we consider them as very representative pieces of the state of art in cell breathing for energy-efficiency. A first reference to cite is [29], where the cell zooming technique is presented. For the algorithms provided here, the MS-BS association mechanisms prefer to concentrate the traffic into the highest loaded BSs, allowing the rest of BSs deployed with very low load or zero load going to sleep mode. The algorithm is presented in two ways: a centralised, where a cell zooming server coordinates the association; a distributed version where MS decides to whom associate with, based on a utility function by the BSs. In the case of the centralised algorithm, the central server executes the cell deactivation in two phases: first the MS are associated to the BSs by using the criterion of associating the MSs to BSs where the spectrum efficiency is the highest. After this first association phase, some of the BSs will be zero loaded and therefore deactivated. In a second phase, those BSs remaining with low load redistribute their load toward those higher loaded, which allows deactivating some more BSs.

In [31], the authors propose to use a centralised server that guarantees sequentiality. This server randomly selects the BSs to switch-off from a list of candidates. Before any switching-off attempt by the central server, the consequences on the network are evaluated. To fill the list of candidates, each BS proposes itself as candidate as long as its load is under a certain threshold A_M . This threshold is very useful to define the behaviour of the RAN. A very low threshold reduces the number of switched off BSs giving priority to the coverage and availability, whereas a high threshold prioritises the energy savings.

In reference [30] an approach known as procooperation is considered. The algorithm is executed independently by each BS, which makes this proposal a fully BS distributed algorithm. Here, the mutual cooperation among BSs permits to make decisions based on three different thresholds. When the traffic is below a threshold A_L the BS decides to sleep. A pair of neighbors is chosen to be the acceptors of the traffic to be released

by this BS. Such acceptor neighbors share in half the redistributed traffic. Before one of the acceptor candidates accepts redistributed traffic, it must check if the new load after redistribution is below another threshold A_S . There is a third threshold A_H that if it is exceeded, the BS can request all surrounding neighbors to take its traffic fully or partially (i.e. in the case there is not enough availability of resources to accept the full traffic). In the case the traffic is fully redistributed this BS goes to sleep mode, whereas if it is not, the BS remains active with a reduced level of transmission power and users associated.

3.3.2 DBCB Proposal Description

Our algorithm, the Distributed BS Based Cell Breathing (DBCB), is supported on an architecture of mutually synchronised $n \times n$ BS sites clusters. Here, the execution of the cell-breathing algorithm is done in a distributed way into the cluster, with a triggered execution BS-by-BS. When the DBCB is executed in a BS j of a certain cluster, it initially requests the normalised load L_h of each surrounding neighbor $h \in \Omega_{B_j}$, where Ω_{B_j} corresponds to the set of active neighbors of j . Those neighbors are not necessarily going to be part of the same cluster. Then, it must be checked if the set of surrounding active BSs is able to accept the full load of the BS j , or in other words:

$$\sum_{h \in \Omega_{B_j}} (1 - L_h) \geq L_j \quad (3.15)$$

Then, the BS j must make a decision based on its own load: if the BS j has a higher value of L_j compared to its adjacent neighbors (i.e. $L_j \geq L_h, \forall h \in \Omega_{B_j}$), the BS does not redistribute and neither goes to sleep. On the contrary case, the set of active neighbors Ω_{B_j} is sorted in descending order based on the normalised load L_h of each active neighbor. The traffic is redistributed in function of the available resources found in Ω_{B_j} , redistributing it, first to the highest loaded in the set. When a certain neighbor h does not have enough resources to receive certain redistributed MS i , it continues with the next BS into the sorted list till finding a neighbor who can accept this traffic. Only if all MSs of set M_j are fully redistributed, the BS j can go to sleep mode; otherwise, if by any reason, everyone of the neighbors block a given redistributed user i , the BS perform a rollback of association changes to be performed, and goes to the previous state, maintaining therefore the initial associations. A detailed flowchart of the DBCB algorithm is provided in Fig 3.2.

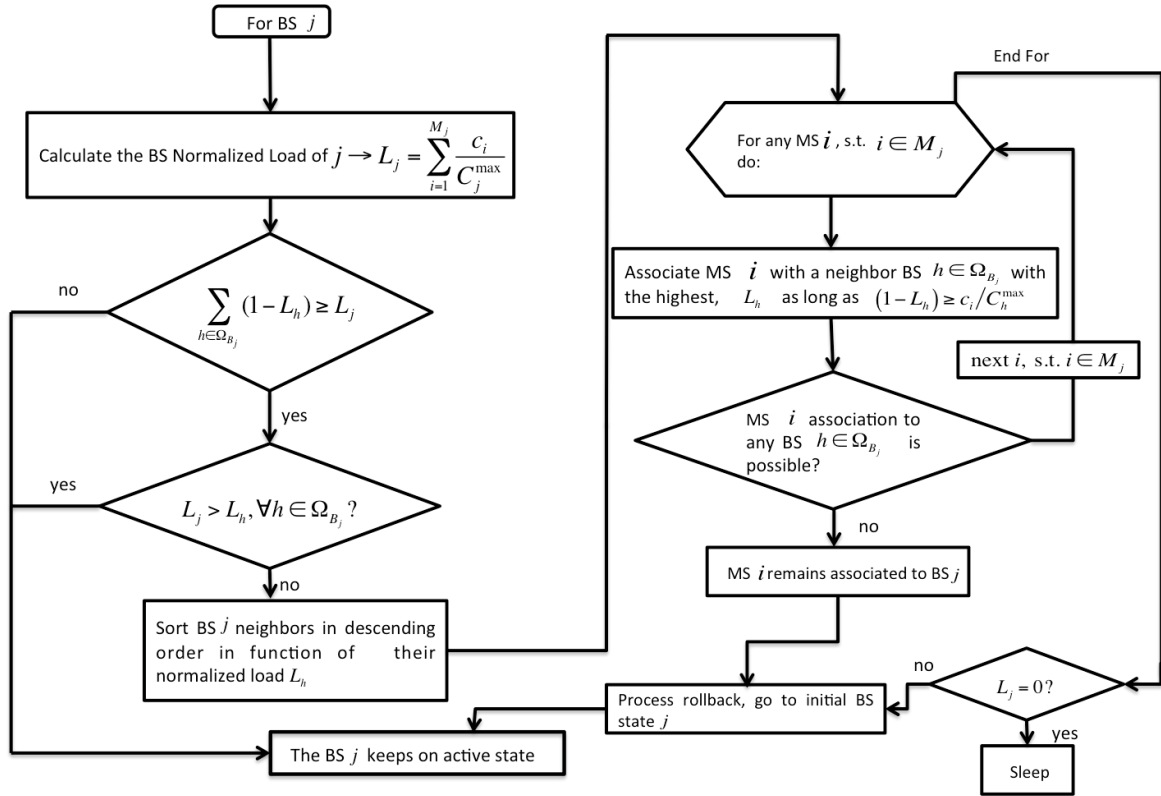


Figure 3.2 – The DCB flowchart for a BS executing the algorithm

The clustered architecture guarantees scalability and feasibility of the algorithm in larger networks. Each cluster has a “cluster head”, that is a designated BS that exchanges messages with other cluster heads of other clusters for synchronisation purposes. The message exchange and synchronisation can be achieved by using the backhaul infrastructure. Inside each cluster there is an algorithm sequence synchronised with the rest of clusters, in order to avoid the conflicts that could appear if two adjacent or neighbouring BSs with common neighbors execute concurrently the algorithm. The first to execute the algorithm into the cluster is the cluster head, and then according to the determined sequence the algorithm is run into each BS. In Fig. 3.3 we present an example of four adjacent 3x3 cell size clusters. We must point out that 3x3 size cluster is the minimal cluster size in order to avoid execution conflicts. In such case, never two BSs of two different adjacent clusters, with the same relative position in the cluster sequence, share common adjacent neighbors. For instance, the cells C1.4, C2.4, C3.4 and C4.4 have the same relative position in each one of their clusters and none of them share common neighbors (see Fig. 3.3). It is therefore possible in such case that cells having the same relative position in the cluster sequence execute the algorithm concurrently without any risk of conflict or a prior network jeopardise. Also notice in this Fig 3.3 that cluster head relative positions were arbitrary chosen. This can be

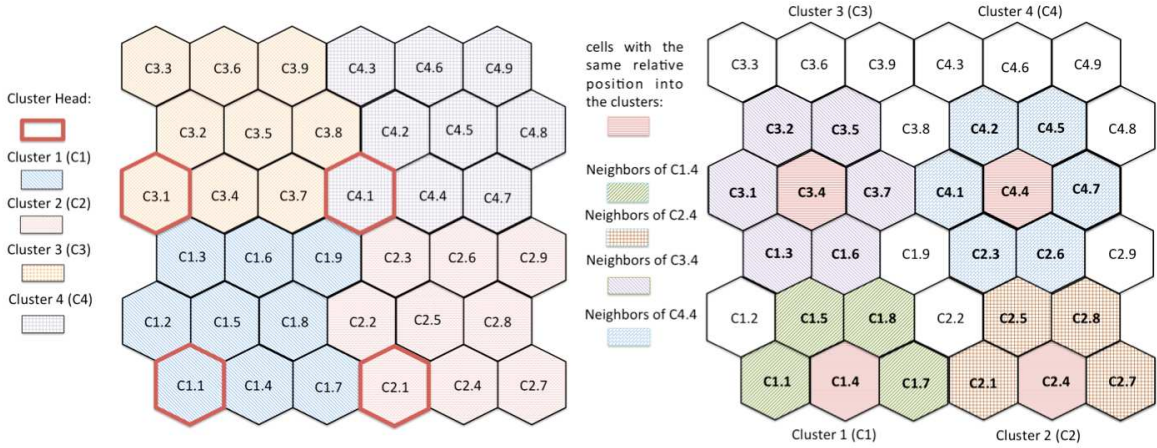


Figure 3.3 – Four 3x3 BS cluster zones: (left) Cluster Zones delimitation and an arbitrary Cluster Head position; (Right) Four arbitrary cells and its corresponding neighbor cells

done as long as the respective relative positions in all the clusters are respected. In case, the cluster head is switched-off (i.e. its BS normal functions) some computing internal components must be active in order to continue the signaling and synchronisation tasks through the backhaul. On the other hand, in case of full unavailability of a cluster head, a “temporary sucesor cluster head” into the cluster must have been previously chosen by the previous cluster head in order to be a backup replacement. This temporary cluster head, however, must respect the previous defined BS algorithm execution sequence, in order to not affect other clusters sequence.

3.4 A Mobile Energy Consumption Aware DBCB Algorithm (MA-DBCB)

Then, we wished to make an enhancement for our already proposed DBCB algorithm also taking the MS side, above all the uplink transmission power. For the new algorithm version, called Mobile Aware DBCB (MA-DBCB), we impose additionally a load threshold A_T that blocks the algorithm execution even if the necessary execution conditions already explained in previous section are fulfilled. We can see some similarities with the A_M threshold used in [31] for controlling the switching-off agressivity. However, here the difference lies on the fact that switching-off decisions are done locally (i.e. a distributed approach). For the MA-DBCB only a BS with a normalised load below the traffic threshold A_T can execute the algorithm. This limits the number of BSs that can be deactivated, which means that also the resulting cell size is controlled.

Additionally, in order to take into account the uplink losses we introduce a new MS-BS metric as follows:

$$M_{MA-DBCB_h} = \left[L_h + \frac{c_i}{C_{max}^h} \right] \cdot SINR_{i-h} \quad (3.16)$$

where $SINR_{i-h}$ is the signal-to-noise ratio of a signal sent by the MS i and measured at the receiver of the BS h , and C_{max}^h the maximum capacity of h . After having calculated this metric value, the BS h transfers this information to the BS j through the backhaul. The $M_{MA-DBCB_h}$ is a metric that takes into account the load of the neighbor h , but also takes into account the distance and losses between the BS h and the MS i , which it was being neglected in our previous DBCB and that reduce substantially the uplink transmission power. The importance of reducing the impact of cell breathing on uplink is crucial in order to not affect the user perception of the MS performance, which could be deteriorated if the mobile phone ran out of battery faster during green cell breathing periods.

3.5 Simulation Results for the DBCB and MA-DBCB techniques

3.5.1 Comparison of the DBCB and MA-DBCB vs. other Cell Breathing Approaches

A Montecarlo simulation was performed to test the performance of different cell-breathing algorithms, including ours. Under this approach, a set of BS sites is deployed in a given area and a set of randomly uniform located MSs must be associated to the RAN in order to be served. The simulation consists of several snapshots with different distribution of MSs on the coverage area. Different values are calculated for each snapshot and then an average is obtained in order to provide the final results. In Table 3.1 we summarise the main simulation parameters.

The algorithms simulated here are: the classic MS/BS association with no sleep mode capabilities (Normal Association); the distributed (DCZ) and centralised cell zooming (CCZ) [29]; the sequential switching off cell breathing (SSOCB) [31]; the protooperation cell-breathing (PCB) [30]; the distributed BS based cell breathing (DBCB) [17] and its mobile aware version MA-DBCB [18]. All algorithms have the same values of blocking percentage for the different values of normalised network load

Parameter Name	Value or Choice
<i>BS site type</i>	3-sector antenna BS
<i>Wireless Standard Technology</i>	3G/CDMA
<i>Intersite Distance</i>	500m
<i>Central Frequency</i>	2100 MHz
<i>Path Loss Model</i>	COST-HATA 231: $L = 137 + 35.7\log(d)$ [121], d in km Shadow Fading Margin=7.5dB Fast Fading Margin= 0dB (uplink); 4dB (downlink) Diversity Gain= 3dB (uplink); 0dB (downlink)
<i>Max Data Rate Capacity</i>	14.4 Mbps per BS site
<i>Spectrum Bandwidth</i>	5MHz
<i>Data Rate per MS</i>	256kbps (fixed)
<i>Number of Sites</i>	(6x6) 36 sites in total 4 (3x3) clusters for DBCB
<i>BS sector parameters</i>	$P_j^{Tx-max} = 40W$; $P_j^{fixed} = 300W$ $P_j^{sleep} = 50W$; $\eta=5$; BS Max. Antenna Gain = 17.5dBi; BS Cable losses = 2dB BS Noise Figure = 5dB
<i>MS parameters</i>	$P_i^{fixed} = 500mW$; $P_i^{Tx} = 750mW$ $\gamma_i = 0.5$; MS Antenna Gain = 0dBi; MS Body Loss = 2dB; MS Noise Figure = 7dB
<i>Number of Montecarlo Distributions</i>	1000
<i>Normalised Load Thresholds</i>	PCB: $A_H = 0.9$; $A_L = 0.3$; $A_S=0.7$; SSOCB: $A_M = 0.25$; MA-DBCB: $A_T = 0.25$

Table 3.1 – Simulation parameters for the simulations in this chapter

into the interval displayed that goes from 0 to 0.5 (aproximatively it goes from 0 to 5%). This latter, given the fact that before each one of the algorithms is executed a MS-BS preassociation is performed and users are accepted or dropped in function of the nominal capacity and the interference levels. After that, all cell-breathing algorithms run following the rule of not dropping more users than those already blocked in this first preassociation phase.

We start our analysis by looking first at the RAN. In Fig. 3.4 we present the number of BSs switched-off in function of different levels of network load. We see how the original version of DBCB is able to switch-off more BSs compared to the rest of algorithms. We also notice that for the MA-DBCB these values are only slightly reduced being very tied to the SSOCB proposed in [31].

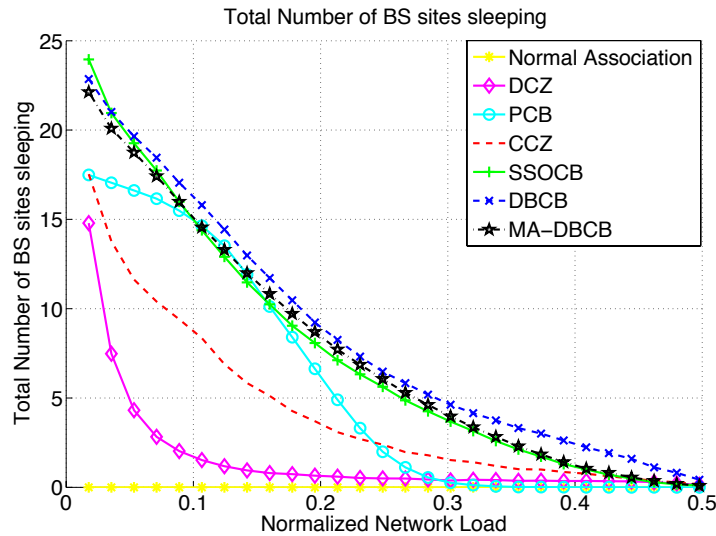


Figure 3.4 – Total Number of BS sites in sleep mode for the different simulated algorithms.

For Fig. 3.5 we see the global consumption including the RAN consumption and the MSs consumption. This consumption is nearly totally influenced by the results on the RAN due to the fact that a BS site consumes a power that goes from 150 watts to 1500 watts approximately, whereas a single MS consumes between 500mW to 2W as well as combined with the fact of having a rather low volume of users in our simulations. However, the MS energy consumption is something important for the user and consequently the user perception is something that must not be neglected by the operator. The users are interested in devices with long battery duration, more in the case where an electrical outlet is not easily available. A MS may need increase its transmission power when the number of active BSs is reduced. This latter given the fact that the MS-BS average distance increases because of having less cells covering larger areas. Moreover, this increment of MS transmission power may be potentially harmful for the human body due to the associated electromagnetic radiation.

Analysing the MS consumption we see in Fig. 3.6 that the DBCB, from the individual user perspective, was not very good compared to the rest of algorithms proposed, whereas we see how the inclusion of the new features in the new MA-DBCB reduces significantly the average MS consumption without a significant loss of energy-performance in the RAN. Actually, we can see some little improvement of performance for MA-DBCB compared with algorithms like the SSOCB from the MS point of view. For instance in Fig. 3.7, we see reductions of the MS transmission power up to 13% at very low load (normalised loads below 0.1) when we compare MA-DBCB and SSOCB. We notice how if we reduce the BS density and cell size increases, some MSs will have to transmit farther, therefore increasing the needed transmission power and compromising

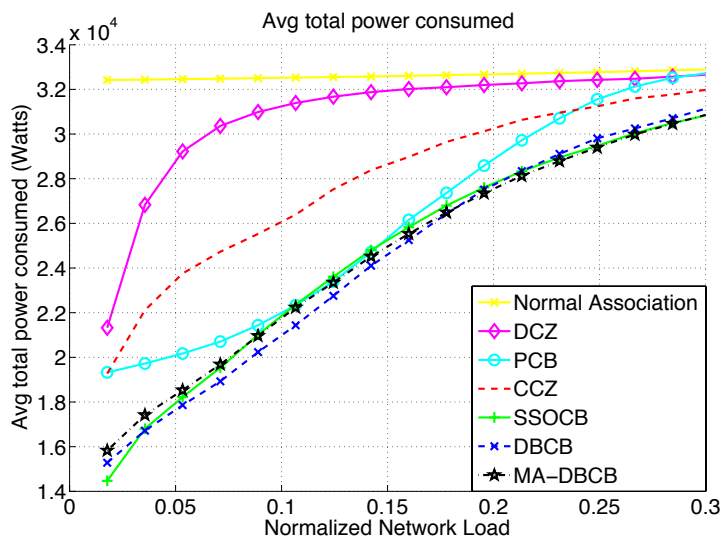


Figure 3.5 – Total power consumption for the RAN and the set of MSs for the different algorithms simulated

their battery lifetime. Finally, we can see the maximum transmission power reached by the MSs deployed for different levels of load for the different cell-breathing algorithms in Fig. 3.8. We see again a noticeable improvement if we compare MA-DBCBC to DBCB.

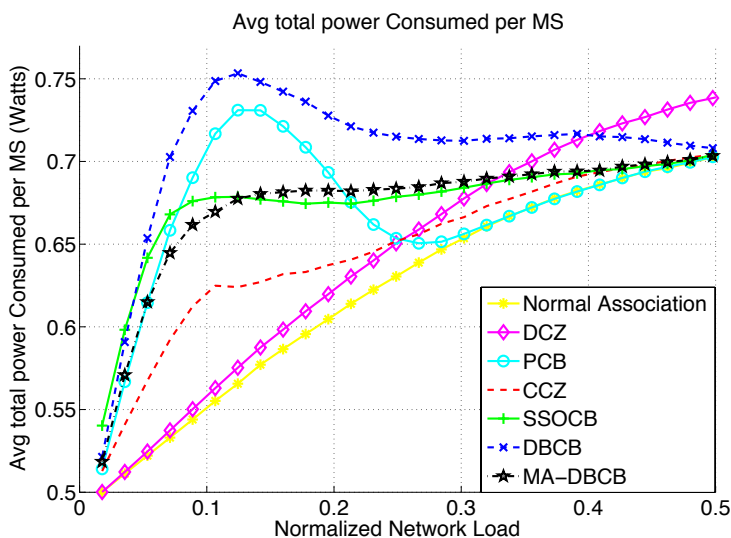


Figure 3.6 – Average MS power consumption for the different cell breathing algorithms simulated

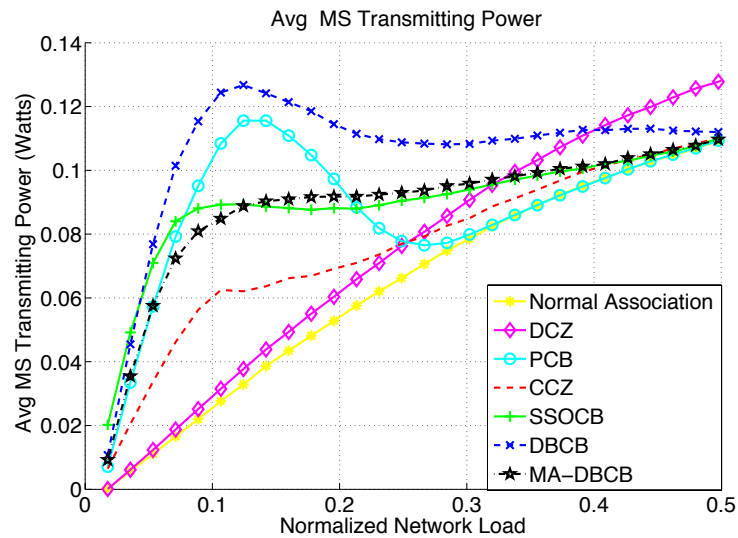


Figure 3.7 – Average MS transmission power for the different cell breathing algorithms simulated

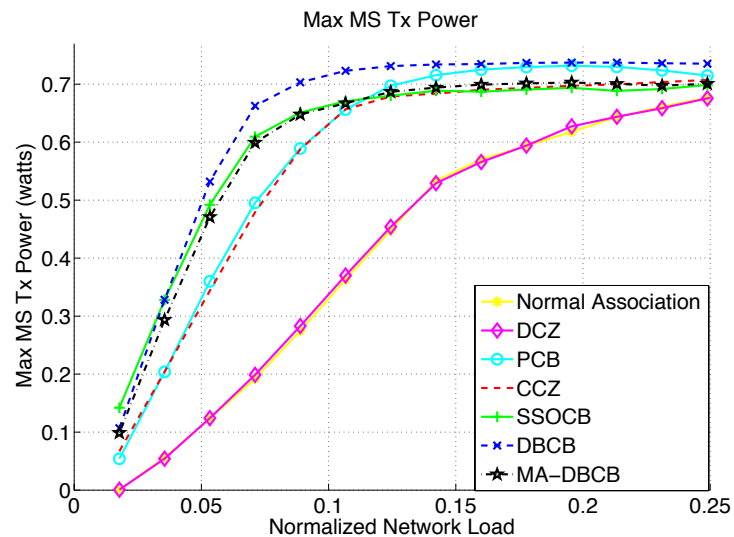


Figure 3.8 – Maximum MS transmission power for the different cell breathing algorithms simulated

3.5.2 Variation of the load Threshold for MA-DBCB

In this second part of the analysis of results we want to show how the use of A_T can help to regulate the number of the switched-off BSs, as well as reduce the resulting transmission power values in uplink due to the use of cell-breathing. For this simulation we maintain the global simulation parameters but we reduce the deployment size to a single 4x4 BS site cluster. In these simulations, the value A_T is globally set, although our technique has the possibility of granularly set this parameter in a BS or cluster

basis if desired. In this Montecarlo simulation, 250 distribution snapshots per simulated point were taken.

In Fig. 3.9 we can notice how as we reduce the threshold value the number of switched-off BS sites is also reduced. Despite the global savings are affected by doing this we must take into account that other elements must be considered when the cell-breathing is implemented. Among these elements, we can cite the constraint given by electromagnetic compliance standards, both for the RAN and the MS terminal.

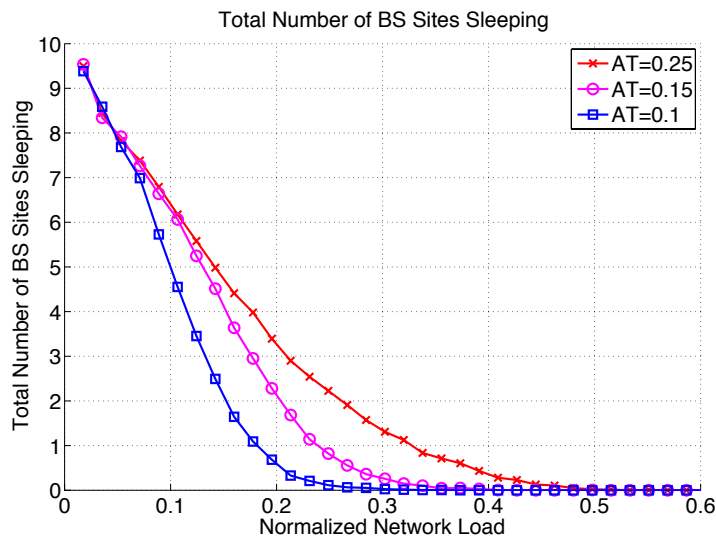


Figure 3.9 – Total Number of BS sites in sleep mode as we vary the load threshold A_T

In Fig. 3.10 we present the average and maximum obtained MS transmission powers. Here, as consequence of having reduced the number of switched-off BS sites due to decreasing A_T , the cell sizes and associated distances are also reduced. This latter permits therefore to reduce the needed transmission power for uplink.

3.6 Chapter Outcome

3.6.1 Concluding Remarks

In this chapter we presented the Distributed BS Based Cell Breathing (DBCB), a novel green cell breathing algorithm that presents both high performance and good possibilities of implementation. With this algorithm we wanted to overcome some drawbacks of previous proposals such as the scalability constraints and the risk of having one-point failure in network coordination by a centralised approach, as well as the lack of performance associated to distributed approaches. In our approach, the algorithm avoids the

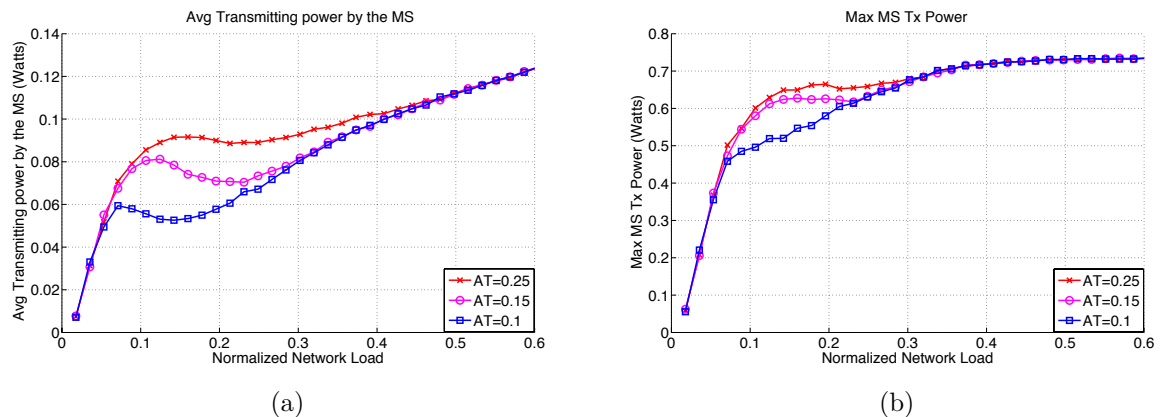


Figure 3.10 – a) Average MS Transmission power and, b) Maximum MS Transmission power, as we vary the load threshold A_T .

use of a central coordination server and rather includes synchronised clusters. A cluster head exchanges messages with other cluster heads for synchronisation and also controls the algorithm execution sequence within the cluster. It was shown that in order to avoid any conflict of adjacent BSs and/or BSs with shared neighbors concurrently executing the algorithm, a minimum cluster size of 3x3 cell must be considered.

Then we have studied the effects of cell-breathing on the RAN and the MS energy consumption, highlighting the existing trade-off between both sides. The fact of reducing the density of active BSs implies greater cell sizes and therefore greater MS-BS average distances, which consequently means higher MS transmission power for some farther MSs. Then, we propose a variant of the previously defined DBCB algorithm and we called it, the Mobile Aware DBCB (MA-DBCB). Among the new features, we included the utilisation of the SINR in the association metric in order to take into account also the MS-BS distances and the losses associated. In addition, a BS load threshold is added in order to limit the number of BSs that execute the algorithm, which introduces a knob that permits to control the balance of consumed energy between the RAN and the individual MS consumption. We have strongly emphasised the importance of this, due to the fact that for operators not only is important the RAN energy costs but additionally the resulting user perception that can be affected by things like a shorter battery lifetime of the MSs due to the absence of closer available BSs.

3.6.2 Future Work

For the future work, the robustness of this algorithm in practical network conditions (e.g. the capacity changes when the cells expand and contract), the optimal size of the cluster in function of signalling and management needs as well as the detailed mechanism of cluster synchronisation are interesting future research issues to be deeply analysed. Also we think that in such an approach, further enhancements like the possibility of setting the A_T threshold by means of a learning mechanism would be an interesting axis of research in order to provide a full self-organised solution. This could be an interesting enhancement due to the possibility of adapting the RAN network behaviour to the fluctuating network conditions as well permitting a dynamic awareness and reaction of the network to crucial functioning constraints like those imposed by electromagnetic compliance and user mobility issues.

The Cell-Breathing in a Heterogeneous Network Environment

4.1 Introduction

In this chapter we describe a novel proposal based on the combination of the cell breathing technique, specifically the DBCB and MA-DBCB algorithms, with the capabilities of a heterogeneous network deployment composed of two layers of Macro and femtoBSs as presented in our article “*Analysis of a green cell breathing technique in a hybrid network environment*” [36]. The use of this second layer of femtoBSs allows us to have two mechanisms of Macro-BSs offloading consisting of the cell breathing and switching-off at the macrocell layer accompanied by the macro-to-femto offloading mechanism (see Fig. 4.1). We call this new proposed technique the femto-DBCB. For the simulation scenario we have wanted to think of the future of mobile networks by considering the LTE technology and its associated models with other elements like the 3GPP Closed Subscriber Group concept conceived for defining access policies in the femtocell layer.

4.2 A Cellular Network Scenario with a Heterogeneous Cell Topology

In this section we describe the new considered system model for the heterogeneous network environment. Some major changes were done, first, in order to migrate from 3G/CDMA to LTE, and second, in order to reduce the simplicity of the model presented in chapter 3. We initially describe the heterogeneous network, composed of a classic MacroBS cellular network and a second layer of femto-BSs. Then, we make an update of the considerations taken for the devices in this chapter and the model considered for

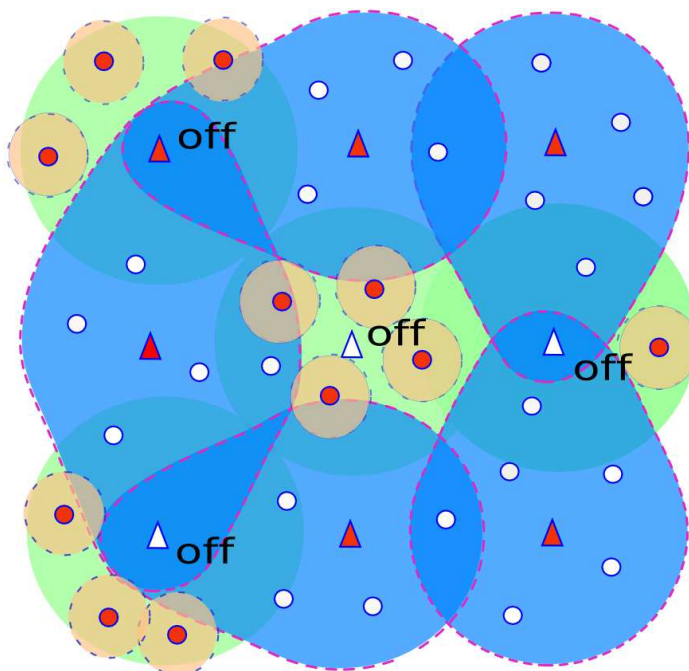


Figure 4.1 – The Femto-Cell Breathing Approach: in blue, covered area by the active BSs (red triangles) from the macrolayer; in yellow, area covered by the active femtoBSs (red circles); green area corresponds to coverage holes. Devices in white are switched-off.

the femtoBSs. Also the transmission channel path loss and shadowing characteristics are described.

4.2.1 A Macro/femto radio access network

For the heterogeneous RAN deployment, we have two sets: a set Ω of N Macro-BSs and another set Φ of K femto-BSs. Whereas Ω is deployed in a uniform way over the coverage area (e.g. a hexagonal deployment) the set Φ is deployed by using a random uniform distribution. This latter is actually accurate with real life where home-installed femto-BSs are not installed under a predictable pattern. Additionally, there is a third set Ψ that corresponds to M MSs also randomly deployed under a uniform distribution.

We consider a LTE network with simulation parameters given later in Table 4.1. Each user i has a maximum attainable bandwidth c_i that can be calculated by the Shannon formula as:

$$c_i = \omega_i \log(1 + \gamma_i) \quad (4.1)$$

where ω_i corresponds to the portion of spectrum assigned to the user i , i.e. the sub-channel size, which could also be represented by a fixed number of resource blocks; and γ_i corresponds to the needed SINR to obtain c_i . Each Macro-BS sector have a spectrum band assigned W_M with reuse factor equal to 1. On the other hand, for the femto-BSs we consider a second non-overlapped band called W_F . The reason of this latter is to avoid a complex mechanism to manage the macro-femto intercell interference. The analysis of the proposed idea of this chapter when overlapped frequency bands are considered is an interesting question that is left for future research.

Additionally, we consider for the femtolayer that mixed access policies are being set. From the MS user point of view, the network, in some sense, is seen as a black box, which could block the admission by access lists. We find in that mixed architecture some femtoBSs configured in open access mode, whereas some others belong to closed subscriber groups (CSG), as defined in 3GPP standards [1], therefore blocking the access to any not authorised MS. Such blocking evidently is fully independent of the one that could exist if a lack of resources for MS admission is present. We consider this element associated to the potential future scenarios, where due to access and service policies, the networks will only provide access to specific radio resources for some permitted users, as it already occurs for some technologies like WiFi. We denote the MS blocking access probability to the femtolayer due to CSG access policies as ξ .

4.2.2 Network Devices Model

First we want to describe the main changes for the Macro-BS and MS model with respect to the previous chapter. For the Macro-BS system we keep a similar power model based on a fixed and a variable component for active mode and a given power value during sleep mode. Here, we added however some assumptions for BS coverage not taken into account in the previous chapter. In this chapter the BS switch-off mechanism has been improved by fully separating each sector into a BS site. It means that sectors can be switched-off individually. The cell-breathing mechanism executed in each sector is limited in power in order to strictly compensate the holes of switched-off neighbor sectors. This is actually something more realistic than allowing to a BS j to grow only limited by P_j^{Tx-max} . In the previous chapter, we were only calculating the transmission power needed to create each MS-BS association, neglecting the associated pilot power and also how it grows very rapidly in function of distance as shown in reference [123]. We take the values of pilot power considered in this reference for different intersite distances for the transmission power budget.

On the other hand, for the case of the MS side, we consider only the transmission power value and we forget the rest of elements of its overall consumption, just focusing in the fact of checking if uplink power is enough to establish the MS-BS association. It is not into the scope of this chapter study again the uplink consumption. Therefore, we consider that a MS i has a transmitting power P_i^{Tx} , limited to a maximum value P_i^{Tx-max} .

For the femto-BS power model, we consider a low-Power RF front end. Here, a femto-BS k has power consumption P_k , in active mode, which is more or less constant and independent of transmission power as presented in [47]. The coverage is constrained additionally by a maximum transmitted power P_k^{Tx-max} for a femto-BS k . In our simulation model, it is considered that at the beginning all femto-BSs deployed start in sleep mode with an associated power P_k^{sleep} , and as long they are required for the Macro-to-femto offloading process they get active with a power P_k .

We must mention that specific implementations issues are not addressed in this work. It can be noted, in current LTE specifications, the dynamic change of cell coverage (cell breathing) is not included. We expect it to be added in future releases due to the advantages obtained when proper RRM algorithms are applied as estimated in this work.

4.2.3 Transmission channel characteristics

For this chapter we used specific path loss models specified in [124] for the Macro and femtolayer transmission respectively. Differently to the previous chapter we added the shadowing contribution represented by a lognormal random variable. If we express the path loss L in logarithmic magnitude by taking into account also the shadowing, we obtain the following expression [125]:

$$L_{dB}(d) = L_{dB}(d_0) + 10\alpha \log\left(\frac{d}{d_0}\right) + X_\sigma \quad (4.2)$$

where, d_0 corresponds to a reference distance; d corresponds to the transmission distance; α is the attenuation factor or path loss exponent; and X_σ corresponds to a zero-mean normal distribution with standard deviation equal to σ . The specific parameters utilised for the path loss models are given later in Table 4.1.

4.3 Combining the Cell-Breathing and the Macro-to-femto Offloading: The femto-DBC

One of the basic principles of our proposal, the femto-DBC, is to extend the possibilities of offloading and deactivating any unnecessary macro BSs by the combination of cell breathing at the macro-layer and the use of the femto-layer capabilities. When the load is being redistributed, a Macro-BS j first tries to redistribute its load to the femto-BS layer. Then, if the load is just partially redistributed a phase two is performed where a cell breathing algorithm is executed to redistribute the remaining load. The algorithms used at this second phase apply the approaches proposed in the algorithms of [17][18], which correspond to the Distributed BS Based Cell Breathing (DBC) and Mobile Aware Distributed BS Based Cell Breathing (MA-DBC) respectively. Before describing our proposal algorithm, we remind the basic concepts of DBC and MA-DBC.

The DBC algorithm [17] consists of two main features: firstly, every BS runs the algorithm independently. A BS only needs to know the available resources of its neighbouring BSs to make any decision about the traffic redistribution and establish then the potential traffic acceptors. In some cases (typically low traffic) the BS can reduce its load to zero and then go to sleep mode. Secondly, the algorithm is based on a cluster architecture that controls the scheduling algorithm execution. The coverage area is divided in clusters of $n \times n$ cells composed of several grouped BSs where one is the cluster head. Each cluster head communicates to others cluster heads and exchange signaling messages. This communication permits to schedule and synchronise the BSs that are going to execute the algorithm in each cluster, which is executed BS-by-BS. All those features are common for the DBC and MA-DBC algorithms.

On the other hand, the MA-DBC [18] is an enhancement of the DBC that takes into account the MS transmission power by providing a balance between the RAN consumption and the individual MS consumption. The original DBC algorithm chooses the neighbor acceptors by taking those with higher load. This permits to concentrate the traffic in some few highly loaded BSs and deactivate the rest. The global energy consumption is evidently smaller but the MS-BSs average transmission distances will be longer and so the transmission power for the MSs will globally increase. The MA-DBC algorithm deals with this problem by including two new features: (i) a re-association metric is used for choosing the target BS taking into account the losses and distances between the BS and the MS to be redistributed. This metric is function of the measured SINR level of a reference signal and the acceptor neighbor load; (ii) a BS local load threshold A_T limits the BSs to execute the algorithm therefore influencing

the number of BS to be deactivated. Only a BSs with a normalised load below A_T can execute the cell-breathing algorithm. By using this, we are then able to tune the number of deactivated BSs and therefore the cell sizes. Although it is possible to set this threshold in a BS or cluster basis, for simplicity, in this chapter we fix globally this threshold to $A_T = 1$ and then any BS can execute the algorithm whatever its current load is.

In this chapter, we propose a cell breathing and switching-off algorithm for a network having a macro layer and femto-layer, i.e. a hybrid cellular topology. As we will see, the use of a femto-layer increases the network capacity without a noticeable impact in the energy consumption if the Radio Resource Management (RRM) mechanisms are properly designed. The idea is that a great part of the savings come from redistributing traffic to the femto-layer and then switch-off the offloaded Macro-BSs. The use of cell breathing is a way to increase the chance that a Macro-BS j can be fully offloaded even if the femto-layer only achieved a partial offloading. Specifically for the first phase of femto-DBCB, when a Macro-BS j needs to redistribute its traffic, it first informs all femto-BSs in the set Φ_j , which corresponds to all femto-BSs of Φ within the range of j , that the redistribution is to be performed. We consider that each femto-BS counts with a low power receiver/sniffer that permits to listen to incoming signals during sleep mode (i.e. a User Aware Activity device - UAA) as presented in [33]. In such case, the femto-BSs in Φ_j sniffs the radio channel in order to detect any ongoing call served by the Macro-BS j and then inform the MSs of the possibility of handover. To minimise the transmission power in downlink and uplink, the femto-BS-MS association is based on preferring the femto-BS with the best SINR value. A brief description of the functional blocks of the offloading and deactivation mechanism is given in Fig. 4.2.a.

An important problem to solve for the hybrid network approaches is the coverage holes and the access spot reactivation. Classically, the mobile networks at any cost avoided the existence of those holes. Agreeing with such principle, the cell breathing is a technique that responds to such necessities by guaranteeing the full coverage by extending the size of the remaining active BSs in the deployment. Nevertheless, it is not the same situation with the use of femto-BSs given the fact that here the access points are deployed randomly and corresponding femtocells do not necessarily overlap. In the case that a Macro-BS goes to sleep mode and the femto-BSs around take charge of the zone, we may have coverage holes, which cannot be avoided but must be handled by any means [58]. A proposal to deal with this issue has been presented in [126]. Here, a MS is able to send wake-up or reverse paging messages to inform the access points of its presence. This is particularly useful for scenarios where a user is in a zone where the main Macro-BS is deactivated and the MS is not covered by any other active

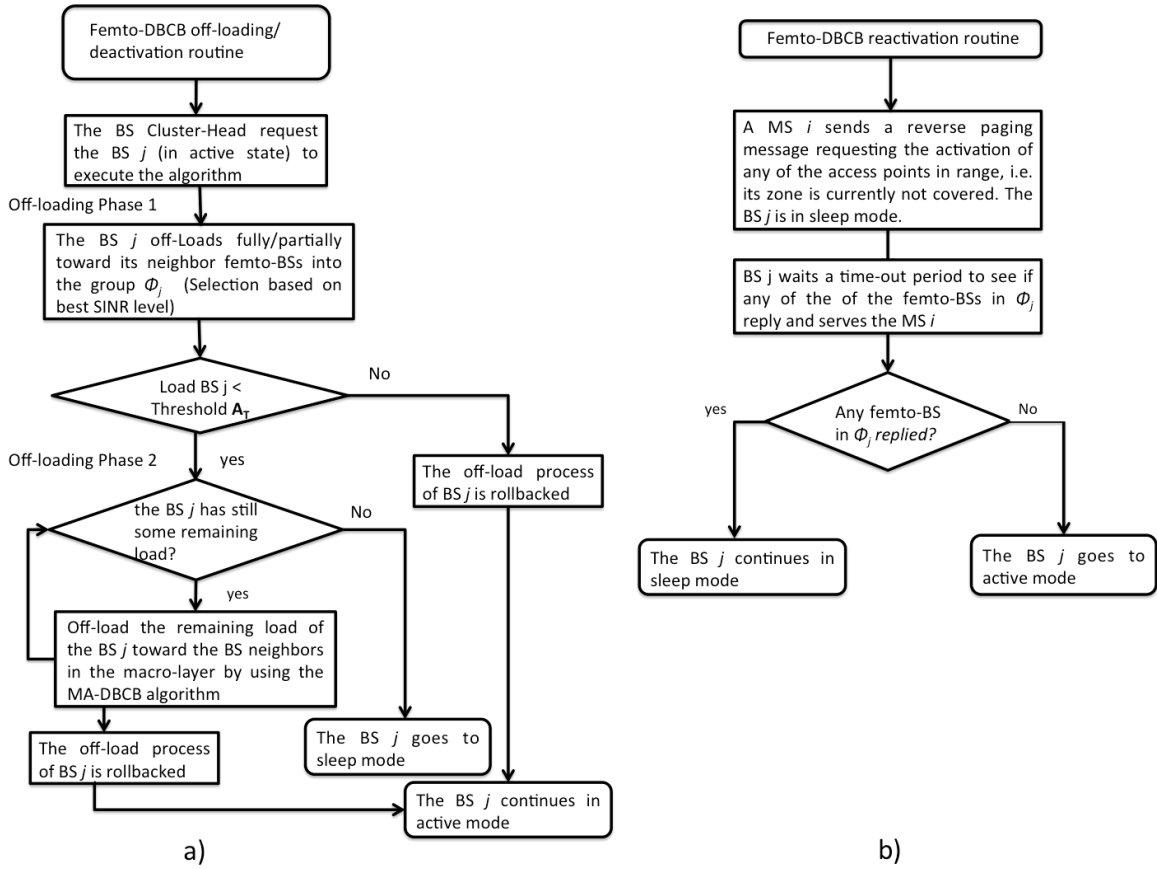


Figure 4.2 – The femtoDBC flowcharts: a) offloading/deactivation mechanism, b) BS reactivation process.

small access point. In our proposal, we consider this functionality. In such sense, the reactivation of a femto-BS k or, as last resource, a Macro-BS j is triggered by a reverse paging message of an incoming MS. A diagram of such reactivation process is shown in Fig. 4.2.b. This reactivation mechanism is also very worthful taking into account that normally in literature a MacroBS deactivated with cell-breathing techniques needs to be periodically reactivated in order to readapt the number of cells and the sizes to the fluctuating traffic conditions (see for instance [29]). By using a triggered reactivation based on MS requests, we avoid this periodical reactivation that is not very efficient in real scenario conditions.

4.4 Analysis of the femto-DBCB and other Het-Net Approaches

4.4.1 Comparison of the Mechanism with other approaches

To test and compare our proposal, we modified our Montecarlo simulator by bringing the LTE architecture and basic fundamentals of this technology. The simulations parameters are presented in the Table 4.1. The femto-DBCB is compared against the following mechanisms: a Macro-Only BS-MS classic association mechanism with no BS switching-off capabilities; the DBCB/MA-DBCB algorithm [17][18] and the two mechanisms based on the proposals of [33] and [73] for hybrid networks. For all hybrid network algorithms simulated (i.e. ref. [33][73] and femto-DBCB), we consider that femto-BSs are initially deactivated. Specifically, for the hybrid network comparison algorithms of [33] and [73], the main process comprises two basic functions: (i) the one-by-one activation of the femto-BSs that receive the incoming traffic of the Macro-BSs, and (ii) the offloading of the Macro-BSs toward the femto-BSs in order to empty and deactivate any unnecessary active Macro-BS. The algorithm associated to [33] uses UAA femto-BSs in order to detect the calls associated to the Macro-BSs. After each detection, the users are redistributed toward the femto-BSs in order to empty the Macro-BSs. In the case of the mechanism associated to [73], a centralised server performs the MS reassociation and the iterative activation of femto-BSs in the following manner: (i) take all the set of MSs to be redistributed and sort them in ascending order in function of the number of potential femto-BSs available in range to associate with. The MSs will be checked in that order, and then, (ii) for each one of those MSs, make the association preferring the femto-BSs with more potential MSs to associate with; (iii) in each iteration remove any MS already associated to a femto-BS from the list of participants and continue with the following MSs where new femto-BSs will be activated until all MS users have been checked. We will call this algorithm the Iterative Femto-Activation (IFA).

All the figures presented are plotted as function of different numbers of users per macrocell. First, we analyse the number of femto-BSs activated by each one of the algorithms. As seen in Fig. 4.3, the femto-DBCB activates more femto-BSs than the other two algorithms supported by femtocells, i.e. UAA and IFA. All algorithms, including femto-DBCB, were implemented following the policy that if the Macro-BS is not fully offloaded after the redistribution, the procedure is rolled back and the Macro and femto-BSs remain in the previous state before algorithm execution. In such case, the femto-DBCB due to the fact that it uses a combined approach of cell breathing

Parameter Name	Value or Choice
<i>BS site type</i>	3-sector antenna BS
<i>Wireless Standard Technology</i>	LTE
<i>Intersite Distance</i>	500m
<i>FemtoBS max coverage radius</i>	100m
<i>Central Frequency</i>	2000 MHz
<i>Spectrum Bandwidth W_M/W_F</i>	20MHz/5MHz
<i>Path Loss Model</i>	For 2GHz [124]: $L = 127 + 30\log(d)$, d in km (femto) $L = 128.1 + 37.6\log(d)$, d in km (Macro)
<i>lognormal shadowing standard deviation</i>	10db(Macro) /4dB(femto)
<i>Data Rate per MS</i>	512kbps (fixed)
<i>Resource Block per User</i>	10 (fixed)
<i>Number of Sites</i>	16 BS sites (4x4)
<i>BS sector parameters</i>	$P_j^{Tx-max} = 40W$; $P_j^{fixed} = 200W$ $P_j^{sleep} = 100W$; $\eta=2.5$; BS Max. Antenna Gain = 14dBi; BS Cable losses = 2dB BS Noise Figure = 5dB
<i>femto-BS parameters</i>	$P_k^{Tx-max} = 100mW$; $P_k = 10W$ $P_k^{sleep} = 3W$; femtoBS Antenna Gain = 5dBi; femtoBS Noise Figure = 5dB
<i>femtoBSs per Macro-BS site</i>	10 (fixed)
<i>femtoBS Distribution</i>	Randomly Uniform
<i>MS parameters</i>	$P_i^{Tx} = 200mW$ MS Antenna Gain = 0dBi; MS Body Loss = 2dB; MS Noise Figure = 9dB
<i>MS Distribution</i>	Randomly Uniform
<i>Probability of being blocked by the femto-layer due to CSG access policies, ξ</i>	0.25
<i>Number of Montecarlo Distributions</i>	300

Table 4.1 – Simulation parameters for the simulations in this chapter

and macro-to-femto redistribution, has more chance to succeed in deactivating some extra Macro-BSs, which is confirmed in Fig. 4.4. Therefore, as more successful offloads are achieved in femto-DBCBC, more active femto-BSs will be needed. Fig. 4.5 shows the RAN power consumption, i.e. femto + macro-layer, of each algorithm. The femto-DBCBC is the one with the smallest consumption due to what has been already seen in Fig. 4.3 and Fig. 4.4. Despite the fact that more femto-BSs are active in femto-DBCBC, the contribution of the femto-layer consumption to the overall consumption is negligible and what really counts is the number of deactivated Macro-BSs.

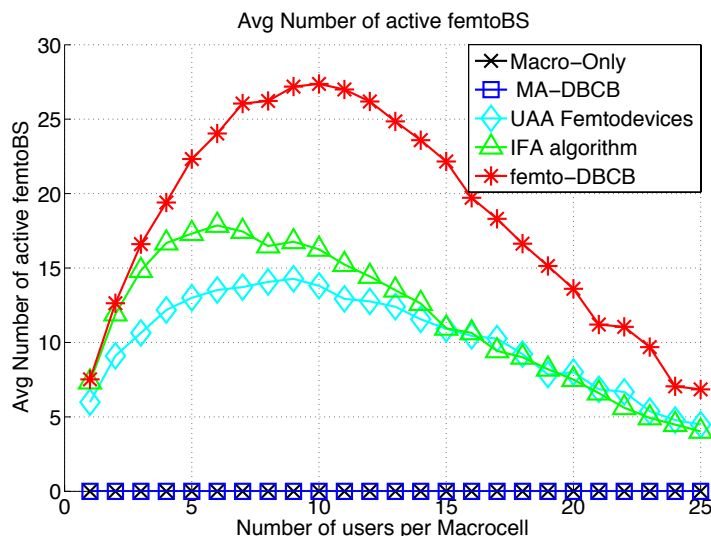


Figure 4.3 – Number of active femto-BSs for each algorithm.

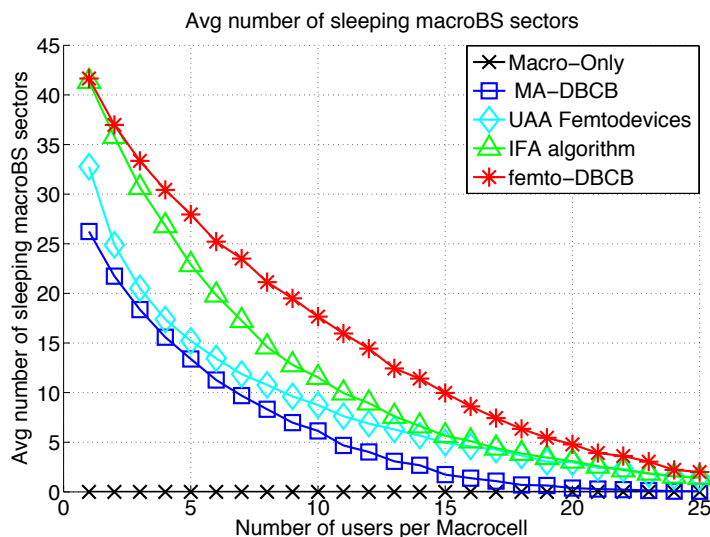


Figure 4.4 – Number of deactivated Macro-BS sectors for each algorithm

Something to point out from the analysed figures is that just by the fact of applying Macro-to-femto offloading (i.e. UAA approach or IFA algorithm), the obtained savings are already better compared with the cell breathing only approach (i.e. MA-DBC). With cell breathing only, the savings can uniquely be obtained by the optimal utilisation of Macro-layer infrastructure, which is restricted by a limited radio resource capacity. These limitations disappear by adding the femto-layer without a great impact on the RAN consumption. However, the use of a femto-layer approach is prone to coverage holes, something that can be avoided in classic cell breathing at the macro-layer. This explains our preoccupation on including a mechanism for coverage holes handling in our proposal for the zones where the cell breathing is not being applied.

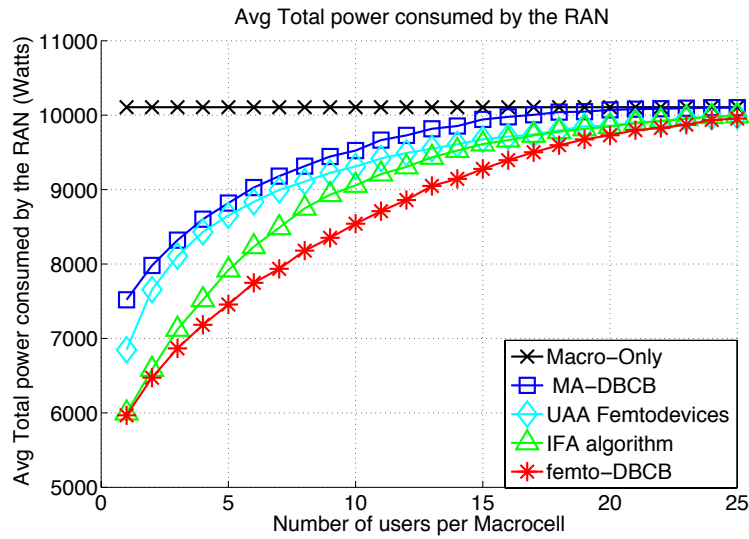


Figure 4.5 – Total power consumption by the RAN for each algorithm

4.4.2 The effect of the 3GPP CSG access policies on femto-DBCBC

After having compared the femto-DBCBC technique to other approaches, we want now to study how the availability of the femtolayer due to use of closed subscribers groups (CSG) can affect the functioning and performance of the femto-DBCBC. Firstly, if we take a look in Fig. 4.6 we notice how as we have higher values of ξ , i.e., higher probability of having MSs being blocked by access policies at the femtolayer, the number of femtoBSs that go to active mode as expected is lower.

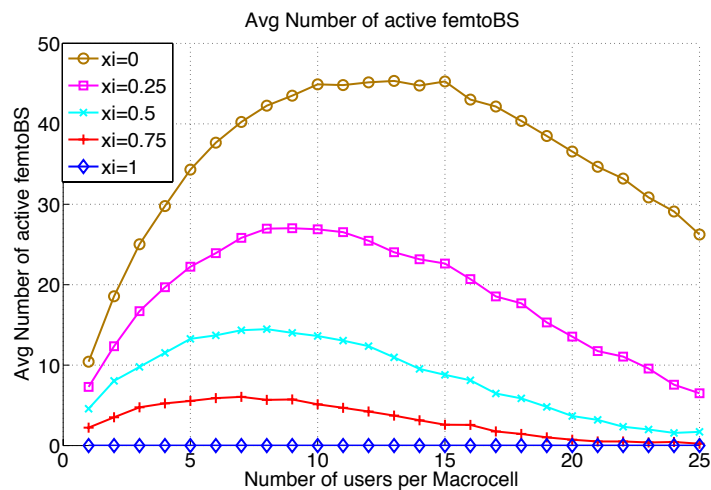


Figure 4.6 – Number of active femto-BSs for each value of ξ (ξ).

On the other hand, we can see in Fig. 4.7 how at the same time the number of Macro-BS sectors switched-off is reduced due to macro-to-femto offloading becomes a weaker option for traffic redistribution, i.e. increased value of ξ . We can see, for example, how when $\xi = 1$, the only option for offloading should be the cell-breathing component (i.e. MA-DBC algorithm). Here, we see however little discrepancies with the number of Macro-BSs switched-off by the MA-DBC only approach in Fig 4.4. The classic MA-DBC guarantees that the whole area is covered by the remaining active Macro-BSs due to cell expansion and then in that case, more Macro-BS sectors need to remain active to assure the coverage. In contrast, for the femto-DBC, if a Macro-BS is zero loaded, during the executing of the offloading/switching-off algorithm, no Macro-BS neighbors will be requested to stay active nor expand their coverage, and the area remains uncovered. If any MS appears later requesting for service in an uncovered area, it must use the reactivation request based on reverse paging messages to reactivate any of the surrounding BSs.

Finally, for Fig. 4.8 we can see how as the femtolayer components becomes unavailable due to access policies, the corresponding energy savings become reduced due to the need of redistributing traffic and expanding more macrocells in some zones in order to execute the Macro-BS offloading. We see again how even for high values of ξ the consumption is lower compared to the classic MA-DBC presented in Fig. 4.5 . This is again because we rely on the reactivation and coverage holes handling technique presented and therefore more uncovered zones will be tolerated.

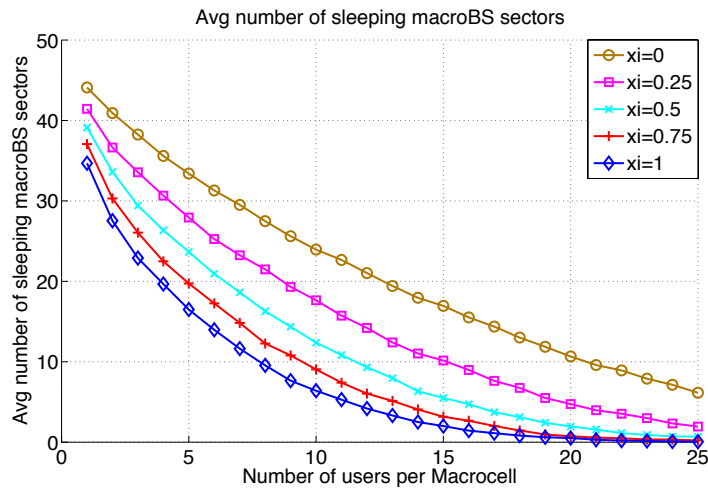


Figure 4.7 – Number of deactivated BS sectors for each value of ξ (ξ).

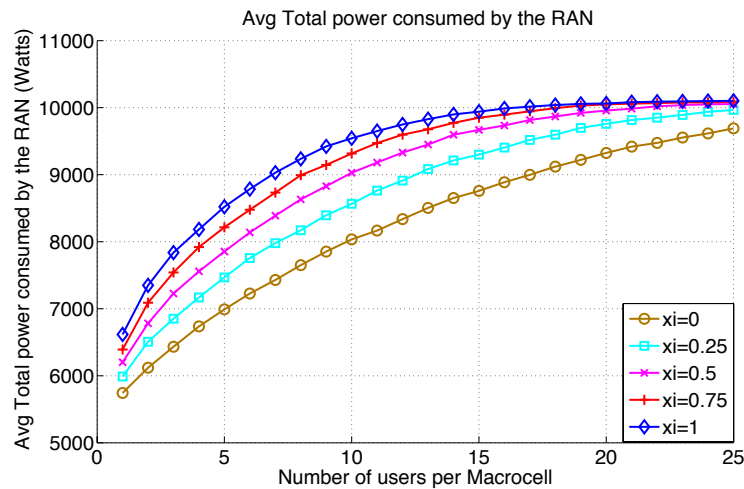


Figure 4.8 – Average power consumption by the heterogeneous access network for each value of ξ (ξ).

4.5 Chapter Outcome

4.5.1 Concluding Remarks

We have presented an energy efficient technique that combines the features of cell breathing and the hybrid network approach. In this chapter, we confirmed how the efficiency is enhanced when cell breathing and the hybrid approach work together by making it possible to increase the number of deactivated Macro-BSs in scenarios where additionally CSG access policies exist. We have seen how by varying the probability of being blocked by the femto layer due to access policies, it can affect the overall power consumption of the RAN. However, we saw how at the limit of total unavailability of the femtoBSs due to the described issue, it always exists at the background the cell-breathing component.

It has also been observed in our results that just by using a Macro-to-femto offloading approach the energy efficiency performance is better than the cell-breathing-only approach. This is because of the features presented by femto-BS layer, such as high capacity and low power, which makes it possible to granularly shape RAN consumption, reducing the need for high-consumption Macro-BSs in active mode to guarantee the coverage. However, the price to pay is that such energy savings are obtained at the expense of introducing coverage holes. This is something that is avoided with the classic cell-breathing. In order to overcome this, a reactivation and coverage holes handling strategy was proposed.

4.5.2 Future Work

In order to make this proposal feasible, deeper research must be done into mechanisms like reverse paging messaging and low-power sniffing techniques, which will be useful for the BS reactivation mechanism and the handling of potential coverage holes as a consequence of relying on a femto-layer approach for Macro-BS deactivation.

Moreover, our research work in heterogeneous network, as we will discuss in chapter 6, is to find an adaptable mechanism for more complex heterogeneous networks. Those networks as we will see, can be composed of BSs with different levels of capacity, coverage and energy consumption regimes. Some first results of our research direction in that aspect will be shown in that chapter by introducing a multi-metric offloading approach. We expect to refine this approach later by introducing learning mechanisms.

Electromagnetic Compliance for the Cell-Breathing and the Combined Cell-Breathing/Het-Net Approach

5.1 Introduction

In this chapter, we study the implications of using our previously presented MA-DBCB and femto-DBCB techniques, in terms now, of the electromagnetic radiation compliance. The basis of this chapter is our article “*Electromagnetic radiation compliance under the use of green cell breathing and hybrid network approaches in LTE*” [37]. Our study starts from the hypothesis that the use of cell breathing could potentially exceeds the existing radiation limits established in the regulation on electromagnetic exposure for mobile networks due to the effect of cell adaptation. We set the scope of this study only to the downlink, but we know that similar effects are brought on the MS side due to the increase of transmission distance.

We analyse the problem taking into account the different electromagnetic fields legal requirements and then estimate the received electric field for different cellular scenarios for LTE: a macro-only scenario, a macro scenario with cell-breathing, i.e. MA-DBCB, and then a hybrid approach (femto/macro) under the use of femto-DBCB. As it is concluded, our simulations results show that the percentage of threshold violations is increased by the use of cell breathing. Those thresholds are taken from ICNIRP

recommendations [2] and country regulations [127]. Our study is done for different levels of traffic and number of switched-off Macro-BSs which implies different levels of received power and associated electromagnetic radiation due to remaining active BSs and their cell size expansion.

5.2 General Background

5.2.1 Context and Regulation on the Electromagnetic Radiation Exposure for Mobile Networks

An important preoccupation in the world of mobile networks is the increase of energy consumption. This comes together with an increase in the associated carbon footprint from such sector. The literature has studied and reported with large details these concerns in many references already provided in this document (see for example, [9][10][11][12]). In the framework of the Green Radio and the energy efficient mobile networks, another important issue that should be analysed is the level of electromagnetic radiation emitted as product of wireless transmission. Although, the undesired effects of the electromagnetic (EM) radiation are not totally clear today, it is a concern of governments, scientific community and public opinion to avoid any adverse consequence on human health and environment.

In that sense, public authorities are taking measures in order to avoid any harm for the general public and the network workers. The organisation body that provides recommendations on EM exposure limits, hazard avoidance and protection is the *International Commission on Non-Ionizing Radiation protection* (ICNIRP). The guidelines for exposure limits are given in [2]. Specifically, for the radiofrequency band from 2 to 300 GHz, the electric field exposure limit due to radio BS transmission has been established as 61 V/m for the general public and 137 V/m for workers. Those acceptable limit thresholds are the required in many countries including France. Other countries prefer to increase the precautions by taking lower exposure limits. Examples of this latter are Belgium and Switzerland that take 7 and 10% respectively of the reference levels for the discussed RF band [127]. In order to determine the EM field limits compliance, there exists documentation that provides the methodology for performing the EM measurements for radio equipment. In the case of Europe, the corresponding documents are the EN-50383 [128] and EN-50492 [129] of CENELEC, that describe the measurement techniques used for the radio base station systems.

There also exists concerns on the uplink side, i.e. the transmission power from the MS and the associated absorbed power by human head/body. Here, the compliance limit is not given by electric field intensity, but by another value known as specific absorption rate (SAR), which measures the energy absorption rate of a given tissue due to the exposure to an incident electromagnetic radiation [2]. The definition of SAR is given by [130]:

$$SAR = \frac{\sigma \cdot E_i^2}{\rho} \quad (5.1)$$

where, σ corresponds to the tissue/material conductivity (S/m), ρ corresponds to the volumetric density (kg/m^3) and E_i (V/m) to the incident electric field intensity. For studies on the human body, it is common to find tables for the values of σ and ρ for the different tissues, and specifically for σ , also for different frequency bands (see for instance [131, 132]). The calculation method for SAR in the uplink scenario is complicated due to the proximity of the human head to the phone, which obliges to study the electromagnetic wave behaviour into the near field zone. This latter is something difficult to treat by analytical expressions given the fact that propagation cannot be studied by a simple planar wave model. Therefore the MS compliance studies are rather based on electromagnetic simulation like it is the case of the Finite Differences in Time Domain Method (FDTD) (see for instance [131, 132]) or on the other hand, the use of direct test measurements. In this thesis we start by focusing on the EM downlink studies and we leave the uplink as a perspective of research in the future.

5.2.2 Estimation Method for the Electric Radiated Field Produced by the RAN Downlink Transmission

For our study, we do not conduct any measurement survey. Instead, we worked by means of computer simulations by considering a mobile coverage area composed of several BSs. Then, a superposed layer of sample points is disposed in concentric rings surrounding each BS as presented in Fig. 5.1. Each one of these points receives and sums the contribution of power of all BSs as:

$$p_{(x,y)}^{Rx} = \sum_{j=1}^N p_{j,(x,y)}^{Rx} + \sum_{k=1}^K p_{k,(x,y)}^{Rx} \quad (5.2)$$

where:

- $p_{(x,y)}^{Rx}$ is the sum of all power contribution at a point with (x, y) coordinates.
- $p_{j,(x,y)}^{Rx}$ is the power received at a point with (x, y) coordinates originated by a Macro-BS j .
- $p_{k,(x,y)}^{Rx}$ is the power received at a point with (x, y) coordinates originated by a femto-BS k .
- N and K correspond to the total number of Macro-BSs and femto-BSs in the deployment respectively.

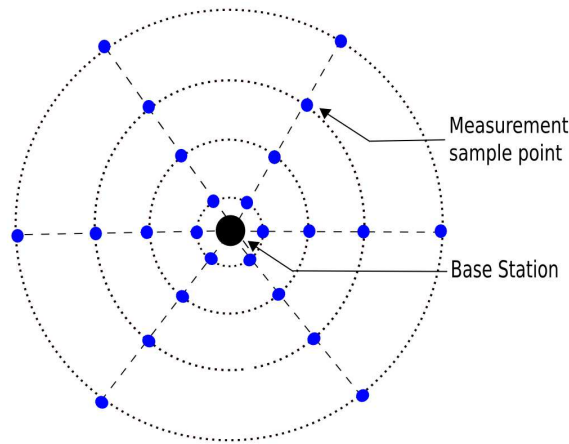


Figure 5.1 – Deployment of the sample measurement points surrounding a Macro-BS

In order to convert the received power in each one of the layer sample points to a value of electric field we use a method that can be found commonly in literature based in the antenna factor (AF) (see e.g, [133]). We assume that each one of those sample points has a receiver antenna with coupled impedance load Z_0 and receiver gain G_r . The idea on the estimation procedure is to obtain the value of incident electric field E deriving it from the value of voltage V measured on Z_0 . Normally the value of this Z_0 is 50Ω . The existing ratio between E and V is known as antenna factor (AF). The general equation for the AF is the following [134]:

$$AF = \frac{E}{V} = \sqrt{\frac{4\pi\eta}{G_r Z_0 \lambda^2}} \quad (5.3)$$

where λ corresponds to the wavelength of the incoming signal and η is the intrinsic impedance of the medium. For the free space case with $\eta = 120\Omega$ and $Z_0 = 50\Omega$, the AF is equal to [135]:

$$AF = \frac{E}{V} = \frac{9.73}{\lambda\sqrt{G_r}} \quad (5.4)$$

Passing the value of AF to dB we obtain [136]:

$$AF_{dB} = 20\log(f_{MHz}) - G_{rdB} - 29.8 \quad (5.5)$$

where, f_{MHz} corresponds to the central frequency of the incoming signal in MHz. After having computed this AF, we can calculate the value of E by using Eq. 5.3 with $\eta = 120\pi\Omega$ as:

$$\begin{aligned} E &= V\sqrt{\frac{480\pi}{G_r Z_0 \lambda^2}} = \sqrt{\frac{V^2}{Z_0}}\sqrt{Z_0}AF \\ \frac{V^2}{Z_0} &= p_r \end{aligned} \quad (5.6)$$

where p_r corresponds to the power received. By using 5.5 and 5.6 and using a logarithmic scale of magnitudes, we obtain the value of E :

$$E = 10^{\left(\frac{p_{rdBm} - 13 + AF_{dB}}{20}\right)} \quad (5.7)$$

5.3 An Analysis of the Consequences of Using Cell-Breathing and Het-Net Approaches on the Network Electromagnetic Compliance

In this simulation, we deploy a similar macrocell deployment as given in Chapter 4, with a hexagonal topology with an inter-site distance of 500m. For the femtolayer, 160 femto-BSs (10 per macro-BS site) are randomly deployed by using a uniform distribution. The probability of a MS being blocked by a femto-BS due to 3GPP CSG control access policies [1] is $\xi=0.25$. The simulation parameters remain the same as those given in chapter 4.

The layer of measurement points used contains 384 points deployed in a set of concentric rings surrounding each Macro-BS site. Each ring contains 6 points separated

60 degrees. We deployed 4 rings per Macro-BS site at 10, 30, 60 and 120 meters of the BS site center position. For the simulation we took 2 different limit exposure thresholds: a threshold of 10% of the limit reference level for general public, as used in countries like Switzerland (6.1V/m) [127]; second, a more exigent threshold of 2% of the reference level (1.2V/m). We can mention this value here as an example due to the interest of the region of Paris of becoming more exigent in EM limits for the general public [137].

The study conducted consisted of detecting in each of the snapshots of the Monte-carlo simulation the number of sample points where the thresholds were exceeded. As point of reference, we take the Fig 5.2 that corresponds to the number of switched-off Macro-BSs and the number of active femto-BSs respectively (same results provided for MA-DBCBC and femto-DBCBC in Figs. 4.3 and 4.4). Here we see that a higher number of Macro-BSs is switched-off compared to the MA-DBCBC, when the femto-DBCBC is applied. The performance improvement comes from the extra capacity and low consumption features of the femtolayer introduced.

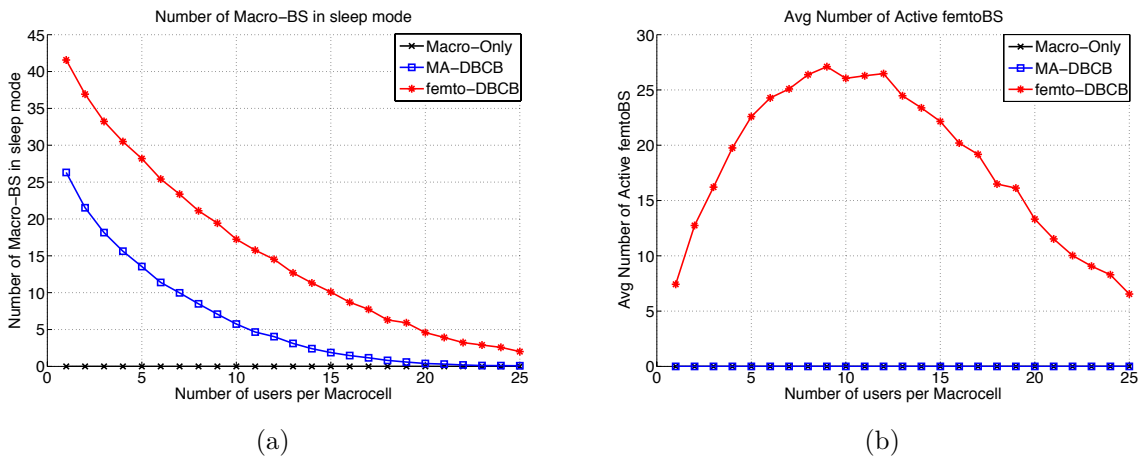


Figure 5.2 – a) Number of Macro-BS sectors in sleep mode for different number of user per Macro-BS site, b) Number of femto-BSs activated for different number of users per Macro-BS site. Those values also correspond to those obtained in chapter 4 in Figs. 4.3 and 4.4.

Then, for Fig. 5.3 we have the percentage of sample points where the electric field exceeded the 10% of the reference level and for Fig. 5.4 we have the same for the case of having a limit threshold of 2%. We notice that the utilisation of cell breathing, i.e., MA-DBCBC, carries a noticeable impact in the percentage of points that exceeds the defined thresholds. This is given the fact that transmission power increases for some BS sectors in cell breathing, which implies a higher associated radiation. For the case of femto-DBCBC we have a strong reduction of the alarm percentages due to the fact that many zones are only covered by femto-BSs. It is although noticeable that as the

traffic increases, the number of alarms increases for femto-DBCBC due to cell breathing becomes necessary to offload some Macro-BSs.

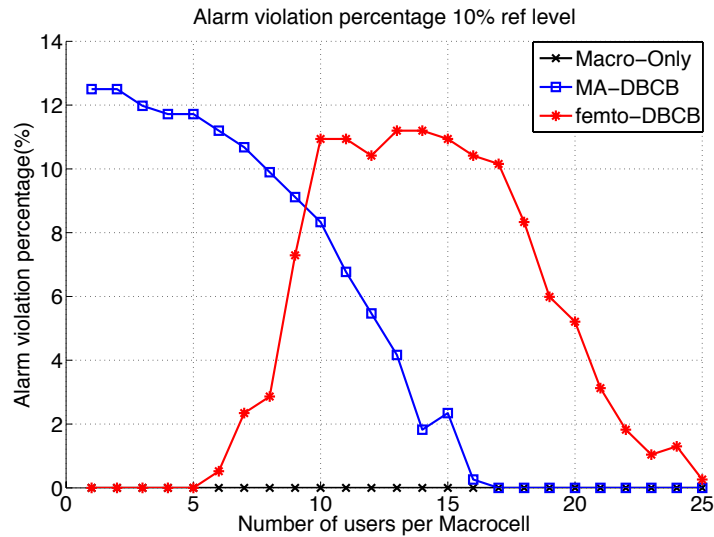


Figure 5.3 – Percentage of Alarm violations when a threshold of 10% of reference level for general public is used (6.1 V/m).

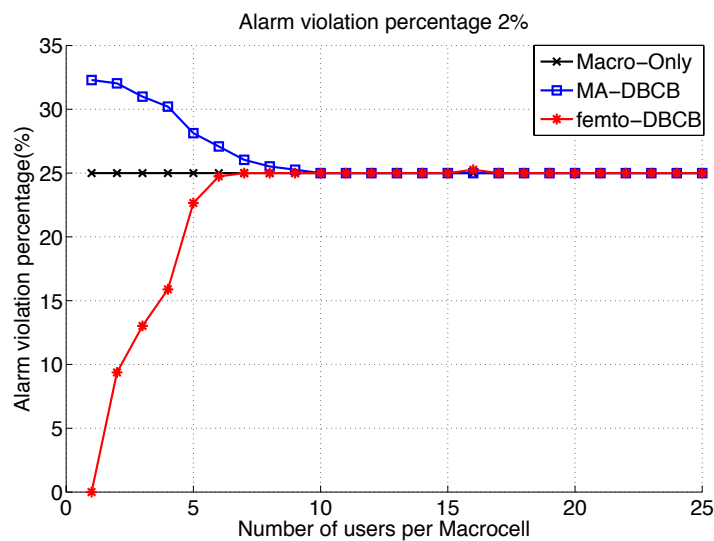


Figure 5.4 – Percentage of Alarm violations when a threshold of 2% of reference level for general public is used (1.2 V/m).

By using a correct mobile and switching-off technique, it could prevent the increase of radiation levels. For instance, in the case of MA-DBCBC and femto-DBCBC, the problem can be mitigated, by using the load threshold A_T discussed in Chapter 3. Those BSs close to sensitive places like schools, hospitals or crowded spots can be configured with lower values of A_T . This reduces the possibility of a Macro-BS of being switched-off and also of having MacroBS neighbors expanding their cell size,

which increases the associated emitted radiation. A learning mechanism could also be used for setting such threshold A_T in function of traffic patterns.

5.4 Chapter Outcome

5.4.1 Concluding Remarks

In this chapter, and to the best of our knowledge, for the first time it has been analysed the effect of cell breathing on EM exposure limits. We have remarked in our simulations how the reduction of the number of active BSs and the subsequent increase of transmission power from the remaining active BSs, increases the electric field levels in the coverage area. In such sense, it is necessary a more profound study of this issue in order to reduce any potential risk on human health due to the introduction of cell-breathing techniques on behalf of more energy savings. Such EM levels are, however, importantly reduced when the cell breathing is combined with small cell devices due to the reduced level of transmission power of such equipment. Given also for the same presented reasons, it is possible to set a dense layer of small cell access points in order to avoid in the most of cases the need of requesting a Macro-BS neighbor for coverage backup.

5.4.2 Future Works

Based on this study, we can say that harder work is needed on creating adapted and preventive planning methodologies for cell breathing implementation when electromagnetic compliance constraints are introduced. For future work, it is recommended to study the uplink side, where the MS transmission power is also increased due to cell size expansion after the switching-off process in cell-breathing.

A Multi-Metric BS Switching-Off Algorithm for a Highly Heterogeneous Cellular Network Environment

6.1 Introduction

In this chapter, we continue our analysis on the network level by proposing a novel multi-metric approach of BS switching-off and cell-breathing applied to a hybrid/heterogeneous network supported on macro/femto deployments. This time, however, we conduct our studies in highly heterogeneous environments. Into the analysis, we intend to study the impact of the BS power model advances for active, idle and sleep mode. Given it is expected a higher efficiency of electronic components in the years to come and renewable energy technologies are becoming a real alternative, the BS component enhancement approach constitutes itself as a strong enabler for the upper levels techniques. Among the causes of the progressive change on the BS power model we should remark the important work done on power amplifier architectures, which reduces the overall consumption power as well as avoid the use of air-cooling systems in some BS architectures. Here in this chapter, we discuss how this progress at the component level and the changes of the BS power model will affect the algorithms and techniques of energy saving proposed for the network level in the years to come. In addition, we will highlight how the scenarios for the RAN deployments in both the short and long terms become more and more complex with heterogeneous architectures composed of BSs from different technological generations, resource capacities and sources of energy.

6.2 Highly Heterogeneous Environment

For this chapter, we have different simulation scenarios based on different BS models. By mixing the characteristics of power regimes, capacity and type of energy supply, we have what is clearly a highly heterogeneous scenario. In such kind of scenario making decisions on which BS should be switched-off and which BS should receive the offloaded traffic is a more complicated matter where several elements come to play a role: MS-BS distance, BS load, BS power consumption, combined use of renewable/non-renewable energies, etc.

The main deployment macro/femto structure is the same as the one already considered in Chapters 4 and 5 with a femto and a macrolayer. The main simulation parameters shown in Table. 4.1 are again used. However, in order to create the scenarios of this chapter we have made some changes in the Macro-BS power models to make a more heterogeneous environment at the macrolayer level. In the two following subsections we are going to describe such changes.

6.2.1 Macro-BS Power Models and renewable supply power considerations

The power models we use are those compiled in [115] from ICT-EARTH Project. We consider in the scenarios studied that a group of Macro-BSs is powered by a combination of renewable and non-renewable sources. We call this group of Macro-BSs Ω_R , $\Omega_R \in \Omega$. The Macro-BSs into Ω_R could be partially powered in a random percentage χ by a renewable source. Such a percentage χ goes from 0 to 100% of the total power supply. The idea is to bring more heterogeneity into the simulation scenario.

The original sources of the power models presented by [115] are [39] [138][139], all published works into the framework of ICT-EARTH Project. First of all, we introduce the state of art (SOTA) 2010 model presented in [138]. In this model, the BS site is composed of three sectors, two antennas per sector. According to this article, the total BS consumption (i.e. taking the three sectors and the six antennas) for full active mode is 1292W whereas for idle state (zero load) is 712W. The power level for sleep mode is 378W. A second model [39] corresponds to a predicted model for 2014 taking into account the latest advances in BS circuitry. We call it as coined in [115] the “Market 2014 BS model”. From [139] a third model is extracted, which corresponds to a BS model before 2010 with DTX (discontinuous transmission mode) features, a technology that allows sleep modes states during idle periods in the transmission. This model we call it, “BS enhanced with DTX”. Finally, [115] presents an “Idealised BS

Model” pushed toward the theoretical limits. This last model is not something forecast yet for the short term. In Table 6.1 and Fig 6.1, we present the different power levels for the already described models. The values correspond to the power levels of a single antenna of a BS sector.

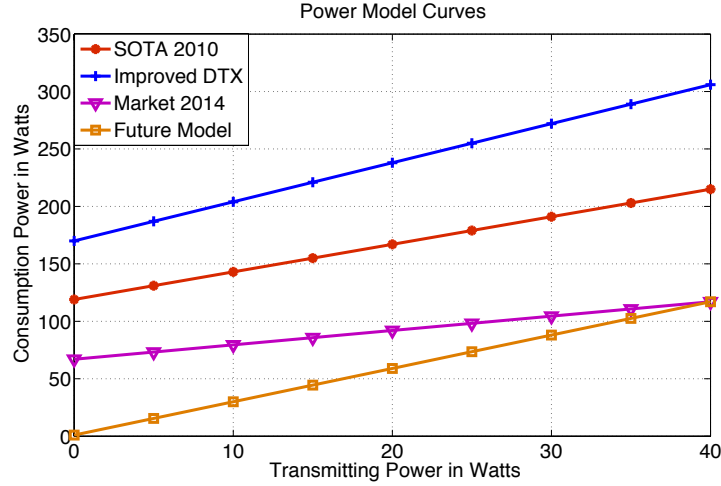


Figure 6.1 – Power Model curves extracted from [115].

Power Model	P_j^{fixed}	η	P_j^{sleep}
BS SOTA 2010	119W	2.4	63W
BS Enhanced with DTX	170W	3.4	25W
Market 2014 BS Model	67W	1.25	25W
Idealised BS Model	1W	2.9	1W

Table 6.1 – Macro-BS Power model values presented in [115]

6.2.2 Macro-BS population distribution for each scenario analysed

In our simulations, 2 scenarios are taken into account. In the first scenario a 20% of the Macro-BSs belong to Ω_R , the group of BSs that use a partial or full supply of renewable energy. For the second scenario, this value corresponds to 80% of the Macro-BSs. To choose the value of χ for each Macro-BS into the subgroup Ω_R we use a uniform distribution. Moreover, the two scenarios adopt a different percentage of Macro-BSs using one of the different power models shown in the previous subsection. For the first scenario the population of Macro-BSs is shared in the following manner: 40% of BSs use the model “BS enhanced with DTX”; another 30% use the model “SOTA 2010”; a 20% of Macro-BSs is using the model “Market 2014”; and finally a 10% of the Macro-BSs use the “Idealised Model”. This scenario represents the case where a larger percentage of Macro-BSs uses legacy technology and just a few correspond to the

latest platforms. The second scenario does totally the opposite in order to represent the evolution of the architecture several years later: just a 10% of BSs use the model “BS enhanced with DTX”; then a 20% uses the model “SOTA 2010”; another 30% of Macro-BSs use the model “Market 2014”; finally a 40% of the Macro-BSs goes for the “Idealised Model”. The scenario descriptions are summarised in Table. 6.2.

Scenario	Population Distribution with each Power Model	Population Percentage of BSs using renewable sources
<i>Scenario 1</i>	40% BS enhanced with DTX; 30% SOTA 2010; 20% Market 2014; 10% Idealised Model	20% of BSs
<i>Scenario 2</i>	10% BS enhanced with DTX; 20% SOTA 2010; 30% Market 2014; 40% Idealised Model	80% of BSs

Table 6.2 – Macro-BS population distribution for the two scenarios.

6.3 The Highly Heterogeneous Environment Aware DBCB Algorithm (HHEA-DBCB)

6.3.1 Basic Proposal

The proposal presented in this chapter is an enhancement of the femto-DBCB already described and studied in chapter 4 and 5. This new algorithm is conceived to make it adaptable to a hybrid network with different regimes of consumption and BS types. In such a kind of environment, a BS can be either from a legacy technology or maybe a very highly efficient recent BS system; some BSs can be fueled with fossils energy, some others could be fed by the electric distribution system, whereas others could be powered up by renewable energy. Moreover, in a network of such characteristics we can have BSs with different ranges of coverage, i.e. Macro, micro, pico, femto-BSs. We know that such a kind of heterogeneous environment is a potential real scenario currently and for the years to come. In this kind of environments, it is maybe not quite fair to make the MS-BS re-association/offloading based only on one single parameter, e.g. Load, SINR, Consumed Power, etc, given the fact that one single parameter could cause the offloading/redistribution of traffic be sent to a less energy efficient or “not so green” BS.

In such case we need to establish a set of metrics and a more powerful procedure to choose the BSs at the moment of traffic redistribution. The novelty of our new

proposal, the Highly Heterogeneous Environment Aware - DBCB (HHEA-DBCB) is focused precisely on that issue. The procedure is explained in the following.

First of all we are not going to consider anymore two sets of femto and Macro-BSs Ω and Φ separately, but we consider a new single set $\Upsilon|\Omega \cup \Phi = \Upsilon$ where all BS are contained. Into this set any BS, no matter its type (i.e. femto, Macro), has a global ID g . For any BS, the first step here is to receive the incoming traffic and establish what we call the pre-association phase. In this pre-association phase, an incoming MS i is accepted by the BS g that provides the highest SINR $\hat{\gamma}_{g,i}$, s.t. $\hat{\gamma}_{g,i} = \max(\gamma_{g,i}), |g \in \Upsilon$. After all the MSs are pre-associated to a BS, the next step is to make the decision of redistributing or not. First, we call $\Upsilon_{g',i}$, the set of potential candidates to redistribute a MS i currently associated to g . Second, we establish a set of P metrics with weight priorities for metric selection Π_g for a BS g that consists of:

$$\begin{aligned} \Pi_g &= (\pi_{g,1}, \pi_{g,2}, \dots, \pi_{g,p}, \dots, \pi_{g,P}) \\ \text{s.t. } & \pi_{g,1} > \pi_{g,2} > \dots > \pi_{g,p} > \dots > \pi_{g,P} \end{aligned} \quad (6.1)$$

Such set of weight priorities Π_g is used in order to define the sequence of each of the P different metrics used to select a BS neighbor acceptor $g' \in \Upsilon_{g',i}$ for a MS i . The metrics are checked one-by-one in order to compare all the neighbors into $\Upsilon_{g',i}$. Now, we call $\Theta_{g,i}$ the matrix used to store the information of the metrics to redistribute a MS i from g to a $g' \in \Upsilon_{g',i}$. Such a matrix has a size of $[\Upsilon_{g',i}] \times P$ and we call each metric value of the matrix $\theta_{(i,g',p)}$. When for a given metric comparison with priority weight $\pi_{g,p}$, there are two or more BSs into $\Upsilon_{g',i}$ tied with the same metric value, the procedure to break the tie consists of checking the metric with the next priority in sequence with weight $\pi_{g,p+1}$, and see if it breaks the tie or otherwise continue with the next metric in sequence and so on. If the tie persists and all the P metrics were checked, the tie breaks by choosing the BS g' into $\Upsilon_{g',i}$ with the highest global ID. A simplified flowchart of the already described process is shown in Fig 6.2.

6.3.2 Proposed metrics

For a first concrete version our algorithm, we propose a set of 3 basic metrics based on power consumption, BS load and distance. Each one of these 3 metrics is described in the following.

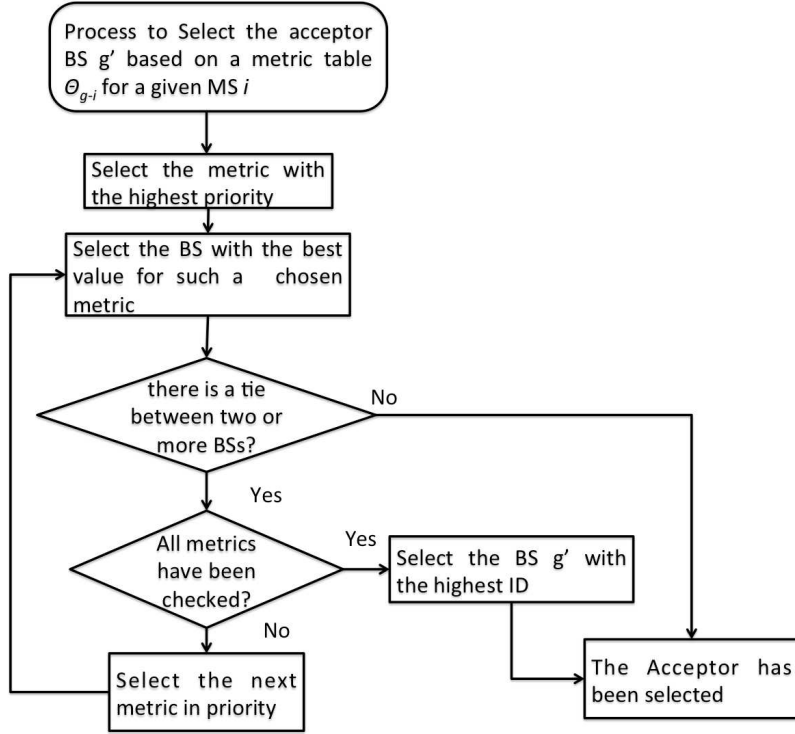


Figure 6.2 – Flowchart of the multimetric approach of HHEA-DCB.

The first metric to consider for a potential acceptor g' is the *non-renewable BS consumed power component for a given transmission power P^{Tx}* , we note it as $P_{g'(NR)}(P^{Tx})$ and describe by the following expression:

$$P_{g'(NR)}(P^{Tx}) = P_{g'}(P^{Tx}) - P_{g'(R)}(P^{Tx}) \quad (6.2)$$

where:

- $P_{g'}(P^{Tx})$ is the total consumed power of the BS g' with a transmission power equal to P^{Tx} .
- $P_{g'(R)}(P^{Tx})$ is the renewable consumed power component for the BS g' with a transmission power equal to P^{Tx} .

We give to this metric the highest weight $\pi_{g,1}$, the Priority Level 1 (see Fig. 6.3), and therefore the first to check in the decision-making procedure. For this metric, we only take into account the power fed by a non-renewable source and skip any contribution from any other source considered as green due to the fact it can be considered as “costless”.

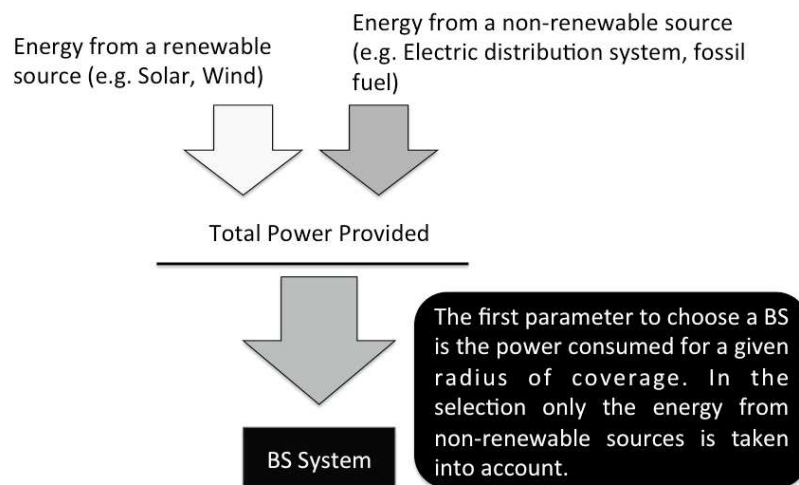


Figure 6.3 – First criterion of selection for an acceptor BS: the non-renewable power consumption figure.

Then we consider the next two other metrics based on SINR and BS Load. For the scope of this thesis we give a fixed higher priority to the load metric, however it would be interesting to extend the study by giving a higher priority to the SINR level, having an algorithm behaviour oriented to care a little more about on the MS transmission power than the RAN overall energy consumption (see Fig. 6.4). In our studied case in this chapter, we prefer first highly loaded BSs in order to concentrate the traffic in few BSs therefore maximising the number of deactivated BSs.

In our selection, for the load metric, more specifically, we take a normalised load metric similar to Eq. 3.2. We consider that a BS g' has a normalised load $L_{g'}$ given by the following equation:

$$L_{g'} = \sum_{M_{g'}} \frac{\omega_i}{W_{g'}} \quad (6.3)$$

where,

- ω_i is the portion of spectrum allocated to any MS i .
- $M_{g'}$ is the number of MSs associated to g' .
- $W_{g'}$ spectrum band assigned to g' .

Therefore, when it is necessary to break the tie with the normalised load metric, a BS g prefers in order to re-associate the MS i , the neighbor g' with the highest $L_{g'}$. This

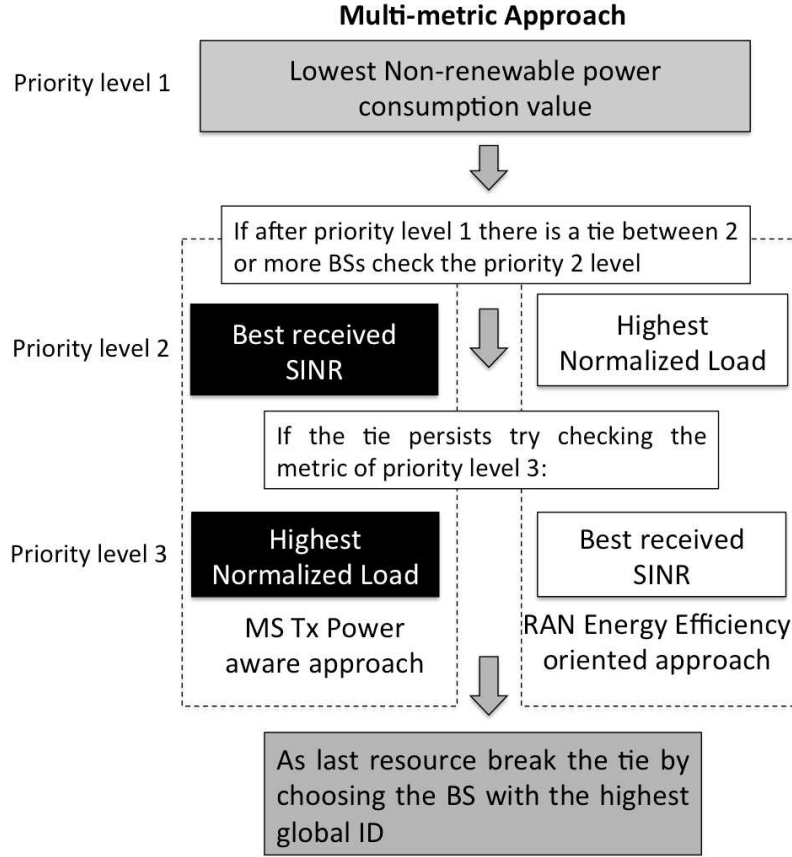


Figure 6.4 – Based on priority different paths can be used for the sequential metric checking in the proposed Highly Heterogeneous Environment Aware Cell Breathing Algorithm (HHEA-DBCBC) implementation.

strategy permits to concentrate traffic in few access spots. For the case of breaking the tie based on the SINR level, a BS g chooses the neighbor g' with the highest offered SINR $\hat{\gamma}_{g',i}$ as expressed in the following expression:

$$\hat{\gamma}_{g',i} = \max(\gamma_{g',i}), |g' \in \Upsilon_{g',i} \quad (6.4)$$

6.3.3 Example of the HHEA-DBCBC functioning

A way of implementing the BS acceptor selection is to create what we call a “BS ranking table” that sorts all values of $\Theta_{g,i}$ to facilitate the search of the best BS g' . In such a table, all potential BS acceptors are classified by means of the set of weighted metrics previously described. Here, after retrieving all the necessary metric informations from each potential BS acceptor, the group of candidates is sorted in function of the weight of each one of the metric types. This table is created every time a MS i is about to be

redistributed. Such a task is done by each BS executing the offloading procedure with no central server involved.

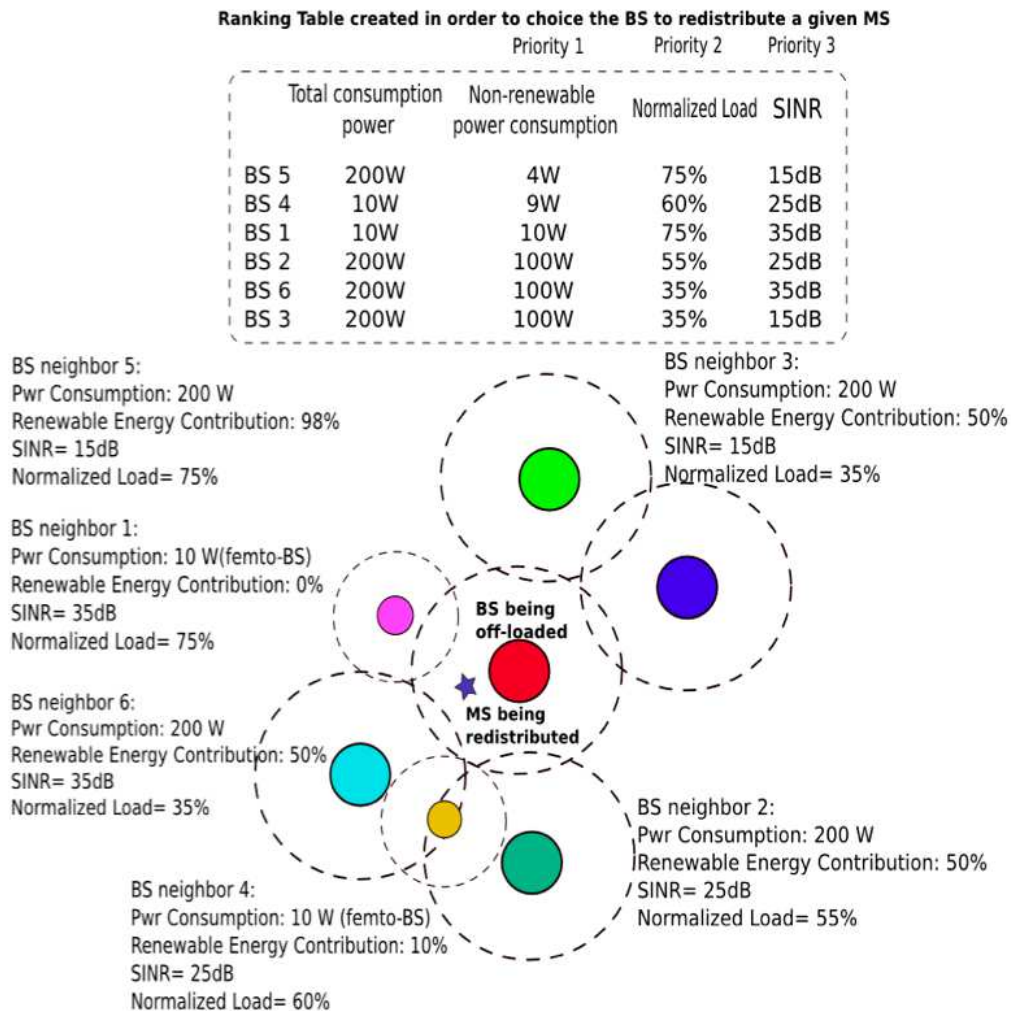


Figure 6.5 – Example of the creation of a ranking table in order to classify a group of BSs and select the BS acceptor.

In Fig. 6.5 an example is provided where the ranking table is created for redistributing a given MS. In this example, there are 6 potential BS acceptors, i.e. BS 1 to BS 6. In order to make the decision, the different informations from each BS are retrieved, i.e. the total power consumed, the percentage of renewable energy contribution, the measured SINR and the normalised load. We see how the BSs are sorted following the priority metric sequence: non-renewable power (priority level 1), normalised load (priority level 2) and the SINR level (priority level 3). As shown in the ranking table of Fig. 6.5 the best candidate for BS acceptor is the BS5 because of its very reduced non-renewable energy consumption of just 4W (98% of the input is renewable), despite the fact its full consumption is 200W. The BS Load and SINR metrics are left in a second place. Also in the example we can see the existing tie in the priority 1 metric

between BS2 – BS3 – BS6, having a total consumption of 200W with 50% of renewable energy contribution. We see that the way to break the tie is to use the metric of priority level 2, in this case the normalised load. For the discussed example the BSs are sorted in descending order as a function of the normalised load, i.e. BS 2 with 55% and BS 3-BS 6 tied with 35%. The tie of the priority 2 level is broken when the SINR level (priority level 3) is taken into account.

6.4 Analysis of HHEA-DBCB and Comparison vs. Other Approaches

For this chapter we made some modifications in the established rules of MS-BS association compared to the chapters 3, 4 and 5. Previously in chapter 3, all MSs were preassociated to a given Macro-BS in the access network for each one of Montecarlo snapshots. Then, the MSs, by using one of the cell breathing algorithms analysed in that chapter were redistributed to other Macro-BS neighbors in order to perform the BS offloading and deactivation. Later, for chapters 4 and 5, it was possible to perform also the redistribution toward the neighbor femtoBSs. In this chapter, we change the rules and we allow also from the beginning to select the best BS, whether femto or macro, for pre-association by using the best SINR criterion. After that, the redistribution/offloading algorithms are executed.

Although we keep the main simulation parameters shown in chapters 4 and 5, we remember that scenarios are highly influenced by the already discussed characteristics presented in section 6.2. In a first scenario we prefer to deploy more BSs with higher consumption regimes where additionally a very low percentage of these BSs are powered by renewable technologies or use the “Idealised Model” presented in [115]. In contrast, for the second scenario we give higher percentages in the distribution of population to the groups of BSs fully or partially powered by renewable energies as well as the Idealised Model. In order to compare our new proposal we took the macro-to-femto offloading algorithm proposed in [33] and our previously proposed algorithm femto-DBCB [36].

6.4.1 Scenario 1: An important majority of legacy BSs and a very low percentage of BSs based on renewable energy sources

The population distribution in this first scenario is: 40% of the Macro-BSs use the model “BS enhanced with DTX”; 30% of the Macro-BSs use the model “SOTA 2010”; 20% of the Macro-BSs use the model “Market 2014”; 10% of the Macro-BSs use the “Idealised Model”. A 80% of Macro-BSs are fully powered by non-renewable energies and the remaining 20% uses fully or partially a renewable source.

In Fig. 6.6 we see how less femto-BSs are active in the HHEA-DBC proposal. The reason is that different to previous approaches that provide the macro-to-femto offloading feature as it happens with the algorithm based on UAA devices proposed in [33] or our previously proposed femto-DBC, the new proposal HHEA-DBC provides a general mechanism of offloading. In our algorithm all BSs are considered as equals and therefore is possible to have here cases of macro-to-macro, macro-to-femto offloading, but also is possible to have femto-to-macro or femto-to-femto cases. In this scenario femto-BSs using the HHEA-DBC algorithm can whether offload to a femto-BS neighbour, which is highly loaded and then concentrate the load there, but also they can redistribute to a Macro-BS with a lower consumption, i.e. a BS using the “Idealised Model” or a BS supplied fully or partially by renewable energies.

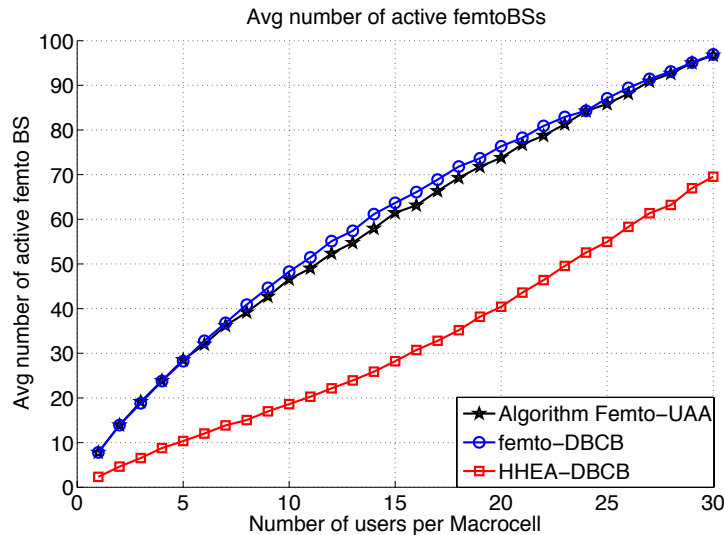


Figure 6.6 – Number of active femtoBSs for the simulated algorithms (Scenario 1)

On the other hand for Fig. 6.7 we see how the proportion of deactivated Macro-BSs is also greater for HHEA-DBC. The explanation comes again of combining the power and the load as the top element in the decision making process. As we saw in Chapter 4,

for femto-DBC and also the UAA approach presented by [33], we have only macro-to-macro and macro-to-femto offloading. Specifically, for the macro-to-femto, the decision is based on the best SINR offered by the neighbors. For HHEA-DBC, on the other hand we are going to concentrate the load in any BS (whether Macro or femto) with low consumption and high associated load. Therefore, the load is concentrated in some few femto-BSs as well as some low non-renewable power consumption Macro-BSs. This strategy permits to offload a little bit more of Macro BS sectors than with the other two techniques, without unnecessarily activating a great number of femto-BSs. Finally, when we analyse the RAN overall consumption in Fig. 6.8, we see that by having less Macro-BSs and femto-BSs active and besides using those with the lowest non-renewable power consumption component, the power consumption levels for the RAN are reduced substantially. In this graph, only non-renewable consumption is considered.

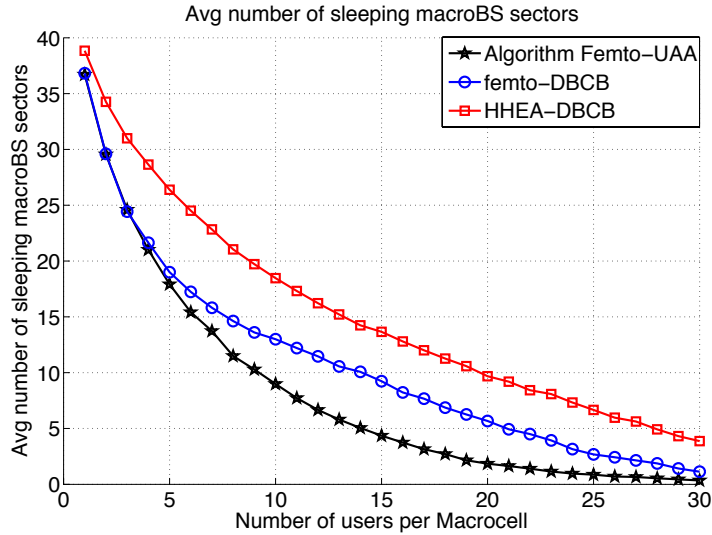


Figure 6.7 – Number of sleeping Macro-BSs for the simulated algorithms (Scenario 1)

6.4.2 Scenario 2: An important percentage of renewable energy and Idealised Model BSs and low percentage of legacy BSs

The population distribution in this first scenario is: 10% of the Macro-BSs use the model “BS enhanced with DTX”; 20% of the Macro-BSs use the model “SOTA 2010”; 30% of the Macro-BSs use the model “Market 2014”; 40% of the Macro-BSs use the “Idealised Model”. A 20% of Macro-BSs are fully powered by non-renewable energies and the remaining 80% uses fully or partially a renewable source.

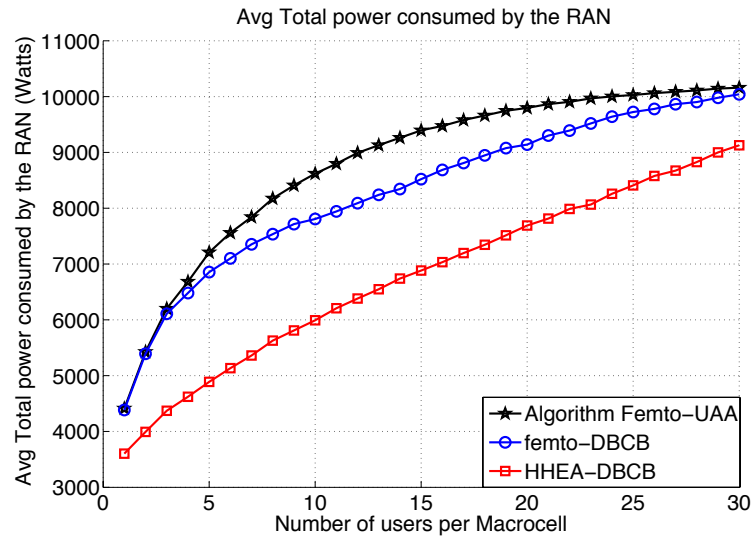


Figure 6.8 – Average RAN consumption power for the simulated algorithms (Scenario 1). Only consumed power from non-renewable sources is considered.

In Fig. 6.9 we see how the number of active femtoBSs for the femto-DBC and the algorithm based on UAA devices keep the same figures compared to the previous scenario, whereas for HHEA-DBC this number is substantially reduced. This can be explained based again on the fact that HHEA-DBC counts with the feature of being able to offload the femto-BSs by using other femto-BSs or also by using Macro-BSs at a lower power regime or supported on renewable energies. Here specifically, HHEA-DBC exploits the advantages of a macrolayer with a great number of Macro-BSs using fully or partially renewable sources, a very interesting option for traffic offloading. We cannot take advantage of this with the other two algorithms (i.e. Algorithm based on UAA devices and the femto-DBC) due to the fact they are totally unaware of the power regimes at the macrolayer. The resulting drawback of this for the femto-DBC and the algorithm based on UAA devices, it is that as we increase the traffic load, we simply are going to use more and more femtoBSs, which are not going to be necessarily efficiently loaded.

For Fig 6.10 we see the number of MacroBS deactivated for the different algorithms simulated. Here, we can see how the gap that we saw in scenario 1 is smaller. The explanation of this comes from the fact that in this scenario many femto-BSs are offloading the traffic toward the macro-layer due to a lower power regime of many of those Macro-BSs compared to the femtoBS power model. Finally, we can see how also in this scenario the HHEA-DBC outperforms the other two algorithms by choosing the BSs with the lowest consumption and highest normalised load to remain active (Fig. 6.11). We can notice how these curves are less softer than in scenario 1. This is because of the variability of the contribution of renewable source energies for each

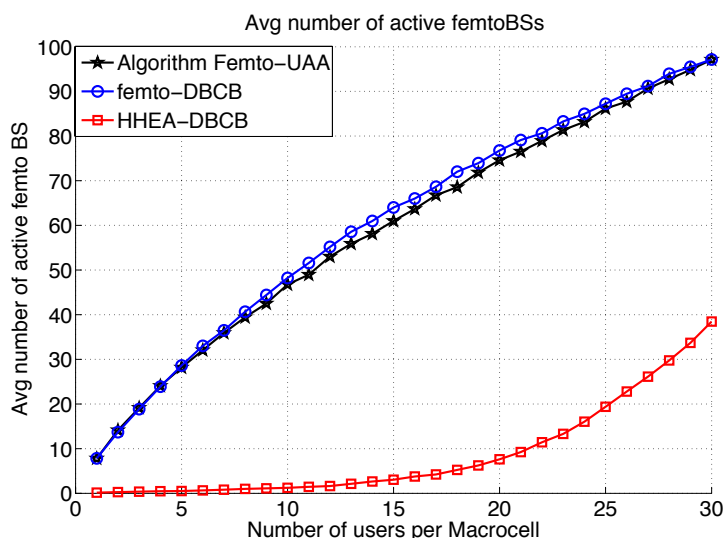


Figure 6.9 – Number of active femto-BSs for the simulated algorithms (Scenario 2)

MacroBS in each one of the Montecarlo snapshots, i.e. the percentage χ defined in section 6.2.2. This latter is not quite noticeable in the first scenario because only 20% of the BSs were powered fully or partially by renewable sources.

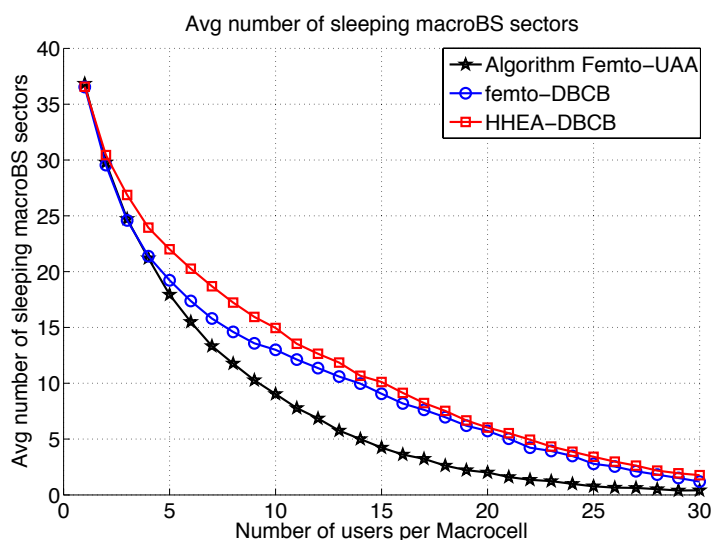


Figure 6.10 – Number of sleeping Macro-BSs for the simulated algorithms (Scenario 2)

6.4.3 Potential Improvements of the HHEA-DBCBC by Including a Learning Strategy

The Cognitive Radio and the learning techniques as we mentioned in section 2.5 are clear enablers for other techniques in upper layers according to the classification model

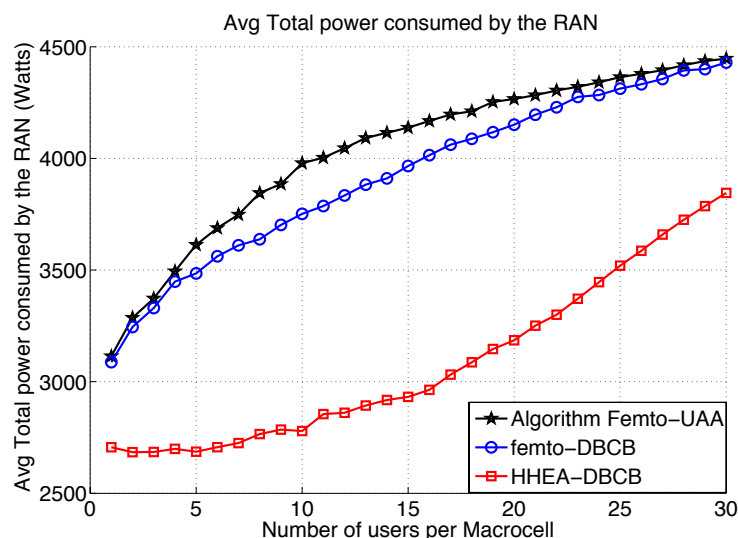


Figure 6.11 – Average RAN consumption power for the simulated algorithms (Scenario 2). Only consumed power from non-renewable sources is considered.

presented in Chapter 2. This latter, given the capability of sensing and learning about the surrounding conditions, something that improves the decisions made by an energy-efficient mechanism. The Algorithm described in this chapter can be improved by means of learning strategies. One aspect which could be learnt by the BS is the most appropriate BS neighbour acceptor selection strategy, given a particular set of circumstances. At the beginning, BSs would be selected randomly when they are tied after the priority level 1 check. After that, the probability of selection being dependent on a reward level associated with each state, i.e. a combination of BSs activated simultaneously.

The BS that executes the modified HHEA-DBC algorithm then memorises the neighbour BSs selected and the time episode associated with that specific selection. This will be performed each time the algorithm is executed over a window of time. This window period must be established in order to detect a BS selection combination by comparing the results in each execution point in the window with past executions in previous windows. During each execution a different combination of BSs are applied. A central node (i.e. the cluster head, for instance) can calculate the overall saving into the cluster after the execution of the algorithm by all the BSs associated.

After each window period, the BSs that participated in an energy saving increase at a given time episode with respect to previous windows, receive a reward, which is dependent on the level of energy saving. The higher the reward received, the higher the chance of being chosen again as BS acceptor at the same time period in the window.

6.5 Chapter Outcome

6.5.1 Concluding Remarks

In this chapter we have provided a new multimetric technique for BS redistribution/offloading in switching-off schemes for a highly heterogeneous environment. We have seen that by giving a higher priority to the power consumption and the load level is possible to concentrate the network load in some few BS working with low consumption power levels or with a high supply contribution from renewable energies. It has been observed how the algorithm strategy always makes very good choices for the two simulations scenarios proposed, where we have varied the population distribution of BS types (i.e. the power model) at the Macro-layer. Moreover, this algorithm has the additional advantage of allowing different ways of offloading (macro-to-femto, macro-to-macro, femto-to-macro, femto-to-femto), which makes this proposal much more flexible at the moment of reorganising the MS-BS reassociation and the traffic redistribution, something that permits to reduce even more the unnecessary active infrastructure.

6.5.2 Future Works

A convenient next stage to this work is to apply learning and cognitive approaches in order to create fully autonomous self-organised energy-efficient radio access networks. Such learning approaches must help the BS systems to make wiser decisions for offloading and redistributing traffic for the highly heterogeneous scenarios portrayed in this chapter. Moreover, such mechanisms must allow a better resource allocation, which optimises not only energy consumption, but also other elements like the spectrum efficiency, where it exists a very well known trade-off. Also the discussion can be extended into this approach by giving different weight values to define the priorities into the algorithm and see its influence on the performance.

7.1 Conclusions

This work intended to provide contributions to the Green Radio and resource allocation domain. Firstly in chapter 2, our state of art studies have permitted us to organise the vast literature in energy-efficiency for mobile networks by means of a classification model with a defined hierarchy of layers, where bottom approaches, e.g, BS component enhancement, Cognitive Radio, become enablers of the overall saving produced at upper layers, e.g, Energy Aware RRM, Cell Breathing, Heterogeneous architectures, etc. Moreover, this classification model has allowed also the comparison of the different approaches, as well as giving the possibility of establishing means of potential integration of the different techniques.

After that, we presented a family line of mechanisms for energy-efficient mobile networks taking as core of the proposal an algorithm that we called Distributed BS Based Cell Breathing (DBCB). Based on the original proposal, we provide different enhancements bringing progressively more powerful and sophisticated techniques. Firstly, in chapter 3 we presented the DBCB and we applied it for a Macro-only cellular network with 3G/CDMA characteristics. For the simulations results, we obtained that this technique is able to outperform other distributed approaches and have similar or slightly better performances compared to the state of the art centralised cell breathing approaches. This came additionally with the advantage of being clustered/distributed, which makes the approach more robust to failures than such techniques depending on decisions from a single central server. Then, we performed some ameliorations of the DBCB approach bringing the improved MA-DBCB. The purpose of this algorithm was to correct the strong aggressiveness presented by DBCB in terms of BS offloading and switching-off, due to its functioning principle based on concentrating load in few highly loaded spots. This latter affected the MS performance given the fact that transmission distances became longer (i.e. transmission power increases), due to the cell-breathing resulting cell sizes after the switching-off process. This undesired effect was, above

all experienced for those MSs located in the cell edge borders. In order to overcome that, we developed a metric based on BS load and SINR in order to provide a softer behaviour that also took into account transmission distances. Furthermore, in order to provide a more flexible and configurable scheme we added also the possibility of setting, in a BS basis, a load threshold A_T that prevented the BS algorithm execution. By doing this latter, our goal was to limit the number of switched-off BSs, as well as the associated transmission distance increase. The impact of this changes according to the obtained results did not affect importantly the attained RAN savings obtained but rather helped us to regulate the average and maximum transmission power for the uplink.

Later in chapter 4, we continued our work by proposing to combine the cell-breathing with the extended capacity provided by Macro/femto heterogeneous radio access network. For this next stage, we migrated our network environment by introducing the LTE technology and its standards. The presented technique, the femto-DBCB, was conceived to increase the number of Macro-BS switched-off by relying on the additional possibility brought by the macro-to-femto offloading feature. This combination of approaches brought different new positive aspects to show into our global proposal. Firstly, the femto-DBCB technique exhibited a better performance than any of the approaches based on a single technique, whether the cell-breathing or macro-to-femto offloading, by permitting to switch-off more BSs at the macrolayer; second, we provided an integral solution that took into account not only how to switch-off but also how to reactivate the devices, something that permitted to deal with the coverage-holes existing when a macro-to-femto offloading approach is applied. It is also important to mention that in this stage of our project the impact of 3GPP CSGs in the performance of the proposals was analysed, something that to the best of our knowledge was not done before.

In addition, the chapter 5 permitted to analyse the electromagnetic compliance in downlink for the proposed approaches in the previous chapters, i.e., MA-DBCB and femto-DBCB. We saw in this chapters how the cell-breathing technique can potentially violate the established thresholds found in the international regulation to this subject. We think, however, that in the case of MA-DBCB it is possible to regulate such a behaviour by using the load threshold A_T in order to limit in some critical areas the number of switched-off BSs, e.g., nearby hospitals, schools, very crowded places, something that sacrifices the energy saving but that also permits to reduce the radiation exposure on human beings. On the other hand, for femto-DBCB we observed how the use of the macro-to-femto offloading component permitted to substantially reduce the

radiation levels due to the use of the femto-BS infrastructure and a lower transmission power associated.

To close the set of contributions provided in this thesis, in chapter 6 we presented a final algorithm called HHEA-DBCB aimed to highly heterogeneous environments where a BS may have different characteristics of power consumption, type of energy supply, coverage and radio resources. The technique was supported on a multimetric decision scheme that permitted to take into account different elements, i.e, SINR, Load, Power consumption, in order to decide to which neighbour BS (whether macro or femto) redistribute the traffic. The fact of giving higher weight to the power consumption and the load, permitted to concentrate the load in few spots with a low power regime or powered by renewable energies, something that permitted to increase the power saving by being aware of the whole environment.

7.2 Future Work and Perspectives

After the work discussed throughout this document some topics remain still open. We have identified some aspects for further study that we will describe in the following.

There are several open topics that we could study related to the cell-breathing and specifically our presented proposals in this thesis. For instance, the optimal cluster size for the DBCB architecture is an interesting subject to analyse in order to provide an optimal response to the fluctuating changes in the mobile network traffic. Also it would be interesting to see the potential enhancement of including in our proposed techniques and architectures, the use of other radio devices like relays.

Another very interesting perspective is to delve deeper on learning mechanisms as a mean to improve our proposals. This knowledge we acquire in learning mechanisms could be also useful in other aspects. For instance, for less complex scenarios, the threshold A_T autosetting for the MA-DBCB technique is something important to develop. We think it should be possible to set optimal values for such a threshold in a BS basis adapted to daily traffic patterns. This value A_T must be adapted to the different constraints given by the environment because of the following reasons: i) we have the electromagnetic constraints to respect, something that becomes more critical in zones with a high density of children or aged people population as we already commented for places like schools or hospitals; ii) we need to take into account the MS performance that repercutes in user perception. In real life, for some coverage zones with poorer coverage and service availability, e.g. rural or remote areas, vehicular/train scenar-

ios, to put in place very aggressive switch-off schemes can deteriorate more the service conditions.

Also our multimetric approach for highly heterogeneous networks, as we had already discussed in chapter 6 is well suited to be implemented supported on learning and cognitive radio techniques. This will permit more accurate and rapid decisions in environments that are maybe highly heterogeneous in terms of power regimes, coverage characteristics or device resource capacity, but also however quite predictable in a time basis. This is something that we consider highly priority in our research, which is additionally very feasible thanks to the collaboration that we already established with prof. David Grace and his team in the University of York.

In addition, we mention the potential gains when mixing our proposals with the pricing strategies. It would be interesting to see algorithms where the users bargain and trade with resources, make decisions and contribute to provide a more efficient behaviour of the network based on reward approaches.

We also intend to continue our work on electromagnetic compliance for cell-breathing. After having studied the downlink side, we think is also very important to analyse the uplink, where the power transmitted by the mobile phone and absorbed by the head and body is not negligible. This study needs however of expertise on electromagnetics measurements and tests, as well as potentially, the need of using sophisticated electromagnetic simulation. For that, we have established a collaboration with the colleagues of the Microwaves Department of Telecom Bretagne, specially with prof. Christian Person. Thanks to that we think very feasible to perform further analysis and studies associated to the electromagnetic compliance of our proposed techniques.

List of Publications

Peer reviewed Journals

- L. Suárez, L. Nuaymi and J.M Bonnin, "An overview and classification of research approaches in green wireless networks," in *EURASIP Journal on Wireless Communications and Networking 2012*, April 2012.

International Conferences

- L. Suárez, L. Nuaymi and J.M Bonnin, "Energy performance of a distributed BS based green cell breathing algorithm," in *Proceedings of International Symposium of Wireless Communication Systems (ISWCS) 2012*, Paris, France, Aug 2012.
- L. Suárez, L. Nuaymi and J.M Bonnin, "Analysis of the overall energy savings achieved by green cell-breathing mechanisms," in *Proceedings of Sustainable Internet and ICT for Sustainability (SustainIT) 2012*, Pisa, Italy, Oct 2012.
- L. Suárez, L. Nuaymi, C. Person and J.M Bonnin, "Electromagnetic radiation compliance under the use of green cell breathing and hybrid network approaches in LTE," in *Proceedings of IEEE 24th International Symposium on Personal, Indoor and Mobile Radio Communications: Workshop on End-to-End Green Cellular Networks*, London, United Kingdom, Sep 2013.
- L. Suárez, L. Nuaymi and J.M Bonnin, "Analysis of a Green-Cell Breathing technique in a hybrid access network environment," in *Proceedings of IFIP Wireless Days (WD) 2013*, Valencia, Spain, Nov 2013.

Book Chapters

- L. Nuaymi and L. Suárez, "Respiration de cellules dans les réseaux cellulaires green", *Techniques de l'Ingenieur*, France, May 2013

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