ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΩΣ
UNIVERSITY OF PIRAEUS
Τμήμα Ψηφιακών Συστημάτων

Διδακτορική Διατριβή

Ενεργειακά Αποδοτικά Δίκτυα Ασύρματων Επικοινωνιών

ΓΕΩΡΓΙΟΣ ΚΥΡΙΑΖΗΣ

Πειραιάς

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Διδακτορική Διατριβή

του

Γεωργίου Κυριαζή

Η Διατριβή Υποβάλλεται για την Εκπλήρωση των Απαιτήσεων Απόκτησης Διδακτορικού Διπλώματος

Πειραιάς

Ιούνιος 2017

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Γεώργιος Κυριαζής

Πτυχιούχος Τμήματος Ψηφιακών Συστημάτων Πανεπιστημίου Πειραιώς

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ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΩΣ
UNIVERSITY OF PIRAEUS
Department of Digital Systems

PhD Dissertation

Energy-Efficient Wireless Communication Networks

GEORGIOS KYRIAZIS

Piraeus

June 2017

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ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΩΣ
UNIVERSITY OF PIRAEUS
Department of Digital Systems

Energy-Efficient Wireless Communication Networks

PhD Dissertation

of

Georgios Kyriazis

In Partial Fulfilment of the Requirements for the Degree
Doctor of Philosophy

Piraeus

June 2017

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Διδακτορική Διατριβή

Ενεργειακά Αποδοτικά Δίκτυα Ασύρματων Επικοινωνιών

Γεώργιος Κυριαζής

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PhD Dissertation

Energy-Efficient Wireless Communication Networks

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ΠΕΡΙΛΗΨΗ (GREEK)

Στα ασύρματα δίκτυα επικοινωνιών, με πλήρη ανασχεδιασμό της διάρθρωσης, λειτουργίας και κατανομής των πόρων αυτού του ιδιαιτέρως περίπλοκου μηχανισμού σε όλα τα επίπεδα λειτουργίας του, μπορεί να εξοικονομηθεί σημαντικό ποσοστό της καταναλισκόμενης ενέργειας. Κατάλληλες υποδομές ανταλλαγής και λήψης αποφάσεων, οι οποίες θα παρέχουν στο σύστημα διαχείρισης του εκάστοτε δικτύου τη δυνατότητα να γνωρίζει το βέλτιστο τρόπο με τον οποίο θα μπορεί να ανταποκριθεί στις συνεχώς μεταβαλλόμενες ανάγκες και συνθήκες του περιβάλλοντός του, κρίνονται απαραίτητες και πρέπει να υλοποιηθούν διότι θα συμβάλλουν στην επίτευξη υψηλού βαθμού βελτιστοποίησης της ενεργειακής απόδοσης των ασύρματων δικτύων τηλεπικοινωνιών.

Η παρούσα Διδακτορική Διατριβή εστιάζει στην ενεργειακά αποδοτική λειτουργία των δικτύων κινητής, που είναι μία εκ των δύο σημαντικότερων τεχνολογιών ασύρματης πρόσβασης. Εστιάσαμε στην αναθεώρηση του τρόπου λειτουργίας των σημείων ασύρματης πρόσβασης, τα οποία αναλίσκουν το 80% της απαιτούμενης ενέργειας για την ομαλή λειτουργία ενός δικτύου κινητής. Προτείναμε νέα προφίλ λειτουργίας, εκπομπής και εξυπηρέτησης της τηλεπικοινωνιακής κίνησης στο σύνολο των σημείων πρόσβασης, στοχεύοντας στην υψηλότερη μείωση της ενεργειακής τους κατανάλωσης, με παράλληλη παρακολούθηση και διατήρηση του επιπέδου των υπηρεσιών που προσφέρεται στον τελικό χρήστη. Από θεωρητική προσέγγιση, αποδείξαμε ότι το συγκεκριμένο μοντέλο προσέγγισης της μείωσης της ενεργειακής κατανάλωσης των δικτύων κινητής εντάσσεται στην κατηγορία προβλημάτων χωρητικότητας και χωροθέτησης που ανήκει στην κατηγορία NP-Δύσκολων προβλημάτων. Εφαρμόσαμε τεχνικές εύρεσης της μέγιστης ενεργειακής εξοικονόμησης σε καθένα από τα μοντέλα συστήματος δικτύων κινητής που εξετάσαμε, και διατυπώσαμε τα αντίστοιχα προβλήματα ενεργειακής βελτιστοποίησης. Εξετάσαμε ποικιλία παραμέτρων και εκδοχών στα ανωτέρω προβλήματα, όπως: α) ομογενή και ετερογενή μοντέλα τοπολογιών, β) διάφορες τεχνικές ραδιοπρόσβασης, γ) στατικά μοντέλα και μοντέλα κίνησης χρηστών, δ) διαφορετικής ποιότητας προσφερόμενες υπηρεσίες, καθώς και ε) εφαρμογή μοντέλων οπισθοζεύξεων, και αναδείξαμε ευριστικά σχήματα εξεύρεσης βέλτιστων ενεργειακά λύσεων, ικανά να ελαχιστοποιήσουν την ενεργειακή κατανάλωση των δικτύων κινητής ανά στιγμιότυπο ή ανά ημερήσιο κύκλο της λειτουργίας τους, διατηρώντας παράλληλα την ποιότητα των υπηρεσιών στα επιθυμητά επίπεδα.

Λέξεις - Κλειδιά: Ενεργειακά Αποδοτικά Δίκτυα, Ασύρματες Επικοινωνίες, Σχεδιασμός Δικτύων Κινητής, Βελτιστοποίηση Δικτύων Κινητής, Πράσινες Τηλεπικοινωνίες.

ABSTRACT

In wireless communication networks, with a full redesign in structure, operation and resources' distribution at all levels of operation of this very complex mechanism, a significant amount of the consumed energy can be saved. Proper decision-exchange and support infrastructures, which will provide to the network management services the ability to meet the ever-changing needs and conditions of the environment, are considered as necessary, in order to achieve a high degree of energy efficiency optimization in wireless broadband communications.

This PhD Dissertation focuses on energy-efficient operation of one of the most common wireless access technologies, namely mobile/cellular communications. We focused on the wireless access points' operation, which consume up to 80% of the total energy required by an operational wireless mobile network. We introduced new operational, transmission and traffic load servicing profiles in the set of wireless access points, aiming at the higher reduction of their energy consumption, while maintaining and monitoring the level of services offered to the end user. From a theoretical perspective, we classified this particular energy aware model into the category of the capacitated facility location problems, which are NP-hard. We applied exhaustive techniques for estimating the upper bound in each of the mobile network's system models we examined, and we formulated the corresponding power consumption optimization problems. We examined a variety of different parameters and variations, such as: a) homogeneous and heterogeneous topology models, b) different radio access techniques, c) static users and user mobility patterns d) variety of offered services, as well as and e) application of backhaul models, and introduced energy-efficient heuristic schemes capable of finding the optimal solution from a power consumption perspective, per snapshot and/or per daily operation of a wireless communication network, while maintaining the quality of services at the desired levels.

Keywords: Energy Efficiency, Network Design, Cellular Networks, Green radio Communications, Wireless Communications, Mobile Optimization Schemes.

ΠΡΟΛΟΓΟΣ (GREEK)

Ευχαριστώ το Θεό που με αξίωσε να ολοκληρώσω τη Διατριβή μου.

Είμαι ιδιαιτέρως χαρούμενος την ώρα αυτή που γράφω τις τελευταίες γραμμές της Διδακτορικής μου Διατριβής. Τι ωραίο ταξίδι, πραγματικά! Ταξίδι γνώσης, αναζήτησης, υπερπήδησης πολλών δυσκολιών, απόλυτης συγκέντρωσης, πνευματικής ανάπτυξης και πλούσιων συναισθημάτων, που δεν θα μπορούσε να με οδηγήσει στην Ιθάκη μου χωρίς τη στήριξη σπουδαίων τόσο επιστημόνων όσο και ανθρώπων στη ζωή μου.

Σε αυτό το σημείο, θα ήθελα να ευχαριστήσω εκ βάθους καρδίας τον Αναπληρωτή Καθηγητή Άγγελο Ρούσκα για την καθοδήγηση και την επικουρία του καθ' όλη τη διάρκεια των σπουδών μου. Παρομοίως τον Καθηγητή Παναγιώτη Δεμέστιχα για την αμέριστη συμμετοχή του. Βεβαίως, θα ήθελα να εκφράσω την ειλικρινή ευγνωμοσύνη μου στον Καθηγητή Μιλτιάδη Αναγνώστου, που χωρίς την υποστήριξή του δεν θα ήταν δυνατό αυτό το ταξίδι. Επιπλέον, θα ήθελα να ευχαριστήσω τα μέλη της εξεταστικής επιτροπής, τον Καθηγητή Γεώργιο Καρέτσο, τον Αναπληρωτή Καθηγητή Δημήτριο Βέργαδο, τον Αναπληρωτή Καθηγητή Δημοσθένη Βουγιούκα, καθώς και τον Αναπληρωτή Καθηγητή Χαράλαμπο Σκιάνη.

Αφιερώνω τη διατριβή μου στην Αγαπητή μου Μητέρα και στον Αξιολάτρευτο Αδελφό μου, που στέκονται ωσάν ακοίμητοι φρουροί δίπλα μου όλα αυτά τα χρόνια. Επίσης, στους καλούς μου φίλους Ραχάντ και Σπυριδούλα, για την πραγματική τους υποστήριξη. Τέλος, *στον πατέρα μου εκεί ψηλά*…

Με εκτίμηση,
Γεώργιος Κυριαζής

FOREWORD

I thank God for giving me all the help and determination to complete my Dissertation.

I am particularly happy right now that I am writing the last lines of my PhD Dissertation. What a great journey it was, really! A journey full of requests, adverse conditions and diversity of feelings where strong will, focus and continuous efforts led to knowledge and mental growth. I shall confess that without the support of great both scientists and humans in my life, it would have been impossible for me to arrive in my Ithaca.

At this point, i would like to thank from the bottom of my heart the Associate Professor Angelos Rouskas for his guidance and support during my PhD studies. Likewise, the Professor Panagiotis Demestichas for his unreserved participation. Certainly, i would like to express my deep gratitude to the Professor Miltiadis Anagnostou, since without his support this journey would had not begun. Also, i would to like to thank the members of the examination committee, the Professor Georgios Karetsos, the Associate Professor Charalabos Skianis, the Associate Professor Dimitrios Vergados and the Associate Professor Demosthenes Vouyioukas.

Last but not least, i dedicate my PhD Dissertation to my Dear Mother and my Adorable Brother, who are standing as sleepless guardians beside me all these years. Also, to my dear friends Rachant and Spyridoula for their real support. Finally, *to my father up there*…

Yours sincerely,
Georgios Kyriazis

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CHAPTER 1. INTRODUCTION

Climate changes and environmental protection are two of the most critical challenges that humanity is facing. Reckless exploitation and squandering of the natural resources lead to significant increases and challenges in the energy market. As our society strives for environmentally friendly solutions, during the last decade green technologies are widely adopted and new technologies are being evaluated based on their carbon footprint. From this chain of changes, the telecommunications industry cannot be absent and is driven to a thorough examination of its environmental and social responsibilities and of course of its energy balances. In this effort of reducing wasteful consumption of energy resources, various research efforts have been made towards systems' efficient operation with reduced emissions.

1.1 Wireless networks and power consumption

"After its invention, the telegram took 90 years to spread to four-fifths of developing countries; for the cell phone, the comparable diffusion was 16 years." R. J. Samuelson, Washington Post. Wireless mobile communications are maybe the most evolutionary widespread technology that we passionately embrace and eagerly adopt its advances almost for three decades now. A technology that was commercially introduced in 1991 and has reached 7.5 billion worldwide mobile subscriptions till Q3/2016, marginally more than the world population nowadays, while forecasts predict to reach up to 9 billion in 2022 [1]. Smartphones will cross the four/fifths of the mobile data traffic and the 50% of global devices and connections by 2020. Mobile data traffic volume is expected to have an eight-fold increase by 2022, reaching almost 70 exabytes per month from 8.5 exabytes per month in Q3/2016 [2].

This prodigious growth rate of mobile data traffic in turn continuously renders the necessity of even more in number and in performance wireless communication infrastructures. Small cells (microcells (micro), femtocells (fem), picocells (pico)) have outnumbered the vast number of 7.5 million macrocellular (macro) Base Stations (BS) established. BSs' number is expected to follow the mobile subscriptions' increase trend, with a rough estimation of one BS per one thousand mobile subscriptions. Furthermore, BSs are continuously improved for supporting multiple air-interfaces, modulation formats and frequency bands, aiming at higher capacity, throughput and coverage levels, but at the same time their current consumption levels and operational policies makes them major candidates for energy savings. In plain numbers, the operation of mobile networks, 2G/3G/4G networks with both voice and data services included, consumed averagely 140 TWh/year and their global GreenHouse Gas (GHG) emission footprint reached up to 0.13 Gigatons carbon dioxide equivalent (GtCO2e) of GHGs in 2016 [3][4]. Additionally, BSs' operation can consume up to 70-80% of the total network's average power consumption with a poor overall energy efficiency of 3.1% [5]. The above facts indicate that operators should seek for applicable energy efficient strategies to BSs' operational lifecycle.

Traditional mobile network planning and operation are driven by the idea that any user request should always be served at any given time and place. Therefore, current mobile networks design targets at the busy hour traffic load, thus are continuously operational with always on transmitting power, in order to guarantee both Quality of Service (QoS) to mobile customers and network coverage in the area of interest. In practice, networks are over-provisioned with excess capacity most of the time as the actual telecommunication traffic load during an ordinary daily network operation cycle experiences high traffic load fluctuations. During low traffic periods, such as nights or holidays or in some sparse spots where the traffic load is temporarily getting very low due to the user mobility, many BSs are underutilized but still, being active, consume a great amount of power. Considering the fact, that the non-working time (including holidays and night time) is more than half of the year, mobile networks are wasting substantial portions of energy without carrying significant workload [6][7]. Thus, the effective usage and reduction of the active BSs for matching mobile traffic intensity can reduce in a great aspect, system's carbon footprint and unnecessary spent energy, especially in operating scenarios with low traffic demands.

1.2 Upcoming radio access evolution in mobile communications

A new era is coming in mobile telecommunications named as IMT-2020 which commercially is known as 5G. Commercial launch of 5G services is scheduled for 2020 and is anticipated to reach 25 million subscriptions worldwide by the end of 2021, supporting mostly mobile broadband and fixed services [8]. 5G mobile networks will consist of a group of access technologies and connectivity solutions capable of addressing the challenges and demands that arise from the upcoming data volume and telecommunication burdens expected beyond 2020 [9]. This technology will bring to the mobile market:

- *Ultra-fast data rate speeds*:
    - 20/10 Gbps peak data rates in downlink/uplink in indoor and dense outdoor environments,
    - Several 100 Mbps in urban and suburban environments,
    - The minimum achievable speed should be at least 10 Mbps for every user.
- *Vast increase in mobile networks capacity*: Due to the upcoming tremendous increase of the mobile data volume and the wirelessly connected devices, the number of Access Points (AP) will be exponentially increased offering much higher overall system capacity. This technology is going to set new paradigms in mobile networks administration towards the proper cooperation among network elements and devices with seamless and secure connectivity management.
- *Extremely low latency and robust availability:* Modern applications, such as self-driving, real-time control, communication and administration in industrial environments, augmented reality etc., require low end-to-end latency at a range of 1 ms or less with very low outage probability of 0,001‰.
- *Higher mobility:* Users on the move will enjoy similar service experience as if they were static, expanding the form of high data rate and robust connectivity to high speed mobility scenarios.
- *Energy-efficient networks*: The vast number of APs should be operated in the most energy efficient way, providing wireless access coverage even to the most sparsely populated areas.

A significant part on this upcoming massive increase of the access interface is the reliable, energy efficient and low cost communication towards the core network. Regardless of the solution used for high speed access and data rates, backhaul will need to be faster and to transfer higher volume of data. Therefore, in order to avoid economical and performance bottlenecks in the 5G networks' performance and implementation, backhaul must be prioritized in the 5G network design and implementation agenda.

1.3 Motivation, objectives and anticipated impact of our Dissertation

This Dissertation deals with the energy consumption in wireless mobile networks. Many efforts have been made aiming to the most energy-efficient way of their operation in both academic and industrial communities. The main reasons behind this, are the current high energy consumption and emissions footprint of the mobile networks and the alarming predictions of the rapid growth of the data volume to support in the next years. To this direction, we identified the main culprit of the power consumption in mobile networks' operation and we focused on minimizing its effects towards their optimal energy-efficient operation. The largest fraction of energy consumption in wireless networks is spent in the wireless access, mainly due to networks' greedy operation policies, which aim on peak traffic load rates while at the same time ignore traffic load intensity. Thus, we focused on the wireless access part of the wireless networks, by studying operational models of wireless networks and identifying solutions that would improve their energy consumption.

The main points of our Dissertation's contributions are the followings:

- *Energy optimization problems' formulations*: part of our research methodology was to identify and classify from a theoretical perspective of various energy optimization problems in wireless communication networks and formulate the corresponding optimization problems.
- *Energy optimization problems' solutions*: for every optimization problem we formulated, we proposed low computational complexity heuristics, capable of producing prompt, reliable and efficient solutions from a power consumption perspective, while guaranteeing given QoS requirements.
- *Proposed heuristics' flexibility*: The energy optimization schemes that we introduced, are designed for being transparently applicable almost to any mobile network topology.
- *High degree of energy efficiency*: in all scenarios examined, we achieve optimum or close to the optimum energy efficiency, by utilizing the most energy efficient wireless networks resources and points of attachment. Various Key Performance Indicators (KPI) have been examined during the proposed heuristic evaluation, imposing that each heuristic can solve the corresponding optimization problem in a variety of applications and wireless networks' formations.
- *Versatility of our energy-efficient solutions*: we verified the application of our proposed energy-efficient solutions to current mobile networks' technologies, while alongside we targeted on upcoming mobile network trends; our solutions can be utilized in a variety of network applications, especially on high-dense mobile networks, for:
    - identifying the optimal sets of data cells capable of serving current and unexpected network traffic load with the least required energy in homogeneous or heterogeneous wireless networking environments,
    - cell offloading and proper network dimensioning in the most energy efficient way,
    - association of mobile subscribers to specific AP for guaranteeing their QoS service in the most energy efficient way,
    - activation and utilization profiles of APs to match traffic load and/or per daily lifecycle operation of a mobile network towards its effortless operation with the minimum power consumption possible,
    - dynamic management of Remote Radio Heads (RRHs) and selection of the optimal radio antenna sectors from the available BSs for serving current and

unexpected network traffic load, targeting at the highest possible power alleviation.

1.4 Structure of Dissertation

Below we will provide a brief overview of our Dissertation. Each Chapter describes in detail the research activities performed.

1.4.1 Chapter 2

In Chapter 2, an extended literature review of various research approaches regarding the energy consumption, the energy efficiency and green operational policies in wireless communication networks is presented. Furthermore, in this Chapter we present our approach on energy efficiency in wireless broadband networks and its classification, together with a high-level view of the variations we examined throughout this Thesis.

1.4.2 Chapter 3

In Chapter 3, we focus on the energy optimization in homogeneous mobile networks. We evaluate two different system models of mobile networks running Wideband Code Division Multiplexing Access (WCDMA) and Long Term Evolution (LTE), two of the most utilized Radio Access Technologies (RAT) nowadays which according to [1] will continue being the spinal cord of wireless communications at least until 2022, for investigating energy efficient solutions on various cellular networks' traffic load scenarios and services. The corresponding energy optimization problems per energy efficient approach used are presented. Different heuristics were proposed for finding the optimal solutions to the above optimization problems from a power consumption perspective. The contributions of this Chapter have been previously included in papers [10] and in [11], where the latter is being under review.

1.4.3 Chapter 4

In chapter 4, we focus on the energy optimization in heterogeneous mobile networks. We introduce various heuristics which are benchmarked in a similarly configured LTE mobile network system model, investigating the optimal energy-efficient solution to the proposed and formulated energy optimization problems under different traffic load scenarios and traffic load distributions. The performance of the proposed heuristics and their impact to Key Performance Indicators (KPI) are also evaluated. The contributions of this Chapter have been included in papers [12], [13] and [14].

1.4.4 Chapter 5

In Chapter 5, the impact of backhaul is discussed and evaluated in heterogeneous mobile environments. Wireless in-band backhaul is utilized as backhaul transport method. The corresponding energy optimization problem is formulated. Different energy efficient heuristics are introduced for tackling the corresponding power consumption minimization problem. Their performance is evaluated in heterogeneous mobile network topologies with LTE Radio Access. The impact of the backhaul transmissions to heterogeneous networking environments is also evaluated, from a power consumption perspective. The contributions of this Chapter have been included in papers [15] and [16].

1.4.5 Chapter 6

Finally, in Chapter 6 we summarize this Dissertation's concepts and main conclusions and remarks and provide related future research directions.

CHAPTER 2. ENERGY EFFICIENCY IN MOBILE NETWORKS

2.1 Trends towards energy efficiency in mobile networks

In recent years, mobile communications have become mainstream for supporting a new era of digital commodities, entertainment and interactions. The advert of smartphones, laptops, tablets and smart gear (watches, car multimedia systems etc.) has triggered the utilization of new bandwidth-intensive applications across the board, such as mobile video streaming, mobile video conferencing, mobile web browsing, while multiple operators offer mobile data plans as home internet access services; all the above lead to escalation of the mobile data volume transmitted. Mobile data volume is increasing in a very fast pace, around ten times every five years [17], which in turn renders the necessity of denser and more powerful mobile networking infrastructures. Such cellular networks operation, involving multitudinous sets of radio BSs, consumes enormous amount of power with disconcerting carbon footprint levels, nearly 80% of which is attributed to BSs' operation [18][19][20][21][22], as shown in Figure 2.1. The figures are indicative; ICT infrastructure is responsible for approximately 3% of the world energy consumption and 2% of the equivalent CO2 emissions and the exponential growth of wireless data traffic, calls for an ultra-dense deployment of the wireless access components of next generation mobile networks. As a consequence, the number of physical AP will be increased, which in turn will yield a huge power consumption elevation. Therefore, it is of higher priority to consider how to decrease the costs of operating such a substantial number of BSs. Traditionally, the cellular networks are dimensioned so as to successfully sustain the predicted peak traffic load without taking into account user activity, mobility patterns and traffic load variations, thus most of the energy

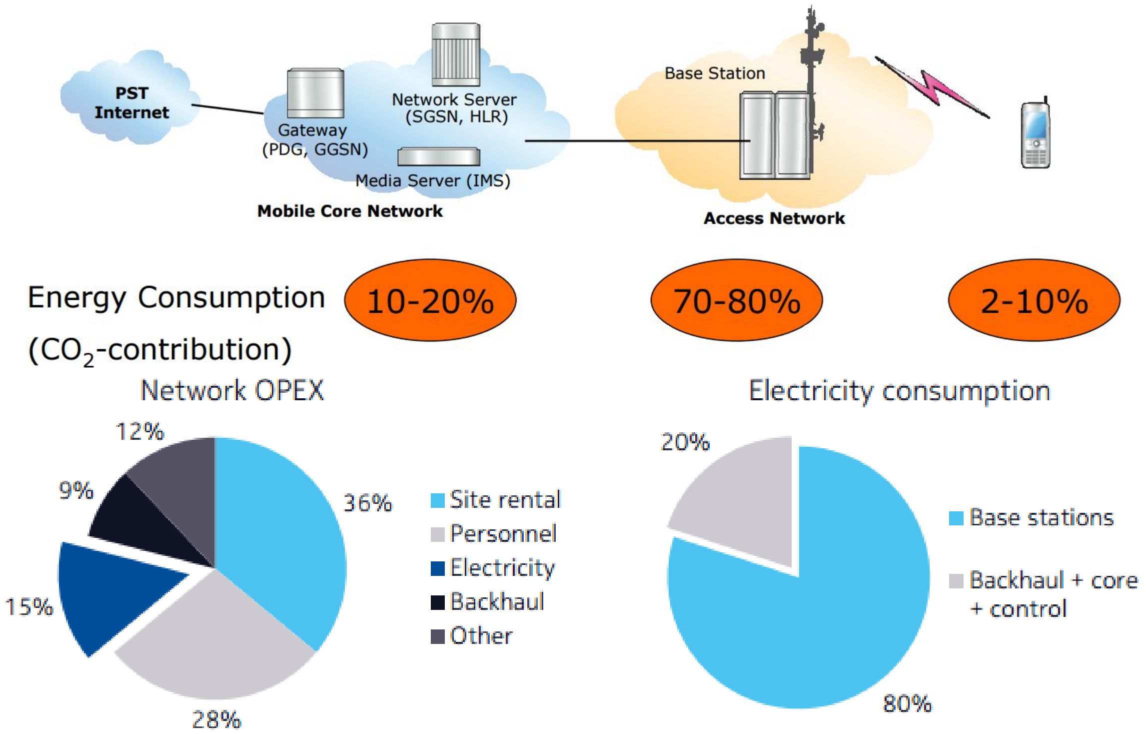


Figure 2.1: Mobile network power consumption breakdown [21][22].

consumed is wasted without carrying useful payload. However, although technical issues such as spectral efficiency and QoS provisioning have been extensively studied, little has been achieved in terms of energy consumption in mobile networks.

Improving energy efficiency in cellular networks requires a multi-directional approach. A so called green solution in cellular networks, aims to reach a compromise between energy efficiency and some target performance metrics, while the prediction of energy consumption levels expected can help in everyday energy consumption reduction [23][24]. Wireless spectrum resources are limited and their abnormal utilization may lead to bottleneck especially in dense networking environments. It can be poised with proper dynamic channel allocation, which can exploit wireless channels' spatial reusability and achieve high channel allocation efficiency. Such strategies have become more and more important in wireless networking [25][74]. Moreover, context-awareness is important in designing energy and spectrum efficient user association low complexity techniques [26].

A careful planning of wireless networks operation is crucial for increasing their energy efficiency, since utilizing just the necessary AP for serving mobile network's traffic load can save significant amounts of energy, but may disturb system's performance and coverage probability [27]. Mobile relays/APs, whose best positioning is essential for optimum performance, can be utilized for providing appropriate QoS levels towards mobile User Equipments (UEs) [28]. Mobile relay's power consumption depends on its velocity for a given packet throughput, whilst exploiting mobile transmission opportunities brings up some interesting tradeoffs in their practical implementation [29]. In high rate scenarios, mobile relays consume much less energy for their operation compared to static relays, which in combination with a careful network planning can offer seamless handovers with negligible outage probabilities [30].

Wireless powered communication networking systems are candidates for transferring certain amount of energy between dedicated energy sources to high energy consuming services. In collaboration with dynamic energy sharing techniques, an unlimited wireless powered communication AP chain can be established with much less investment than dedicated power supply network infrastructures [30]. Additionally, directional antennas of small cells in heterogeneous environments can improve wireless energy transfer efficiency and device operating time [32], while co-channel interference from macro BSs and overlaid small APs can be beneficial for harvesting the energy from ambient RF signals [33].

The Device-to-Device (D2D) communication technique enables the storage unit at user devices to be exploited for content sharing according to the social relations among users. This technique can lead up to about 50% energy reduction per successful content delivery, by adaptive selection of the appropriate content delivery mode, based on transmitter deployment, cellular links reuse, delivery coverage, channel quality and QoS requirement [34][35].

2.2 Related energy efficient techniques

Network management in mobile networks have attracted the interest of the research community especially in the last years. The evolution in cellular communications request sophisticated management of its core operational elements in order to meet the anticipated performance and energy efficiency goals. To this end, several high promising power alleviation approaches have been presented. Energy-efficient allocation of network's resources with the aid of improved power allocation schemes, can improve overall network's energy consumption [36]. The edge caching technique in heterogeneous wireless networks, where cache can be deployed at various places in the mobile networks, can increase the networks' overall energy efficiency in a regime of medium to very high demand of UE requests [37][38]. Additionally, joint sub-channel and power allocation schemes including phantom cells were also investigated in heterogeneous mobile topologies, offering improvements in capacity and throughput performance [39]. Joint power and admission control schemes aiming at spectral and energy efficiency can result to network capacity improvements with elevated payload efficiency in the uplink transmission [40], while offloading heterogeneous networks traffic from on-grid powered AP to green powered AP, may harvest up to 50% of power consumption per day [41]. Last but not least, joint power control and cell load schemes can effectively boost the average cell and user throughput performance in small cell networks, which suffer the void cell issue, thus the information transmission per energy spent is increased [42].

Proper dimensioning of network resources is the key for direct energy consumption reduction on current network deployments and has been evaluated extensively in the recent research literature. Cells' size, density, and deployment strategies, sleep/idle mode and cell breathing techniques, iterative minimal set covering algorithms to determine the minimum set of active BSs, were utilized to reduce the power consumption in heterogeneous network deployments [13][14][43][56]. Deployment strategies, based on BS usage along cellular networks [57], or optimizations techniques [58] have significant improvements in power consumption, while optimal BS location deployment with uniform [59] or non-uniform [60] user distribution can effectively reduce total spent energy, over 96% in specific traffic scenarios. Novel BS management schemes that consider network planning are considered in [61], an energy efficient cost effective optimization framework is presented in [62], while joint optimization of planning and management is proposed in [63]. An extended survey of the current status in green mobile networking underlines some novel research axes in the domain and particularly those based on BS resource allocation and on/off operation strategies [64].

Energy aware network management strategies such as cell zooming/breathing or alternating the operational status of BSs to match the daily traffic variations yields different subsets of available BSs to serve the same geographical area at different time periods. Thus, large energy fractions can be saved without affecting the provisioned QoS. Cell zooming is a similar energy efficient technique that adjusts the coverage radius of a BS by fine tuning its transmission power according to network's traffic load demands. Mainly, this technique is used for reducing the power consumption of wireless networks in medium to low network traffic load conditions. BSs coverage radius is reduced by reducing BSs transmission power when UEs are dispersed closer to BSs or BS transmission beam is concentrated at specific areas to cover possible coverage holes or possible increases in traffic load demands; this cell zooming technique approach is known as zoom in. BSs are expanding their coverage radius by increasing their transmission power, in order to cover any area coverage weakness left, when some BSs are switched off for saving energy; this cell zooming technique variation is known as zoom out. Usually, applications of cell zooming technique dynamically combine both zoom in and out variations. There is an upper limit in both maximum and minimum BS's cell radius coverage and BS's transmission power, and from a power consumption perspective there is an optimum value which defines the cell radius/transmission power levels in each of the available BSs, so that the energy efficiency for a given network traffic load is maximized. Traffic load on mobile networks exhibits large variations during the day, where requested data rate access demands fluctuate per UE, area and per time, thus continuous adjustments to BS's coverage area are mandatory for achieving the highest possible energy efficiency when using the cell zooming approach.

Different cell zooming approaches have been evaluated, for improving overall network's energy efficiency. Joint analysis of energy efficiency and area spectral efficiency identifies the possibility of achieving higher energy efficiency by using cell zooming techniques for reducing the operating number of BSs and associating the available UEs to the remaining network resources [65]. Traditional grid and energy renewable source powered multi-tier BSs cooperation can be assisted by specialized cell zooming approaches resulting higher energy efficiency and lower emission production [66][67]. Cell zooming with proper power control reduces cells' overlap and intercell interference, which leads to lower outage probabilities and increased energy efficiency in dense small cells mobile environments [68].

Another high energy saving network management approach in cellular networks investigates the hibernation/sleep scheduling or even the complete shutdown of some BSs. Sleep mode techniques, such as static or dynamic activation/deactivation of BS according to traffic load [69], latency and capacity variations [70], and optimal control of wake up mechanisms [71], can yield great energy savings, especially in cases of lower network traffic load, for example in nights or holidays, where the remaining active BSs are utilized to cover the network traffic demands. Sleep mode approach hibernates the transmission part of a BS, while its auxiliary equipment remains activated. This technique can alleviate up to 60% the power consumption of a BSs compared to a fully activated one and requires less time for transition between sleep to transmit mode and vice versa [72][73]. Sleep mode in ultra-dense small cell networks can highly reduce mobile networks' power consumption in both downlink and uplink transmissions but also in uniform and non-uniform UE distributions, with proper adaptations to the BSs' operational state and to the transmission power of the active BSs, while in some scenarios can also improve the data rate access and reduce UE transmission power [74][75][76][77].

The BSs' ON/OFF power alleviation approach, fully deactivates some BSs, thus nullifies their power consumption when are set in OFF state, since not only the transmission part but also the auxiliary equipment of these BSs is shutdown. Such approaches offer dynamic planning of network resources and address user association problem with user association mechanisms adapted to the dynamic BSs' operational state. The reduction of this energy efficient approaches to known NP-hard problems, namely the knapsack and minimum-weight disc cover problems, triggers the implementation of lower complexity solutions for estimating the closer to optimum solution in each of the problem examined [78][79]. Actually, BS ON/OFF strategies can greatly alleviate cellular networks' power consumption. Several mechanisms for the proper toggling of the BS operational status exploiting different traffic load aware optimization techniques, have been studied in the context of homogeneous and heterogeneous wireless mobile networks which delivered quite satisfactory energy consumption gains over the examined scenarios [80][81][82][83].

Cooperation of cell zooming with BSs on/off strategies, increases area energy efficiency in dense heterogeneous cellular environments, where the increase of the outage probability, emerging by the deactivation of the high consuming overlaid macro BSs, can be mitigated by increasing the number of small cells with slight concessions in network's overall energy efficiency [84]. An example of such energy efficient techniques cooperation, is depicted in Figure 2.2, where some BS are turned OFF and active BSs' coverage radius is adjusted accordingly using cell zooming techniques, in order to serve current UEs' wireless access demands.

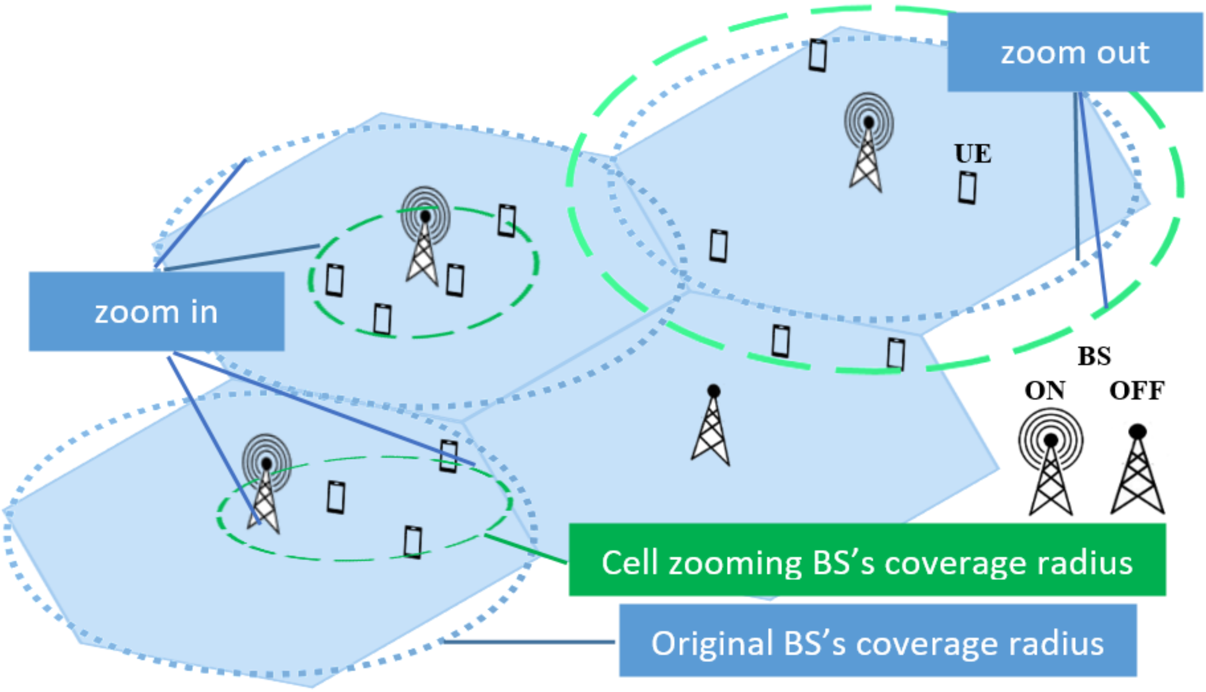


Figure 2.2: Cooperation of Cell zooming with BSs' ON/OFF approach.

Physical infrastructure and spectrum sharing among multiple Mobile Network Operators (MONs), such example is shown in Figure 2.3, in combination with cooperative BS switching off schemes, can lead to high power consumption alleviation with significant reduction of OPEX without affecting end user's QoS [85][86][87].

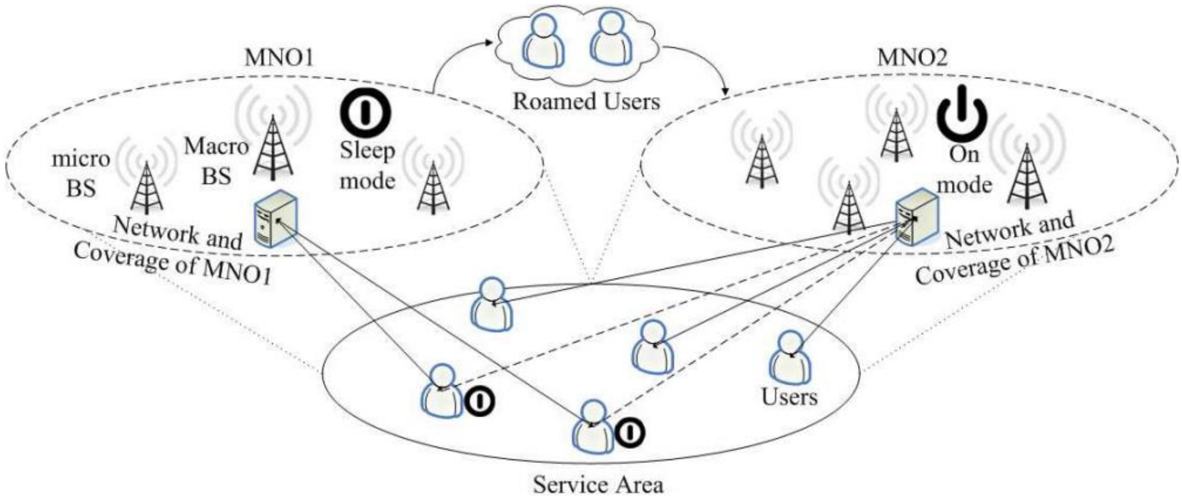


Figure 2.3: A set of MNOs, owning and managing different radio access network (RAN) infrastructures, provide service to a common area. Each MNO can decide to switch off its RAN for a certain time period and roam its traffic to another MNO. The process is transparent for the end-users [85].

In order to provide high mobility support in upcoming 5G networks, optimizations in traffic loads and data offloading capabilities should be introduced [88]. Whereas the increasing number of UE complicates the user association process in dense heterogeneous environments, the joint spectrum and energy efficiency maximization approach in wireless networks is essential for elevating their useful payload transmission levels [89]. A larger traffic mean arrival rate always results in a longer average delay and higher network power consumptions. Speed scaling can reduce the energy consumption in both wireless and wired networks, with a fair trade-off between traffic delay and energy consumption [90]. Applying different Service Level Agreements (SLA) to the end users introduces challenging performance and implementation difficulties when energy efficiency is the top priority in a mobile network's design and operation [91].

The most energy efficient network slicing should be dynamically determined by specialized concepts, like software define networking and network function virtualization, for appropriate handling of the context faced, aiming at resource consumption and utilization improvement whilst guaranteeing the QoS to the UEs in a given area [92]. Additionally, cognitive radio technology in combination with stochastic process can effectively mitigate interference, which is the decreasing performance factor in indoor environments of dense deployed small scale AP, and enhance energy efficiency and improve overall network throughput [93]. Real time cloud computing, optimized by stochastic joint Remote Radio Heads (RRHs) activation and beamforming, can increase the overall energy efficiency of the network by deactivating as many RRHs and fronthaul links as possible [94]. Furthermore, power consumption in cloud radio access networks can be reduced by up to 70% with optimized Base Band Unit (BBU) resources' allocation to RRHs [95]. Discontinuous transmission and antenna adaptations radio resource management mechanisms at lower target data rates and power control on high target data rates can reduce the power consumption of a BS's power supply by up to 40% [96].

The main conclusion from the above literature and current trends review in mobile networks' energy efficiency, is that collaboration among network elements and technologies with an energy efficient redesigned target in both structural and administration levels, is the key for sustainability and power consumption alleviation in the upcoming dense cellular infrastructures. The majority of these improvements will not be constructed from scratch, but will be embedded into current cellular infrastructures, encapsulating new green radio access techniques and equipment that can provide a seamless transition between current and new radio technologies. Viable expansion of cellular networks can be ensured by proposing energy efficient approaches for handling the forecasted volume traffic demands. Additionally, due to the increasing number of radios, solutions that reduce the power consumption of a RAN as a whole are required.

2.3 Dissertation approach and system model

The scope of our Dissertation is to propose techniques to minimize the overall power consumption of wireless mobile networks. In wireless communication networks, a full redesign in structure, operation and resources' distribution at all levels of operation of this very complex mechanism, can harvest significant amount from the consumed energy. The main point in this reconstruction, is the reconsideration of the wireless access points' operation, which are responsible for the largest fraction of wireless networks' power consumption, by introducing new operation, transmission and traffic load servicing profiles, redistribution of their physical location and redesign of their construction materials. Wireless points of attachment (BS, relays, AP) are expected to grow rapidly in order to sustain the anticipated traffic volume increase in the next years. Besides the energy optimizations, which can be applied at hardware level, e.g. improving transmitters' and power amplifiers' efficiency, reducing power losses, utilizing renewable forms of power supply etc., prudent placement and utilization of BSs will be the key for a controlled and efficient, from a power consumption perspective, network operation.

Our goal is to optimize the operation of a wireless broadband telecommunication network with respect to energy consumption, without sacrificing QoS requirements. Since networks are usually designed under full network load conditions, they are severely underutilized most of the time and the equivalent power resources are consequently wasted. Mobile network planning for BS utilization should take into account the given traffic load, to yield an optimally dimensioned network, able to serve the offered load under the given QoS requirements. That way, the required power for its operation is squeezed down to near-optimum levels, without affecting QoS.

To this direction, we used the set of BS of a mobile network and their resources as inputs to a general power consumption minimization problem, which aims to serve a set of UEs in the most energy efficient way without compromising their QoS. Thus, in our approach, the problem at hand is to find the most appropriate subset of the existing BSs, which are adequate to serve the requested telecommunication demands of the UEs without compromising QoS requirements. Therefore, intuitively, we can assume that the number of BS in operation should be kept minimum, thus utilizing more efficiently a lower number of resources, (e.g. the most efficient resource could be the one which transmits the highest useful payload), in order to serve a given traffic load in a reference area with least energy consumption.

In our system model, we assume that each BS may occupy one out of two possible states, namely operational (ON) and non-operational (OFF). When a BS is set to the ON state, the equivalent maximum transmitted Radio Frequency (RF) power per BS is limited and depends on the type of BS, either macro, micro, etc., where each type of BSs contains sets of similarly configured BSs. Every operational BS has an inherent energy cost which is fixed and is the same per type of BS. This cost is independent of the load accounting for the power consumption generated by the minimum power required by the Power Amplifier (PA) and auxiliary subsystems. Furthermore, each UE served by a BS inflicts an additional variable power consumption cost to the system, due to the extra energy consumed for transmissions by the equivalent PA.

As we show later in the text, such problem modelling falls into category of Capacitated Facility Location Problems (CFLP), bounded by a Single Sourcing (SS) constraint, which are NP-hard. It is a capacitated problem since resources of each BS are limited, e.g. BSs have limited transmission power where different RAT can comprise different number of physical transmission resources (Resource Blocks (RBs), subchannels or codes). It is a facility location problem, because the optimal placement of BSs aims at the minimization of the fixed power consumption (fixed costs) and the required RF variable transmission power (transportation costs). Finally, the Single Sourcing constraint is applied, since each UE may be served by one and only one BS. CFLP has been studied in [97][98], where, among others, heuristic methods and Linear Programming (LP) have been proposed for obtaining a feasible solution. Nevertheless, these methods are computationally complex and their implementation regarding the management of a telecommunication system, where decisions have to be both reliable and prompt, is not applicable.

A proper way to investigate and provide feasible solutions to NP-hard problems, is breakdown of the main problem in smaller and simpler subproblems and provide feasible solutions in each of these subproblems with smaller dimensions, by using heuristics procedures. We also employ exhaustive search techniques at small problem instances to obtain an upper bound on system performance per subproblem examined. We also introduce greedy energy efficient heuristics which are of lower computational complexity and can be executed in polynomial time, and show that are capable of providing the closest to optimal solution in each problem examined in a reasonable timeframe.

Our approach includes a variety of RAT, topologies, services, and backhaul connectivity, ensuring that the proposed solutions have been investigated in a variety of mobile network technologies and application scenarios. In Figure 2.4 we depict a high level representation of the formulations examined for investigating the general energy consumption minimization problem in wireless mobile networks.

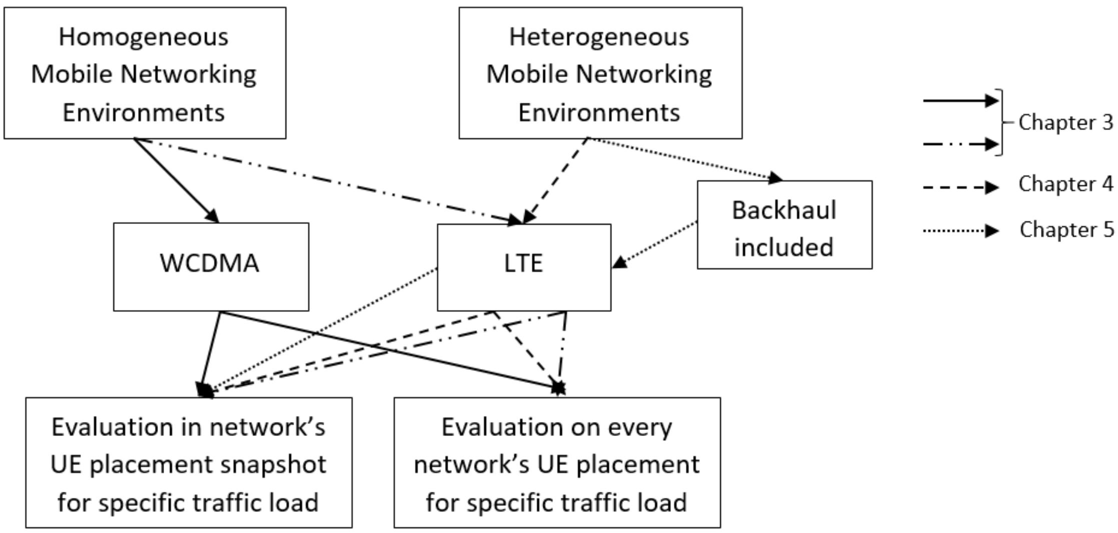


Figure 2.4: High level representation of the variations examined for investigating the energy consumption minimization problem in wireless mobile networks.

In Chapter 3, we introduce energy efficient heuristics in homogeneous mobile networking environments whose RAN utilizes LTE or WCDMA RAT. Our heuristic schemes, determine the power consumption optimal set of network elements and resources able to serve the corresponding traffic load present in the network. In Chapter 4, we investigate the power efficiency optimization in heterogeneous mobile broadband environments whose RAT is LTE. Again, we propose greedy energy efficient heuristics to determine the power consumption optimal set of network elements and resources which can serve the corresponding traffic load present in the network. Finally, in Chapter 5, backhaul, whose strong impact to power consumption levels of heterogeneous cellular networks' operation is discussed, is inserted as an important variable to the power consumption minimization problem formulation. The proposed energy efficient schemes measure the impact of the low-cost backhaul connectivity solution we implemented to mobile networks' operation and performance from a power consumption perspective, and serve the corresponding traffic load of the network in the most energy efficient way.

CHAPTER 3. ENERGY EFFICIENCY IN HOMOGENEOUS MOBILE NETWORKS

3.1 Introduction

Currently, the majority of wireless cellular networks have typically been deployed as homogeneous networks using a macrocellular-centric planning process. In our study, a homogeneous mobile network system model is a network of BSs in a planned layout, with BSs located at the center of adjacent hexagon-style formatted cells, having similar transmit power capabilities, receiver sensitivity and antenna patterns, and communicating with the core network by sharing similar backhaul connectivity. Moreover, assuming an equal distribution of subscribers throughout the service area, BSs in homogeneous topologies serve roughly the same amount of UEs, all of which receive similar data flows and QoS without any access restrictions. These traditional networks although are gradually becoming obsolete, especially on urban and sub-urban territories as they are unable to handle the increasing burden placed on their available resources by the various "heavy-weight" requirements of emerging applications, they will continue to operate for the next years, at least in rural areas and in urban areas whose annual growth and technology adoption rates remain in lower levels.

In this section, we present our work which focused on energy efficiency in homogeneous mobile topologies. We introduced energy efficient techniques which focus on proper network's elements and resources utilization, capable of serving given traffic loads of UEs randomly dispersed within a reference area, while ensuring the predefined QoS constraints. Given a set of possible BSs and user requests, we first formulate the problems of finding the most appropriate, with respect to power consumption, subset of BSs that can satisfy the corresponding load without compromising the QoS requested. Since, the formulation falls in the category of CFLP bounded by Single Sourcing constraint, we propose polynomial low-complexity heuristics that are capable of providing useful results on the usage and BSs activation percentages for varying traffic loads. Then, we exploit these findings to propose BSs activation heuristic schemes, which can be applied in each of the deployed network topology examined, to serve the corresponding traffic load while guaranteeing the predefined QoS requirements. Our techniques are evaluated in homogeneous mobile topologies whose RAN is running on WCDMA or LTE RAT. LTE and WCDMA are the main RATs for voice and data services worldwide, and are expected to remain the dominants RATs at least for the next five years, as shown in Figure 3.1 [1]. Therefore, we validate the applicability of our proposed energy efficient schemes in current network topologies and technologies, establishing a solid platform of power alleviation techniques which can be used as a reference for green solutions in mobile networking environments.

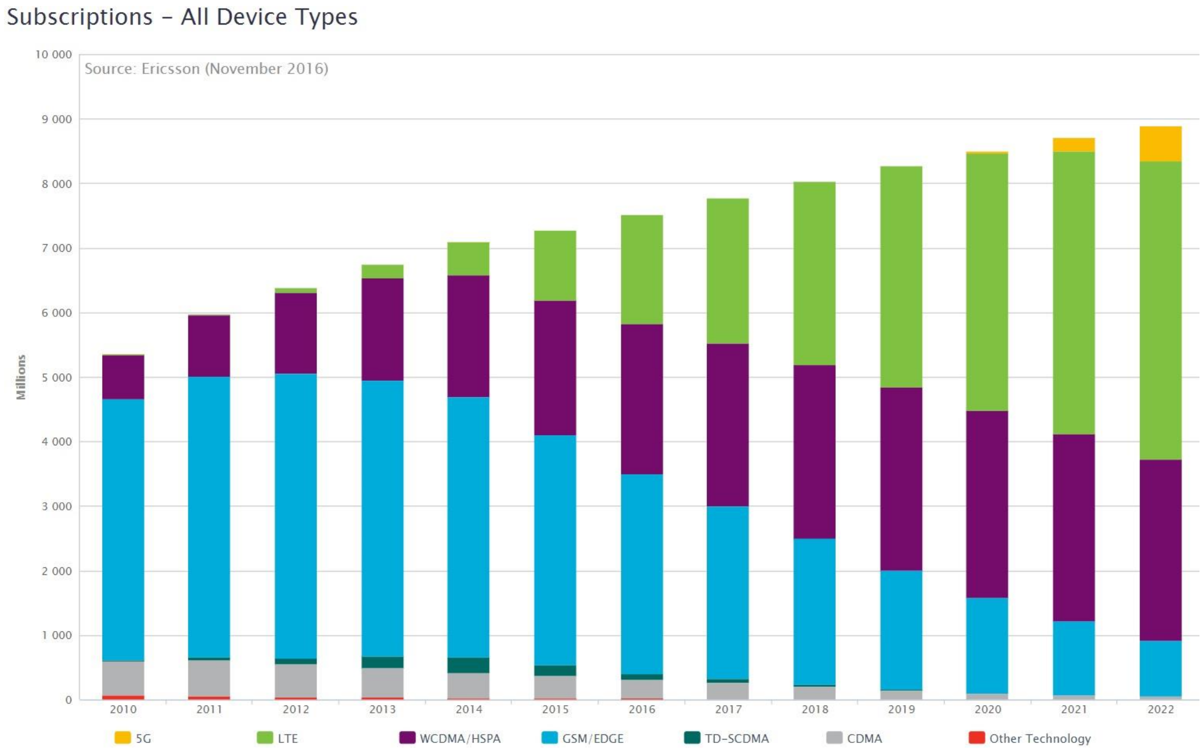


Figure 3.1: Worldwide RATs' share for mobile subscriptions [1].

The remainder of this Chapter is organized as follows. In Section 3.2, we present our WCDMA mobile homogenous network system model (in sub-section 3.2.1), the optimization problem formulation (in sub-section 3.2.2), the corresponding energy efficient heuristics for tackling the energy optimization problem (in sub-section 3.2.3) and simulation results (in sub-section 3.2.4). In Section 3.3 , the same structure pattern of the sub-section 3.2 is followed for the LTE mobile homogenous network system model. Finally, in Section 3.4 , we conclude our work in energy efficient homogeneous mobile topologies.

3.2 WCDMA Homogeneous Mobile Network

3.2.1 System Model

We consider that this system model utilizes Wideband CDMA RAT and we focus on the study of the forward channel, thus downlink transmissions within each Radio BS are orthogonal and communication is assumed as power and interference limited. In our model, we consider that due to multipath propagation the downlink signals are not perfectly orthogonal, and the Signal to Interference plus Noise Ratio (SINR) perceived by user i, when served by base station j, with bit rate R_i, can be expressed as [99]:

$$SINR_{ji} = \frac{G_i \cdot \psi_i \cdot P_{ji}^{(r)}}{\sum\limits_{k \in BS_j^{\text{int}}} P_{ki}^{(r)} + (1-a) \cdot P_{ji}^{(r)} + P_N} \tag{3.2.1.1}$$

where $G_i = \frac{W}{R_i}$ is the processing gain equal to the spreading factor SF_i of the assigned OVSF code, W is the chip rate, α is the orthogonality factor ($0 \leq \alpha \leq 1$), $BS_j^{(int)}$ is the set of the interfering base stations neighbouring to j, $P_{ki}^{(r)}$ is the power received at user i from base station k, ψ_i is the fraction of the total transmitted power from the serving base station intended for user i, and P_N is the thermal noise power.

We assume a wireless network where a set of J identical macrocellular radio Base Stations lies in a two-dimensional area and consider a scenario, where possible BS locations are predefined at fixed grid network geographical positions and I User Equipments are randomly and uniformly distributed inside this area. UEs request the same type of service, whose QoS is predetermined by the minimum required $SINR_{min}$.

Our ultimate goal is to determine the optimal, with respect to power consumption, subset of those BS locations whose corresponding BSs will be active in order to serve a certain load of I UEs randomly dispersed in this area, without violating QoS requirements for each user served, and with acceptable levels of outage probability. We proceed with our problem formulation in two discrete steps:

(a) first, we iteratively formulate and solve a very large number of instances of the Random Load Optimal BS Subset (RLOS) problem. In each RLOS we generate a random traffic load snapshot consisting of I randomly placed UEs in the geographical area and determine the optimal BS subset that can serve all UEs with minimum power consumption and requested QoS.

(b) we then collect the data of the optimal BSs subsets and attempt to determine the most proper BS subset which can serve any random set of I UEs under a certain outage probability.

3.2.2 Random Load Optimal BS Subset Problem Formulation

Every BS j is associated with a fixed power cost $P_j^{(f)}$ which encompasses the power consumption generated by the power required by its power amplifier and supporting systems. Besides that power cost, the downlink communication transmission from a serving BS j to a UE i incurs an additional variable power cost $P_{ji}^{(t)}$, due to the extra energy consumed by the power amplifier for that transmission. The relation between the power transmission cost $P_{ji}^{(t)}$ from BS j to UE i and the total received power $P_{ji}^{(r)}$ received at UE i from BS j depends on the pathloss PL_{ji}, which in our case incorporates both Line-Of-Sight and Non-LOS propagation conditions i.e.:

$$P_{ji}^{(r)} = P_j^{(t)} - PL_{ji} \tag{3.2.2.1}$$

Therefore, the BS selection problem can be formulated as an optimization problem as follows:

$$\min\left\{ \sum_{j=1}^{J} P_j^{(f)} \cdot y_i + \sum_{i=1}^{I} \sum_{j=1}^{J} P_{ji}^{(t)} \cdot x_{ij} \right\} \tag{3.2.2.2}$$

Subject to:

$$\sum_{i=1}^{I} P_{ji}^{(t)} \cdot x_{ij} \le P_j^{(t)}, \ j = 1, \ldots, J \tag{3.2.2.3}$$

$$\sum_{j=1}^{J} x_{ij} = 1, \ i = 1, \ldots, I \tag{3.2.2.4}$$

$$\sum_{j=1}^{J} SINR_{ji} \cdot x_{ij} \ge SINR_{\min}, \ i = 1, \ldots, I \tag{3.2.2.5}$$

where the following binary decision variables are introduced:

$$x_{ij} = \begin{cases} 1, & \text{if RBS } j \text{ is serving user } i \\ 0, & \text{otherwise} \end{cases} \tag{3.2.2.6}$$

which indicates whether UE i is served by BS j, and

$$y_j = \begin{cases} 1, & \text{if } \sum_{i=1}^{I} x_{ij} > 0 \\ 0, & \text{otherwise} \end{cases} \tag{3.2.2.7}$$

which indicates whether a BS is active and serves some UEs or inactive and serves no UE.

The objective function presented in (3.2.2.3) aims at the optimization of the energy efficiency of the network, by minimizing the sum of the fixed (left part) and variable (right part) energy costs, inflicted by the activity of certain BSs and the corresponding power transmissions. Constraints (3.2.2.4) impose that the transmissions in the downlink of each BS

j are power limited by the maximum transmission power $P_j^{(t)}$ of BS j, while constraints (3.2.2.5) impose that each UE must be served by one and only one BS. Constraints (3.2.2.6) represent the demand constraints and impose that each UE receive the minimum required SINR. Note that intercell and intracell interference at (3.2.2.6) is overestimated as the values are computed assuming full transmission power from the interfering cells and the same cell. RLOS belongs to the class of Capacitated Facility Location Problems, bounded by Single Sourcing constraint (CFLP-SS) [97].

In the following section, we present the heuristic algorithms we developed to tackle the above problem.

3.2.3 Energy Efficient Heuristics

3.2.3.1 BS selection algorithm for RLOS problem

The considered environment is a macrocellular one and as such the fixed power cost at the left part of the optimization function in (3.2.2.2) clearly dominates the total power cost. In addition to that, we assume that all BSs are similarly configured to transmit at the same maximum power. Thus, determining the optimal subset of BSs for minimum power consumption is equivalent to determine the minimum number of BSs to serve all UEs. This intuitively requires that every BS in the optimal subset should serve as many UEs as possible. In the following, we will describe a heuristic algorithm that greedily assigns UEs to BSs, based on the aforementioned idea. The algorithm iteratively attempts to assign as many UEs as possible to a selected BS, it then excludes this BS and the assigned UEs from further consideration and continues with the remaining UEs and BSs until all UEs have been assigned to some BS. The flowchart of the procedure is given in Figure 3.2.

Initially we generate a random snapshot of uniformly distributed UEs within the coverage area and determine their service requirements. Our algorithm computes a 2-dimensional matrix, for the downlink transmission of BS j to UE i, for each $j = 1, \dots, J$ and $i = 1, \dots, I$ which contains the least required transmission power $P_{ji}^{(t)}$ for the transmission between BS j and UE i. The computation takes into account intracell interference, intercell interference from the first layer of adjacent BSs, thermal noise and SINR threshold required by the service under consideration. For each remaining BS j and UE i, we sort $P_{ji}^{(t)}$ in ascending order and calculate the maximum number of UEs, $N_{UE,j}^{max}$, that can be served by the available transmission power of $P_j^{(t)}$ of BS j. We select BS k such that $N_{UE,k}^{max} = \max_j \{N_{UE,j}^{max}\}$. If more than one BS can serve the same maximum number of UEs $N_{UE,j}^{max}$ (i.e. $|S_{BS}| > 1$ in the flowchart of Figure 3.2), then we select the one which needs to transmit the less power to serve the corresponding $N_{UE,k}^{max}$ UEs. Once BS k is determined, we consider BS k as active and associate the corresponding UEs to this BS. We exclude this BS and its associated UEs from further consideration. The same

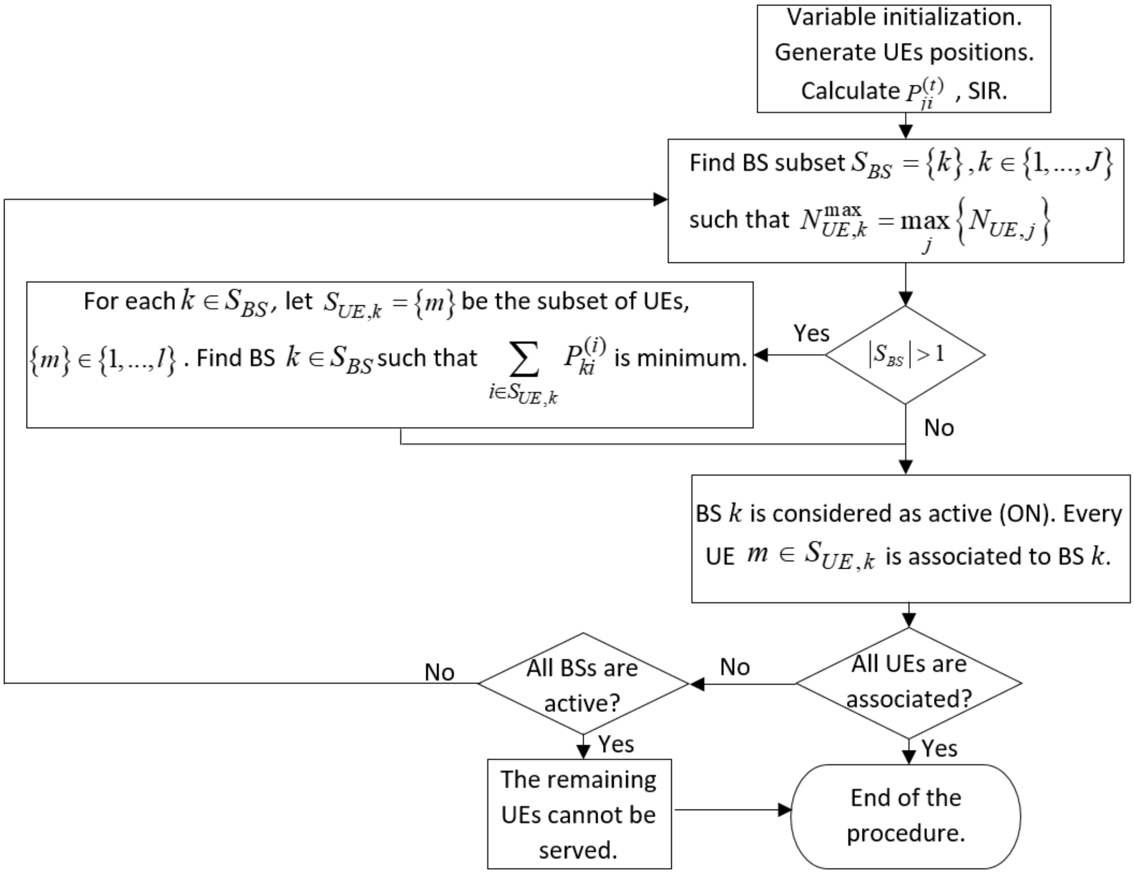


Figure 3.2: BS Selection algorithm flow.

procedure is repeated until no more UEs are left. If at the end there are UEs not associated to some BS but there are no BS left, the procedure ends without finding a feasible solution.

Our algorithm is basically consisting of three basic steps. At the first step, we calculate the least required transmission power $P_{ji}^{(t)}$ for the transmission between BS j and UE i, $j = 1, \dots, J$ and $i = 1, \dots, I$, which takes $O(J \cdot I)$ time. At the second step, we sort J columns with I elements which needs $O(J \cdot I \cdot log(I))$ time. In the third step, we perform $J \cdot I$ checks to determine the max number of UEs for every BS, thus the time for the third step is again $O(J \cdot I)$. All three steps are executed for J times at most, and the overall complexity time of our algorithm is $O(J^2 \cdot I \cdot log(I))$.

3.2.3.2 BS activation algorithms for certain load

Until now we provided a heuristic algorithm to determine a minimum number of BSs and the actual BSs to serve a certain snapshot of I randomly and uniformly distributed UEs over the service area, each one requesting a WCDMA service. However, our ultimate goal is to select the optimal subset of BSs that can serve any random snapshot of the same I number of UEs with an acceptable level of outage probability. Our approach is to solve a very large number of static offline RLOS problem instances and deduce the most appropriate subset that manages to serve any random instance of the same traffic load level with an acceptable outage probability. We propose two heuristic variations for this problem.

a. Activation Probability Heuristic (APBH)

Step 1: For a certain traffic load, in other words for a certain number I of UEs each one requesting the same WCDMA service we generate a high number of L random placement snapshots of I UEs. For each random snapshot, we formulate and solve the corresponding RLOS problem. Let $p_j^{(on)}$ be the probability that a BS j is active, $N_{mean}^{(on)}$ be the average number of active BS, after solving the aforementioned L RLOS problems and $N_{min}^{(on)}$ the minimum number of necessary active BS that has occurred for some RLOS instance.

Step 2: We sort the list of BSs in descending order of their activation probability $p_j^{(on)}$ and start to activate BSs from the top of the list downwards until $N^{(on)} = N_{min}^{(on)}$ BSs are set $S_{BS}^{(on)}$ as active. Let $S_{BS}^{(on)}$ be the set of the active BSs.

Step 3: We ignore the rest $J - N^{(on)}$ BSs and formulate and solve again a very high number L of slightly modified RLOS problems: in each RLOS problem (a) the set of available BSs is $S_{BS}^{(on)}$, and (b) we allow that some UEs may not receive service, in other words there is a chance that some UEs will not be assigned at all at any BS and will be blocked. We denote by $p_{out}^{(L)}$ the outage probability after solving the L modified RLOS problems.

Step 3.1: **If** $p_{out}^{(L)} > p_{out}$ then we set $N^{(on)} \leftarrow N^{(on)} + 1$, we update $S_{BS}^{(on)}$ by adding the next BS from the list of the ordered BSs and go to the start of **Step 3**,

Step 3.2: **Else** the set of active BSs to serve the requested load of I UEs is $S_{BS}^{(on)}$ and the outage probability is $p_{out}^{(L)}$. End of the procedure.

b. Activation Probability and Minimum Coverage Overlap Heuristic(APMCOH)

This heuristic is similar to APBH, with one difference in the way the BS are set to the ON state when the sorted list is examined in Step 2 and Step 3.1. When searching for the $N^{(on)}$ BSs, the list of BSs that are sorted according to their activation probabilities may be traversed more than once because the BS are selected only if a coverage criterion is not violated as explained in the following: In the first examination of the list we only activate BS that have zero coverage or else are at least 3 BS away from the already activated BSs. In the second examination of the list we only activate BS that are at least 2 BS away from the already activated BSs and so on. At the end, we may have left only with BSs whose neighbours are all activated and thus the only resolving criterion is the activation probability.

3.2.4 Simulation Results

3.2.4.1 Simulation Description

The performance evaluation of the proposed algorithms was made with the help of a system-level simulation tool developed in MATLAB. Different traffic load conditions were examined, by differentiating the number and the positions of the UEs per scenario run. The BS selection scheme for the RLOS problem together with the two BS activation schemes APBH and APMCOH were implemented and compared against an exhaustive search procedure that provided the best results. Our approach was to first solve a large number of RLOS problem instances for a variety of traffic loads and consequently estimate a good starting point for the BS activation schemes for the corresponding same load to provide the requested service within acceptable outage boundaries. To minimize the induced uncertainty, all results have been computed by averaging the results from 2000 runs per scenario load examined.

Within a 5 x 5 Km^2 grid area there exist $J = 25$ fixed locations of identical macro cellular BSs using omnidirectional antennas. Furthermore, I UEs are randomly and uniformly distributed within this coverage grid region. We focus on downlink communication with High Definition (HD) voice as primary service provided and each UE requests the same minimum threshold bitrate. The average energy consumption of each BS is considered as 865W/h, which incorporates both fixed power cost $P_j^{(f)}$ and variable power cost $P_{ji}^{(t)}$ [100]. Table 3.1 summarizes the values of the main parameters of the simulation model.

We assume worst case scenario of interference, where intra and inter cell interference are present and impact the SINR at the mobile users of the system given by Equation (3.2.1.1). The grid area of our study is assumed to be covered by buildings with area building density 20% and path loss is calculated according to the CCIR path loss model [101]. WCDMA access technology is used, with 5 MHz bandwidth and simultaneous call acceptance of approximately fifty calls per cell [102] thus cell capacity is fifty UEs and total system capacity is 1250 UE (100% system load).

Table 3.1: System model simulation parameters.

Parameter	Value
Frequency	1800 MHz
Bandwidth	5 MHz
Service	HD Voice, 12.2 Kbps
BS max transmit power	20 W (43 dBm)
UE antenna sensitivity	-106 dBm
BS height	15 m
UE height	1.5 m
Outage probability	5%
Thermal noise	-107 dBm
Processing Gain	25 dB
Eb/No	5 dB
Orthogonality factor	0.5
Building coverage density	20%
Type of Macro BS antenna	Omnidirectional
Number of users	50-1100 (4%-88% load)
Simulation iterations	2000 per system traffic load step
Average BS consumption	865 W/h [100]
Path loss model	CCIR [101]

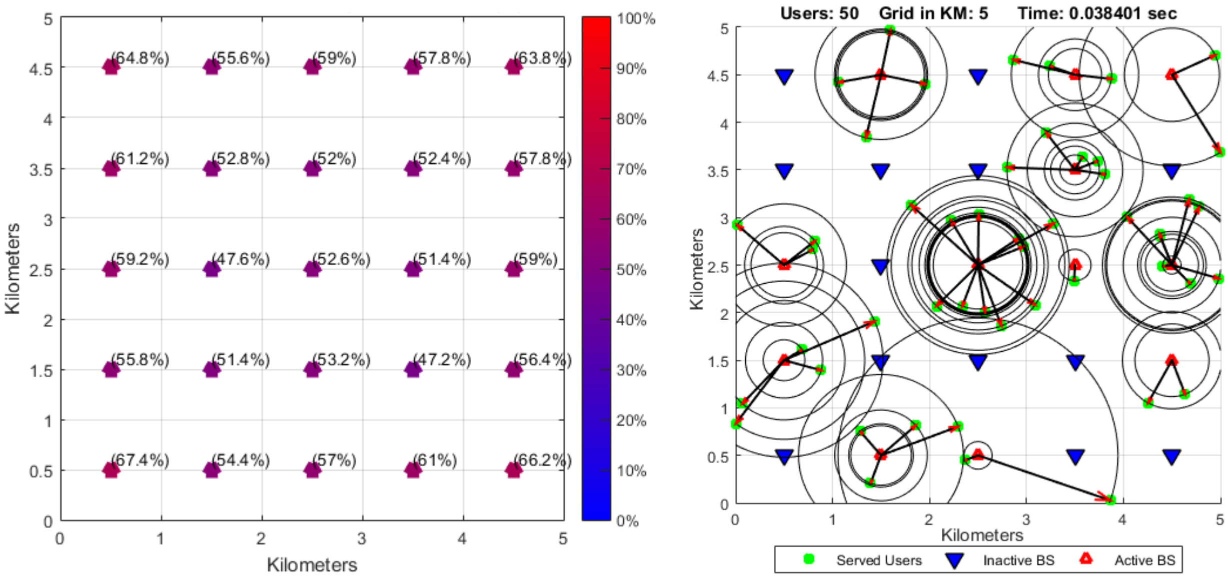
3.2.4.2 Performance evaluation results

We create random snapshots for varying traffic levels from 4% up to 88% of system load by uniformly distributing a corresponding number of UEs inside the grid area. For each traffic load we create $L = 2000$ random placements of UEs and formulate and solve the corresponding RLOS problems to get the values for $N_{min}^{(on)}$ and $N_{mean}^{(on)}$ which are shown in Table 3.2. The first value gives the minimum number of necessary BSs to serve the corresponding traffic load that was the outcome of the BS selection algorithm for some UE random placement, while the second value gives the average number of necessary BSs to serve that traffic load.

Table 3.2: RLOS results for $N_{min}^{(on)}$ and $N_{mean}^{(on)}$ after 2000 simulation iterations.

Number of UEs	System Load (%)	$N_{min}^{(on)}$	$N_{mean}^{(on)}$
50	4	10	14.15
100	8	13	19.10
150	12	16	21.90
200	16	20	23.49
250 - 300	20 – 24	21	24.30
350	28	22	24.86
400 - 450	32 – 36	20	24.96
500	40	21	24.98
550	44	22	24.98
600	48	21	24.98
650 – 800	52 - 64	22	24.98
850 - 1050	68 - 84	23	24.99
1100	88	24	24.99
1150 – 1250	92 - 100	25	25.00

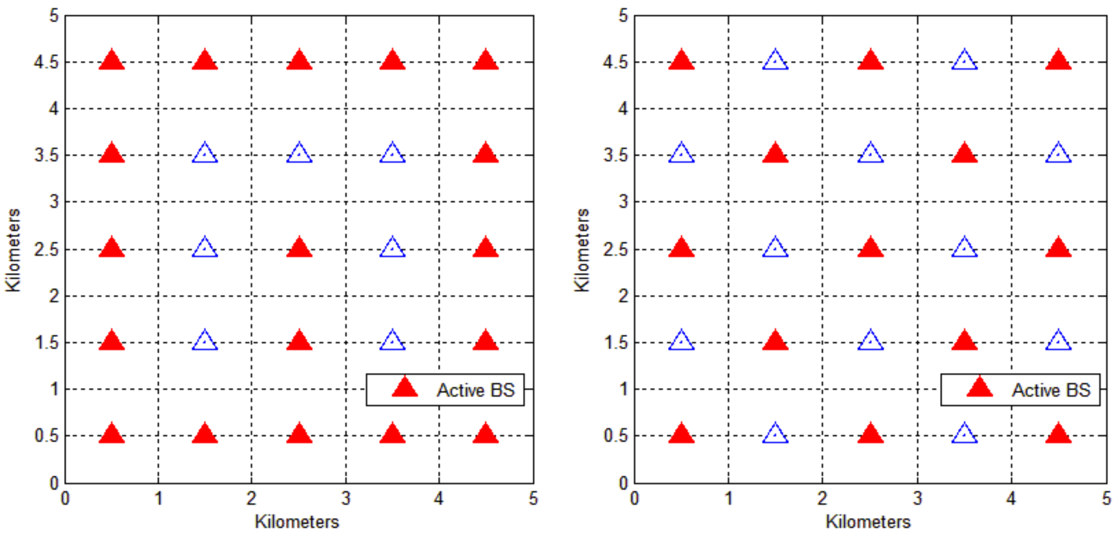
Additionally, for each traffic load we also calculate $p_j^{(on)}$, that is the probability that a BS j is active. For example, the $p_j^{(on)}$, activation probabilities are shown in Figure 3.3(a) next to each BS for a 4% load. A snapshot of RLOS operation for the same traffic load of 4% in a typical wireless mobile broadband area, which corresponds to our simulation reference area, is depicted in Figure 3.3(b). 12 BS were utilized to serve the traffic load of 50 UEs (4%), which were selected from the RLOS algorithm among the 25 available BS with a total snapshot's calculation time of 38,4 ms. The presentation of this snapshot gives us a better illustration of RLOS execution times for associating UEs to BSs in the most power efficient way and RLOS outcome per snapshot in general; each arrow's edge and circle's perimeter points at the UE which is served by the corresponding BS, which BS is in the centre of each circle and the start point of each arrow. Finally, values of Table 3.2 are used as input to the BS activation schemes APBH and APMCOH which are used next to compute the necessary BS subset to serve each traffic load with an acceptable outage probability of $p_{out} = 5\%$.



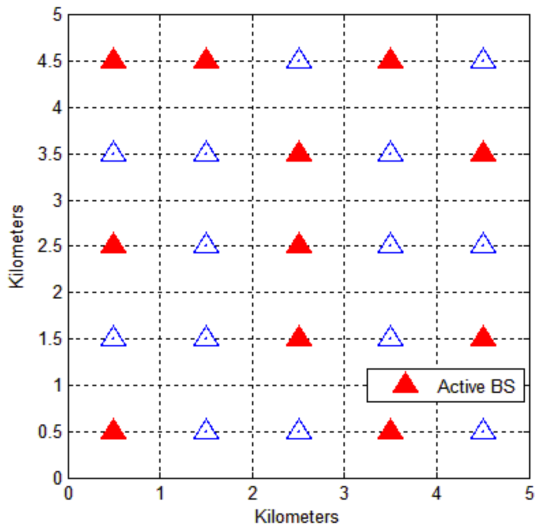
(a) (b)

Figure 3.3: BS activation probabilities for traffic load of 4% and a snapshot of RLOS algorithm's operation for the same traffic load are shown in (a) and (b) respectively.

The results when applying APBH, APMCOH and exhaustive search for 4% traffic load are given in Figure 3.4(a), (b) and (c). As we can see APBH yields 18 BSs necessary to serve any uniformly random placement of 50 UEs with outage probability of 5%, while APMCOH yields only 13 BSs to serve the same traffic load with the same outage probability. Compared to the traditional operating strategies that activate all available BSs, the two proposed heuristic activation schemes APBH and APMCOH provide a significant reduction of 28% and 48% respectively at the number of necessary BSs which are translated to a significant energy reduction. An additional reduction is possible if we look at the results of the exhaustive search procedure where the traffic load of 50 UEs can be served with 5% outage probability by at most 11 BSs.



(a) (b)



(c)

Figure 3.4: BSs activation schemes results for 4% system load with APBH in (a), with APMCOH in (b) and with exhaustive search in (c). Red (blue) triangles represent active (inactive) macro BSs.

The results when applying APBH, APMCOH and exhaustive search for increasing traffic loads and maximum allowable outage probability 5% are given Figure 3.5. This corresponds to a 56% reduction in the power consumption compared to the fully operational topology of 25 BSs. The results reveal that the number of active BSs necessary to serve the corresponding traffic load is significantly lower than the full operational topology of 25 BSs at low loads, but the benefit is becoming lower as the offered traffic load increases.

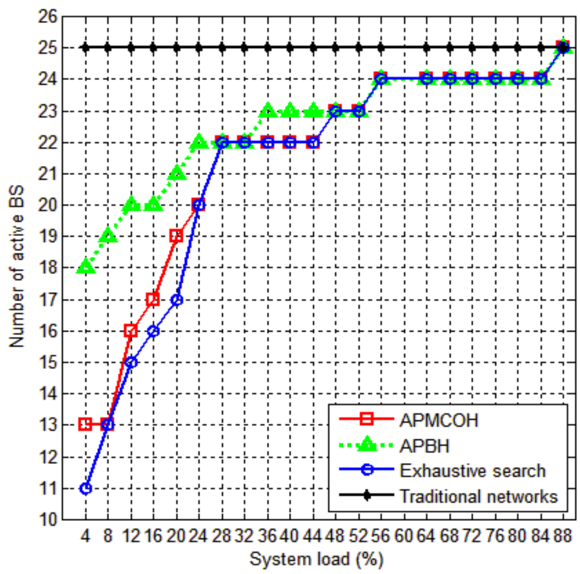


Figure 3.5: BS activation results for increasing traffic loads and $p_{out} \leq 5\%$.

APBH activation scheme, although works well at low to medium load compared to the fully operational topology, its results are far away from the results of the other two methods, especially at very low loads. On the other hand, our APMCOH BS activation scheme that takes into account not only BS activation probabilities but also the coverage area overlap of active

BSs, manages to yield results which are very close to the exhaustive method at all traffic loads. Both schemes manage this better behaviour within the acceptable outage probability limits as shown in Figure 3.6, where we can see for increasing traffic loads the actual outage probability when the corresponding subset of BSs of Figure 3.5 is active.

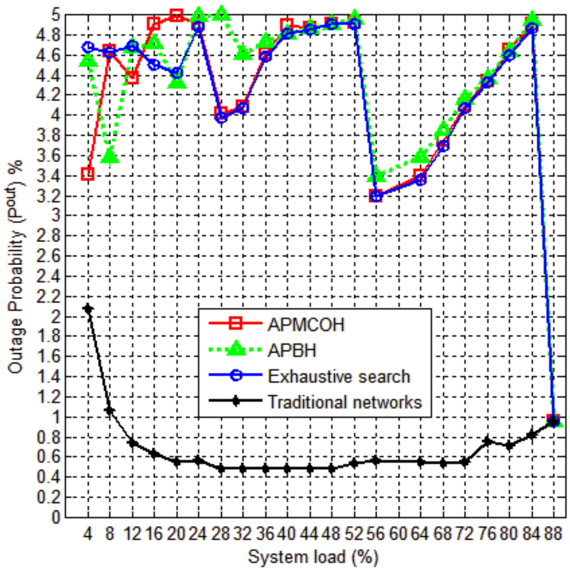


Figure 3.6: Outage probability levels per system load for different algorithm approaches.

Finally, in Figure 3.7 we translate the benefit from using fewer BS for operating the system at different traffic loads to energy savings. As it is shown, the energy consumption is clearly lower and energy savings can reach up to 12KWatts/h. Energy consumption gains by activating fewer BSs are significant higher on low traffic load demands and are fading, but still present, even when system operates close to its practical maximum actual load.

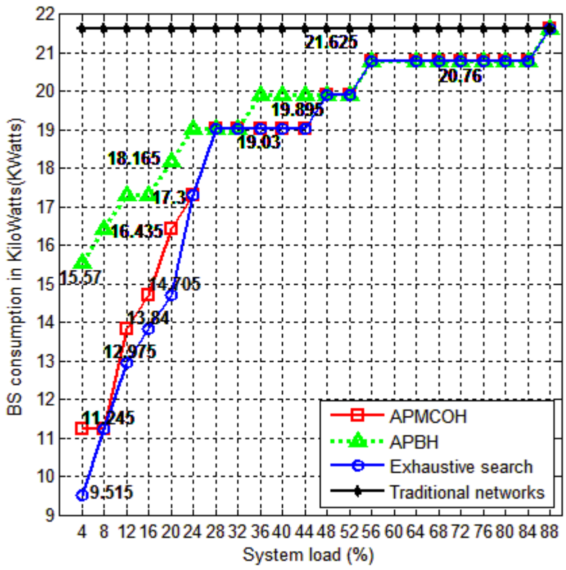


Figure 3.7: System model average energy consumption per traffic load for traditional and proposed approaches.

3.3 LTE Mobile Homogeneous Network

3.3.1 System Model

We consider a service area which is planned to operate with a set of BSs whose locations are fixed and determined a-priori. Under different user traffic requests, a subset of those BSs would probably exist and suffice to cover the same service area with the same QoS requirements. Our approach basically divides the problem of energy efficient BS operation in two separate steps. The first subproblem is to find the subset with the minimum number of BSs from the original set of BSs that is adequate to satisfy the given user traffic requests. It is obvious that different traffic requests or user placements would possibly yield a different optimal subset of BSs. This problem is described and formulated as an optimization problem and two energy efficient optimization schemes, namely the BAse station Location Status Optimizer (BALSO) [82] and the opTimal poWer consumption schEme for rAdio access networKs (TWEAK) [83], are proposed to tackle it. In the second step, we determine the optimal, with respect to power consumption, subset of BSs which should be active in order to serve any random placement of a certain number of UEs dispersed anywhere in this area, without violating the QoS requirements for each user served, and within acceptable levels of outage probability.

The downlink of a Single-Input Single-Output Orthogonal Frequency Division Multiple Access (SISO OFDMA) network, resembling LTE RAT, is considered in our problem formulation. Thus, the available bandwidth is split into N_s frequency resource blocks. Transmissions occur on a frame-by-frame basis, where each frame t consists of several OFDMA symbols and lasts T_f ms. Time and frequency orthogonality are preserved by assigning each block/frame resource to one user at most, thus eliminating intra-cell interference. However, a different number of blocks may be assigned to each user in the same frame. The channel knowledge for each frame is considered to be perfect, which is a valid assumption for slowly moving users. A portion of the resources is dedicated to signaling/reference transmission, thus bounding the resources available for serving useful payload.

Each BS may occupy one out of two possible states, namely operational (ON) and non-operational (OFF). When a BS is set to the ON state, the equivalent maximum transmitted RF power per BS is limited. Every operational BS has an inherent energy cost which is fixed and equal to f. This cost is independent of the load and is shown in Table 3.3, accounting for the power consumption generated by the minimum power required by the PA and auxiliary subsystems. Furthermore, the utilization of subchannel k when UE i is served by BS j inflicts an additional variable cost c_{ijk} , due to the extra energy consumed by the equivalent PA. In the following, we proceed with the presentation of the first subproblem formulation. We will refer to this subproblem as the *Optimal BS Subset* (*OBSS*) problem.

Table 3.3: Typical power consumption distribution in macro cell radio access equipment [103].

Parameter	Value
Power amplifier	50-80% (~1200 W)
Air conditioning	10-25% (~300 W)
Signal processing	5-15% (~200 W)
Power supply	5-10% (~100 W)

3.3.2 Optimal BS Subset (OBSS) problem formulation

The solution of OBSS depends on the current location of mobile requests and would also be applicable in a future scenario with coexisting signaling and data cells. However, in the examined current cellular network model these results are only helpful as input to the second subproblem. The variables necessary for our problem formulation are given in the following table:

Table 3.4: OBSS problem variables.

J	Number of potential Base Stations
I	Number of UEs
K	Maximum number of subchannels per BS
a_i	Guaranteed Bit Rate (GBR) demand of UE (in Kbps)
b_j	Capacity of BS measured in number of subchannels
f	Fixed power cost of a switched 'ON' BS
c_{ijk}	Power cost of assigning channel k of BS j to UE i
BR_{ijk}	Achieved Bit Rate when assigning channel k of BS j to UE i

OBSS can now be formulated as an optimization problem, as follows:

$$\min \left\{ \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} c_{ijk} \cdot x_{ijk} + f \sum_{j=1}^{J} y_j \right\} \tag{3.3.2.1}$$

Subject to:

$$\sum_{k=1}^{K} x_{ijk} \leq 1,\ i = 1, \ldots, I,\ j = 1, \ldots, J \tag{3.3.2.2}$$

$$\sum_{j=1}^{J} x_{ij} = 1,\ i = 1, \ldots, I \tag{3.3.2.3}$$

$$\sum_{j=1}^{J} \sum_{k=1}^{K} x_{ijk} \cdot BR_{ijk} \geq a_i,\ i = 1, \ldots, I \tag{3.3.2.4}$$

where the following binary decision variables are introduced:

$$x_{ijk} = \begin{cases} 1, \text{ if channel } k \text{ of BS } j \text{ is assigned to user } i \\ 0, \text{otherwise} \end{cases} \tag{3.3.2.5}$$

which indicates whether channel k of BS j is assigned to UE i,

$$x_{ij} = \begin{cases} 1, & \text{if } \sum_{k=1}^{K} x_{ijk} > 0 \\ 0, & \text{otherwise} \end{cases} \quad (3.3.2.6)$$

which indicates whether BS j serves UE i, and

$$y_j = \begin{cases} 1, & \text{if } \sum_{i=1}^{I} x_{ij} > 0 \\ 0, & \text{otherwise} \end{cases} \quad (3.3.2.7)$$

which indicates whether a BS is ON and serves some UEs or OFF and serves no UE.

The objective function presented in (3.3.2.1) aims at the optimization of the energy efficiency of the network, by minimizing the sum of the variable and fixed energy costs inflicted by the utilization of certain BSs and the corresponding subchannels. Constraints (3.3.2.2) impose that each channel of each BS is assigned to one UE at most, while constraints (3.3.3.3) in combination with (3.3.3.6) impose that each UE must be served by one and only one BS. Finally, constraints (3.3.3.4) represent the demand constraints and impose that each UE should get its minimum requested demand.

In the following section, the energy efficient heuristics utilized for tackling the aforementioned optimization problem are presented.

3.3.3 Energy Efficient Heuristics

3.3.3.1 Energy Efficient optimization schemes for OBSS

Both schemes take into account a set of potential locations for placing BSs, as well as a set of UEs that should be served by the network, according to certain predefined QoS requirements. The final goal is to extract the optimal subset of BSs that are able to fulfil these requirements, while minimizing the overall energy consumption of the RAN. The advantages are multifold, as both schemes respect QoS constraints, have low complexity, and achieve close to optimum energy efficiency.

a. BAse station Location Status Optimizer – BALSO

The algorithm minimizes the overall energy consumption of the network by toggling the power status of the BSs of the system from the OFF to the ON state to meet the actual needs and demand of the users. Figure 3.8 depicts the execution flowchart of the proposed algorithm.

The discrete steps of BALSO are as follows:

i. First, a list of registered UEs and available BSs is created. A certain number of BSs may be switched ON at this stage, accounting for fundamental and irreplaceable entities within the topology of a provider's network. The remaining available BSs are considered as switched OFF, corresponding either to existing BSs having their power state set to OFF status, or new potential ones, depending on the investigated scenario.

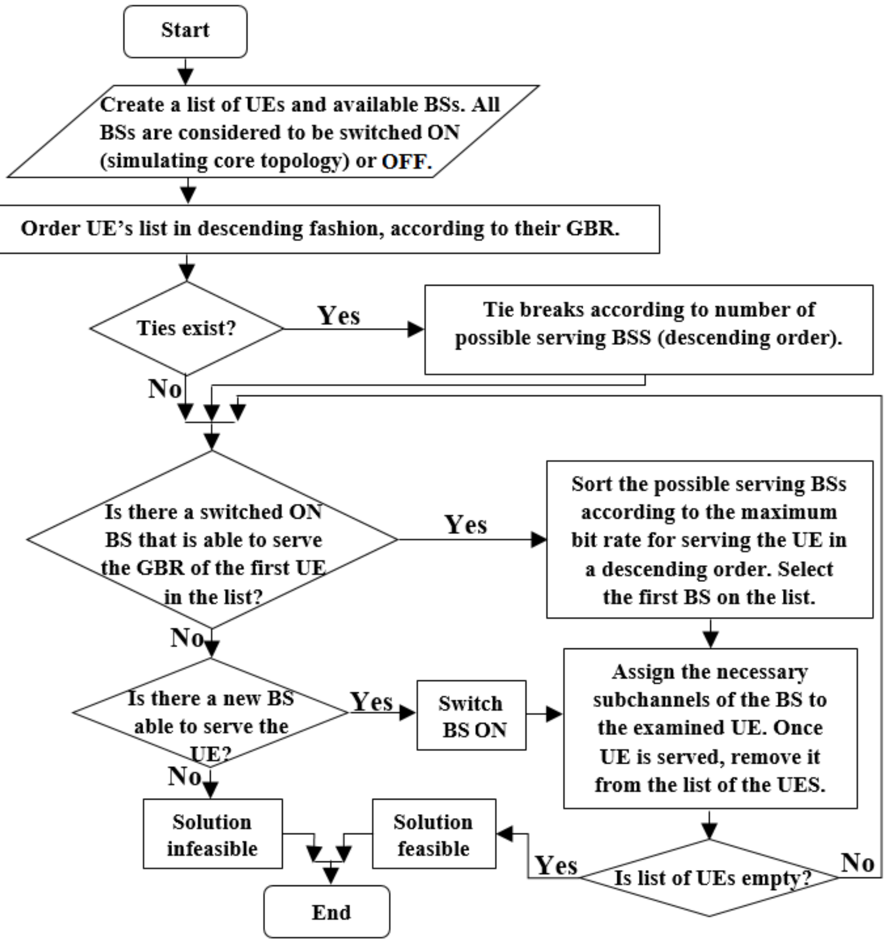


Figure 3.8: Flowchart of the BALSO algorithm.

ii. The list of UEs is ordered according to their GBR in descending fashion. In case ties exist, these are settled by prioritizing the UEs which detect the least number of BSs able to cope with fully satisfying their GBRs. This information is derived from the Channel State Information (CSI) blocks exchanged between the users and the network. Channel information per resource block is converted through the Shannon's capacity formula to Bit Rate (BR) per resource block and thus each UE roughly estimates the QoS which could be provided by the available BSs.

iii. Processing the ordered list of UEs, we are seeking a BS capable of satisfying the GBR of the Head-of-List (HoL) UE (the UE that possesses the first position of the formed list). The following scenarios may occur:

   a. If only a single already switched ON BS is able to meet the requirements, this sole candidate is selected as the serving BS.
   b. If multiple capable already switched ON BSs are found, the one which may provide the maximum BR to the UE prevails. This choice is based on the assumption that this BS will be able to meet the requirements with the minimum amount of resources, due to the fact that it has reported to the UE the best channel conditions during the CSI messages exchange. Thus, the complexity of the algorithm is reduced, as it is not

necessary to calculate all possible combinations among the UE and the resource blocks of the BSs.

c. If no already switched ON BS that is able to satisfy the UE is found, a search, among switched off BSs, takes place. If only one BSs can serve this UE, the execution proceeds by toggling the BS status to "ON" and selecting it as the serving BS. If more candidates exist, priority is given to the one having the minimum Geographical Overlap (GO) with the already switched ON BSs. Considering that each BS has an area of coverage that could be presented with a circular shape of defined radius, GO metric is derived via geometric equations, calculating the common area of overlapping circles. Thus, it is ensured that the network maximizes its area of coverage, while maintaining the QoS of existing users. Otherwise, if the search for a serving BS is futile, the solution of this snapshot is considered as infeasible and the algorithm exits.

iv. The resource allocation regarding the selected BS takes place. The minimum required subchannels for serving the examined UE are assigned and the equivalent actual BR and power consumption imposed to the system are recorded. Afterwards, the HoL UE is removed from the list.

v. The execution terminates either by successfully examining and assigning all UEs in the list to some BS, or by detecting infeasibility in the above step iii.c.

BALSO performs GBR calculations among switched ON BSs and UEs and assigns UEs to the available BSs, in order to utilize the minimum amount of resources of these BSs (step iii.b). Thus, it first tries to fully utilize the already existing switched ON BSs before attempting to examine new candidates for toggling them to the ON state. Consequently, fewer BSs are expected to become active to satisfy a given traffic load. When a new BS is necessary to satisfy the traffic demand, the search for minimum resource consumption as well as minimum GO, tends to favor the activation of remote BS. In addition, BALSO is designed with an inherent competency to accommodate various network topologies, QoS requirements and RATs. For example, for a High Speed Packet Access (HSPA) system, the aforementioned analysis still holds, with a few minor modifications (e.g. the physical resources of the network would be codes instead of subchannels). Finally, it should be noted that if the full network (where all BSs are switched ON) constitutes a feasible solution, then the proposed algorithm never reaches infeasibility, as under all circumstances the final setup to be examined by BALSO is the one of a full network. The proposed algorithm exhibits low polynomial-order complexity since it involves only sorting, searching and comparison operations among system elements (BSs, UEs and subchannels).

b. opTimal poWer consumption schEme for rAdio access networKs - TWEAK

Unlike BALSO, TWEAK minimizes the overall energy consumption of the network by toggling the power status of the BSs of the system from the ON to the OFF state to meet the actual needs and demand of the users. Figure 3.9 depicts the execution flowchart of this algorithm.

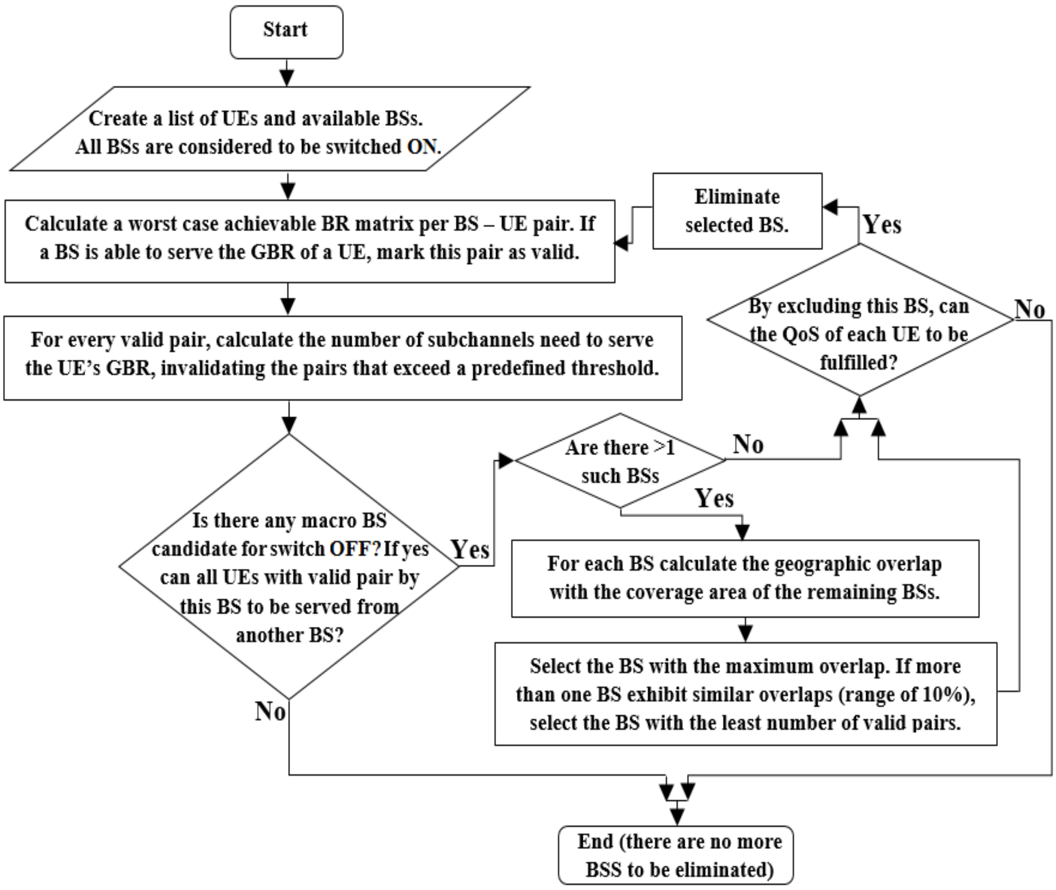


Figure 3.9: Flowchart of the TWEAK algorithm.

A thorough description of the steps follows.

i. First, a list of registered UEs and available BSs is created. All BSs are considered to be switched ON for the time being.

ii. The achievable BR matrix for each BS and UE pair is calculated in a worst-case fashion (i.e. the inter-cell interference taken into consideration corresponds to worst conditions, namely every subchannel of each BS is actively transmitting data, thus causing interference to the equivalent channels of adjacent BSs). In order to calculate the BR matrix, CSI blocks exchanged between the users and the network, as well as Shannon's capacity formula are utilized. If a BS is able to fulfil the QoS requirements of a UE, this BS – UE pair is marked as being valid. At this stage, each UE may participate in more than one pairings, though during the actual radio resource assignment stage the SS constraint has to be respected.

iii. For each valid pair, the number of needed subchannels is estimated. In case this number exceeds a predefined threshold lying in the order of 33% of the total subchannels of each BS, then the examined pair is invalidated. It should be noted at this point that this invalidation takes place, since committing an exaggerate amount of resources of a BS to a single UE constitutes an inexpedient tactic for the proper management of the resources of the network. Considering a generalized paradigm, a carefully planned network should be right sized enough in order to be able to serve each UE by employing the most suitable BS, thus avoiding reckless use of valuable resources.

iv. It is examined whether some BSs exist that could have all of their valid pairs invalidated, while at the same time every UE is still included in at least one of the remaining valid pairs. In other words, it is examined whether certain BSs could be eliminated from the network, while maintaining the capability of the RAN to serve all subscribers, by reallocating UEs to other access points. The following scenarios may occur:

   a. No such BS exists. Therefore, all BSs are absolutely necessary for guaranteeing the smooth operation of the network.
   b. Only one BS meets this criterion and it is selected for further investigation at step v.
   c. Several BSs are able to meet this criterion. In this case, each one of these BSs is examined iteratively, by calculating the overlap of its geographic coverage area with the cumulative coverage area of all other remaining BSs. The BS which possesses the maximum overlap is selected for further investigation at step v. In case two or more BSs exhibit similar overlaps (in the order of ±10%), the considered tie is broken by opting for the one having the least number of valid pairings with UEs (inferring that potential elimination of this BS will inflict negligible consequences to the network's functionality).

v. If a BS has prevailed in this stage, then the feasibility of the actual radio resources assignment is checked, under the constraint that each UE should acquire at minimum it's GBR. If the outcome of this validity check is positive, then the selected BS is eliminated from the network and the algorithm starts over from step ii, in the absence of this radio access point. On the contrary, if the result is negative, no further action is undertaken.

vi. The execution of the algorithm is terminated either by entering step iv.a, or by reaching a negative outcome in step v.

Opposite to BALSO, TWEAK performs its calculations while initially having all the available BSs set to the ON operational state. Among the active BSs, it searches for BSs which can be powered OFF, while preserving the UEs QoS constraints. Like BALSO, TWEAK can be applied to different network topologies, RATs and QoS and has low polynomial complexity.

3.3.3.2 Base Station Activation Algorithm

The aforementioned optimization schemes determine a minimum number of BSs to serve a certain snapshot of I randomly and uniformly distributed UEs over the service area. The outcome of the previous algorithms strongly depends on the location and QoS requirements of mobile requests and would be applicable in a scenario with coexisting signaling and data cells to determine the most appropriate set of data cells to serve a specific placement of UEs requesting service. However, in the context of this work, our ultimate goal is to select the optimal subset of BSs that can serve any random snapshot of the same I number of UEs without violating system QoS constraints and within an acceptable outage probability threshold $p_{out}^{(FOT)}$ which is defined as the acceptable Full Operational Topology (FOT) outage probability level. Our approach is to iteratively formulate and solve a large number of OBSS instances, using BALSO and TWEAK. In each instance, we generate a random traffic load snapshot consisting of I randomly placed UEs in the geographical area and determine the optimal BS subset that can serve all UEs with minimum power consumption and requested QoS. We collect the data of the optimal BSs subsets and with the help of our BS activation heuristic, attempt to determine the most proper BSs subset which can serve any random set of I UEs, whilst preserving the planned outage probability level.

a. Activation Probability and Coverage Overlap Scheme

Step 1: For a certain traffic load level, in other words for a certain number I of UEs each one requesting the same minimum GBR, we generate a high number of L random placement snapshots of I UEs. For each random snapshot, we formulate and solve the corresponding OBSS. Let $p_j^{(on)}$ be the probability that BS j is active, after solving the L OBSS instances and $N_{min}^{(on)}$ be the minimum number of necessary active BS that has occurred for some OBSS instance.

Step 2: Let S_{BS} be the list of BSs sorted in descending order of their activation probability $p_j^{(on)}$ and $S_{BS}^{(on)}$ be the list of candidates for activation BSs. BSs with $p_j^{(on)} = 0$ are excluded from S_{BS}, while $S_{BS}^{(on)}$ is initially empty. The BS activation procedure begins by moving the first BS from the S_{BS} list to the $S_{BS}^{(on)}$ list.

> **while** the S_{BS} list is not empty and all BSs have not been transferred to the $S_{BS}^{(on)}$ list **do**: {The list S_{BS} is parsed and the BS, whose area coverage overlap with all BSs in $S_{BS}^{(on)}$ is minimal, is selected and moved to $S_{BS}^{(on)}$. Ties are resolved by selecting the BS with the highest $p_j^{(on)}$.}

Step 3: We start activating BSs from the top of the $S_{BS}^{(on)}$ list downwards until $N^{(on)} = N_{min}^{(on)}$ BSs are set as active. Let $S_{BS}^{N^{(on)}}$, be the set of these $N^{(on)}$ active BSs.

Step 4: We ignore the rest $J - N^{(on)}$ BSs and formulate and solve again a large number L of slightly modified OBSS problems: in each modified OBSS instance (a) the set of available BSs is $S_{BS}^{N^{(on)}}$, and (b) we do allow that some UEs may not receive service, and measure the corresponding outage probability. We denote by $p_{out}^{(L)}$ the measured outage probability after solving the L modified OBSS.

> **If** $p_{out}^{(L)} > p_{out}^{(FOT)}$ **then** we set $N^{(on)} \leftarrow N^{(on)} + 1$, we update $S_{BS}^{N^{(on)}}$, by adding the next BS from list $S_{BS}^{(on)}$ and goto start of **Step 4,**
>
> **else** the set of active BSs to serve the requested load of I UEs is $S_{BS}^{N^{(on)}}$. Exit.

3.3.4 Performance evaluation and discussion

3.3.4.1 Simulation setup

The performance of the proposed algorithm was evaluated using a system-level simulation tool developed in MATLAB. All the fundamental elements of a complete cellular network were simulated, each one to an adequate extent for the required precision of our study. All the attributes of the network were adjustable, while the sessions were statically created at the beginning of each simulation run. Different traffic load conditions were examined, by differentiating the number of UEs and the GBR of each UE in each run. Furthermore, an upper bound for the optimum energy efficiency is acquired per snapshot by means of exhaustive search. During the exhaustive search, all possible scenarios regarding the status of BSs and assignments of subchannels to UEs are investigated and the corresponding power consumptions are recorded. The numerical results derived from the simulation execution are normalized against the power consumption calculated for a fully operational topology.

Within the coverage area of the network, a number of J potential locations for BSs have been prescribed. Moreover, I UEs have been injected into the system, accounting for service consumers dispersed in uniformly order. It should be noted at this point that the BRs are calculated in the following using Shannon's formula, based on a worst case transmission scenario. Moreover, rates are upper-bounded by the highest Adaptive Modulation and Coding (AMC) scheme available to the system (namely 64 QAM). Table 3.5 summarizes the values of the main parameters of our simulation model.

Table 3.5: Values of main simulation parameters.

Parameter	Value
J	9
N_s	25
BW	5 MHz
I	Four different UEs sets of 5, 15, 30 and 50 UEs
a_i	Three simulation campaigns: 500, 750 and 1000 Kbps
f and c_{ijk}	According to values in Table 3.3
Propagation model [82]	C3 (bad urban)
Radio Access Technology	LTE

3.3.4.2 Performance evaluation results

A typical 1x1 Km^2 region of a broadband wireless network was evaluated during the simulation campaign. Figure 3.10 depicts a representative grid of the investigated topology, with nine possible, geographically distributed within the coordinate system, BSs entities and 30 UEs randomly and uniformly distributed inside the grid area. Three scenarios were taken into consideration as far as the GBR of UEs is concerned, namely 500, 750 and 1000 Kbps, corresponding to low to medium, medium and medium to high traffic load within the network.

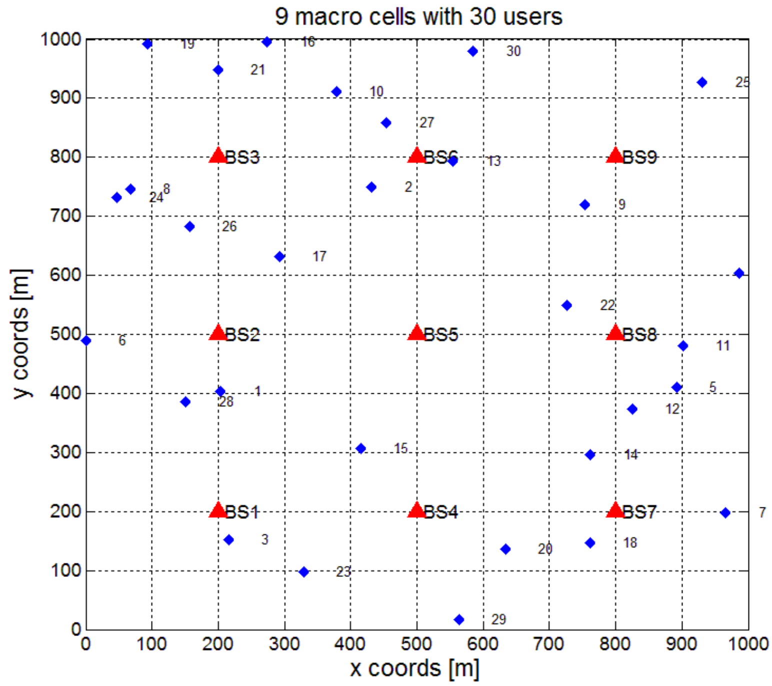


Figure 3.10: A typical network topology (red triangles represent BSs, blue diamonds UEs).

The average energy consumption of both energy optimization schemes, per GBR and number of present UEs, is shown in Figure 3.11. The results are normalized against the consumption of a fully operational topology, where all nine possible BSs are switched ON. For comparison purposes, a lower bound for the energy efficiency is given alongside, calculated via the aforementioned approach of exhaustive search.

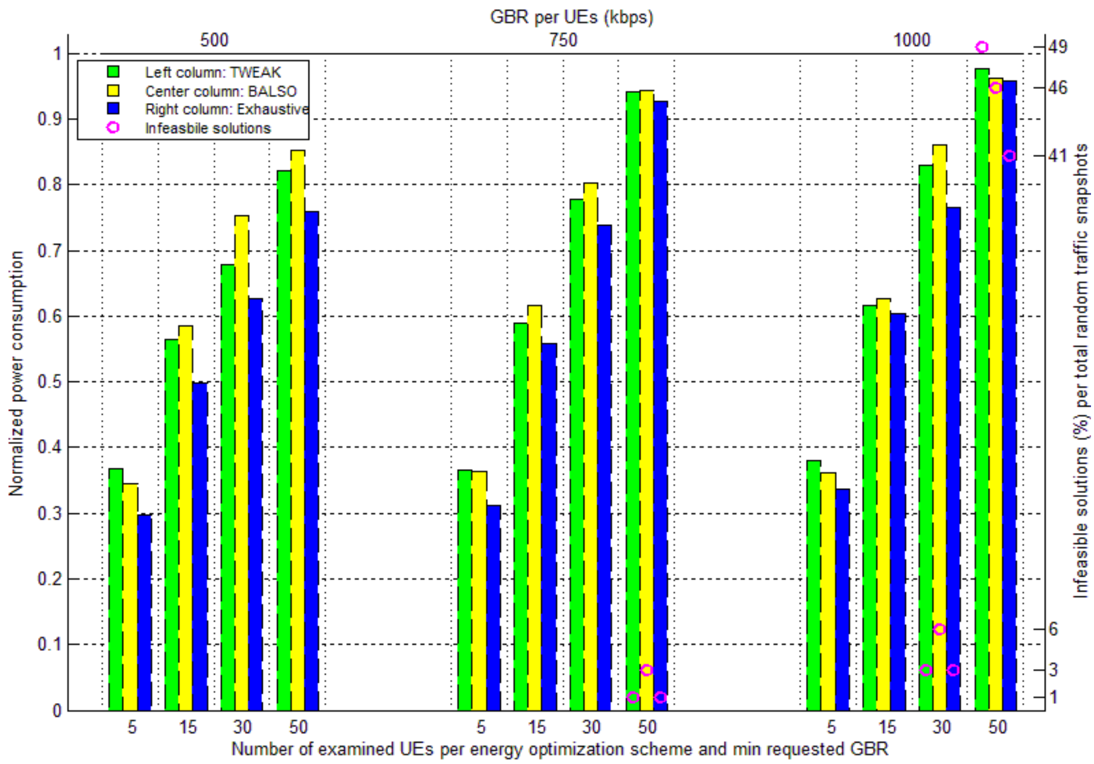


Figure 3.11: Normalized BALSO and TWEAK energy consumption against lower bound and infeasible solutions percentages.

It is evident that a significant reduction in power consumption is achieved, while the trend outlined by the lower bound threshold is also followed. BALSO scheme achieves better performance when 5 UEs are present and almost matches TWEAK power consumption on highest random traffic loads, where the system is utilized at its maximum potentials, and infeasible solutions are appearing even with the use of exhaustive search (30 UEs and 1000 Kbps GBR or 50 UEs with 750 or 1000 Kbps GBR). On the other hand, TWEAK scheme achieves energy efficiency closer to the optimum levels, for moderate to higher number of UEs.

The main reason of this performance differentiation lies on the operational nature of each algorithm. At lower traffic load, fewer BSs are necessary, while as the traffic load increases more BSs should become active. BALSO starts with an empty set of active BSs and activates one BS at a time trying to associate as many UEs as possible for each BSs. Thus, when only few BSs are necessary, BALSO manages to activate the fewer BSs as it activates a new BS only when this is absolutely necessary. However, when more BSs are necessary to serve the load, BALSO's greedy behavior does not yield the most power efficient set of active BSs. On the other hand, TWEAK starts with all BSs active and deactivates one BS at a time by transferring its users to other BSs. At high loads fewer BSs need to be deactivated and TWEAK manages to make the right selections, while at low loads more BSs need to be deactivated and the greedy choices of TWEAK fail to yield the optimal set of BSs.

Quantitatively, the mean improvement for the 500 Kbps GBR scenario, compared to the non-optimized topology, is starting from 65% and 63% for 5 UEs, lowers to 41% and 43% for 15 UEs, then drops to 24.7% and 32% for 30 UEs and to 14.7% and 18% for 50 UEs, when using BALSO and TWEAK, respectively. The overall gaps between the proposed algorithm and the ideal solution are 9.43% and 7.16% respectively, a fact which assures near optimum functionality of both developed methods. It is also worth noting that both optimization schemes have provided feasible solutions for every single run and did not encounter any premature termination of execution due to any kind of inherent weakness of the algorithms to solve the snapshot.

The average energy efficiency of the optimization schemes for the three examined GBR scenarios is shown in Figure 3.12, through the well-known bit per joule metric. Once again, the results are normalized against the energy efficiency of a fully operational network with all nine BS operational, while the upper bound is available by means of exhaustive search.

A similar trend on the behavior of the algorithms is observed compared with the non-optimized topology. The achievable gain for 500 Kbps GBR is in the order of 190% and 172% for 5 UEs, 70% and 77% for 15 UEs, 33% and 47% for 30 UEs and finally 17% and 22% for 50 UEs, for BALSO and TWEAK optimization schemes respectively. As expected, the number of UEs demanding a certain service hugely affects this energy performance metric.

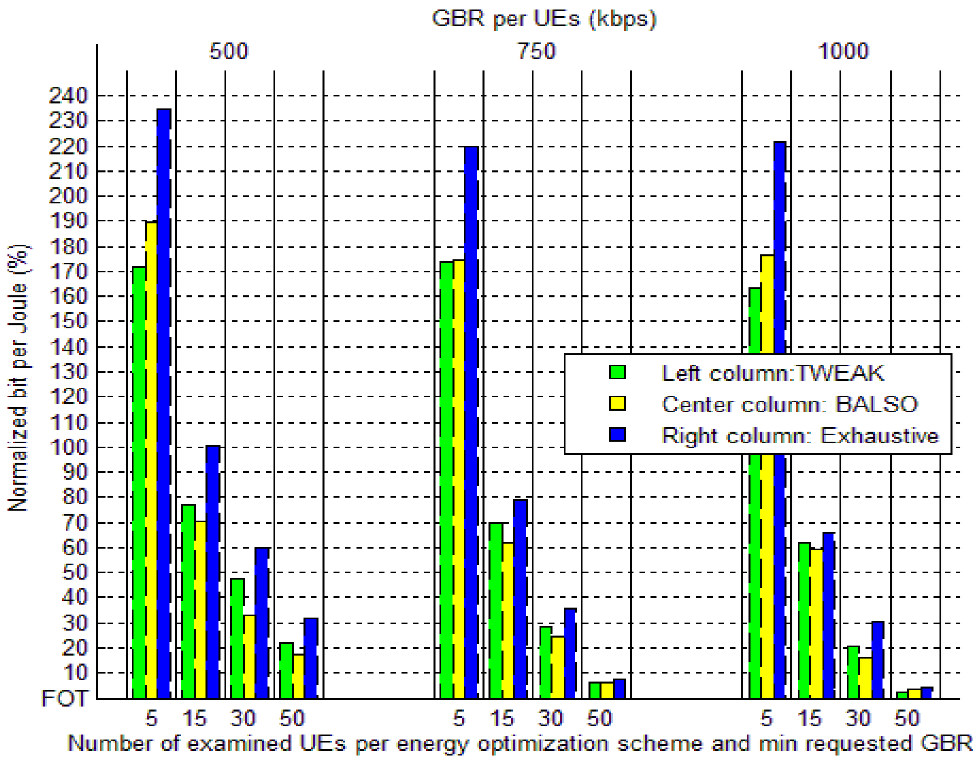


Figure 3.12: BALSO and TWEAK energy efficiency comparison with upper bound, normalized against bit per joule efficiency of fully operational topology (FOT).

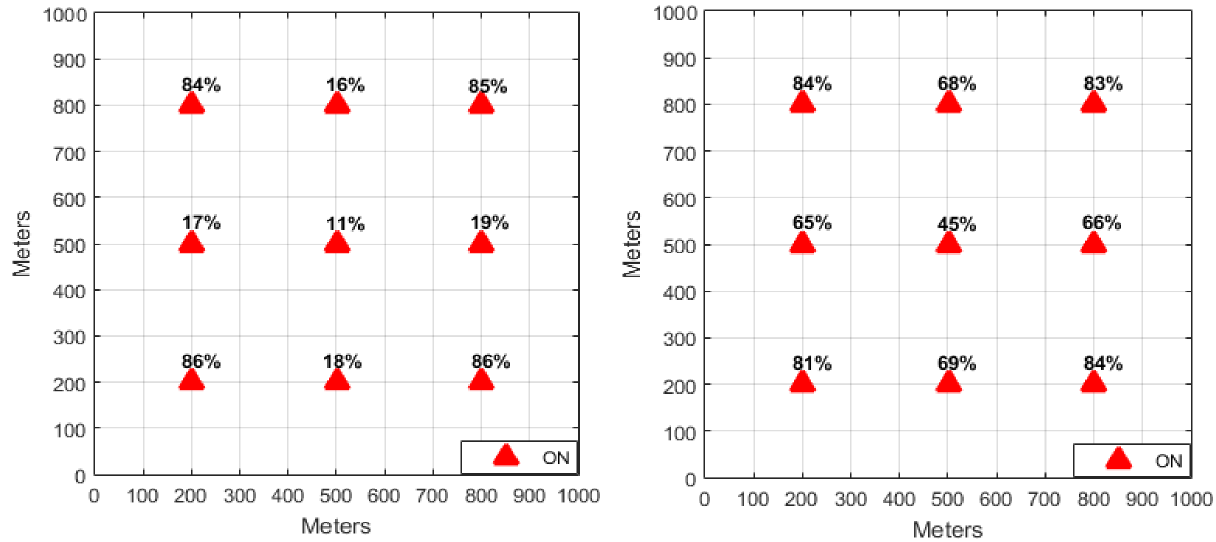
The average achievable bitrate to all users per requested GBR, is as shown in Table 3.6, where TWEAK obtains closer to optimum average bitrate in all simulation scenarios examined. This is in accordance with the more power efficient behaviour of TWEAK on medium to higher loads. For example, at 30 UEs and 500 Kbps GBR, the exhaustive search yields an average GBR of 776,4 Kbps, TWEAK 780,5 Kbps while BALSO 804,1 Kbps. Thus, BALSO achieves higher average bit rate at the expense of power consumption. However, at low traffic loads BALSO achieves a good balance among power consumption and throughput capacity, as for the same GBR of 500 Kbps and traffic load of 5 UEs, BALSO provides 4.56% higher average bitrate (834,2 Kbps) than TWEAK (797,8 Kbps) with almost 3% less power consumption.

Table 3.6: Average achievable GBR per algorithm and minimum requested GBR (Kbps).

Algorithm	Minimum requested GBR	Average achievable GBR			
		5 UEs	15 UEs	30 UEs	50 UEs
Exhaustive	500	756,6	770,1	776,4	795,6
	750	997,7	1008,6	1008,2	1022,6
	1000	1246,4	1264,2	1273,8	1284
TWEAK	500	797,8	789,8	780,5	806,4
	750	1024,4	1015,5	1012,6	1025,2
	1000	1275,6	1271,1	1275,2	1281,3
BALSO	500	834,2	815	804,1	811,8
	750	1063,6	1033,9	1026,2	1027,1
	1000	1294,8	1288,4	1285	1284,6

3.3.4.3 BSAS results

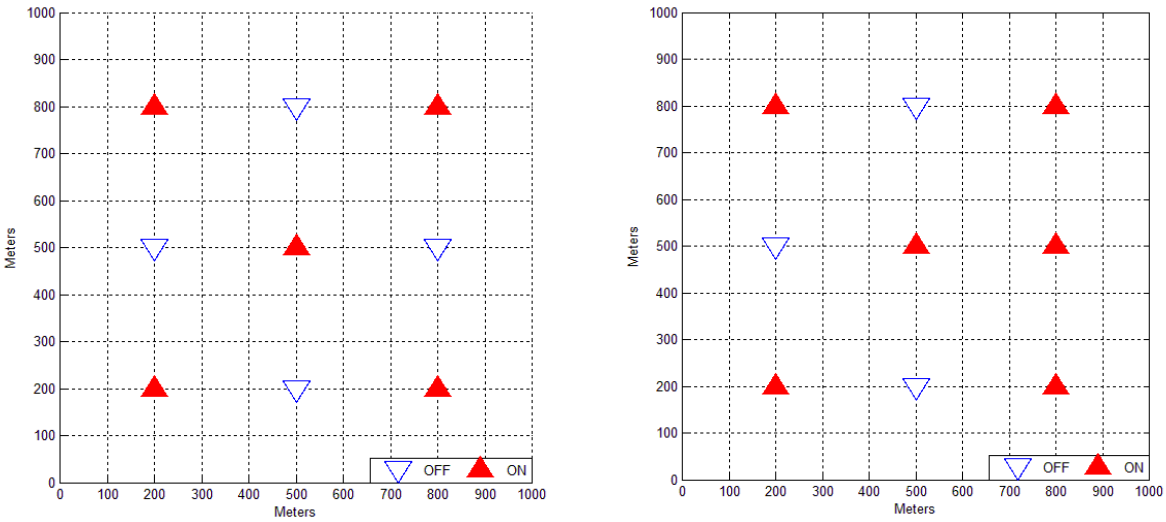
For each user traffic load we create $L = 200$ random placements of UEs and formulate and solve the corresponding OBSS to collect the values of $N_{min}^{(on)}$. Additionally, for each traffic load we also calculate the probability $p_j^{(on)}$ that BS j is active. These values are used as input to the activation scheme to compute the necessary BS subset to serve the corresponding traffic load level.



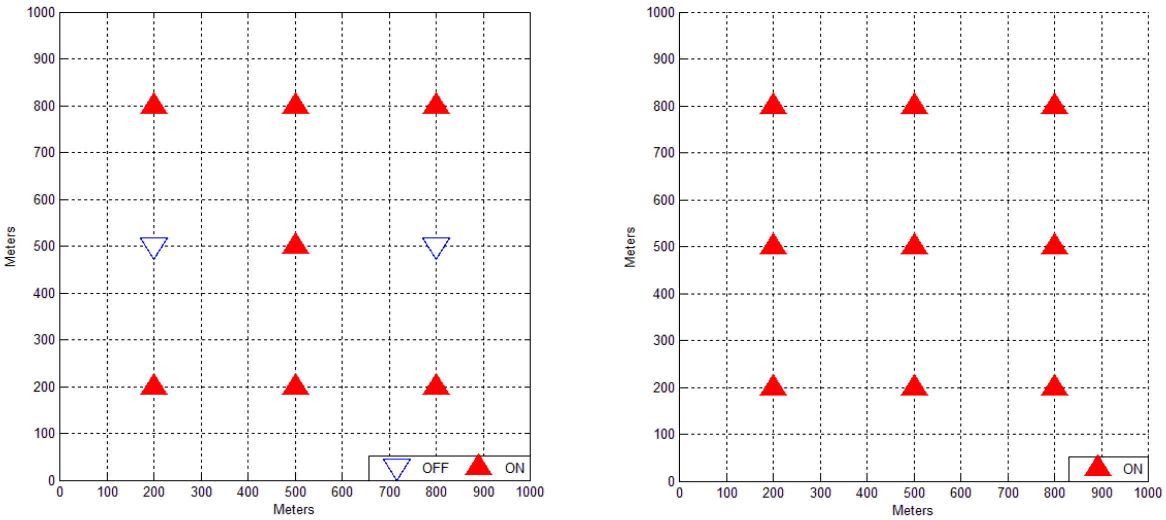
(a) (b)

Figure 3.13: Average BS activation percentages for 750 Kbps GBR and (a) 15 and (b) 30 UEs. Red triangles represent macro BSs.

We show the BS activation probabilities for 15 UEs and 30 UEs in Figure 3.13(a) and (b). The results when applying the BS activation scheme for 5 UEs requesting a GBR of 750 Kbps are given in Figure 3.14, with solid red triangles representing active BSs. In the activation profiles of Figure 3.14(b), any BS j, $j = \{2,4,6,8\}$ can be present in the active set of BSs without significant variation in the overall power consumption depicted in Figure 3.15(a).



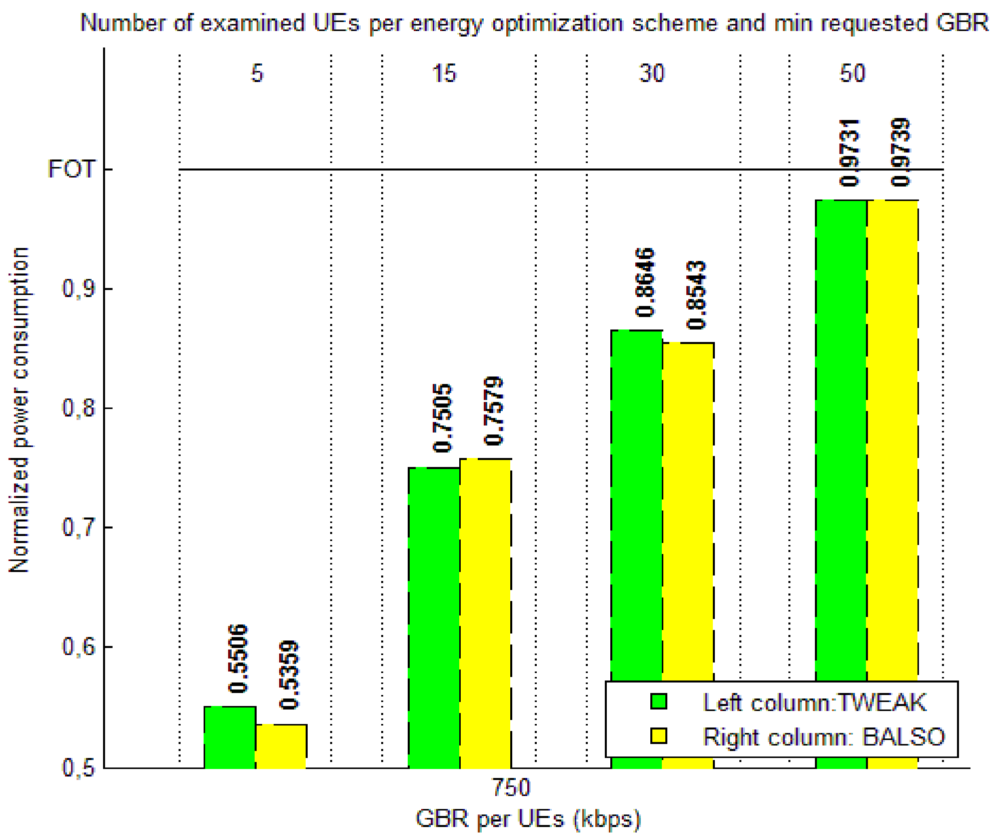
(a) (b)



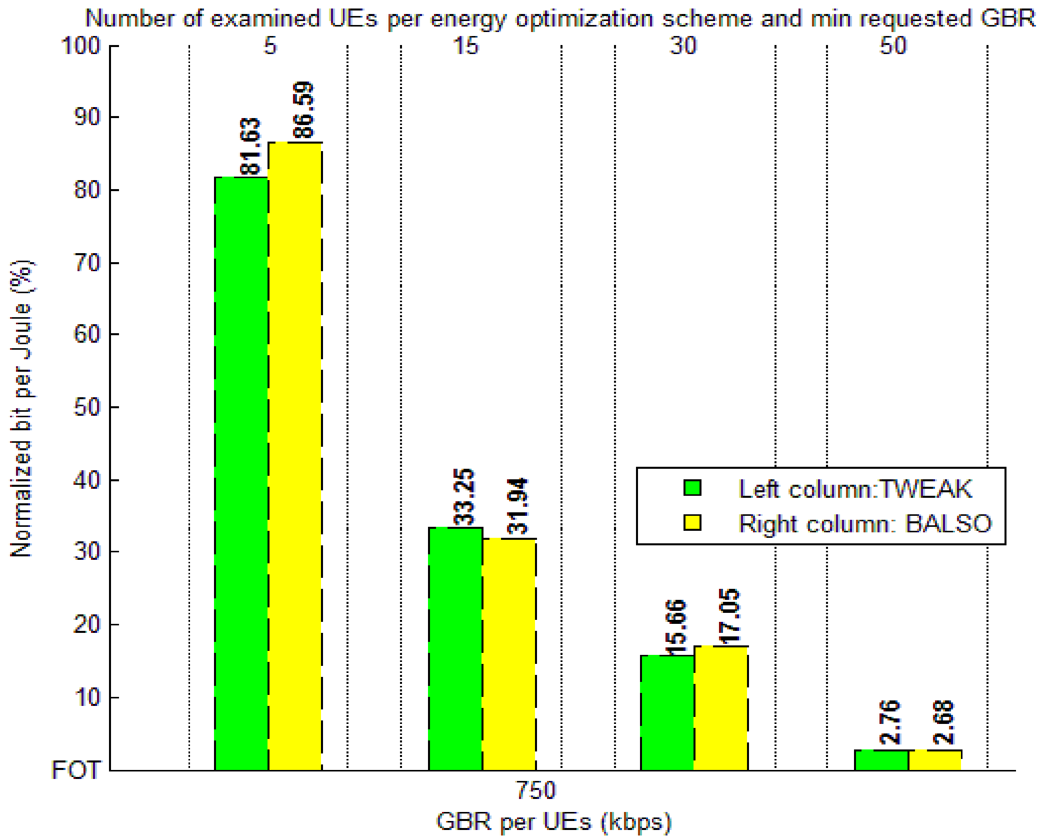
(c) (d)

Figure 3.14: Active BS for profiles of 750 Kbps GBR and (a) 5, (b) 15, (c) 30 and (d) 50 UEs. Red upwards (blue downwards) triangles represent active (inactive) macro BSs.

As shown in Figure 3.15, our proposed BS activation scheme yields 46.41% power savings and 86.59% bit per joule improvement for 5UEs without violating user's QoS, by utilizing five out of the nine available BS. However, when comparing the effect of using either TWEAK or BALSO on the activation scheme, we observe that both behave similarly, which is easily justified because the number of active BS plays the most important role on energy consumption, rather than the communication between BSs and users.



(a)



(b)

Figure 3.15: Energy efficiency of BS activation scheme, normalized against FOT power consumption (a) and bit per joule efficiency (b).

3.3.4.4 Daily Profiles

We further proceed and estimate the effectiveness of our activation scheme, during daily network operation traffic variations. As we saw in Figure 3.11, the offered traffic exceeds the capacity of our test network deployment when 50 UEs are used. For this reason, we assume that normal operation requires an upper bound of 30 UEs in our simulation environment, which can be served under various minimum GBR demands with a negligible infeasible solution percentage 3%. In other words, we assume that the capacity of our network topology is 30 simultaneously active UEs requesting 750 Kbps to avoid infeasibility results and estimate the ultimate effectiveness of our schemes during daily operation.

In Figure 3.16, a real daily traffic profile is shown as a fraction of the maximum number of active users per unit of time [61]. The day is divided into four time periods; two with medium traffic demand, one with low traffic demand and one with high traffic demand. Assuming a maximum of 30 users with 750 Kbps GBR, the low traffic demand corresponds to a maximum of 5 UEs active, the medium traffic demand corresponds to a maximum of 15 UEs active and the high traffic demand corresponds to a maximum of 30 UEs active. For each traffic profile, the necessary number of active BS is also shown in Figure 3.16 according to the activation profiles of Figure 3.14.

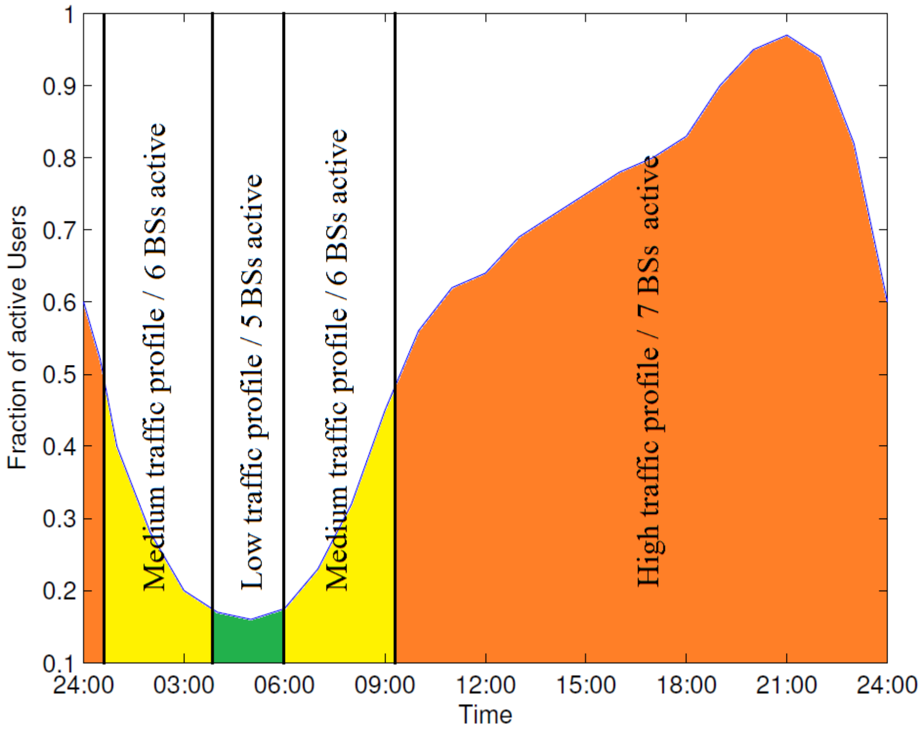


Figure 3.16: Fraction of active users per time according to the real daily traffic profile [7][61].

The overall daily energy gains are depicted in Figure 3.17; heterogeneous mobile network power consumption can be reduced by up to ~28.4% and can transmit ~31.5% more information per joule when BALSO and the proposed BS activation schemes are applied during its daily operation.

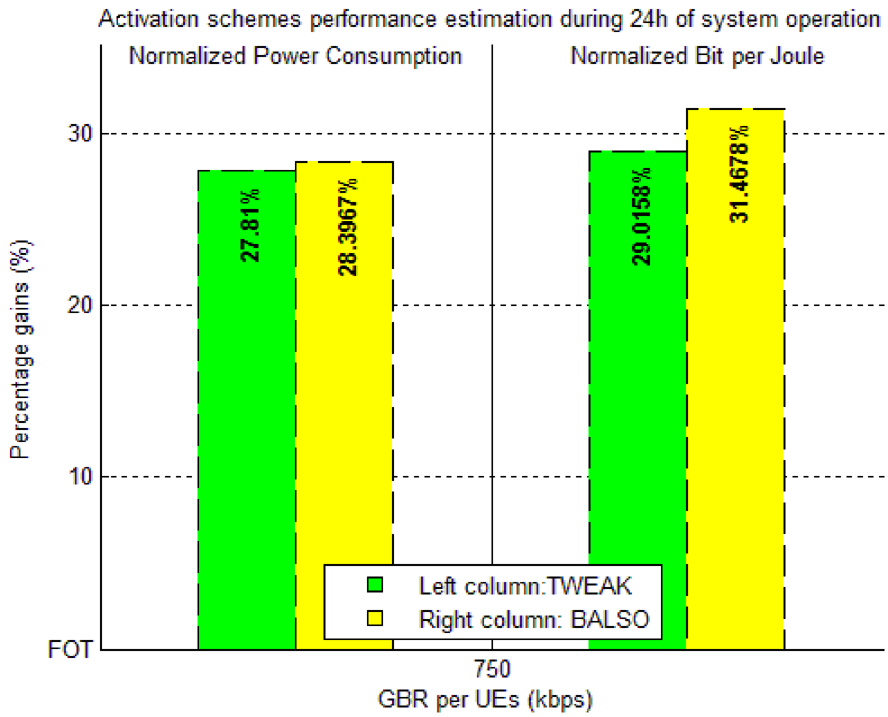


Figure 3.17: Overall normalized power consumption and bit per joule percentage improvement over FOT, according to the real daily traffic profile.

Finally, to prove the applicability of our activation schemes in realistic scenarios, it is essential to reassure that the network operation transits smoothly from one BS activation profile to the next in a feasible manner. Thus, for the daily traffic profile of Figure 3.16, we propose the transitions shown in Figure 3.18 where the transition between consecutive BS activation profiles is straightforward, by toggling BSs either ON or OFF. It is worth noting that the BS activation profile of medium level traffic in Figure 3.18 is equivalent to the BS activation profile of Figure 3.13(b).

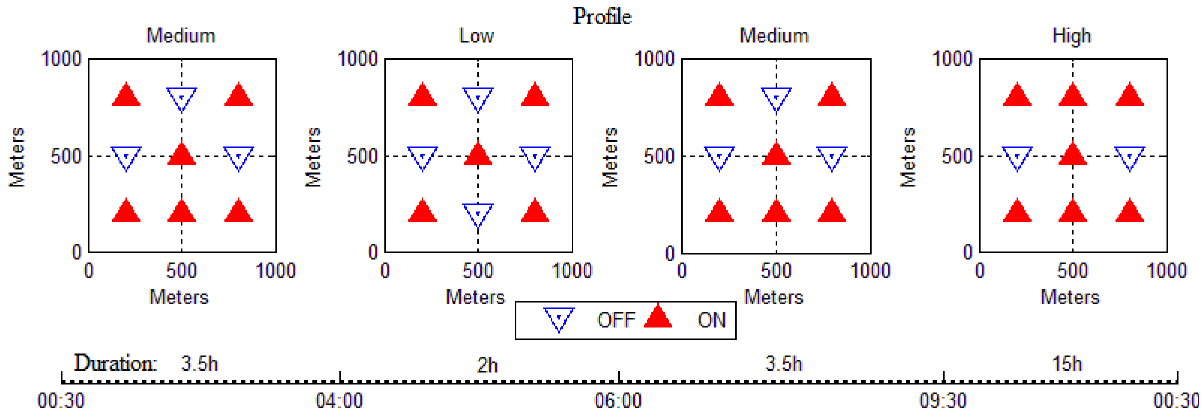


Figure 3.18: Proposed activation profiles during the day. Red upwards (blue downwards) triangles represent active (inactive) macro BSs.

3.4 Summary

In this Chapter, we investigated the energy efficiency in homogeneous mobile networking environments. We presented the corresponding power consumption minimization problems in each of the two homogeneous system models we evaluated, which were running on WCDMA and LTE RAT respectively, and introduced low-complexity greedy heuristics capable of reducing the power consumption in homogeneous mobile networking environments. Each energy optimization scheme derives the optimal subset of BSs necessary to serve a certain user traffic load. We compared the performance of our proposed heuristics against the optimum, which was acquired per snapshot by means of an exhaustive search, where all potential solutions were investigated and the most energy efficient one was selected as the optimum, and it was shown which of the proposed heuristic performs the best in each scenario evaluated. We exploited our energy optimization schemes, by solving a large number of similar problem instances, to estimate the required number of BS and acquired BS activation probabilities of the examined topology to serve certain load level. Next, we proposed BS activation schemes, according to the BS activation percentages and minimum common BS coverage area overlap. We applied our algorithms on different grid network deployments with various traffic loads and services, and showed that our proposals can greatly benefit current network operational policies with respect to energy efficiency, especially on low traffic scenario demands. Finally, we proved the applicability of our proposed schemes by proposing smooth transitions between BS activation profiles for energy efficient daily network operation in each network deployment.

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CHAPTER 4. ENERGY EFFICIENCY IN HETEROGENEOUS MOBILE NETWORKS

4.1 Introduction

Traditional cellular network planning and operation are driven by the requirement that user requests should be served with acceptable quality at any time and any place and that makes mobile networks major candidates for energy savings. In addition, as operators constantly evolve their networks to denser heterogeneous layouts, with overlaying macrocellular base stations coexisting with numerous smaller cells, to cope with upcoming increase in peak mobile data traffic, the energy consumption of mobile networks will continue to grow in the next years. However, mobile networks' traffic dynamic renders significant temporal and spatial variations in various parts of the network, especially during off-peak hours (nights, holidays), which in turn causes underutilization in many BSs of the network for more than half of the year, thus, the wasted energy of the existing cellular networks is remarkable. Consequently, their operational model leads to generous portions of wasted energy without carrying a significant workload, mainly due to the lack of adaptation to the daily traffic variations and demands. This is even more severe for future mobile communication networks, where the size of cells will be lower in order to accommodate more high data rate users and increase the frequency reuse factor, which will further increase the dynamics of the traffic in a specific cell. Thus, it is crucial to adapt the operation of cellular networks to traffic variations, including completely switching off some BSs when the traffic load is lower than a threshold [6][7][104].

In Chapter 3, we focused on energy efficient design and operation of homogeneous cellular networks, and we proposed energy optimization heuristics to determine the most appropriate subset, with respect to power consumption, among an available set of BSs, to serve an existing demand of mobile terminals without compromising QoS requirement. In this Chapter, we adapt our previously proposed heuristics to deal with heterogeneous networks with BSs transmitting at different power levels assuming two models of UEs placement inside the service area, a random uniform static and a random mobility model. Furthermore, for the most complicated of the UEs placement models, the random mobility model, we evaluate the impact of operating just the necessary number BSs to serve a certain traffic demand, on key performance indicators (KPIs) of the network, such as handover rate and data throughput.

More specifically, the first contribution presented in this Chapter is the introduction of a formal formulation of the heterogeneous mobile network's optimization problem to find the most energy appropriate subset of BSs together with the introduction and extensive evaluation of two heuristic algorithms to tackle the aforementioned problem, namely the corresponding Heterogeneous Base station Location Status Optimizer (HBALSO) and Heterogeneous opTimal poWer consumption schEme for rAdio access networKs (HTWEAK) heuristics that attempt to minimize the overall energy consumption of the heterogeneous RAN. Next, we apply these energy optimization schemes in a large number of problems with different random uniform and mobile user placements for the same traffic load level to derive useful results of the BSs usage and activation percentages. Our second contribution is to exploit these findings and propose two efficient BS activation schemes, which can be applied in the same deployed network topology, to come up with the most appropriate BS subset to serve the corresponding traffic load level, without violating the users requested QoS and acceptable outage probability thresholds. In our third contribution, we evaluate the impact on data throughput and handover rate when we employ those active BSs subsets to serve the corresponding user's demand. Our algorithms were tested in a sufficient variety of traffic loads. Via extensive simulation runs, the determined optimal BS operational profiles were proven adequate to provide transparent network operation to the mobile users, without violating their QoS guarantees. We evaluated the proposed optimization schemes and BS activation heuristic, in a sufficient variety of traffic loads to produce proper and realistic BS activation profiles for daily continuous time network operation. This is the fourth contribution of this Chapter and results indicate quite satisfactory energy savings and overall network bit per joule increase, compared to ordinary FOT operation. The advantages of our optimization schemes are multifold, namely they (i) respect QoS constraints, (ii) have low complexity, (iii) achieve close to optimum energy efficiency, and (iv) are general and flexible in accommodating heterogeneous network topologies.

The Sections of this Chapter are structured as follows: in Section 4.2 we present some related work. In Section 4.3 we describe our heterogeneous network system model. In Section 4.4 the mathematical formulation of the power optimization problem in heterogeneous wireless networks is described, while in Section 4.5 the energy optimization heuristics to tackle this problem are presented. The performance evaluation of each energy efficient scheme proposed is given in Section 4.6 , and finally, this Chapter is concluded in Section 4.7 .

4.2 Related work

Scheduling and alternating the operation of a vast number of BSs, is a very complex problem associated with many challenges. In particular, by changing the active APs in the network, the affected users may experience different interference conditions and consequently different data throughput at different time periods. Similarly, the operation or silence of BSs will have an impact on the handover rate experienced by the network during the daily lifecycle [105]. Distributed minimization of downlink transmit power according to users' throughput requirements and channel conditions at each cell or to different Resource Blocks (RBs) can yield large performance improvements and network throughput increase [106][107], while novel multicast protocols [108][109] and cell breathing control, based on User Equipment (UE) reports of their channel quality information, can maintain balance between system throughput and allocation fairness among UEs. Frequent toggling of the operational status of the BS PA component can reduce power consumption up to 80 %, while energy aware network re-configuration methods can flexibly react to load variations minimizing energy consumption [110][111][112][113] [114]. Moreover, extended surveys of current and upcoming status in green mobile networking underline the novel axes in this research domain can be found in [115][116][117][118].

4.3 Heterogeneous Mobile Network System Model

As wireless broadband networks are usually planned for full traffic load conditions, encountered for limited time periods, the systems are severely underutilized most of the time and the equivalent power resources are consequently wasted. Thus, it is essential to design new planning policies and opportunistic use of resources should be considered. On a practical level, BS planning should consider the prevailing traffic load conditions and yield a network operating with the least number of BSs, thus squeezing the required power consumption down to a near-optimum level, without compromising QoS requirements.

In this work, we consider a service area which is planned to operate with a set of heterogeneous BSs, whose locations are fixed and determined a-priori. Under given user traffic requests, a subset of those BSs would probably suffice to cover the same service area with the same QoS requirements. Our approach basically divides the problem of energy efficient BS operation in two separate steps. The first subproblem is to find the subset with the minimum number of BSs from the original set of BSs that is adequate to satisfy a given set of user traffic requests. It is obvious that different traffic requests or user placements would possibly yield a different optimal subset of BSs. This problem is described and formulated as an optimization problem and two energy efficient optimization schemes, namely the HBALSO HTWEAK, are proposed to tackle it. In the second step, we determine the optimal, with respect to power consumption, subset of BSs which should be active in order to serve any random placement of a certain number of UEs dispersed anywhere in this area, without violating the QoS requirements for each user served, and within acceptable levels of outage probability.

We assume a wireless network of $J_M + J_m$ BSs, where J_M (J_m) are identical macrocellular (microcellular) BSs. The set of all BSs lies in a two-dimensional area and we consider a scenario, where possible BS locations, without loss of generality, are predefined at fixed grid network geographical positions. I User Equipments (UEs) are randomly and uniformly distributed inside this area, each one demanding a Guaranteed Bit Rate (GBR), which can be either static or following a random walking model for a period of time τ with random variable speed s_i and random direction vector v_i which switches speed and direction after a random time interval $t_{s,v}$. An appropriate WINNER propagation model is adopted incorporating Line-Of-Sight (LOS), as well as Non LOS (NLOS) conditions [119]. Inter-cell interference is also considered, as well as small scale fading and shadowing according to the selected BS for examination. We focus on the downlink of a multiple cell SISO OFDMA network, resembling LTE RAT. A system bandwidth (BW) comprising N_S frequency resource blocks according to the LTE terminology is assumed. Transmissions occur on a frame-by-frame basis, where each frame consists of several OFDMA symbols and lasts T_f ms. Time and frequency orthogonality are preserved by assigning each block/frame resource to one user at most, thus eliminating intra-cell interference, however a different number of blocks may be assigned to each user in the same frame in an OFDMA-like manner. Several downlink resources are devoted to signaling/reference transmissions, hence only a portion of the system power is dedicated for serving useful payload.

Each BS may occupy one out of two possible states, namely operational (ON) and non-operational (OFF). When a BS is set to the ON state, the equivalent maximum transmitted RF power per BS is limited and depends on the type of BS, either macro or micro. Every operational BS has an inherent energy cost which is fixed and equal to $f_M(f_m)$ if the BS is macro (micro). This cost is independent of the load and is shown in Table 4.1, accounting for the power consumption generated by the minimum power required by the PA and auxiliary subsystems. Furthermore, the utilization of subchannel k when UE i is served by BS j inflicts an additional variable cost c_{ijk}, due to the extra energy consumed by the equivalent PA.

Table 4.1: Typical power consumption distribution in macro and micro cell radio access equipment [103][120].

	Power consumption	
Equipment	Macrocellular	Microcellular
Power amplifier	50-80% (~1200 W)	75-90% (~145 W)
Air conditioning	10-25% (~300 W)	0% (0 W)
Signal processing (analog/digital)	5-15% (~200 W)	5-15% (~35 W)
Power supply	5-10% (~100 W)	5-10% (~15 W)

In the following, we proceed with the presentation of the system model and first subproblem formulation. We will refer to this subproblem as the Optimal Heterogeneous BS

Subset (OHBSS) problem. The solution of OHBSS depends on the current location of mobile requests and would also be applicable in a future scenario with coexisting signaling and data cells. However, in the examined current cellular network model these results are only helpful as input to the second subproblem.

4.4 Optimal Heterogeneous BS Subset problem (OHBSS)

Our goal is to optimize the operation of a heterogeneous wireless broadband telecommunication network with respect to energy consumption, while QoS requirements are preserved. Thus, in our approach, the problem at hand is to find the most appropriate subset of the existing BS, which is adequate to serve the requested telecommunication demands of the UEs without compromising QoS requirements. The variables necessary for our problem formulation are given in the following table:

Table 4.2: Problem variables.

$J = J_M + J_m$	Number of potential macro and micro BSs
I	Number of UEs
K	Maximum number of Subchannels per BS
a_i	GBR demand of UE (in Kbps)
b_j	Capacity of BS measured in number of Subchannels
$f_j = f_M(f_m)$	Fixed power cost of a switched 'ON' macro (micro) BS
c_{ijk}	Power cost of assigning channel k of BS j to UE i
BR_{ijk}	Achieved Bit Rate when assigning channel k of BS j to UE i

OHBSS can now be formulated as an optimization problem, as follows:

$$\min \left\{ \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} c_{ijk} \cdot x_{ijk} + \sum_{k=1}^{K} f_j \cdot y_j \right\} \tag{4.4.1}$$

Subject to:

$$\sum_{k=1}^{K} x_{ijk} \leq 1, i = 1, ..., I, j = 1, ..., J \tag{4.4.2}$$

$$\sum_{j=1}^{J} x_{ij} = 1, i = 1, ..., I \tag{4.4.3}$$

$$\sum_{j=1}^{J} \sum_{k=1}^{K} x_{ijk} \cdot BR_{ijk} \geq a_i, \ i = 1, ..., I \tag{4.4.4}$$

where the following binary decision variables are introduced:

$$x_{ijk} = \begin{cases} 1, \text{if channel } k \text{ of BS } j \text{ is assigned to user } i \\ 0, \text{otherwise} \end{cases} \quad (4.4.5)$$

which indicates whether channel k of BS j is assigned to UE i,

$$x_{ij} = \begin{cases} 1, \text{ if } \sum_{k=1}^{K} x_{ijk} > 0 \\ 0, \text{ otherwise} \end{cases} \quad (4.4.6)$$

which indicates whether BS j serves UE i,

$$y_j = \begin{cases} 1, \text{ if } \sum_{i=1}^{I} x_{ij} > 0 \\ 0, \text{ otherwise} \end{cases} \quad (4.4.7)$$

which indicates whether a BS is ON and serves some UEs or OFF and serves no UE.

The objective function presented in (4.4.1) aims at the optimization of the energy efficiency of the network, by minimizing the sum of the variable and fixed energy costs inflicted by the utilization of certain BSs and the corresponding subchannels. Constraints (4.4.2) impose that each channel of each BS is assigned to one UE at most, while constraints (4.4.3) in combination with (4.4.6) impose that each UE must be served by one and only one BS. Finally, constraints (4.4.4) represent the demand constraints and impose that each UE should get its minimum requested demand.

4.5 The Proposed Heuristic Schemes for OHBSS

To tackle the above optimization problem, we proposed the HBALSO and HTWEAK heuristics, whose detailed descriptions are given in the following.

4.5.1 Heterogeneous BAse station Location Status Optimizer (HBALSO)

HBALSO algorithm minimizes the overall network's energy consumption by toggling the power status of the BSs of the system from OFF to ON state. Figure 4.1 depicts the algorithm's flowchart.

i. First, a list of registered UEs and available BSs is created. A certain number of BSs may be switched ON at this stage, accounting for provider's network topological constraints. The remaining available BSs are considered as switched off.

ii. The list of UEs is ordered according to their GBR in descending fashion. In case ties exist, these are settled by prioritizing the UEs which detect the least number of BSs able to fully satisfy their GBRs.

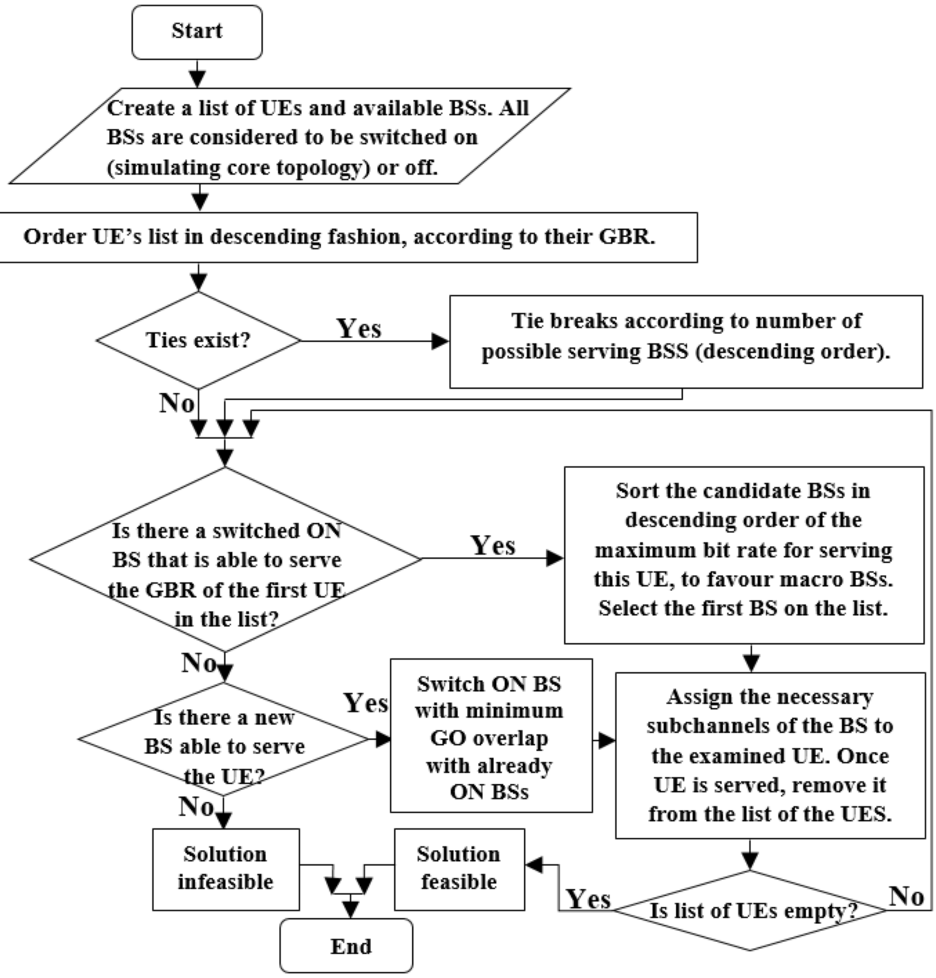


Figure 4.1: Flowchart of HBALSO.

iii. When processing the ordered list of UEs, we are seeking a BS capable of satisfying the GBR of the Head-of-List (HoL) UE (the UE at the first position of the formed list). The following cases may occur:

   a. If only one already switched ON BS can meet the requirements, this sole candidate is selected as the serving BS.
   b. If more than one already switched ON BSs can meet the UE demands, the one which may provide the maximum BR to the UE prevails. This choice assumes that this BS will be able to meet the requirements with the minimum amount of resources. As macro BSs are more probable to provide better BR, this step favours the selection of BSs of that type.
   c. If no already switched ON BS, able to serve the UE, is found, a search among switched OFF BSs takes place. If only one BSs can serve this UE, the execution proceeds by selecting this BS and toggling the BS status to "ON". If more than one candidates exist, priority is given to the one having the minimum GO with the already switched ON BSs. Considering that each BS has an area of coverage, depending mostly on their transmit power, GO metric is derived via geometric equations, calculating those BSs common area. Thus, it is ensured that the network

maximizes its area of coverage, while maintaining the QoS of existing users. Otherwise, if the search for a serving BS is futile, the solution of this problem snapshot is considered as infeasible and the algorithm exits.

iv. The least required subchannels for serving the examined UE are assigned, the equivalent actual BR and power consumption imposed to the system are recorded and the HoL UE is removed from the list.

v. The execution terminates either by successfully examining and assigning all UEs in the list to some BS, or by detecting infeasibility in the above step iii.c.

Summarizing, HBALSO performs GBR calculations among switched ON BSs and UEs and assigns UEs to the available BSs, in order to utilize the minimum amount of resources of these BSs (step iii.b). Thus, it first tries to fully utilize the already existing switched ON BSs before attempting to examine new candidates for toggling them to the ON state. As a consequence, fewer BSs are expected to become active to satisfy a given traffic load. When a new BS is necessary to satisfy the traffic demand, the search for minimum resource consumption as well as minimum GO, tends to favour the activation of remote high power macro BS, at least during the algorithm’s first execution steps. Thus, the low transmit power micro BSs are favoured at later stages of the algorithm to fill gaps left from the macro BSs, and as we will see later in the results section, their activation probabilities are kept relatively low.

4.5.2 Heterogeneous opTimal poWer consumption schEme for rAdio access networKs (HTWEAK)

HTWEAK searches between available operational (ON state) BSs and evaluates which can be set to the OFF state, according to their geographical overlap, in order to extract the optimal energy efficient BS subset able to fulfil UEs demands with QoS preservation. Figure 4.2 depicts the algorithm’s flowchart.

i. First, a list of registered UEs and available BSs is created. All BSs are considered to be switched ON for the time being.

ii. The achievable BR matrix for each BS and UE pair is calculated in a worst-case fashion. If a BS is able to fulfil the QoS requirements of a UE, this BS – UE pair is marked as being valid. At this stage, each UE may participate in more than one pairings, although during the actual radio resource assignment stage the single source constraint must be respected.

iii. For each valid pair, the number of needed subchannels is estimated. If number of subchannels exceeds a predefined threshold of 33% of the total subchannels of each BS, then the examined pair is invalidated. In that way, we avoid committing a large part of network’s portion to a single UE for proper management of the resources of the network.

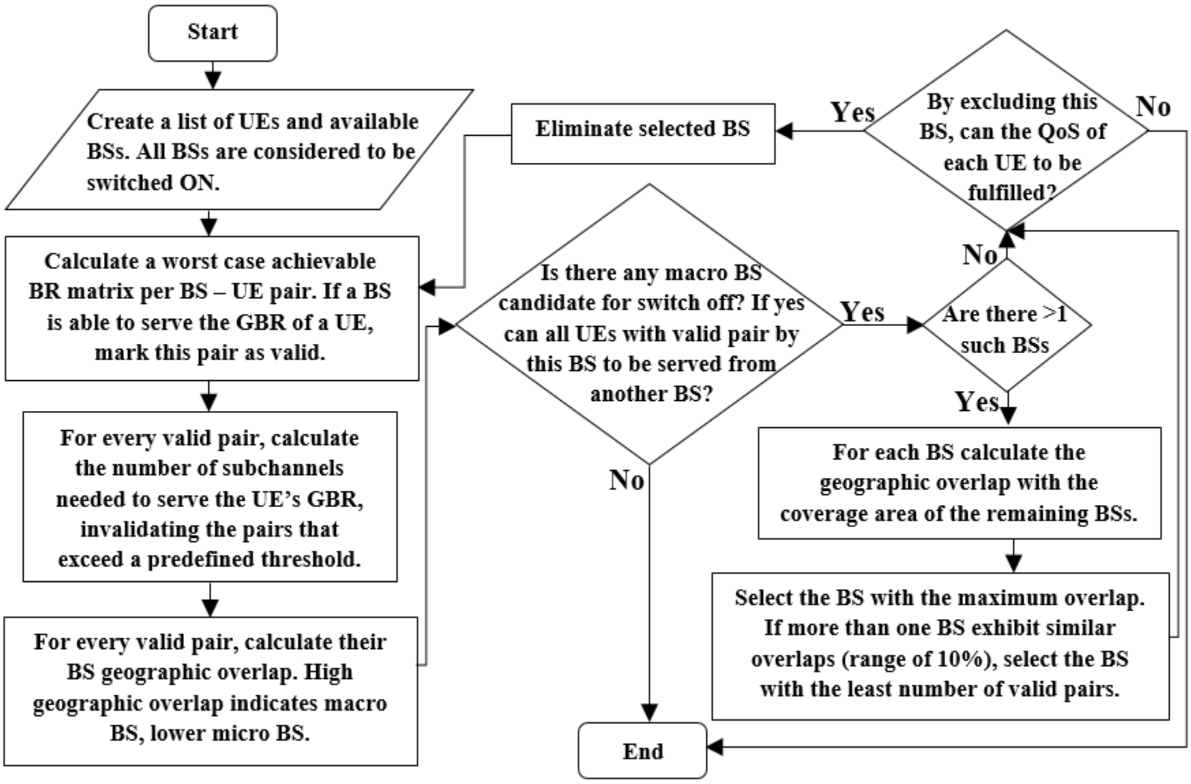


Figure 4.2: Flowchart of HTWEAK.

iv. It is examined, whether some BS exist whose valid pairs could all be invalidated, while at the same time every UE is still included in at least one of the remaining valid pairs. In that case, the corresponding BS can be set OFF and its UEs can still be successfully served by other BSs. The following scenarios may occur:

a. No such macro or micro BS exists. Therefore, all BSs are absolutely necessary for guaranteeing the smooth operation of the network.
b. Only one macro (micro) BS meets this criterion and is selected for further investigation at step v.
c. Several BSs are able to meet this criterion. In this case, each one of these macro (micro) BSs is examined iteratively in descending order of their geographical overlap with the cumulative coverage area of all other remaining BSs. Thus, the high transmit power macro BSs with large coverage overlap are examined first, while the lower transmit power micro BSs are examined with low priority. The BS which possesses the maximum overlap, is selected for further investigation at step v. In case two or more BSs exhibit similar overlaps (in the order of ±10%), the considered tie is broken by opting for the one having the least number of valid pairings with UEs (inferring that potential elimination of this BS will inflict negligible consequences to the network's functionality).

v. If a BS has prevailed in this stage, then the feasibility of the actual radio resources assignment is checked, under the constraint that each UE should acquire at minimum it's GBR. If the outcome of this validity check is positive, then the selected BS is eliminated from the network and the algorithm starts over from step ii, in the absence of this radio access point. On the contrary, if the result is negative, no further action is undertaken.

vi. The execution of the algorithm is terminated either by entering subcase a of step iv, or by reaching a negative outcome in step v.

Opposite to HBALSO, HTWEAK performs its calculations while initially having all the available BSs set to the ON operational state. Among the active BSs, it searches for BSs which can be powered OFF, while preserving the UEs QoS constraints, by examining first the high transmit power macro BSs which are responsible for large portion of the total network's power consumption. Thus, the low transmit power micro BSs are more probable to remain in the final set of active BSs, and as we will see in the results, their activation probabilities are kept relatively high.

4.5.3 The Proposed BS Activation Schemes

The aforementioned optimization schemes determine a minimum number of BSs to serve a random snapshot of I distributed UEs over the service area. However, our ultimate goal is to select the optimal subset of BSs that can serve any random snapshot of the same I number of UEs without violating system QoS constraints and within an acceptable outage probability threshold $p_{out}^{(FOT)}$ which is defined as the acceptable FOT outage probability level. Our approach is to iteratively formulate and solve a large number L of OHBSS instances, using HBALSO and/or HTWEAK. In each instance, we generate a random traffic load snapshot consisting of I randomly placed static or mobile UEs in the geographical area and determine the optimal BS subset that can serve all UEs with minimum power consumption and requested QoS. We collect the data of the optimal BSs subsets and with the help of our BS activation heuristics, namely the HEterogeneous Network Optimal BS Subset (HENOBSS) and Base Station Activation Scheme (BSAS), attempt to determine the most proper BSs subset which can serve any random set of I UEs, whilst preserving the planned outage probability level. In the following, we describe in detail the operational step of each of the proposed BS activation schemes.

4.5.3.1 HEterogeneous Network Optimal BS Subset (HENOBSS)

HENOBSS receives as inputs from the HTWEAK algorithm the BS activation percentages and the minimum number of BSs needed to serve a specific traffic load and returns the optimal BSs subset to serve any random placement of I UEs with certain GBR requirements. Its steps are described below:

i. We first calculate the activation probabilities of each BS for the specific traffic load of I UEs based on the solutions of the L OHBSS instances. Let also N_{min} be the minimum number of the necessary active BS, to serve a given traffic load of I UEs. N_{min} has been the solution outcome of some of the L OHBSS instances. The BSs are inserted into list L_p in descending order of their activation probabilities.

ii. The first BS in L_p which has the highest probability of appearance in the optimal BSs subsets of the L OHBSS instances is moved to the list L_a of active BSs.

iii. Starting from the top, list L_p is traversed downwards and the first BS with zero coverage overlap with all the BSs in the L_a list is moved to the L_a list. This step is repeated until there are no BSs in L_p with zero coverage overlap with all the BSs in the L_a list.

iv. Starting from the top, list L_p is traversed downwards and the first BS with least coverage overlap with all the BSs in the L_a list is also moved to the L_a list. Ties are resolved by selecting BSs with the higher activation probability. This step is repeated until all BSs have been moved from the L_p to the L_a list.

v. We activate the first N_{min} BSs of the L_a list, starting from the top BS and moving downwards.

vi. For the same traffic load of I UEs, we examine again a very large number of UE permutations, and use HTWEAK to check whether the current active set of BSs can serve each randomly and uniformly distributed placement of the I UEs. If not, we increase the number of the operational BSs by adding the next BS from list L_a and repeat step f. This procedure is repeated until the selected BS subset is able to fulfil the GBR requirements in all examined UEs random permutations.

4.5.3.2 Base Station Activation Scheme (BSAS)

Before the description of this scheme, it is necessary to introduce the notion of adjacent tiers of BSs. Consider a reference BS i and its adjacent BS j. The transmission power of BS i (j) is P_i (P_j) and the respective coverage area is A_i (A_j). The Common Coverage Area Percentage ($CCAP$) of the reference BS i and its adjacent BS j is defined as the intersection of the overlapped A_i and A_j areas divided by the total coverage area of the reference BS i:

$$CCAP(i,j) = \frac{A_i \cap A_j}{A_i}(\%) \tag{4.5.3.2.1}$$

It is obvious that $CCAP(i,j) = CCAP(j,j)$, when $P_i = P_j$, that is BSs i and j are similarly configured with equal transmission powers. The closer the BSs are, the more their coverage areas overlap, therefore higher $CCAP$ indicates closer BSs for similarly and equal power configured BSs. However, when BS i is a macrocell and BS j is a microcell, that is $P_i > P_j$, then $CCAP(i,j) < CCAP(j,i)$, as $A_i > A_j$ .Thus, $CCAP$ is also depending on the coverage of the reference cell, which means that a reference cell with smaller coverage yields a higher $CCAP$ value for the same overlap area. In other words, in the case of a macrocell and microcell adjacency, the macrocell $CCAP$ value will be lower than the microcell $CCAP$ value.

Now, for a deployment area with a set of BSs $J = \{1, \dots, J\}$, we can define a tier of BSs adjacent to a reference BS j, as the set of BSs $K = \{k \mid k \in J, k \neq j\}$ such that $CCAP(j, k_1) = CCAP(j, k_2)$ for every $k_1, k_2 \in K$. By sorting tiers of BSs for a reference BS j, in descending order of their $CCAP$ values, tiers for BS j can be ordered as first adjacent tier BSs, second adjacent tier BSs and so on.

BSAS algorithm receives as input the list of available sets of BSs, their activation probabilities and $CCAP$ and as output delivers a reordered version of the input list, which proposes an optimal activation order of the BSs with respect to power consumption. A high level flowchart of OHBSS including BSAS is depicted in Figure 4.3. The detailed description of the BSAS algorithm is given in the following.

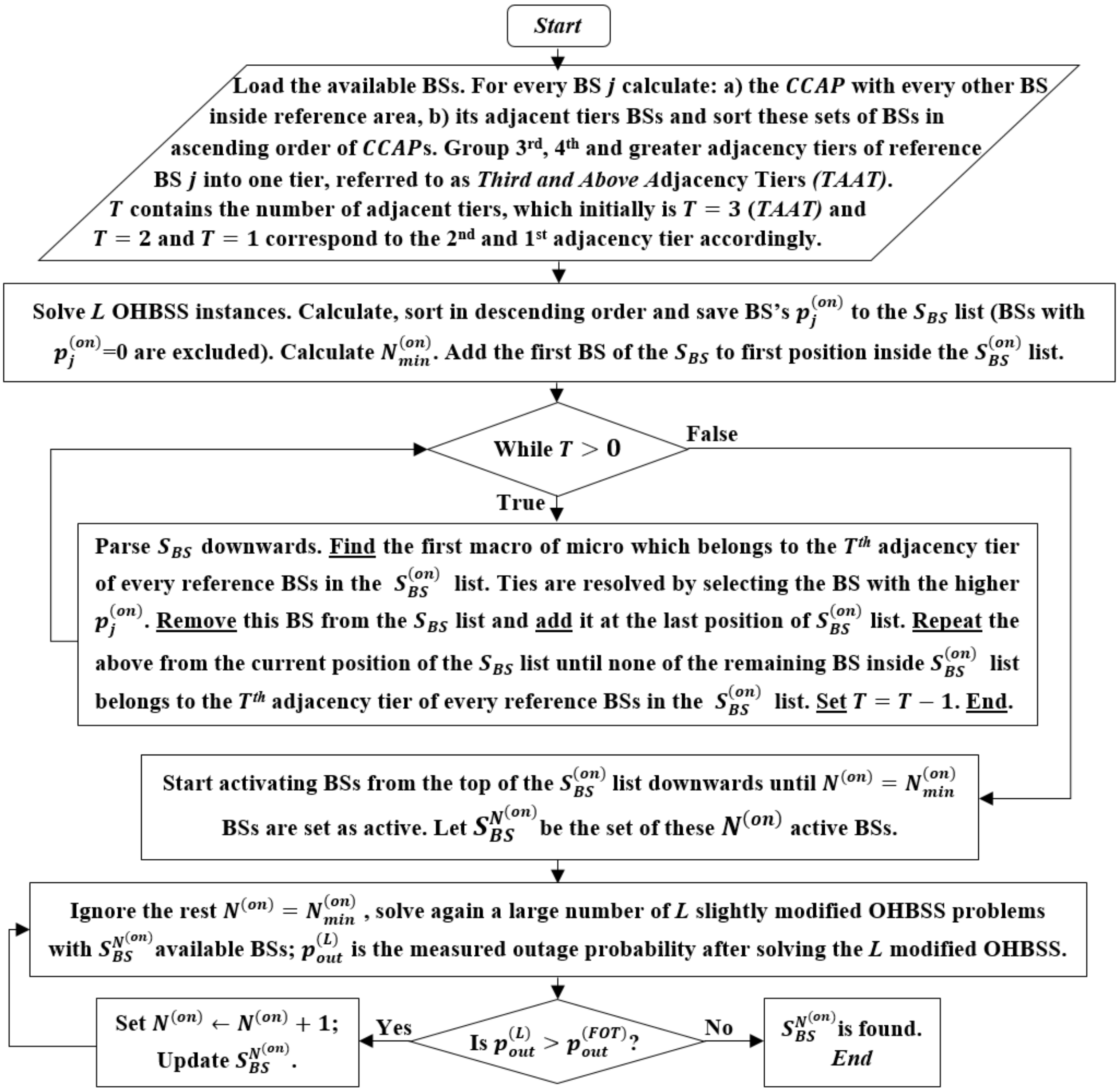


Figure 4.3: High level flowchart of OHBSS and BSAS.

Step 0: For every BS j in the list of available BSs:

(a) Consider this as the reference BS and calculate the $CCAP$ with every other BS in the geographical area,
(b) Calculate its adjacent tiers BSs and sort these sets of BSs in ascending order of $CCAP$s.
(c) Group third, fourth and greater adjacency tiers of reference BS j into one tier, referred to as *third and above* adjacency tiers.

Step 1: For a certain traffic load level, in other words for a certain number I of UEs each one requesting the same minimum GBR, we generate a high number of L random placement snapshots of I UEs. For each random snapshot, we formulate and solve the corresponding OHBSS. Let $p_j^{(on)}$ be the probability that BS *j* is active, after solving the L OHBSS instances and $N_{min}^{(on)}$ be the minimum number of necessary active BS that has occurred for some OHBSS instance.

Step 2: Let S_{BS} be the list of BSs sorted in descending order of their activation probability $p_j^{(on)}$ and $S_{BS}^{(on)}$ be the list of BSs which are candidates for activation. BSs with $p_j^{(on)} = 0$ are excluded from S_{BS}, while $S_{BS}^{(on)}$ is initially empty. The BS activation scheme begins by removing the first BS from the S_{BS} list and adding it to the $S_{BS}^{(on)}$ list as the first candidate for activation.

Step 3:

(a) Allow only BSs which are located far away from the BSs already in the $S_{BS}^{(on)}$ list, to enter this list.

- Starting from the top of the S_{BS} list downwards, find the first macro or micro BSs which belongs to the third and above adjacency tier of every reference BS in the $S_{BS}^{(on)}$ list.
- Remove this BS from the S_{BS} list and add it at the last position of $S_{BS}^{(on)}$ list. Go to the first bullet of step 3(a) and continue the search downwards from the current position of the S_{BS} list.
- If no such BS exists, continue to step 3(b).

(b) Next, allow also BSs which are located at the second adjacency tier of the BSs already in the $S_{BS}^{(on)}$ list, to enter this list.

- Starting from the top of the S_{BS} list downwards, find the first macro or micro BSs which belongs to the second adjacency tier of every reference BS in the $S_{BS}^{(on)}$ list. (Ignore BSs belonging to the second tier of a reference BS in the $S_{BS}^{(on)}$ list, if that reference BS has another BS from its second adjacency tier already in the $S_{BS}^{(on)}$ list.)
- Remove this BS from the S_{BS} list and add it at the last position of $S_{BS}^{(on)}$ list. Go to the first bullet of step 3(b) and continue the search downwards from the current position of the S_{BS} list.
- If no such BS exists, continue to step 3(c).

(c) Finally, allow BSs which are located also at the first adjacency tiers of the BSs already in the $S_{BS}^{(on)}$ list, to enter this list.

- Starting from the top of the S_{BS} list downwards, add the remaining BSs of S_{BS} list to the last positions of $S_{BS}^{(on)}$ list in decreasing order of their activation probability $p_j^{(on)}$.

Step 4: We start activating BSs from the top of the $S_{BS}^{(on)}$ list downwards until $N^{(on)} = N_{min}^{(on)}$ BSs are set as active. Let $S_{BS}^{N^{(on)}}$, be the set of these $N^{(on)}$ active BSs.

Step 5: We ignore the rest $J - N^{(on)}$ BSs and formulate and solve again a large number L of slightly modified OHBSS problems: in each modified OHBSS instance (a) the set of available BSs is $S_{BS}^{N^{(on)}}$, and (b) we do allow that some UEs may not receive service, and measure the corresponding outage probability. We denote by $p_{out}^{(L)}$ the measured outage probability after solving the L modified OHBSS.

If $p_{out}^{(L)} > p_{out}^{(FOT)}$ **then** we set $N^{(on)} \leftarrow N^{(on)} + 1$, we update $S_{BS}^{N^{(on)}}$, by adding the next BS from list $S_{BS}^{(on)}$ and go to start of **Step 5,**

Else the set of active BSs to serve the requested load of I UEs is $S_{BS}^{N^{(on)}}$,. Exit.

In ultra-dense heterogeneous mobile networking environments, a large number of adjacent cells' tiers can exist, especially if we consider multiple tiers of different power transmission capable BSs overlaying in areas of increased traffic (hotspots). Therefore, the notion of adjacent tiers of BSs, which are considered within the implementation steps of the BSAS heuristic, provides us the tool for categorizing the overlapping percentages among the available AP and leverages the selection of the most area efficient AP to serve a corresponding traffic load, based on the given AP utilization inputs from the HBALSO and HTWEAK algorithms.

4.6 Performance evaluation

4.6.1 Simulation setup

The performance of the proposed heuristics was evaluated using a system-level simulation tool developed in MATLAB. All the fundamental elements of a complete cellular network were simulated, each one to an adequate extent for acquiring precise results of our study. All the attributes of the network are adjustable, while the sessions are created at the beginning of each simulation run. Different traffic load conditions are examined, by differentiating the number of UEs in each run. Specifically, we evaluated two different random and uniform UEs placements, (a) the static and (b) the mobile where UEs are moving by following a random walking model. The simulation parameters in each scenario applied, are shown in Table 4.3.

Table 4.3: Simulation parameters.

	Mobile UEs placement	Static UEs placement
Parameter	Value	
Number of BSs, J_M, J_m	9 macro, 16 micro	
Number of UEs, I	5, 15 and 30 UEs	5, 15, 30 and 50 UEs
Available Bandwidth, BW	5 MHz	
Number of subchannels, k	25 subchannels	
GBR of UE i, a_i	500 Kbps	500, 750 and 1000 Kbps
Speed of UE i, s_i	0-5 m/s (mean of 2.5 m/s)	Static
Direction vector v_i	Random	
Duration, $t_{s,v}$	2-6 minutes (mean of 4 minutes)	
Duration of mobility period, τ	20 minutes	
Power costs, f_M, f_m, c_{ijk}	According to values in Table 4.1	
Propagation model [119]	B2 and C3 (bad urban)	
OHBSS algorithm	HTWEAK	HBALSO & HTWEAK
BS activation algorithm	HENOBSS	BSAS
Radio Access Technology	LTE	

A typical 1x1 Km^2 region of an urban broadband wireless network was evaluated. Within the area of interest, J_M macro BSs and J_m micro BSs and I users were dispersed. A representative grid of this scenario is depicted in Figure 4.4, where $J_M = 9$ macro and $J_m = 16$ micro BS possible locations together with $I = 30$ UEs are dispersed inside the service area.

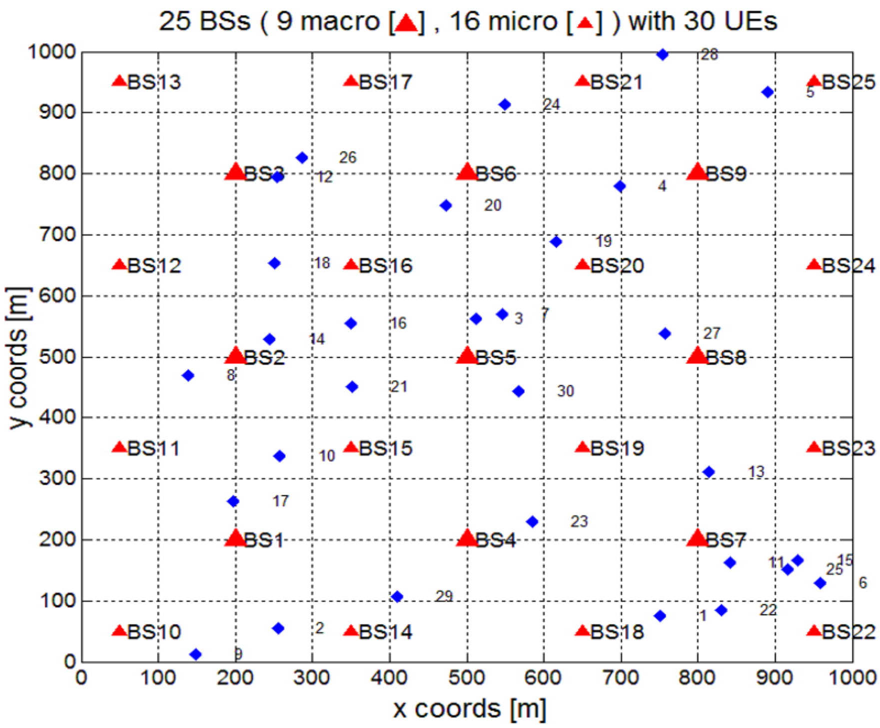


Figure 4.4: A typical grid network topology of broadband wireless network, with 9 (16) macro (micro) BSs (red triangles) dispersed together with 30 UEs (blue diamonds) inside the area of interest.

The fixed power costs f_M and f_m of macro and micro BSs and the variable power costs c_{ijk} are defined according to the values in Table 4.1. The achievable bitrates per subchannel are calculated through the well-known Shannon's formula and are upper bounded by the rate achieved by 64 QAM which is the highest order of the AMC scheme employed.

4.6.2 Results for mobile random and uniform UEs placements

4.6.2.1 Optimal subsets of active BSs extracted by cooperation of HTWEAK and HENOBSS algorithms

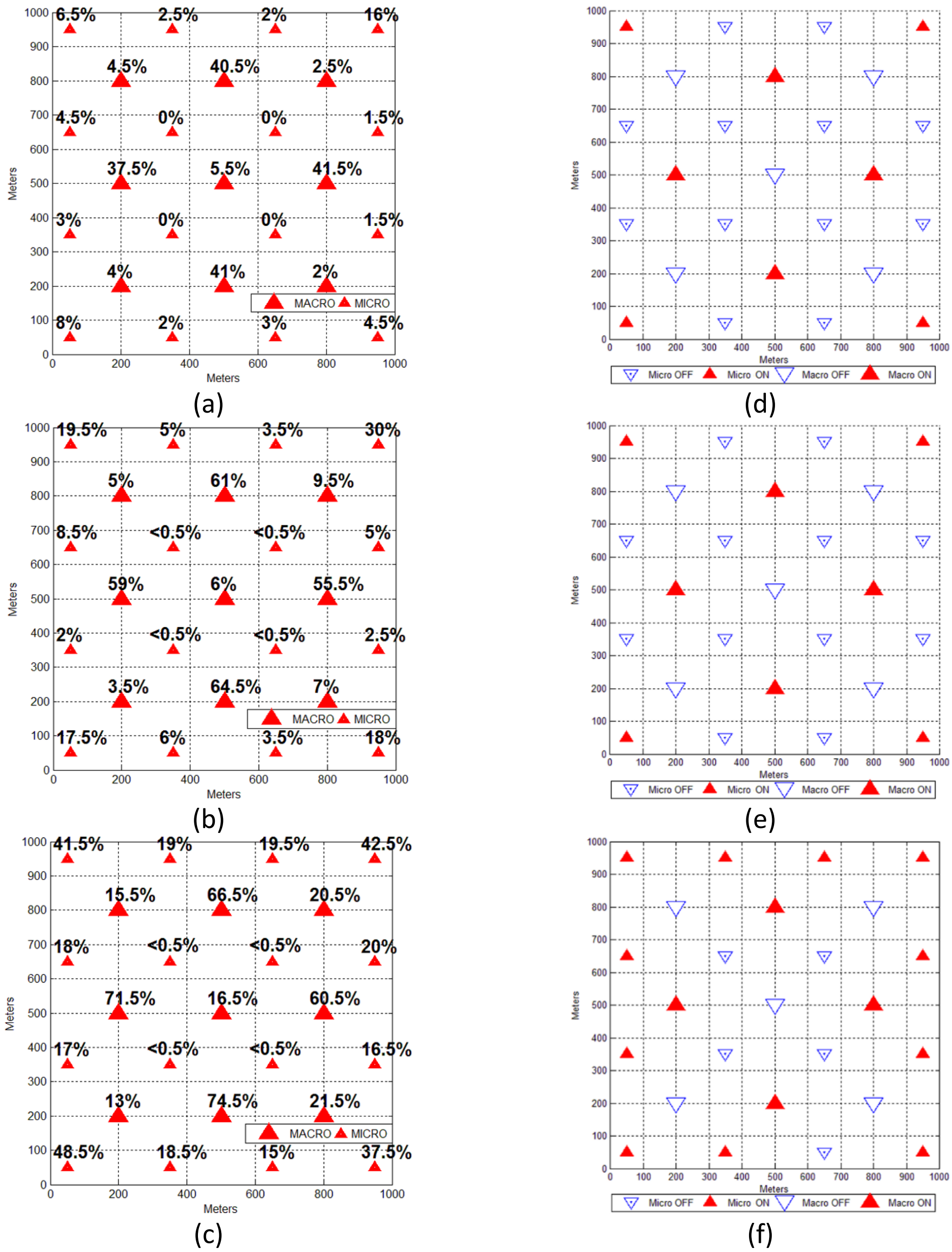


Figure 4.5: BSs activation percentages for traffic load of 5 UEs (a), 15 UEs (b) and 30 UEs (c) and the corresponding BSs activation profiles, shown in (d), (e) and (f) respectively.

We first formulate $L = 1000$ OHBSS problem instances by generating an equal number of UE random placements in the geographical area, and use HTWEAK to compute the optimal subset of BSs that can serve each UE random placement. We then extract the BS activation probabilities and by using the HENOBSS heuristic we come up with the optimal BS subset that can handle any random placement of the same number of I UEs. The BSs activation probabilities are shown at the left part of Figure 4.5 for the traffic loads of 5, 15 and 30 UEs (Figure 4.5(a,b,c)), while the HENOBSS heuristic yielded the corresponding BSs activation profiles, shown on the right part of the same figure. As we can see, HTWEAK together with HENOBSS achieve a rather symmetric utilization of the available access points and distributes network's traffic almost evenly to the available BSs. An additional observation is that for 5 and 15 UEs, the previous algorithms produce the same BS operational profiles (Figure 4.5(d,e)).

4.6.2.2 Energy Consumption Reduction and Impact on Key Performance Indicators

The average energy consumption of the network using the aforementioned operational profiles is depicted in Figure 4.6. The results are normalized against the consumption of a FOT, where all 25 BSs are set to operational state. The proposed BSs activation profiles, which were gathered from 1000 UE permutations, can guarantee the requested GBR for the corresponding traffic load. In addition to that, the total power consumption is kept much lower compared to FOT networks, as shown in Figure 4.6. An up to 72.69% energy consumption reduction is gained, when the traffic load of 5 UEs is present to our network using the operational profile of Figure 4.5(d). Obviously, the more UEs are present, the higher the power consumption, due to (a) the higher number of active BSs and consequently the additional fixed power costs (f_M and f_m), and (b) the higher transmission power cost c_{ijk}. Since the proposed BS activations profiles for 5 and 15 UEs, depicted in Figure 4.5(d,e) are the same, the number and the position of the available access points are the same. Thus, the higher normalized energy consumption in Figure 4.6 is due to the transmission power cost of the additional 10 UEs which utilize more available transmitting resources (i.e. usage of the non-utilized subchannels) to serve this additional traffic load.

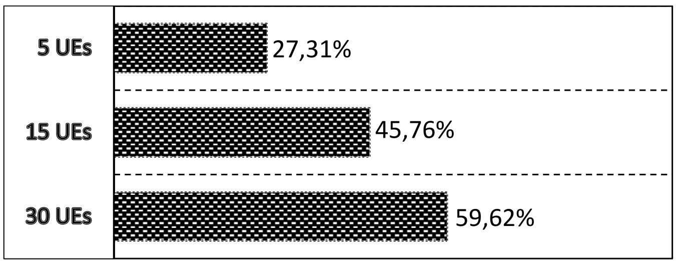


Figure 4.6: Normalized energy consumption against FOT for traffic load of 5, 15 and 30 UES, each one requesting 500 Kbps GBR.

In Figure 4.7, the average handoff rate per UE, normalized against FOT, is shown for a GBR of 500 Kbps per UE. The data were collected with the following procedure: Starting from a random placement of the UEs we employed the random walking model to get the new position of the UEs every minute. We then formulated the corresponding OHBSS problem, assuming that the only available BSs were those belonging to the subset of the BSs operational profiles of Figure 4.5 and used HTWEAK to assign the UEs to the BSs in the most energy efficient way, thus minimizing the transmissions power cost. This procedure lasted for a mobility period $\tau = 20$ minutes and the results shown are the average values of 100 repetitions of this procedure. As it is shown, the introduction of the reduced BSs operational profiles reduces the average handoff rate, comparing to FOT handoff rates, at about 19.1% and 41.7% at a traffic load of 5 and 30 UEs respectively. However, the handoff rate is increased at about 55.8%, at a traffic load of 15 UEs. Since 5 and 15 UEs use the same BSs operational profiles, the significant increase of the handoff rate is due to the HTWEAK assignment procedure that attempts to assign the UEs to BSs in a most energy efficient way, thus leading to frequent changes of the AP to reduce energy consumption. On the other hand, when 30 UEs are present, a higher number of BSs are available in the operational profile of Figure 4.5(f), which reduces the number of handoffs. The conclusion is that during different times of the day, when energy efficient BSs operational profiles are used, the network faces different signaling overhead and the UEs different service perception.

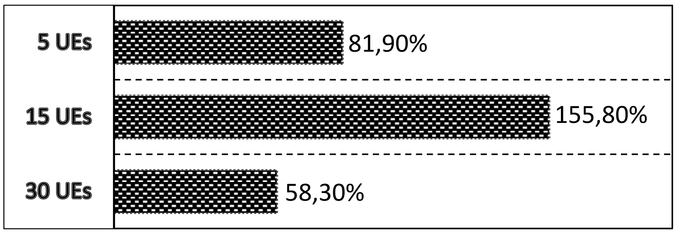


Figure 4.7: Average UE handoff rate normalized against FOT handoffs rates.

Similar information is deduced from Figure 4.8, where the average cell residence time per UE is shown. Cell residence time is inversely proportional to the UE handoff rate. An up to ~24% and ~50% increase on the average cell residence time is noticed for traffic load of 5 and 30 UEs respectively and a ~36% decrease for traffic load of 15 UEs, when BS operational profiles of Figure 4.5 are implemented. As we can see, when FOT is used, cell residence time is rather immune to the traffic load, which means that the UEs perceive similar QoS during the day, but this comes at a significantly higher power consumption cost. On the other hand, the cell residence time in energy optimized networks with fewer operational BSs depends on the offered traffic load and the available subset of BSs.

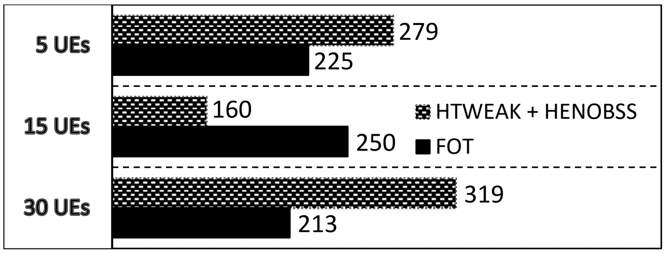


Figure 4.8: Average UE cell residence time (in seconds).

The average achievable bitrate per UE is shown in Table 4.4. As we can see, the introduction of the reduced BSs operational profiles marginally reduces the UE average achievable bitrate and its deviation comparing to FOT networks.

Table 4.4: Average achievable bitrate and deviation per UE, for GBR of 500 Kbps.

	5 UEs		15 UEs		30 UEs	
	HTWEAK	FOT	HTWEAK	FOT	HTWEAK	FOT
Average Bitrate	727.22	747.21	747.55	759.03	750.9	777.32
Standard deviation	270.45	274.09	261.51	272.45	257.47	269.23
Minimum Bitrate	500.15	500.01	500.01	500.08	500.01	500.15
Maximum Bitrate	2042.5	1879.7	2067.6	1989.3	1942.2	2012.4

Finally, the overall gains in throughput versus the total consumed energy, are depicted via the well-known bit per joule energy metric in Figure 4.9. The results are normalized against FOT and an up to 310% increase is observed at low traffic load conditions with 5 UEs. As the traffic load increases, this gain is reduced, since more BSs are necessary to serve such a load.

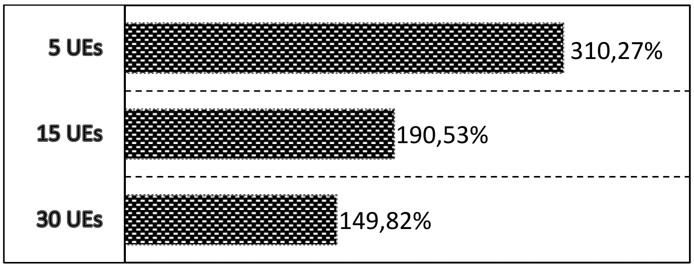


Figure 4.9: Normalized bit per joule efficiency increase by our BS activation profiles and HTWEAK heuristic against FOT networks.

4.6.3 Results for static random and uniform UEs placements

4.6.3.1 CCAP and adjacency tiers

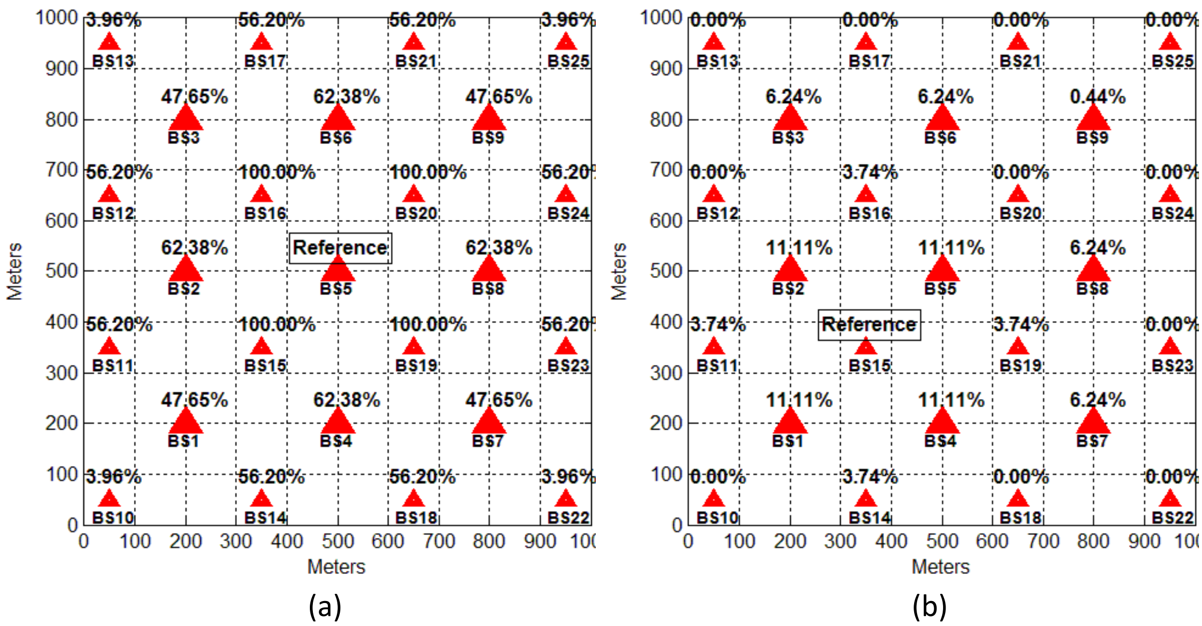


Figure 4.10: Heterogeneous two-tier BS network, where the CCAP of a macro and micro BS, as reference BS, with their adjacent BSs are shown in (a) and (b) respectively. Bigger (smaller) red triangles indicates macro (micro) BSs.

In Figure 4.10, the CCAP percentages are shown, on the two-tier BS type network we used in our simulation environment. Using as reference a macro BS and a micro BS we can defined their adjacency tiers according to their CCAP values. More specifically, with macro BS5 as reference BS (Figure 4.10 (a)), the following BS subsets of BSs adjacency tiers are defined:

1st adjacency tier of BS5 = $\{BS15, BS16, BS19, BS20\}$,
2nd adjacency tier of BS5 = $\{BS2, BS4, BS6, BS8\}$,
3rd adjacency tier of BS5 = $\{BS11, BS12, BS14, BS17, BS18, BS21, BS23, BS24\}$,
4th adjacency tier of BS5 = $\{BS1, BS3, BS7, BS9\}$ and
5th adjacency tier of BS5 = $\{BS10, BS13, BS22, BS25\}$.

Using micro BS15 as reference BS (Figure 4.10(b)), the following BS subsets of BSs adjacency tiers are defined:

1st adjacency tier of BS15 = $\{BS1, BS2, BS4, BS5\}$,
2nd adjacency tier of BS15 = $\{BS3, BS6, BS7, BS8\}$,
3rd adjacency tier of BS15 = $\{BS11, BS14, BS16, BS19\}$ and
4th adjacency tier of BS15 = $\{BS9\}$.

4.6.3.2 Performance evaluation results

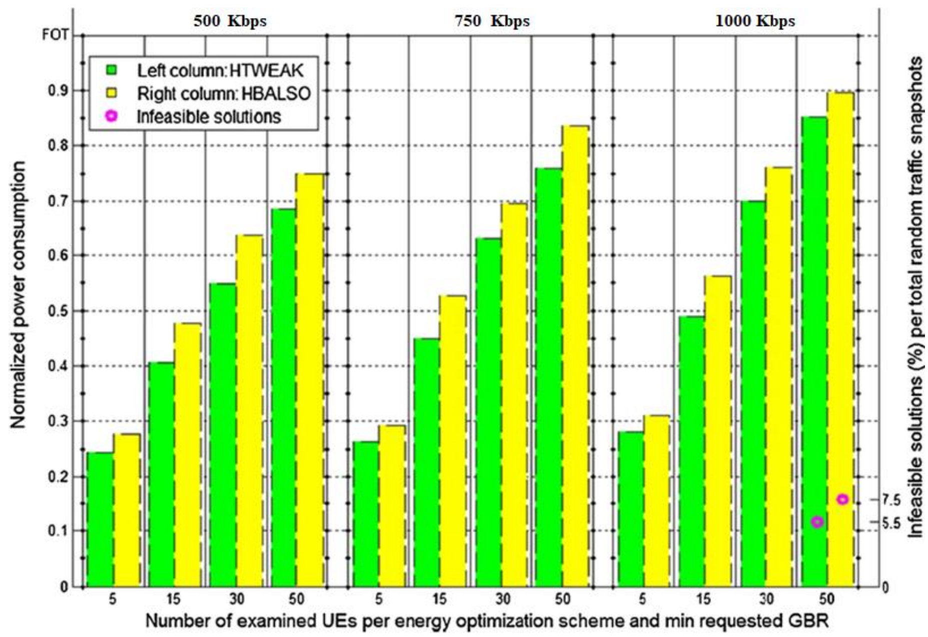


Figure 4.11: Normalized energy consumption and infeasible solutions of HBALSO & HTWEAK algorithms compared to FOT networks.

The average energy consumption of both HBALSO and HTWEAK energy optimization schemes, for varying GBR and number of UEs, is shown in Figure 4.11. The results are normalized against FOT, where all 25 BSs are switched ON. As we can observe at the right hand y-axis of Figure 4.11, only at very high traffic loads, with 50 UEs each one requesting 1 Mbps, the algorithms could not provide a feasible solution at 5.5% and 7.5% of the random traffic snapshots. Comparing to the similar findings in homogeneous environments, see above, it is obvious that the heterogeneity improved overall network service capabilities; the outage probabilities are reduced up to ~840% (~650%) when using HBALSO (HTWEAK), for the same traffic load of 50 UEs in the same reference area which is now covered by macro and micro BSs. Moreover, both algorithms achieve quite satisfactory energy consumption reduction especially at low traffic scenarios, i.e. for 5 UEs the gains are up to 75%, with the HTWEAK being overall better in all executed simulation scenarios. In Figure 4.12, the normalized bit per joule metric is shown where continuous gains against FOT networks are also observed. Gains on low traffic load scenarios are up to 310% and are fading on high traffic demands but are still present for both algorithms. Once again, HTWEAK shows its superiority especially at low traffic loads and tackles this energy optimization problem in a more efficient way.

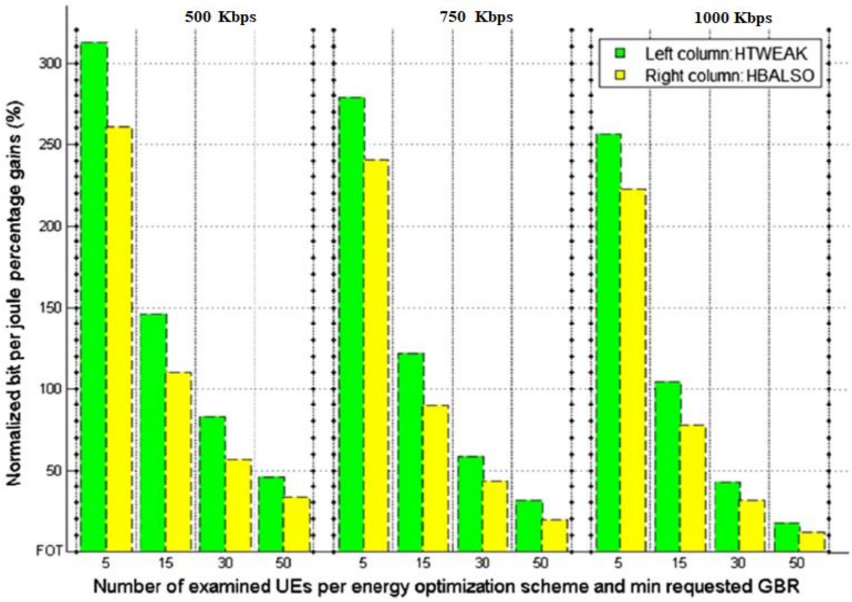


Figure 4.12: Normalized energy efficiency of HBALSO & HTWEAK against FOT networks.

The superior performance of HTWEAK can be justified by observing Table 4.5 and Figure 4.13. In Table 4.5 we depict the average achievable bitrates for each combination of UEs, GBR and scheme used and the corresponding $N_{min}^{(on)}$ values per scenario. As we can see from Table 4.5, HTWEAK allocates total bitrates closer to the requested GBR. For example, with 5 UEs and GBR 500 Kbps, the total requested BR is 2.5 Mbps. As we can see, HBALSO allocates on the average 4.33 Mbps to the examined random snapshots, while HTWEAK manages to allocate only 3.79 Mbps while both schemes utilized the same number of $N_{min}^{(on)} = 1$. In Figure 4.13 we show the average BSs activation probabilities for HBALSO and HTWEAK. In this figure, there are 9 big (16 small) triangles corresponding to the macro (micro) BSs of the network grid.

Table 4.5: Average network data traffic rate, in Mbps, and $N_{min}^{(on)}$ per minimum requested GBR and number of UEs.

# UEs / GBR	5		15		30		50	
	HBALSO	HTWEAK	HBALSO	HTWEAK	HBALSO	HTWEAK	HBALSO	HTWEAK
500	4.33 | 1	3.79 | 1	12.3 | 2	11.5 | 3	24.3 | 4	23.3 | 3	40.7 | 5	39.9 | 6
750	5.33 | 1	5.05 | 1	15.6 | 3	15.3 | 3	30.9 | 4	30.5 | 5	51.7 | 6	51.4 | 6
1000	6.62 | 2	6.37 | 2	19.3 | 3	19.4 | 4	38.6 | 5	38.6 | 5	64.5 | 7	64.6 | 9

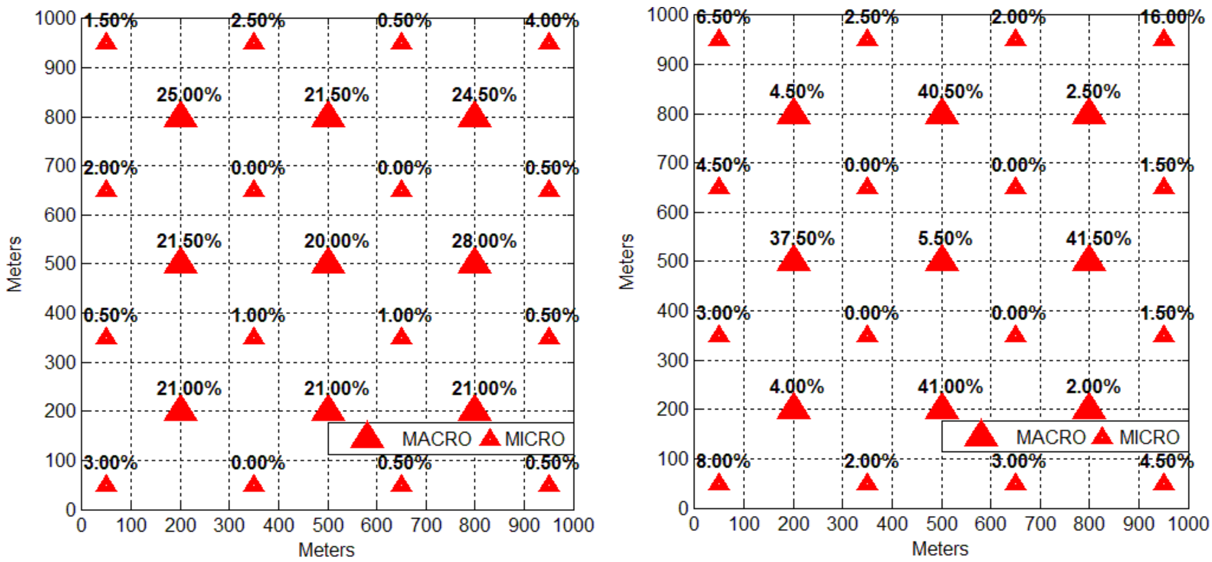


Figure 4.13: BSs activation probabilities for 5 UEs and min requested GBR of 500 Kbps: (a) HBALSO (left) and HTWEAK (right).

As we previously mentioned, the concept of each algorithm is basically different and complementary. It is evident from Figure 4.13(a) that HBALSO achieves homogeneous network operation utilization among the high geographical coverage BSs, distributing network's traffic almost evenly on them, while turning lower transmitting power BSs on in a more conservative manner. As a consequence, it achieves higher average throughput per UE, as can be deduced from Table 4.5, but is more power hungry than the other proposed algorithm. The opposite behaviour is experienced with HTWEAK which favours low power micro BS more, as depicted in Figure 4.13(b), and manages to allocate BRs closer to the requested ones, with clearly more energy efficient consumption results.

4.6.3.3 Optimal BSs sets extracted using BSAS with HBALSO and HTWEAK algorithms.

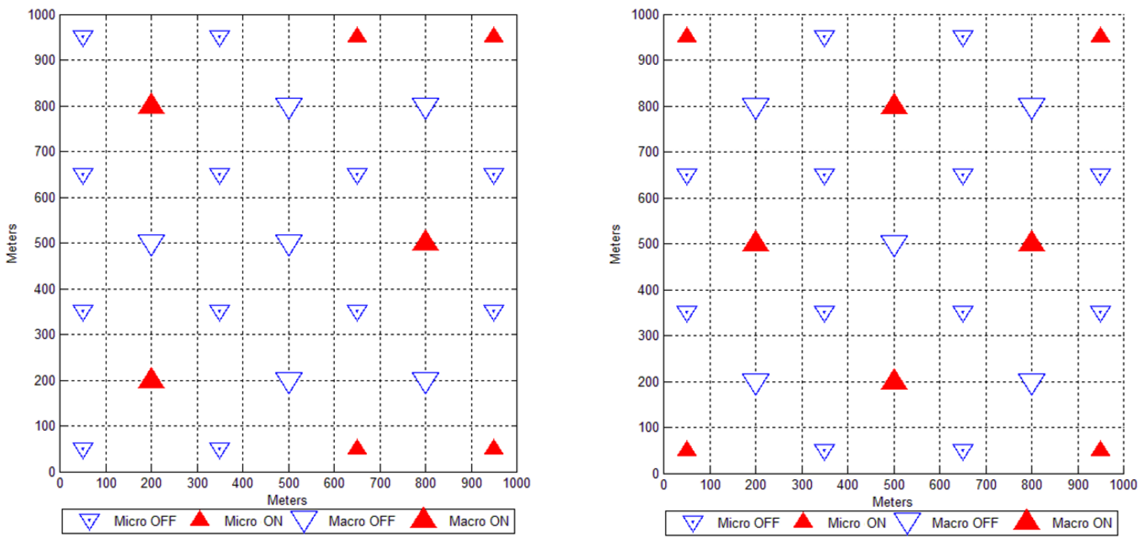


Figure 4.14: BS activation schemes generated by BSAS, for 500 Kbps min GBR and 5 UEs, after application of HBALSO (left) and HTWEAK (right) based BS activation scheme.

The generated activation profiles from our BSAS algorithm for the corresponding minimum GBR of 500 Kbps and traffic load of 5 UEs are shown in Figure 4.14. Furthermore, we generated the BS activation profiles for various traffic loads of the same minimum requested GBR by varying the number of UEs. The generated BS activation profiles for minimum GBR 500 Kbps are shown in Figure 4.15. For the traffic load of 15 UEs, the generated BS activation profiles are similar. Four (four) out of nine (sixteen) macro (micro) BSs were activated, offering uniform network coverage. For 30 UEs, both algorithms tend to favour high transmit power BSs and utilize again the same number of BSs: seven (four) out of nine (sixteen) macro (micro) BSs are set to active. Finally, for 50 UEs, both optimization schemes are utilizing all the available BSs since the traffic load exhausts network's resources.

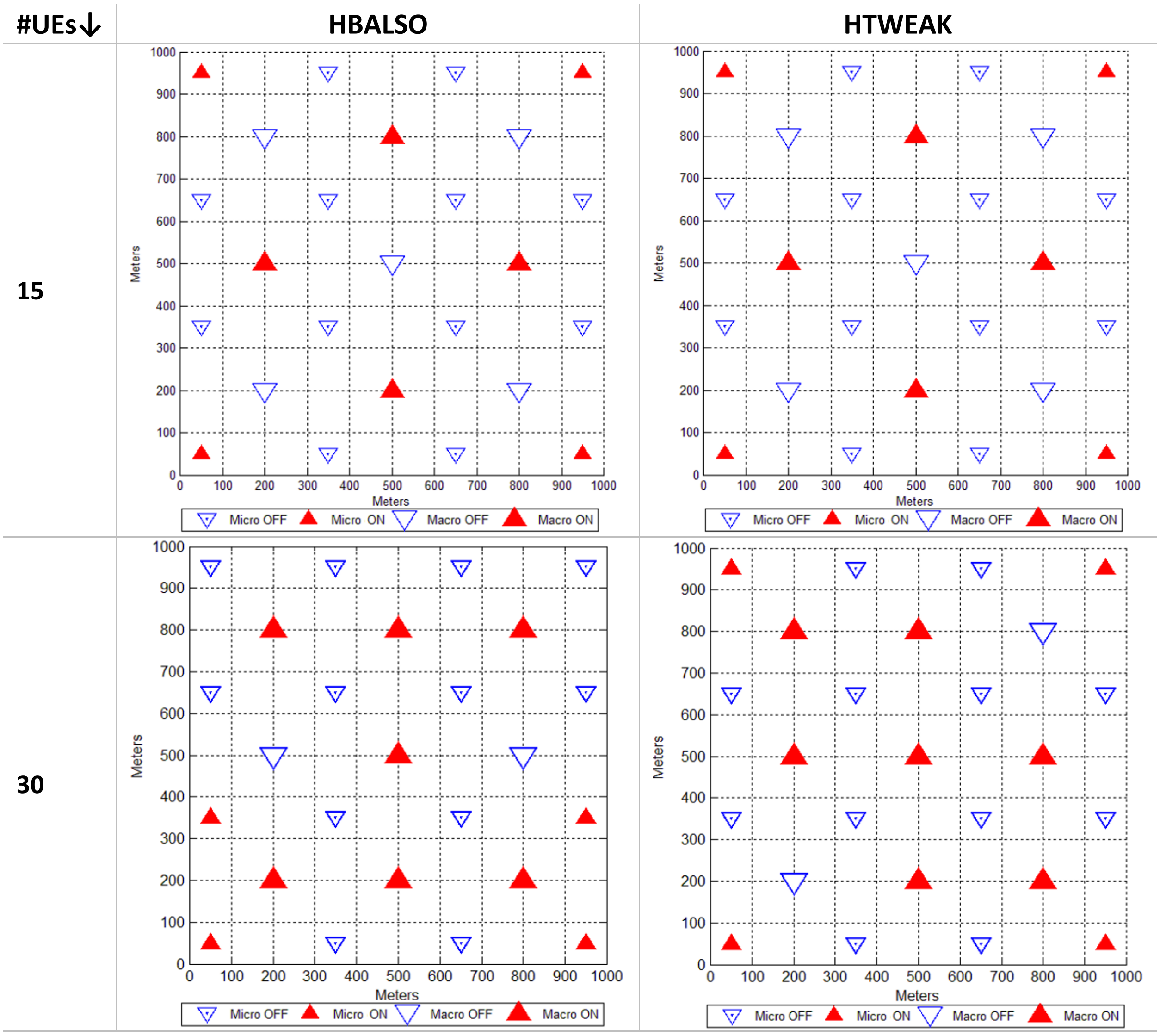
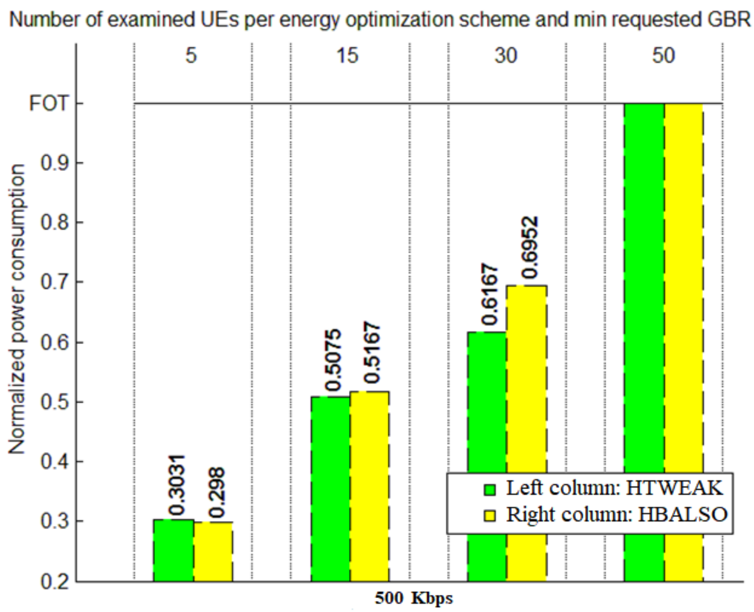
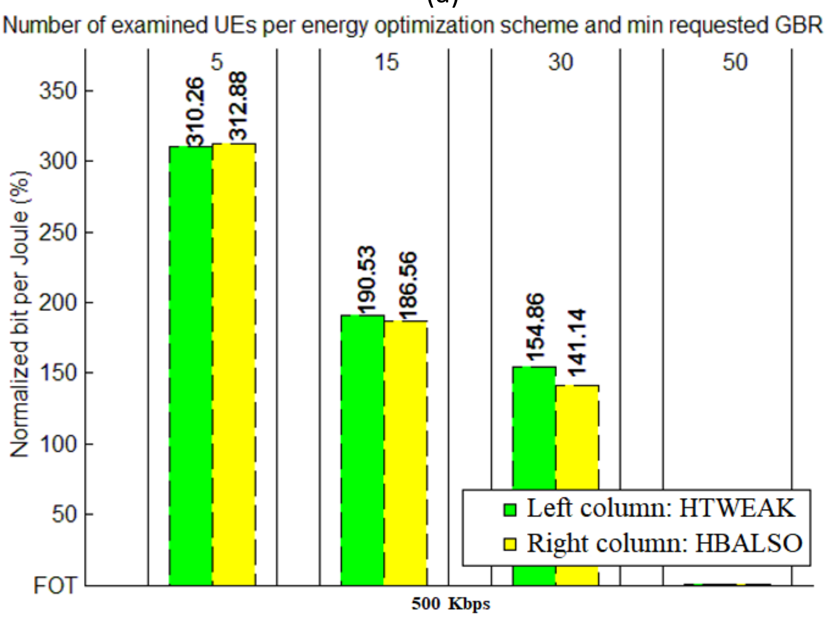


Figure 4.15. BSAS generated BS activation profiles for minimum GBR of 500 Kbps.

We used the proposed BS activation profiles of Figure 4.14 and Figure 4.15 to evaluate the power consumption and energy efficiency performance for both optimization schemes and the respective results are illustrated in Figure 4.16. As shown in Figure 4.16, our proposed BS activation scheme yields up to 70.2% power savings and 312.88% bit per joule improvement for 5 UEs without violating user's QoS, by utilizing three (four) out of the nine (sixteen) available macro (micro) BSs. Furthermore, both energy optimization schemes perform quite similarly at traffic loads with 5 and 15 UEs. However, in the case of 30 UEs, HTWEAK's approach enables BSAS to extract a more efficient BS activation profile, which yields about 8% less power consumption and about 14% more bit per Joule efficiency.



(a)



(b)

Figure 4.16: Normalized power consumption (a) and bit per joule (b) against FOT, with the usage of the BSAS generated BS activation profiles.

4.6.3.4 Daily traffic profiles

In Figure 4.17, a real daily traffic profile is shown as a fraction of the maximum number of active users per unit of time [7]. The day is divided into four time periods; one with low traffic demand, one with medium traffic demand, one with high traffic demand and one with highest traffic demand.

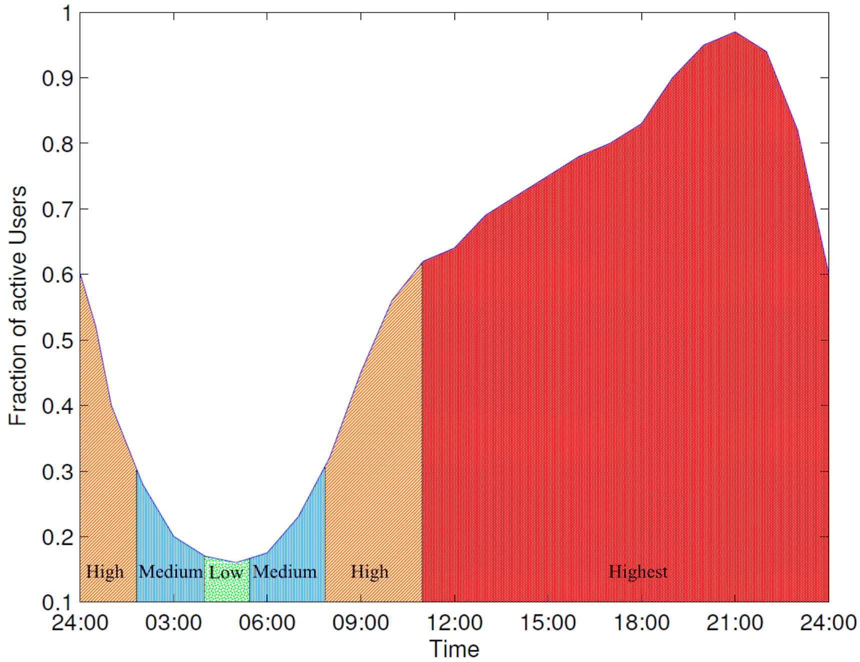


Figure 4.17: Fraction of active users per time according to the real daily traffic profile [7][61].

Assuming a maximum of 50 users with 500 Kbps GBR, the low traffic demand corresponds to a maximum of 5 UEs active, the medium traffic demand corresponds to a maximum of 15 UEs active, the high traffic demand corresponds to a maximum of 30 UEs active and the highest traffic demand corresponds to a maximum of 50 UEs active. For each traffic load, the necessary number of active BSs is taken according to their activation profiles shown in Figure 4.14 and Figure 4.15. We chose to use the BS activation profile per traffic load as shown in Figure 4.14 and Figure 4.15, in order to (a) maximize the total energy consumption gains to our system and (b) provide smooth transition between BS operational profiles. The overall daily energy gains are depicted in Figure 4.18. Overall, we could serve the daily telecommunication traffic in our network by reducing ~23.2% the needed energy while providing ~46.3% more information per Joule compared to FOT networks.

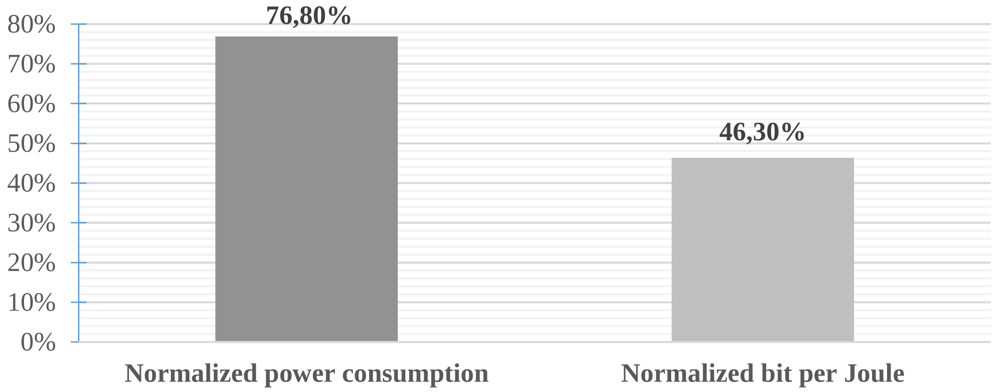


Figure 4.18: Overall normalized power consumption and bit per joule percentage improvement over FOT, according to the real daily traffic profile.

Finally, to prove the applicability of our activation schemes in realistic scenarios, it is essential to reassure that the network operation transits smoothly from one BS activation profile to the next in a feasible manner. Thus, for the daily traffic profile of Figure 4.17, we propose the transitions shown in Figure 4.19, where the transition between consecutive BS activation profiles is smooth, by just toggling the proper BSs to the ON (OFF) state when traffic load increases (decreases).

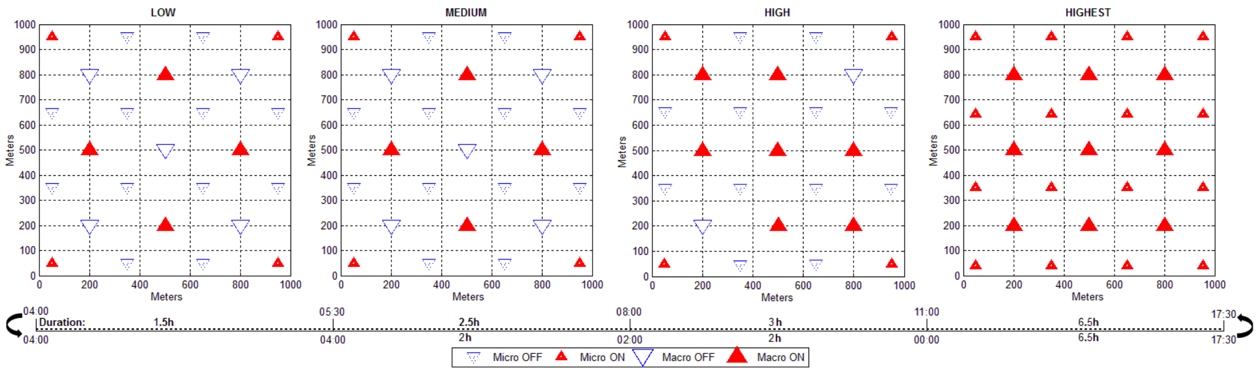


Figure 4.19: Proposed daily activation profiles.

4.7 Summary

In this Chapter, we investigated energy efficient approaches in heterogeneous mobile networking environments. The corresponding power optimization problem was formulated and we proposed two practical energy efficient algorithms for estimating proper dimensioning of heterogeneous mobile networks utilizing LTE radio access technology under certain traffic load conditions and QoS requirements. Next, we proposed two BS activation schemes, according to the BS activation percentage and minimum common BS coverage area overlap. We applied our algorithms on a grid network deployment with various traffic loads. It is obvious that mobile networks can benefit by the introduction of our proposed BS activation schemes; energy consumption and data transmission efficiency can be greatly improved, especially on low to medium traffic load scenarios. Furthermore, we showed that the dynamic adaptation of the network dimensions to match the daily traffic variation yields a different perception on Key Performance Indicators of the network, such as throughput, handoff rate and cell residence time.

CHAPTER 5. BACKHAUL AND ENERGY EFFICIENCY IN HETEROGENEOUS MOBILE NETWORKS

5.1 Introduction

Heterogeneity and densification are the necessary complements in cellular networks for coping the forecasted peak access data rates. With the current mobile data traffic growth rate, current mobile networks' capacity will be soon exhausted. The upcoming wireless communications systems have to achieve a thousand-fold capacity improvement goal, thus, they will be heterogeneous, being made up of both macro and small BSs using different technologies. Denser heterogeneous mobile networks, consisting of overlaying macro and small cells are expected to alleviate traffic congestion and extend network's coverage, throughput and capacity. Considering the effective, efficient and scalable operation of cellular networks as a whole, there is an important variable which determines their successful operation that was usually neglected from thorough evaluation until recently; the backhaul, which plays a major role in wireless broadband networks and is rising in importance on account of the densification of heterogeneous cellular networks. Radio site deployment or evolvement, feasible cells' placement and installation costs, as well as the time needed for site acquisition are determined by backhaul availability. Additionally, overall mobile network's performance relies on backhaul functionality and operational capabilities, since any weakness in backhaul performance will bottleneck mobile network's performance. Densification increases the number of new sites, as well as the number of possible backhaul solutions, complicates network management and increases the total cost of ownership. Therefore, cellular networks' operators need a low-cost, easily applicable and flexible backhaul solution that delivers high performance with the less possible power consumption [121].

5.1.1. Related work and Trends

What is usually neglected in energy efficient approaches in heterogeneous wireless communication networks, including those that we have already mentioned in Chapters 2 and 4, is that small cells operation can inflict a hefty traffic load to the backbone network imposing also a considerable power burden to the system [122][123][124][125]. Backhaul (BH) power consumption can reach up to 38%, 51% and 47% of the total power consumption for uniform traffic and 46%, 64% and 78% of the total power consumption for hotspot traffic, when Millimetre Wave (mmWave), microwave and sub-6GHz BH solutions are employed, respectively [126][126]. BH consumption may vary from 30% to very high levels, which is comparable to the consumption levels of operating the macrocellular BSs [127][128][129]. Moreover, the backhaul impact on architecture deployment and operational costs also emphasizes its significance [130][131]. Thus, mobile networks evolution towards dense heterogeneous networks, with the presence of many smaller Access Points (APs) for providing the desired capacity, renders wireless backhaul worth considering within the scope of the energy-efficient design of heterogeneous networks [132].

5.1.2. Approach and Outcomes

We consider wireless in-band backhaul solution to support ultra-dense cellular environments. Wireless in-band backhaul is defined in 3GPP release 10 of LTE, as the BS-to-AP link which operates in the same carrier frequency as the AP-to-UE link [133]. Wireless in-band backhaul, also known as self-backhauling, is examined as a suitable backhaul solution in rollout strategies where a quite large number of urban small cells are deployed in a very short period of time, as it is capable of supporting NLOS transmissions, but it is also in rural environments, where the distance between AP varies from few hundred meters to few kilometres and usually the radio transmission path is partially obstructed. On the other hand, although backhaul solutions based on the mmWave band can achieve very fast transmission rates, their deployment/application is costly, and limited to LOS deployment scenarios only with restricted effective range. The general idea with self-backhauling in mobile frequency bands is to reuse frequencies and radio interfaces/radio technology, normally used for the mobile access, also for the backhaul. For in-band use, the backhaul and mobile end users will share the same radio interface and share the available capacity on that radio interface [134]. An in-band full-duplex system presents a spectrum reuse scheme to wirelessly backhaul smaller cells with macro BSs without having to orthogonalize allocated spectrum between access and backhaul [135][136].

Wireless in-band relays guarantee low CAPEX costs for wireless backhauling without the need for new spectrum, which is scarce in many countries. Additionally, wireless in-band backhaul solution enables operator to reuse a scarce resource which already possesses.

Furthermore, in low-density rural areas, backhaul competes as the major candidate of the network operating expense [137]. Thus, wireless in-band relay/backhaul solutions can be used as low-cost alternatives for providing connectivity to remote cells covering mountainous or sparsely populated regions, or to temporary coverage cells when major events are being held or disasters strike. The same approach can also be effective for urban scenarios, where dense AP deployments would encounter installation difficulties, such as a large number of utility poles, cables etc. [138][139]. Wireless in-band backhaul was also evaluated as candidate technique for throughput increase in massive MIMO systems [140]. Furthermore, the utilization of lower GHz band spectrum can overcome the Non-Line of Sight (NLOS) issues which other wireless backhaul solutions have to deal with.

The main culprit of power consumption in mobile telecommunication networks is the long-term use of macro BSs, whose operation results in high energy consumption on both transmission and auxiliary equipment components [120]. On the other hand, in the presence of wireless in-band backhauling, favouring the utilization of lower transmission power capable BSs only to minimize network's overall power consumption may not be the optimal approach to follow, since wireless in-band backhaul rests on macro BSs' resources for its operation. Therefore, without macro BSs and micro BSs joint optimization for access and backhaul links coverage, wireless network behaviour may be far from optimal from a power consumption perspective.

The contributions presented in this Chapter are the followings. First, we investigate the impact of wireless in-band backhaul to heterogeneous mobile network's power consumption, by adapting our previously presented in Chapter 4 energy optimization heuristics to embed the wireless in-band BH transmission framework and we evaluate backhaul links' impact to network power consumption and performance against FOT networks. Second, we investigate the joint optimization of backhaul and Access Links (AL) resource assignments considering power consumption in networks with wireless in-band backhaul. To that end, we formulate the power consumption of heterogeneous networks as an optimization problem encapsulating wireless in-band backhaul transmissions. The problem falls into the category of Capacitated Facility Location Problems (CFLP), bounded by Single Sourcing constraint, therefore, we introduce a backhaul-aware energy efficient heuristic for minimizing the energy needed to operate these heterogeneous networks.

The Sections of this Chapter are structured as follows: in Section 5.2 we describe our system model which encapsulates the wireless in-band backhaul framework. In Section 5.3 the mathematical formulation of the power optimization problem is presented and in Section 5.4 we describe the energy efficient optimization schemes in detail. The performance evaluation of each energy efficient scheme proposed is given in Section 5.5 , and finally, this Chapter is concluded in Section 5.6 .

5.2 Heterogeneous Mobile Network System Model including Wireless in-band Backhaul

Our system model consists of J heterogeneous BSs and I UEs, each one requesting a Guaranteed Bit Rate (GBR). GBR defines the required QoS for every UE, served either by macro or micro BS. Wireless in-band backhaul solution is applied as the data transmission method from and to core network between higher transmission power capable BSs (macro) towards lower transmission power capable BSs (microcellular (micro), femtocells, etc.). Network mechanisms are utilized to associate UEs to the available BSs. For this association procedure, different approaches may be applied, depending on network operational requirements. Our network operational strategy aims on network operation with optimal power consumption. Therefore, power consumption should be kept to the minimum possible levels without affecting or with minimum effects on UEs' QoS.

More specifically, we study the forward channel of a multiple cell SISO OFDMA network, featuring LTE RAT. According to the LTE terminology K frequency Resource Blocks (RBs) comprise the system bandwidth and we assume that the total transmit power of each BS is equally distributed among its RBs. Transmissions occur on a frame-by-frame basis, where each frame consists of several OFDMA symbols. Inter-cell interference is also considered, as well as small scale fading and shadowing.

Inside this area, I User Equipment (UEs) are uniformly and randomly distributed, each one demanding access and requesting a GBR. Each UE is served by a specific cell with a set of RBs (corresponding to a specific bitrate) assigned to it to satisfy its traffic request. We assign each block/frame to one forward access or backhaul transmission at most to preserve time and frequency orthogonality and eliminate intra-cell interference. However, the UE suffers from inter-cell interference by neighboring cells that also utilize the same RBs. For the estimation of inter-cell interference signals, we relied on the WINNER II model [119] soft inter-cell interference cancellation method, which is based on the use of more reliable soft-values provided by the decoding process. This approach adds complexity to the system, since a channel decoding step has to be performed for each interferer [141]. Nevertheless, a different number of RBs may be assigned to each transmission in the same frame. We assume a reuse factor equal to 1, so each cell (macro or micro) can utilize all the available RBs. Finally, several downlink resources are devoted to signaling/reference transmissions, hence only a portion of the system power is dedicated to serving useful payload.

We assume that macro BSs are connected to the core network via high capacity reliable connections, e.g. fiber or fixed wireless connection. Wireless in-band BH framework is deployed as the data transmission method between macro BSs and operational micro BSs. Macro BS radio resources, e.g. macro subchannels, are utilized at the wireless in-band backhaul links for transmitting the requested traffic load to the micro BS from the core network, thus the same carrier is utilized for both backhaul and access links, as shown in Figure

5.1. When the UE is served by a macro BS, data are routed from the Mobility Management Entity (MME) / Serving Gateway (S-GW) core network nodes via the high capacity connection to the macro BS and then wirelessly transmitted through the macro BS access link towards the UE. On the other case, where UE is served by a micro BS, data are routed from MME/S-GW node via a high capacity connection to macro BS, then through the wireless in-band backhaul link to the micro BS and finally through the micro BS access link towards the UE.

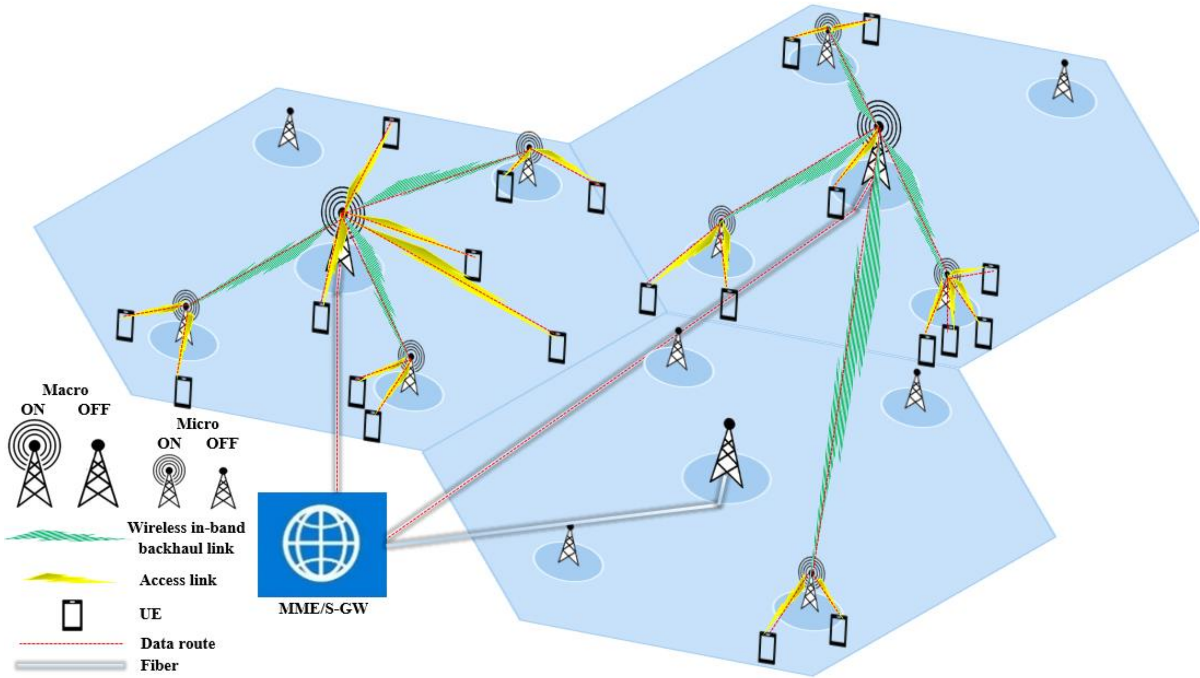


Figure 5.1: Wireless in-band backhaul system model.

Finally, we assume the existence of a perfect controller at the macro BS, which can dynamically distribute data, received from the core network via the high capacity connection, to operational micro BS and UEs that are simultaneously served, with negligible impacts on delay and interference. Last but not least, smaller BS antenna characteristics of micro BSs, e.g. antenna sensitivity, gain, etc., allows high useful payload throughputs per resource block via the air interface of macro BSs, which can be also available to much longer distances compared to mobile UEs' antenna capabilities.

5.3 Energy Optimization Problem Variation

In the aforementioned system model, power consumption is mostly generated by the high transmit power capable macro BS's operation. This is a user transmission independent energy cost accounting for the power consumption generated by the minimum power required by the power amplifier and auxiliary subsystems of an operational macro BS. However, there are also several less significant but non-negligible power consumption components contributing to the overall network power consumption. First, at the access links of the macro BSs, there is a variable power transmission cost due to the extra energy consumed by the equivalent PA, utilizing subchannels of macro BS for access transmissions towards UEs being served by this

BS. Second, wireless in-band BH links are utilizing also macro BS network resources as data transport means from the core network to micro BS. Depending on the micro BSs access link capacity requirements, a non-negligible number of macro BS subchannels may be assigned to such wireless in-band BH transmissions, inflicting an extra variable power transmission cost to the network due to extra utilization of the operational macro BS's PA. Finally, there are power costs associated to the operation of micro BSs: a fixed power cost per operational micro BSs, which is independent of the micro BS access link transmissions, as well as a variable power cost due to the access link transmissions of an operational micro BS.

We now may break down our problem statement as follows:

- The heterogeneous network consists of $n, n = 1,2, \dots, N$, tiers each one consisting of identically configured BSs sets. Assuming that $n = 1$ indicates the macro BSs tier, let J_1 be the number of the macro BSs and $D_1 = \{j | j = 1, \dots, J_1\}$ be the set of these J_1 macro BSs. The second tier set of J_2 BSs is $D_2 = \{j | j = J_1 + 1, \dots, J_1 + J_2\}$, the third tier set of J_3 BSs is $D_3 = \{j | j = J_1 + J_2 + 1, \dots, J_1 + J_2 + J_3\}$ and so on, where J_2 and J_3 denote the numbers of micro and femtocell BSs respectively. Similarly, the number of the available heterogeneous BSs in a n-tier network is $J = J_1 + J_2 + J_3 + \cdots + J_N$ and the N-th tier set of BSs is $D_N = \{j | j = J - J_N + 1, \dots, J\}$. For instance, in the above example we have $n = 3$ tiers of BSs, where $n = 1$ denotes the macro BSs tier, $n = 2$ denotes the micro BSs tier and $n = 3$ denotes the femtocell BSs tier.
- Each BS may occupy one out of two possible states, namely operational (ON) and non-operational (OFF). Each operational BS exhibits a) a fixed power consumption cost f_j derived from its auxiliary equipment utilization, and b) a variable cost v_{ijk}, which is inflicted by the utilization of subchannel k when UE i is served by the access link of BS j with achievable bitrate $b_{ijk}^{(AL)}$, due to the extra energy consumed by the equivalent Power Amplifier (PA), where $i = 1, \dots, I$, $j = 1, \dots, J$, $k = 1, \dots, K$. It is easy to see that operational BSs of disparate BSs' tiers have both variable and fixed power costs different, due to the different nature of their components and equipment.
- Each UE i, $i = 1, \dots, I$, when served by BS j acquires an Access BitRate (ABR), whose lower limit is defined by GBR g_i, therefore a successful association of UE i to BS j ensures the satisfaction of its GBR g_i demand.
- Resources of operational macro BS j may be utilized to transmit the Backhaul BitRate (BBR) that serves the sum of ABRs of some non-macro operational BS m, where $j = 1, \dots, J_1$, $m = J_1 + 1, \dots, J$. Such BH transmissions inflict an additional u_{mjk} variable power cost to the network, due to the utilization of subchannel k of macro BS j with achievable bitrate $b_{mjk}^{(BH)}$, for transmitting ABR data of BS m via wireless in-band BH transmissions, $k = 1, \dots, K$, $j = 1, \dots, J_1$, $m = J_1 + 1, \dots, J$.

As aforementioned, our goal is to optimize the operation of a heterogeneous wireless broadband telecommunication network with respect to energy consumption, while QoS requirements are preserved. Thus, in our approach, the problem at hand is to find the most appropriate subset of the existing BSs, which is adequate to serve the requested traffic demands of the UEs without compromising their QoS requirements and with minimum possible power consumption.

Therefore, having as inputs:

Given: (a) the set of UEs requesting certain traffic requirements and (b) the set of available heterogeneous macro and micro BSs,

our goal is to:

Find: the most appropriate subset of BSs that should be operational to simultaneously (a) satisfy the UEs' traffic demand and (b) minimize overall network power consumption.

The optimization problem can now be formulated as follows:

$$\min\left\{\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} v_{ijk}\cdot x_{ijk}+\sum_{m=J_1+1}^{J}\sum_{j=1}^{J_1}\sum_{k=1}^{K} u_{mjk}\cdot z_{mjk}+\sum_{j=1}^{J} f_j\cdot y_j\right\} \quad (5.3.1)$$

Subject to:

$$\sum_{k=1}^{K}(x_{ijk}+z_{mjk})\le 1,\ i=1,\ldots,I,\ j=1,\ldots,J_1, m=J_1+1,\ldots,J \quad (5.3.2)$$

$$\sum_{k=1}^{K} x_{ijk}\le 1,\ i=1,\ldots,I,\ j=J_1+1,\ldots,J \quad (5.3.3)$$

$$\sum_{j=1}^{J} x_{ij} = 1,\ i = 1,\ldots, I \quad (5.3.4)$$

$$\sum_{j=1}^{J_1} z_{mj} = 1,\ m = J_1+1,\ldots, J \quad (5.3.5)$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K} x_{ijk}\cdot b_{ijk}^{(AL)}\ge g_i,\ i=1,\ldots,I \quad (5.3.6)$$

$$\left(\sum_{m=J_1+1}^{J}\sum_{j=1}^{J_1}\sum_{k=1}^{K} z_{mjk}\cdot b_{mjk}^{(BH)}\right)-\left(\sum_{i=1}^{I}\sum_{j=J_1+1}^{J}\sum_{k=1}^{K} x_{ijk}\cdot b_{ijk}^{(AL)}\right)\ge 0 \quad (5.3.7)$$

where the following binary decision variables are introduced:

$$x_{ijk}=\begin{cases}1, & \text{if channel } k \text{ of BS } j \text{ is assigned to user } i\\ 0, & \text{otherwise}\end{cases} \quad (5.3.8)$$

which indicates whether channel *k* of BS *j* is assigned to UE *i*,

$$x_{ij} = \begin{cases} 1, \text{ if } \sum_{k=1}^{K} x_{ijk} > 0, i = 1,\dots,I,\ j = 1,\dots,J \\ 0, \text{ otherwise} \end{cases} \tag{5.3.9}$$

which indicates whether BS j serves UE i,

$$z_{mjk} = \begin{cases} 1, \text{ if channel } k \text{ of BS } j \text{ is assigned to serve BH transmissions to BS } m \\ 0, \text{ otherwise} \end{cases} \tag{5.3.10}$$

which indicates whether channel k of BS j is assigned to BS m for wireless in-band BH transmissions,

$$z_{mj} = \begin{cases} 1, \text{ if } \sum_{k=1}^{K} z_{mjk} > 0, m = J_1+1,\dots,J,\ j = 1,\dots,J_1 \\ 0, \text{ otherwise} \end{cases} \tag{5.3.11}$$

which indicates whether a macro BS j, $j = 1,\dots,J_1$, serves BBR transmissions,

$$y_j = \begin{cases} 1, \ if \ \sum_{i=1}^{I} x_{ij} > 0, \ j = 1,\dots,J \\ 1, \ \sum_{m=J_1+1}^{J} z_{mj} > 0, \ j = 1,\dots,J_1 \\ 0, \text{ otherwise} \end{cases} \tag{5.3.12}$$

which indicates that fixed power cost is inflicted: a) when BS j, $j = 1,\dots,J$, is operational to serve ABR transmissions, or b) when a macro BS j, $j = 1,\dots,J_1$, is operational to serve BBR transmissions.

The objective function presented in (5.3.1) aims at the minimization of the energy consumption of the network, by minimizing the sum of the variable and fixed energy costs inflicted by the utilization of certain BSs and the corresponding subchannels. Constraints (5.3.2) impose that each channel of every macro BS is assigned as an access link to one UE or as a backhaul link to one non macro BS at most. Similarly, constraints (5.3.3) impose that each channel of every non macro BS is assigned to one UE at most. Constraints (5.3.4) in combination with (5.3.8) and (5.3.9) impose that each UE is served by one and only one BS, while constraints (5.3.5) in combination with (5.3.10) and (5.3.11) impose that the backhaul of each non macro BS is served by one and only one macro BS. Constraints (5.3.6) and (5.3.7) represent the demand constraints. Constraints (5.3.6) impose that every BS will transmit at least each UE's minimum requested demand g_i. Finally, constraint (5.3.7) impose that the sum of BBRs of all macro BSs will support the sum of ABRs of all low transmission power BSs.

This problem belongs to the class of Capacitated Facility Location Problems (CFLPs), restricted by a Single Sourcing (SS) constraint. It is a capacitated problem since resources of each BS are limited. It is a facility location problem because the optimal placement of BSs aims at the minimization of the fixed power consumption (fixed costs) and the required RF transmission power (transportation costs). Finally, the Single Sourcing constraint is applied since each UE may be served by one and only one BS and each micro BS gets its backhaul transmission from one macro BS only.

Unfortunately, it is not straightforward to use the solutions produced by the previously proposed algorithms in heterogeneous mobile environments and simply add the corresponding backhaul transmission power cost. The reason is that the appearance of a micro BS in the optimal subset of operational BSs by default requires the existence of an operational macro BS in the solution as well, to adequately provide for the backhaul link of the micro BS. However, if we use the output of the previously proposed algorithms, there may be situations that the operational state of some macro BSs not appearing in the optimal solution would need to change from the OFF to the ON state, thus altering the total power consumption, which might then be far away from the optimum value. Such cases might be:

- the subchannels of macro BSs appearing in the optimal solution are not adequate to provide the requested payload to cover the micro BSs access links' capacity demands via wireless in-band BH transmissions.
- the set of already operational macro BSs do not have the necessary subchannels to support the wireless in-band BH link requirements.

From the previous discussion, it is obvious that new algorithms are necessary for tackling this problem. The introduction of the wireless in-band BH transmissions intuitively will inflict a corresponding energy cost to the network's operation, especially on low traffic conditions where energy efficiency gains have been calculated being higher due to the utilization of micro BSs only on some traffic load snapshots. Furthermore, the association of network resources to wireless in-band BH transmissions is a cost-effective solution and may increase spectrum efficiency but with some drawbacks; intuitively it is expected to affect network's capacity and performance. For example, in cases where wireless in-band BH links lack the necessary resources to transfer the requested data from the core network to operational micro BSs, the UEs, which are assigned to those micro BSs, may suffer QoS degradation, e.g. throughput degradation or outage probability increase.

In the following section, we present the three greedy heuristic algorithms we introduced to tackle the above optimization problem in a computational efficient way.

5.4 Proposed Heuristics

In our previous Chapter, Chapter 4, we proposed two energy optimization heuristics on heterogeneous mobile networks, namely the HBALSO and HTWEAK, which are proven capable power consumption optimizers on LTE based heterogeneous mobile networks, which led to an up to ~75% energy consumption reduction against FOT networks. Those maximum energy reduction gains were recorded on low traffic load network conditions, where only micro BSs were utilized to serve UE data demands. It was assumed a-priori, that the backhaul transmissions from the core network towards the operational micro BSs are fulfilled via a transparent not-countable mean. Similar approaches have also been extensively used in other energy efficient research efforts on heterogeneous mobile networks. In the following sub-section 5.4.1, we present the adaptations applied to the above heuristics to include backhaul calculations when searching for the optimum assignments. Additionally, in sub-section 5.4.2 we present a low complexity BH aware energy efficient greedy heuristic we developed, which jointly assigns UEs and BH links to most energy efficient set of BSs, namely the EneRgy Efficient Backhaul Oriented base Stations' (EREBOS *).

5.4.1 Sequentially UEs and Backhaul Association

Both HBALSO and HTWEAK take into account a set of UEs that should be served under certain QoS constraints by the network and a set of potential locations for placing the BSs. Thereafter, each scheme utilizes an optimal set of network resources and extracts the optimal set of BSs, $S^{(ON)}$, to serve the corresponding traffic load of the network while retaining the total network's energy consumption to a minimum possible level. Different placements of UEs for the same traffic load, requires new execution of each energy efficient heuristic scheme to obtain new optimal, in terms of power consumption, sets of network resources and operational BSs. Therefore, the above process sequentially assigns UEs to the most power efficient set of BSs and afterwards initiates the BH links assignments procedure. That way, we can collect valuable information about the wireless in-band impact to heterogeneous network's operation, while alongside we alleviate network's power consumption.

Both HBALSO and HTWEAK yield an optimal set $S^{(ON)} = S_M^{(ON)} \cup S_m^{(ON))}$ where $S_M^{(ON)}$ and $S_m^{(ON)}$ are the sets of ON macro and micro BSs, respectively. Obviously, there are also $J_M - |S_M^{(ON)}|$ macro BSs remaining not operational. These BSs are placed in set $S_M^{(OFF)}$. $S^{(ON)}$ list is used as the input to the following *BackHaul Links Assignment (BHLA)* procedure to take into account BH transmissions and yield $S_{M,BH}^{(ON)}$, with all ON macro of $S_M^{(ON)}$ list and possibly other macro BSs to carry the BH transmissions. The combination of HBALSO and HTWEAK with BHLA yields HBALSO with wireless in-band Backhaul (**HBB**) and HTWEAK with wireless in-band Backhaul (**HTB**). BHLA first attempts to serve the BH links of ON micro BSs from the unused capacity of ON macro BSs. However, if this is not possible for every micro BS, then the

***** *EREBOS in Greek mythology, (also known as EREBUS, in Greek: Ἔρεβος, "deep darkness, shadow") was often conceived as a primordial deity, representing the personification of darkness or the region were the dead pass immediately after dying; by using the name EREBOS in our algorithm, we exploit its meaning implying that our algorithm is designed to bring deep green shadow upon network's overall power consumption, greenifying that way its operation.*

procedure continues with activating OFF macro BSs to serve the remaining BH connections. Initially, $S_{M,BH}^{(ON)} = \emptyset$ and $S_{m,BH}^{(ON)} = \emptyset$.

5.4.1.1 BackHaul Links Assignment procedure (BHLA)

Flowchart of the BHLA procedure is shown in Figure 5.2.

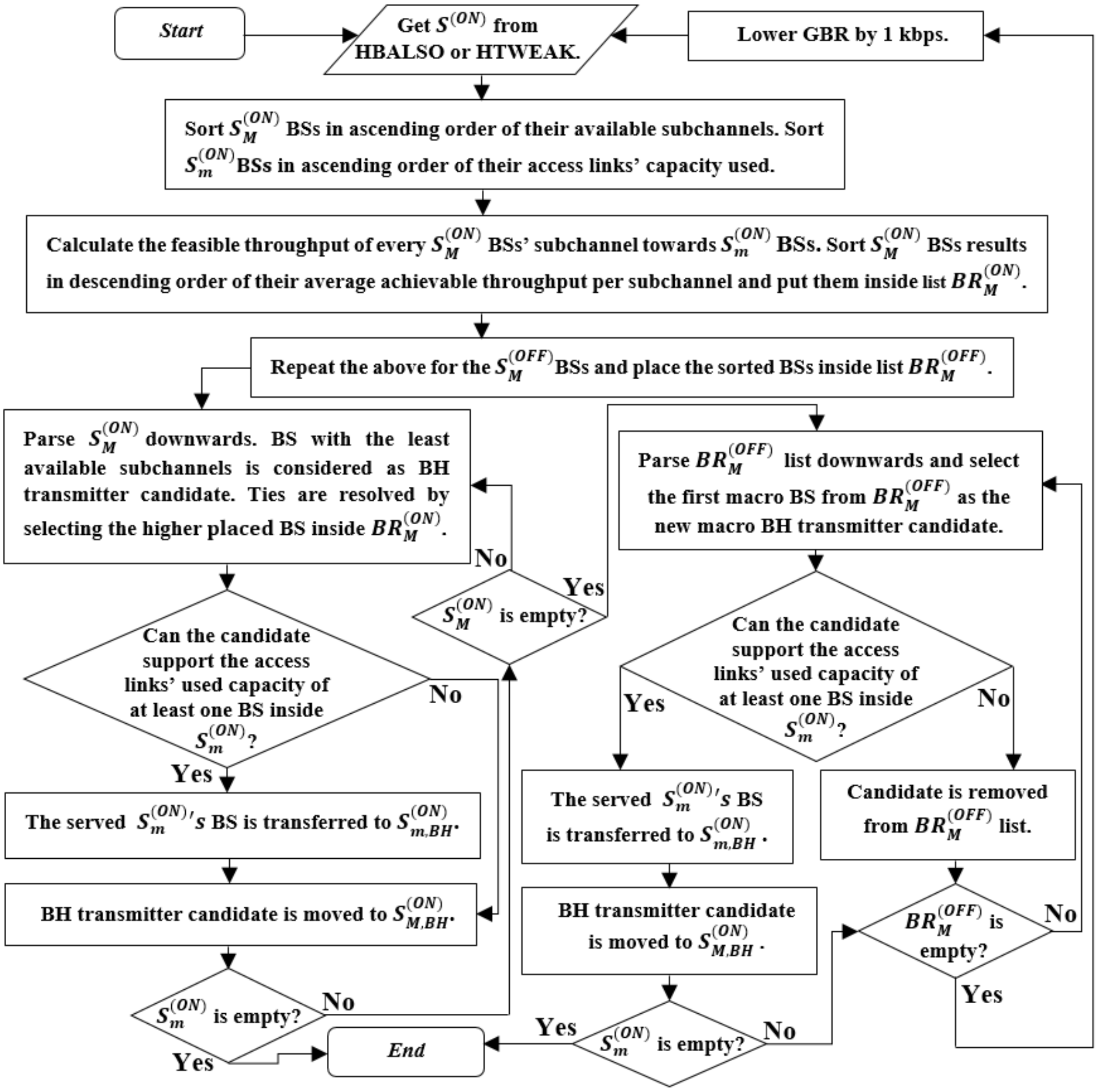


Figure 5.2: BHLA flowchart.

Step 1: For every macro BS $j \in S_M^{(ON)}$ record the available subchannels $a_{ji}, i = 1, \dots, a_j$ and sort BSs in $S_M^{(ON)}$ in ascending order of the number of subchannels a_j. Also, sort micro BSs in $S_m^{(ON)}$ in ascending order of their access links' capacity used.

Step 2.1: For every macro BS $j \in S_M^{(ON)}$with $a_j > 0$, calculate the feasible throughput (bitrate) $b_{jik}, i = 1, \dots, a_j, k \in S_m^{(ON)}$ of subchannel a_{ji}towards every BSs k in $S_m^{(ON)}$. Macro BSs are sorted in descending order, according to the average achievable bitrate $b_j = \underset{i,k}{\text{average}}(b_{jik})$ per subchannel and micro ON BS. The sorted macro BSs are placed inside list $BR_M^{(ON)}$.

Step 2.2: Repeat the same calculations for all BSs in $S_M^{(OFF)}$ set, where all BS's subchannels are now available. Place the sorted BSs inside list $BR_M^{(OFF)}$.

Step 3: Parse $S_M^{(ON)}$ list downwards. The macro BS with the least available subchannels will be examined first and is considered as the *macro BH transmitter candidate* for some micro BS. Ties are resolved by selecting the BS which is higher placed inside $BR_M^{(ON)}$ list. In this way, we get the most out of the already operational BSs with available network resources to be used for BH transmissions.
Parse $S_m^{(ON)}$ list downwards and check whether the macro BH transmitter candidate, selected in Step 3.a, can support the access links' used capacity of at least one or more micro BSs of the $S_m^{(ON)}$ list until its capacity is exhausted or cannot support any more micro BS' backhaul link.

- b.1 If such micro BSs are found, they are removed from the $S_m^{(ON)}$ list and are placed in $S_{m,BH}^{(ON)}$,
- b.2 The macro BH transmitter candidate is removed from $S_M^{(ON)}$ and is placed in $S_{M,BH}^{(ON)}$.
- b.3 If $S_m^{(ON)}$ is empty all micro BS' backhaul links are served. Move all remaining macro BS from $S_M^{(ON)}$ to $S_{M,BH}^{(ON)}$ and EXIT.
- b.4 If $S_M^{(ON)}$ is not empty go to step 3.a.

Step 4: At this step, $S_M^{(ON)}$ is empty and all its BSs have been moved to $S_{M,BH}^{(ON)}$. However, there are still some micro BSs whose BH transmissions are not served yet. So, we are looking for non-operational macro BSs in $BR_M^{(OFF)}$ list to use in order to cover the wireless in-band BH requirements of the remaining micro BSs.
Parse $BR_M^{(OFF)}$ list downwards and select the first macro BS from $BR_M^{(OFF)}$ as the new *macro BH transmitter candidate* for some micro BS.
Parse $S_m^{(ON)}$ list downwards and check whether the macro BH transmitter candidate, selected in Step 4.a, can support the access links' used capacity of at least one or more micro BSs of the $S_m^{(ON)}$ list until its capacity is exhausted or cannot support any more micro BS' backhaul link.

- b.1 If such micro BSs are found, they are removed from the $S_m^{(ON)}$ list and are placed in $S_{m,BH}^{(ON)}$, and the macro BH transmitter candidate is removed from $BR_M^{(OFF)}$ and is placed in $S_{M,BH}^{(ON)}$. Otherwise the macro BH transmitter candidate is simply removed from $BR_M^{(OFF)}$ list.

b.2 If $S_m^{(ON)}$ is empty, all micro BS' backhaul links are served. EXIT.

b.3 If $BR_M^{(OFF)}$ is not empty go to step 4.a.

Step 5: This is the final step: $BR_M^{(OFF)}$ is empty, but there are still some micro BSs whose BH transmissions are not served yet. Thus, the solution for this traffic load snapshot is recorded as infeasible. We lower the users' GBR by 1 kbps and run again HBALSO and HTWEAK to get a new optimal set of $S^{(ON)}$ and go through BHLA once again.

At the end, the final active BS subset derived by the HBB or HTB heuristic is $S_{BH}^{(ON)} = S_{M,BH}^{(ON)} \cup S_{m,BH}^{(ON)}$.

5.4.2 Jointly UEs and Backhaul Association

The EneRgy Efficient Backhaul Oriented base Stations' (EREBOS) activation scheme receives as inputs a set of BSs with different power transmission capabilities at predefined locations and a set of UEs requesting a GBR. EREBOS is executed for certain traffic demand snapshots and achieves the minimization of network power consumption by toggling the necessary BSs to operational ('ON') state. Priority is given to BSs with lower power transmission capabilities which generally consume less energy and are capable of serving the UEs' traffic load while preserving the QoS constraints. In addition, EREBOS considers and evaluates backhaul links requirements towards joint access and backhaul power consumption optimization. Although the algorithm can generally be extended up to n-tiers heterogeneous network topologies, in our work we considered a two-layer heterogeneous network topology which consists of J_1 macro high power transmission capable BSs and J_2 micro low power transmission capable BSs sets. In addition, wireless in-band BH transmissions occur among macro towards micro BSs, only when micro BSs are operational. Each association of a micro to macro BSs for backhaul transmissions, consists a BH pair. Figure 5.3 depicts a high level flowchart of the proposed algorithm.

Intuitively, reducing macro BSs' resources utilization or substituting their operation by smaller scale BSs, whenever and wherever this is feasible, may probably lead to significant power consumption alleviation to network's operation. To this point, EREBOS's philosophy is based on utilization of the smaller scale (in our scenario the micro) BSs first for serving network's traffic load while utilizing macro BSs only when it is necessary, e.g. for BH transmissions or for serving UE which micro BSs cannot serve. Among the possible BS-UE pairs, EREBOS finds which BSs can serve the available set of UEs. When not all UEs traffic requirements and/or BH transmissions can be served by the available set of BSs, GBR requirement g_i is relaxed by reducing GBR by some step value and EREBOS recalculates possible BS–UE pairs and proceeds its calculations from the beginning. A detailed description of the EREBOS's discrete steps follows.

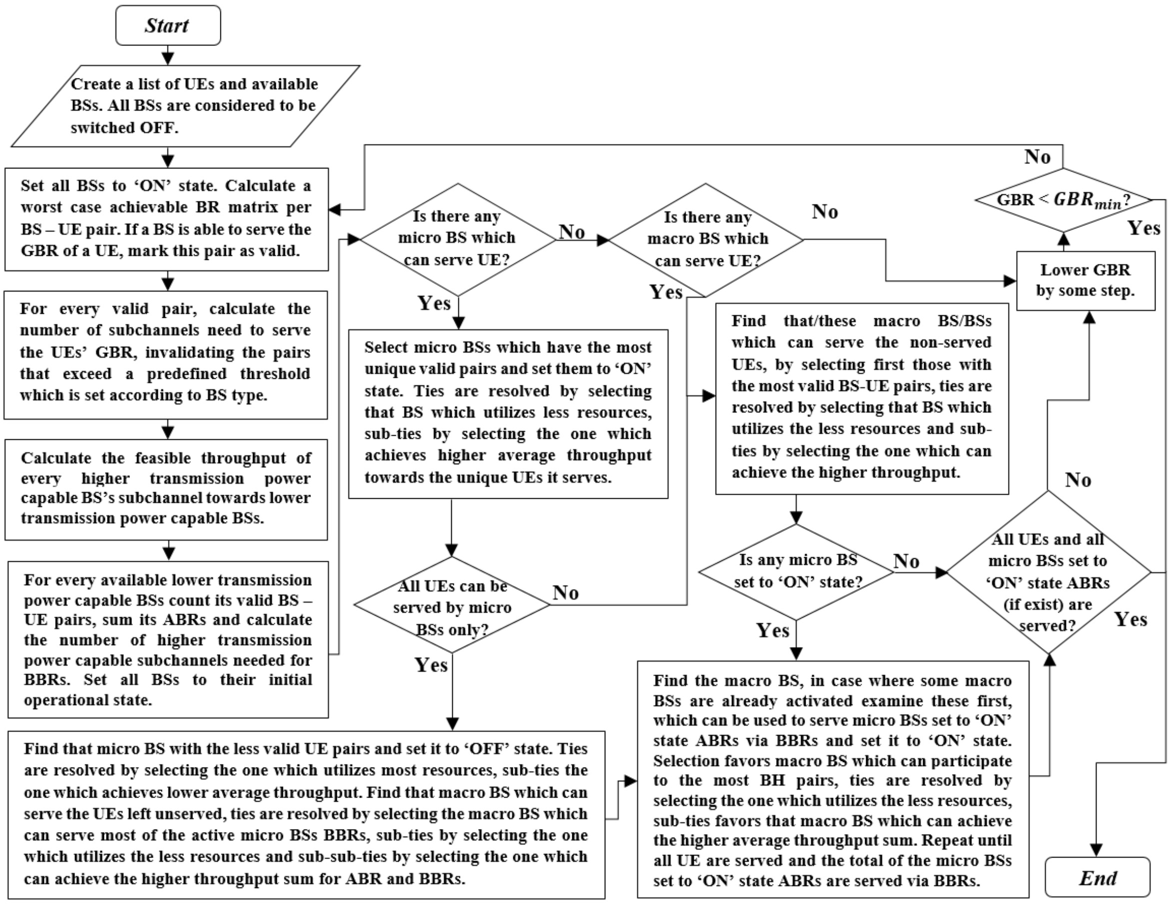


Figure 5.3: Flowchart of EREBOS algorithm.

A list of registered UEs and available BSs is created. We denote by $S_M^{(ON)}$ and $S_m^{(ON)}$ the sets of operational macro and micro BS and initialize these sets as $S_M^{(ON)} = S_m^{(ON)} = \emptyset$.

Step i. We calculate the feasible throughput $b_{ijk}^{(AL)}$ of every subchannel k of BS j to every UE i, $j \in D_1 \cup D_2, i = 1, \dots, I, k = 1, \dots, K,$ in a worst-case fashion, by setting all BSs to 'ON' state at this step. This information is derived from the Channel State Information (CSI) blocks exchanged between the users and the network. Channel information per resource block is converted through the Shannon's capacity formula to BR per resource block (subchannel) and thus each UE roughly estimates the QoS which could be provided by the available BSs.

Step ii. If a BS is able to fulfill the QoS requirements of a UE, this BS–UE pair is marked as being valid. We evaluate the resources' assignment for every BS–UE valid pair as follows: if the number of resources needed exceeds a predefined threshold of the total number of subchannels of each BS, then we consider the corresponding BS-UE association pair as invalid. At this stage, each UE may participate in more than one pairings, although during the actual radio resource assignment stage the single source constraint is respected. Finally, the achievable throughput of all valid BS–UE pairs are stored in a two-dimensional matrix $M_{AB,t}$. The resources needed for each valid BS–UE pair association are stored in a two-dimensional matrix $M_{AB,r}$.

Step iii. We calculate the feasible throughput $b_{mjk}^{(BH)}$ of every subchannel k of BS j towards every BS $m,\ j \in J_1, m \in D_2, k = 1, \dots, K,$ and store the results inside a three-dimensional matrix $M_{BB,t}$ matrix. Therefore, the $M_{BB,t}$matrix contains the feasible throughput per subchannel k of every macro BS when used for BBR transmissions towards each micro BS.

Step iv. We calculate the wireless in-band BH resources needed for every micro BS m as follows. For every micro BS m we calculate the total throughput of all UEs it may serve, which corresponds to the sum of its ABRs assuming that all its BS-UE pairs are enabled. This ABR sum must be transmitted to BS m via wireless in-band BH transmissions occupying resources from some macro BS $j, j \in D_1$. The number of resources needed for BH transmissions towards every micro BS *m* are stored in a two-dimensional matrix $M_{BB,r}$. After this procedure, we revert all BSs' operational state to the state they had at the end of step i, thus all BSs are set again to 'OFF' state.

Step v. _BS Activation Step_: EREBOS favours utilization of the smaller scale micro BSs first for serving network's traffic load while utilizing macro BSs only when it is necessary, e.g. for BH transmissions or for serving UEs which micro BSs cannot serve. The available macro BSs are placed inside S_M list and the available micro BSs are placed inside S_M list. We denote by $S_m^{(C)}$ ($S_M^{(C)}$) the list of micro (macro) BSs that have at least one valid BS–UE pair in $M_{AB,t}$ matrix and thus are candidates for being operational at the end of the algorithm. The following cases exist:

A: Only some micro BSs suffice and can support all UEs

B: A combination of micro and macro BSs is necessary to support all UEs

C: Only macro BSs can support all UEs

D: *Micro and macro BSs cannot support all UEs or macro BSs cannot support the sum of ABRs of all micro BSs. The situation is considered as infeasible*.

Step v.(A): When only micro BSs can support all the traffic load, we first sort $S_m^{(C)}$ in descending order of the number of UEs they can serve and set the first BS of that sorted list to operational 'ON' state. Ties are solved by selecting that BS which utilizes the fewer resources (e.g. fewer number of subchannels) and sub-ties by selecting the BS which can achieve the higher average throughput towards UEs served. The activated micro BS is moved from $S_m^{(C)}$ to $S_m^{(ON)}$ list and we exclude the UEs, with valid pairs to this micro BS, from further investigation. Then EREBOS proceeds with the activation of another micro BS the $S_m^{(C)}$ list, by parsing the list downwards and selecting the next micro BS to move to $S_m^{(ON)}$. This procedure is repeated until all UEs are served from micro BSs.

Since macro BSs are mandatory for serving the BH transmissions and none has been activated yet, the procedure proceeds as follows:

- we locate the operational micro BS which can serve the fewer UEs, ties are solved by selecting the one which utilizes the most resources, sub-ties by selecting the one which achieves the lower average feasible throughput towards the assigned UEs, and we set it to non-operational state and remove it from $S_M^{(ON)}$, and search for a macro BSs to serve the UEs which are no longer served after the deactivation of this micro BS. Ties are resolved by selecting the macro BS which can serve most of the active micro BSs BBRs, sub-ties by selecting the one which utilizes its less resources and sub-sub-ties by selecting the one which can achieve the higher throughput sum for ABR and BBRs. This macro BS is set to 'ON' state, moved to $S_M^{(ON)}$list and removed from $S_M^{(C)}$, if previously placed.

- The already operational macro BS is assigned to serve some of the already activated micro BSs' ABRs whose BH transmissions are not yet served.
- Finally, if some micro BSs' ABRs cannot be served by the already operational macro BS, a new macro BS is utilized, which will not serve any AL links but only BH transmissions. This macro BS is chosen based on the higher number of the BH transmissions it can serve. Ties are resolved by selecting the one which needs fewer resources to serve these BH transmissions and sub-ties based on the higher average feasible throughput it may achieve again towards these BH transmissions. This macro BS is set to 'ON' state, moved to $S_M^{(ON)}$ list and removed from $S_M^{(C)}$ list, if previously placed. This procedure is repeated until all micro BSs ABRs are served by BH transmissions.
  Goto Step vi.

<u>Step v.(B):</u> When all UEs can be served only by a set of micro and macro BSs, the steps to yield $S_m^{(ON)}$ are similar to the steps described in Step v.(A). However, when selecting a macro BS to move to $S_M^{(ON)}$the following differences apply:

- No already activated micro BS is deactivated.
- Macro BS selection criterion is based on the number of most unassigned UEs that macro BS can support. Ties are resolved by selecting the macro BS which can participate in the most BH pairs with some of the micro BSs in $S_m^{(ON)}$, sub-ties are resolved by selecting the one utilizing the fewer resources for AL and BH transmissions.
- Subsequently, already operational macro BSs are evaluated first on whether they can serve BH transmissions towards already operational micro BSs. From the already operational macro BSs, we select the one whose BH transmissions can serve most of the operational micro BSs' ABRs. Ties are resolved by selecting the macro BS with the fewer available resources, sub-ties by selecting the one which achieves the higher average BBR throughput towards the micro BSs it may serve. The above procedure is repeated until all operational micro BSs become members of valid BH pairs.

In case, where some micro BSs' ABR cannot be served by the already operational macro BS, a new macro BS is utilized, which now will not serve any access links but only BH transmissions. The procedure is similar to the one at the last bullet in step v.(A).

Goto Step vi.

Step v.(C): When all traffic can be served by macro BSs only, we sort $S_M^{(C)}$in descending order of the number of UEs they can serve and set to operational 'ON' state the first BS. Ties are resolved by selecting the macro BS which utilizes fewer resources, sub-ties by choosing the one which achieves higher average feasible throughput towards the UEs it may serve. The activated macro BS is moved from $S_m^{(C)}$ to $S_M^{(ON)}$list. The UEs assigned to this macro BSs are excluded from further investigation. The same procedure is repeated until all UEs are being served.

Goto Step vi.

Step v.(D): We record this infeasible solution and we proceed to GBR requirement g_i relaxation, by reducing GBR by some step value (e.g. 1 Kbps), and EREBOS procedure restarts its calculations from Step ii. In case where GBR's new value is lower than a predefined minimum acceptable GBR threshold (e.g. 100 Kbps), this means that current network topology cannot serve the present traffic load requirements.

Step vi. The algorithm terminates either by successful assignment of all UEs to some BSs and all operational micro BSs ABR to BH pairs or by detecting infeasibility.

The proposed algorithm exhibits low polynomial-order complexity since it involves only sorting, searching and comparison operations among system elements and derivatives (BSs types, UEs, subchannels, and throughput). Step i of the algorithm requires $O(J \cdot K)$ time, since there are J BSs with K subchannels at most to examine. At step iii up to $J_1 \cdot J_2$ combinations can be executed, because the maximum number of macro (micro) BSs is $J_1(J_2)$, which takes $O(J_1 \cdot J_2)$ time. Step iv requires $O(J_2)$ time since at most J_2 BSs will be parsed. At steps v.(A-D) up to $J_1 \cdot J_2 \cdot K$ values are sorted which requires $O(J_1 \cdot J_2 \cdot K \cdot log(J_1 \cdot J_2 \cdot K)$ time. Finally, there are I UEs and J_2 BSs to associate at most, thus the overall time complexity is $O(J_1 \cdot J_2^2 \cdot I \cdot K \cdot log(J_1 \cdot J_2 \cdot K)$. The complexity of the proposed greedy heuristic is polynomial and depends on the numbers of macro BSs, micro BSs, UEs and subchannels.

5.5 Simulation Results

5.5.1 Simulation setup

The performance of the proposed algorithms was evaluated using a system-level simulation tool developed in MATLAB R2015a (8.5.0.197613 64-bit) on a desktop pc running Windows 10, Version 1607 (OS Build 14393.693), equipped with an intel i7-4790K processor matched with dual channel DDR3-2400 MHz RAM, loaded with basic daily activities. The simulation environment remained the same as in Chapter 4, in order to extract comparable results. More specifically, a dense urban environment was examined, considering the network coverage area of a 1 x 1 Km^2, where $J_M = 9$ macro and $J_m = 16$ micro BS locations are preconfigured in a grid, as shown in Figure 5.4. The WINNER propagation model is adopted incorporating LOS, as well as NLOS conditions [119]. All the attributes of the network were adjustable, while the sessions were statically created at the beginning of each simulation run. Different traffic load conditions were examined, by differentiating the number of UEs and the GBR of each UE in each run. HBB and HTB algorithms were compared to HBALSO and HTWEAK in order to evaluate wireless in-band backhaul impact to heterogeneous mobile network power consumption. EREBOS was evaluated in terms of energy efficiency against the optimum bound, derived by an exhaustive search method, and against the HTB algorithm, which, as we may see from the results in the following, performed better than the HBB from a power consumption perspective. Additionally, all numerical results are normalized against FOT, where all BSs are switched ON, while all metrics have been calculated by averaging $L = 200$ results per scenario. Furthermore, $I = 5, 15, 30, 50$ UEs have been randomly and uniformly distributed within this region and each UE i requested GBR $g_i = 500, 750$ or 1000 Kbps. Bitrates are calculated in the following using Shannon's formula, based on a worst-case transmission scenario.

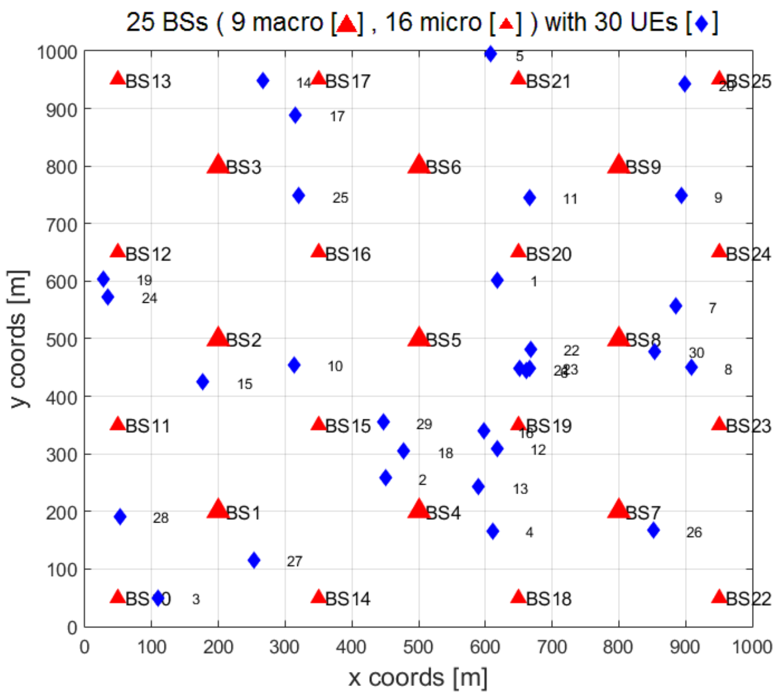


Figure 5.4: The network topology used in our simulations. Big (small) red triangles indicate macro (micro) BSs, blue diamonds represent UEs.

We also compared the results of EREBOS and HTB with respect to the optimum bound on a smaller network topology, consisting of $J_M = 3$ macro and $J_m = 8$ micro preconfigured in a 0.4 x 1 Km^2 reference area, as shown in Figure 5.5. The optimal results were acquired per snapshot by means of an exhaustive search, where all possible solutions were investigated and the most energy efficient one was selected as the optimum, for $I = 2, 5, 10, 15$ UEs and

GBR $g_i = 500$ Kbps. The use of this reduced reference area and traffic load was necessary because of the exponential computational complexity of the exhaustive search method.

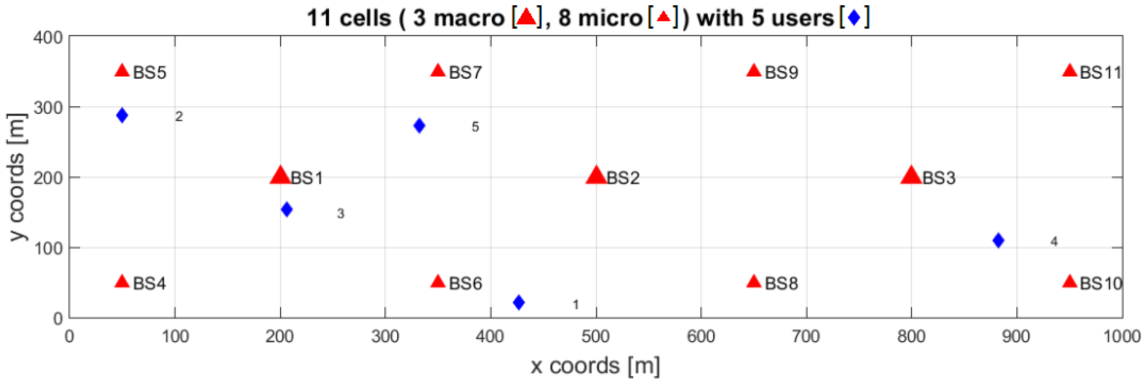


Figure 5.5: The smaller network topology used in our simulations to estimate EREBOS's performance compared to optimum. Big (small) red triangles indicate macro (micro) BSs, blue diamonds represent UEs.

Table 5.1 summarizes the values of the main parameters of our simulation model.

Table 5.1: Main parameters of our simulation model.

Algorithm→		HBB	HTB	EREBOS
Parameter		Value		
Number of BSs	Original topology	9 (16) Macro (Micro)		
	Smaller topology		3 (8) Macro (Micro)	
Number of UEs	Original topology	{5, 15, 30, 50}		
	Smaller topology		{2, 5, 10, 15}	
Number of resource blocks		25		
Bandwidth		5 MHz		
Distribution of UEs		Uniform		
GBR	Original topology	Three simulation campaigns: 500, 750 & 1000 Kbps		
	Smaller topology		500 Kbps	
Typical power consumption of BSs [103][120]	Power Amplifier	~50-80% | Macro (Micro): ~1200 (145) Watts		
	Air conditioning	~10-25% | Macro (Micro): ~300 (0) Watts		
	Signal processing (analog / digital)	~5-15% | Macro (Micro): ~200 (35) Watts		
	Power supply	~5-10% | Macro (Micro): ~100 (15) Watts		
Snapshots per scenario		200		
Propagation model (RAN)		C3 (B2) bad urban - WINNER II model [119]		
Propagation model (BH)		Taken from 3GPP TR 36.814 V9.0.0 specification [142]		
RAT		LTE		

5.5.2 HBB and HTB performance evaluation

5.5.2.1 Power consumption performance against FOT

The normalized average power consumption of HBB and HTB algorithms from the sum of the network's traffic load snapshots is depicted in Figure 5.6. The shown metrics are compared against FOT, where we assume that all BSs are operational and when considering wireless in-band BH transmissions, we include an average BH power consumption cost, calculated from all our simulation runs. Both energy optimization schemes manage to reduce the total network power consumption in all traffic load scenarios and the maximum energy gains occur with the utilization of the HTB algorithm, where the power consumption is alleviated by up to ~78%, for low traffic load network conditions of 5 UEs with 500 Kbps as GBR. A quite strong negative impact of wireless in-band BH transmissions is revealed compared to network's power consumption minimization gains achieved by the corresponding predecessor heuristic; the power consumption of the HTB is increased up to 12% on average at lower traffic loads (500 Kbps) against HTWEAK.

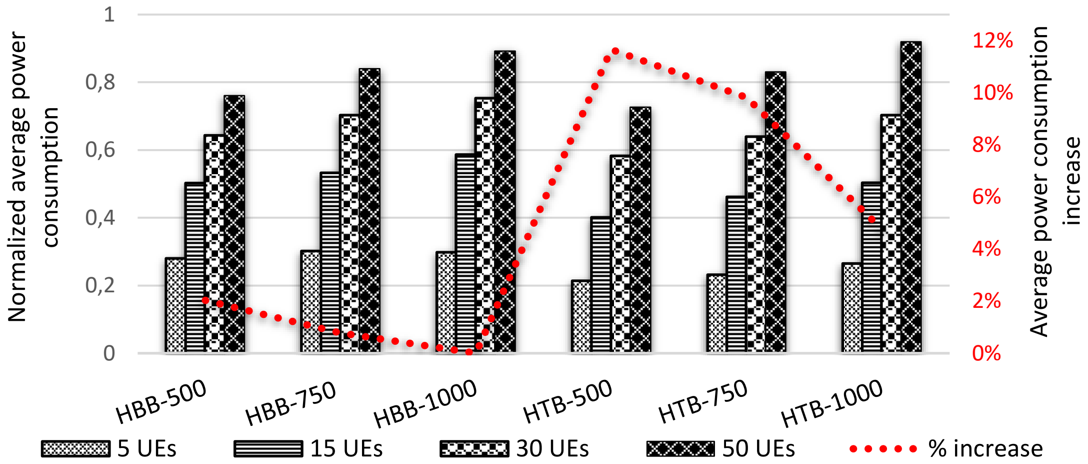


Figure 5.6: Normalized average power consumption against FOT and average power consumption percentage increase between HBALSO-HBB and HTWEAK-HTB.

As mentioned earlier, this was expected due to common operation nature of the HTWEAK and HTB algorithms; each one tries to turn off BSs with high RF power transmissions, which are responsible for the larger portion of the network's total power consumption, yielding many micro BSs in the optimal operational set of BSs. Thus, there is further need for more BH transmissions, which inflicts an extra energy cost. This is shown in our simulations results, by the higher utilization of the macro BS network resources for BH transmissions, as depicted in Figure 5.8.

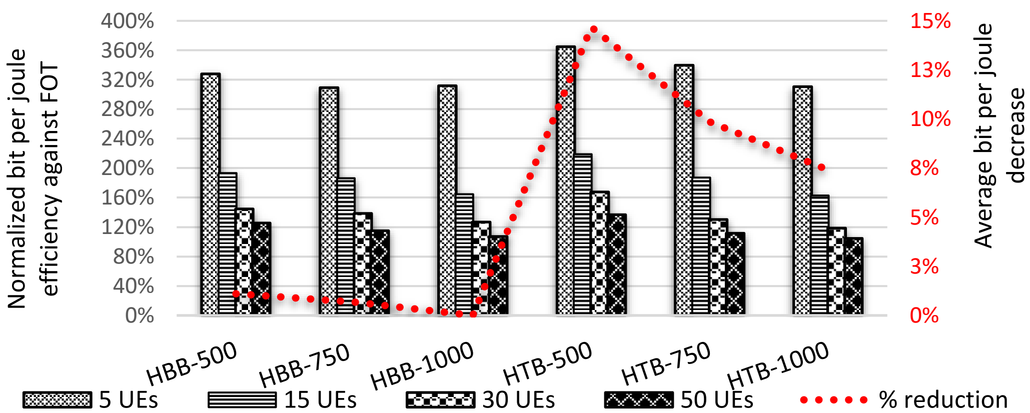


Figure 5.7: Normalized bit per joule efficiency against FOT and average bit per joule percentage decrease between HBALSO-HBB and HTWEAK-HTB.

The well-known bit per joule efficiency metric is depicted in Figure 5.7. Indeed, wireless in-band BH transmissions can be the reason for an average ~15% degradation of the bit per joule efficiency on low traffic loads. However, HTB heuristic still increases bit per joule efficiency up to 365% against FOT on lower traffic loads.

5.5.2.2 Impact to network resources utilization and UEs' QoS

An up to ~20% increase of macro BS resources for wireless in-band BH transmission purposes is recorded on lower traffic load for the HTB algorithm in comparison to the HTWEAK, increase which fades out but still present at ~5% for higher traffic loads. On the other hand, HBALSO and HBB with their common operation nature are proven as being almost power consumption invulnerable by the wireless in-band BH transmissions. Both heuristics tend to utilize the least network resources to serve the corresponding traffic load, thus the higher RF power transmit capable BSs tend to be favoured at most traffic snapshots examined, therefore the need for wireless in-band BH transmissions is kept to relatively low levels because micro BSs are rarely utilized; this can be also verified via a careful examination of the data presented again in Figure 5.8, where HBB's macro resources utilization percentages are higher than the HTB's heuristic, especially on lower traffic loads.

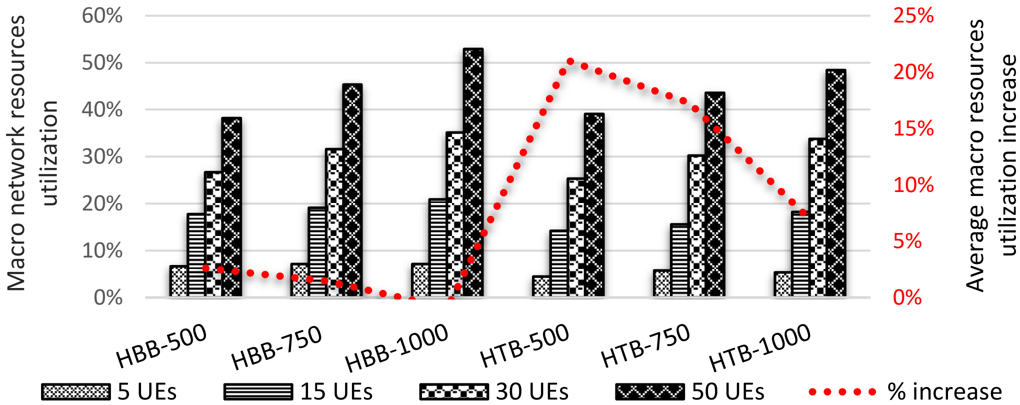


Figure 5.8: Average macro BSs' resources utilization and its percentage increase between HBALSO-HBB and HTWEAK-HTB.

In Table 5.2, we present the average throughput achieved by UEs for the highest traffic load examined and the corresponding percentages of infeasible solutions. As infeasible solution, we declare the weakness of any of our heuristics to provide the GBR to at least one UE. In that case, we allow our heuristics to lower the GBR constraint and record the new GBR allocated to that UE.

Table 5.2: Heuristics' average and minimum achievable throughput, in Kbps, and infeasible solutions percentages for traffic load of 50 UEs. HB (HT) stands for HBALSO (HTWEAK).

# of	GBR	500				750				1000			
UEs	Method	HB	HBB	HT	HTB	HB	HBB	HT	HTB	HB	HBB	HT	HTB
50	*Avg. bitrate*	823.7	810.35	779.52	778.57	1037.7	1033.5	1012.7	1029.1	1282.6	1284.9	1279.7	1274.3
	Infeasibility	0%	0%	0%	0%	0%	0%	0%	0%	6%	7%	5%	11%
	Min BR	500.04	500.05	500.09	500.13	750.16	750.16	750.71	750.08	695.07	701.03	872.13	553.05

Only with HTB heuristic, we record an increase of infeasible solutions up to 120% and a corresponding ~45% GBR reduction at very high traffic load scenarios, where 50 UEs are present and each one is requesting a GBR of 1000 Kbps. On the other hand, HBB heuristic's infeasible solutions percentage and minimum GBR remain at the same levels. Therefore, exhausting networks' resources to provide RAN and wireless in-band BH transmissions simultaneously, increases spectrum efficiency and useful payload, but this may come at an expense of QoS relegation to some UEs, depending on the energy optimization approach used.

5.5.3 EREBOS performance evaluation

5.5.3.1 Performance comparison with the optimal results in smaller topology

EREBOS achieves near optimal average power consumption performance, with an average percentage increase of ~7% compared to the optimum which is calculated by utilizing the exhaustive search method, as depicted in Figure 5.9. Furthermore, EREBOS performs better than the reference HTB algorithm which exhibits an average 11.3% increase when compared to the optimal results. At the lowest traffic load with 2 UEs and GBR at 500 Kbps in the scaled down topology scenario, EREBOS algorithm achieves optimal energy efficiency, where a marginal increase of 0.53% in the average power consumption performance compared to the optimum is recorded. At the same load EREBOS outperforms the HTB algorithm, which achieves an 8,4% increase from the optimum.

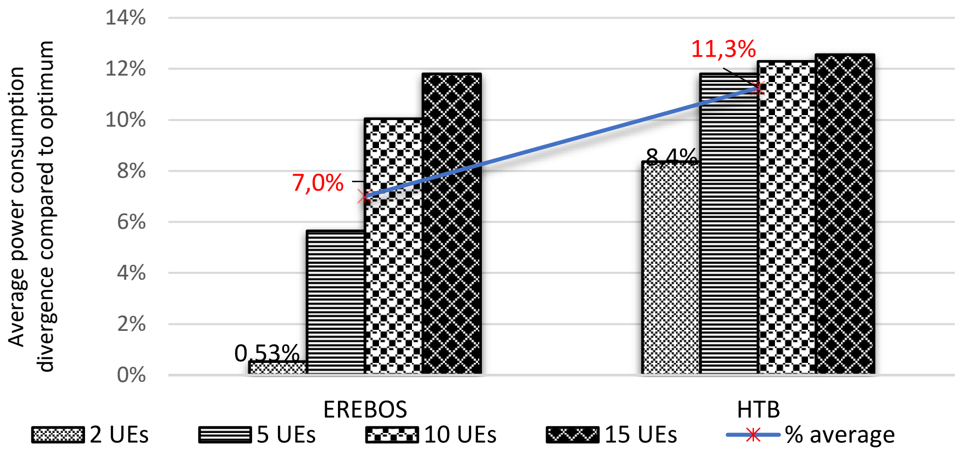


Figure 5.9: Performance of EREBOS and HTB algorithms expressed as power consumption percentage increase compared to the optimum results for traffic loads of 2, 5, 10 and 15 UEs, GBR of 500 Kbps, evaluated in the scaled-down network topology depicted in Figure 5.5.

5.5.3.2 EREBOS and HTB power consumption performance against the FOT consumption

The normalized average power consumption for the sum of the network's traffic load snapshots is presented in Figure 5.10. The shown metrics are compared against a FOT, which is simply a scenario where the network operates with no energy efficient aware scheme, thus assuming that all BSs are operational.

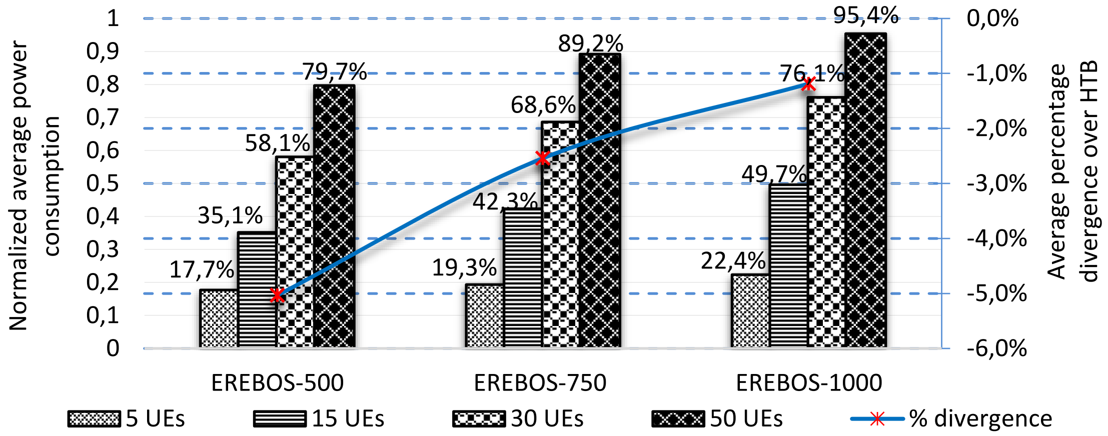


Figure 5.10: Normalized average power consumption against FOT and average percentage divergence among EREBOS's and HTBs' normalized average power consumption performances. 500, 750 or 1000 stands for the GBR (in Kbps) in each scenario applied.

The average power consumption of a FOT network's traffic load is calculated based on the average of all our simulation snapshots' runs, and it includes the sum of (i) the fixed power consumption cost of all BSs and (ii) the average power cost for access and backhaul transmissions, recorded during the evaluation of each algorithm (EREBOS or HTB). EREBOS achieves power consumption reduction in all examined scenarios against FOT and the HTB algorithm. We record an up to 82.3% power consumption reduction compared to FOT at the lowest network's traffic load conditions of 5UEs with 500 Kbps as GBR. Yet, EREBOS performs by up to 5% better compared to the HTB, in terms of normalized average power consumption, again at the same scenario of the lowest traffic load.

The transmission part of a network can operate more efficiently by careful utilization of its resources even when no BS activation strategy is applied. FOT networks' power consumption average metrics were calculated up to 6.7% lower when the EREBOS heuristic's metrics were utilized for estimating FOT network's power consumption, compared to the HTB. EREBOS approach exhibits an energy consumption alleviation trend compared to the HTB algorithm in all scenarios examined, as depicted in Figure 5.11.

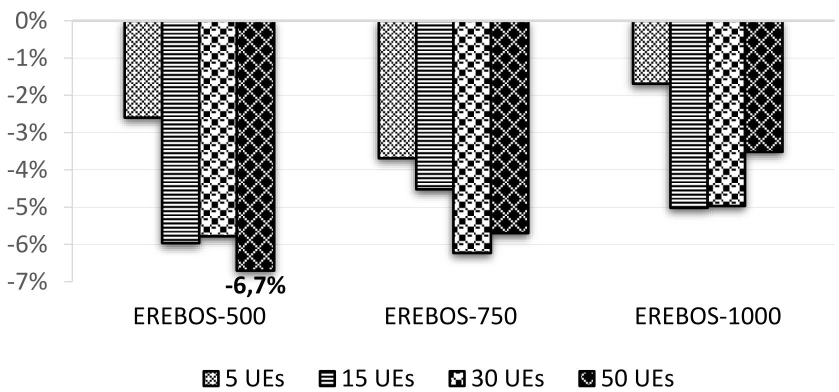


Figure 5.11: FOT network's average power consumption alleviation using as input the EREBOS's metrics compared to the HTB algorithm. 500, 750 or 1000 stands for the GBR (in Kbps) in each scenario applied.

The energy efficiency gains of the EREBOS over FOT is also depicted via the well-known bit per joule metric in Figure 5.12. EREBOS algorithm improves energy efficiency by up to 465% against FOT, where the biggest gains were recorded in lower network's traffic load conditions and outperforms the HTB algorithm at all scenarios examined, achieving up to ~30% increase in the useful payload per Joule.

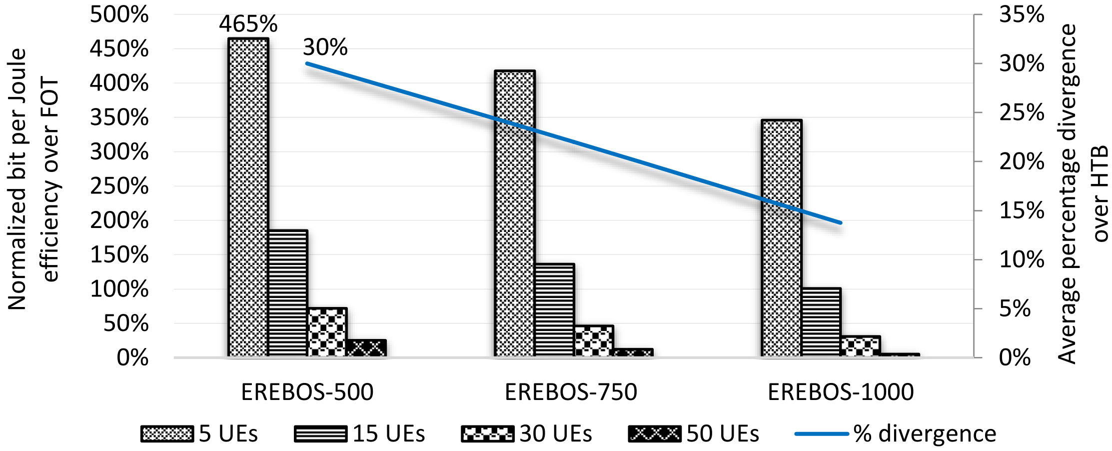


Figure 5.12: Normalized bit per Joule efficiency over FOT and the corresponding average divergence of EREBOS compared to HTB reference algorithm. 500, 750 or 1000 stands for the GBR (in Kbps) in each scenario applied.

5.5.3.3 Comparison of resource utilization

EREBOS's higher utilization of the most efficient network's resources for serving the access links is responsible for the increased alleviation in the total network's energy consumption. Micro BSs resources' average utilization is linearly increased up to ~320% compared to the HTB algorithm followed by a reduction of the macro BSs resources' average utilization, whose energy consumption is much higher, by up to ~38% at the lowest traffic load of 5 UEs examined, as is shown in Figure 5.13.

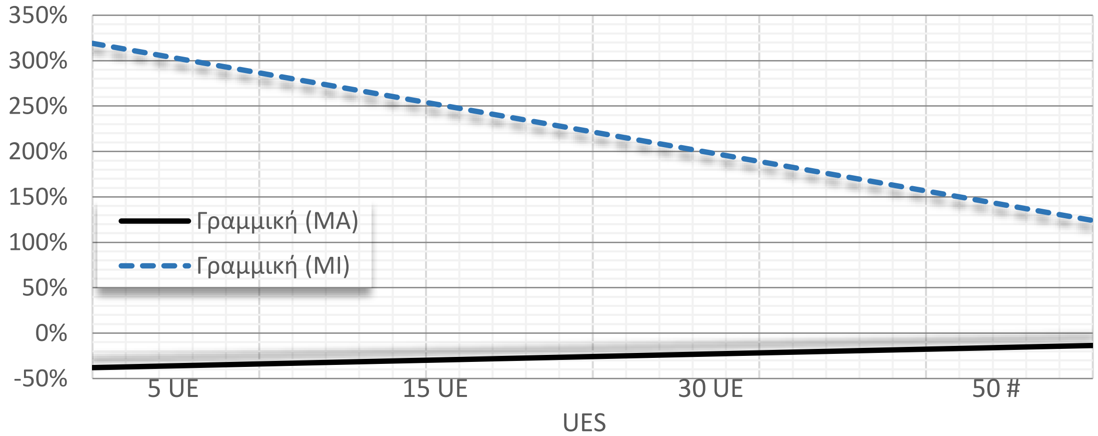


Figure 5.13: EREBOS's linear percentage representation of the network's average resources utilization for various traffic load scenarios compared to the HTB algorithm. MI(MA) stands for Micro(Macro).

5.5.3.4 Power consumption comparison in a daily operational cycle

The overall normalized power consumption and bit per joule percentage improvement over FOT, based on a real daily traffic profile [7] are presented in Figure 5.14. Overall, we could serve the daily telecommunication traffic in our network more efficiently, since according to our calculations the necessary energy for running this heterogeneous mobile network was reduced by ~ 37%, while providing ~92.5% more information per Joule compared to FOT networks. EREBOS algorithm consumes ~2.61% less and provides ~6.2% more information per Joule compared to the HTB algorithm.

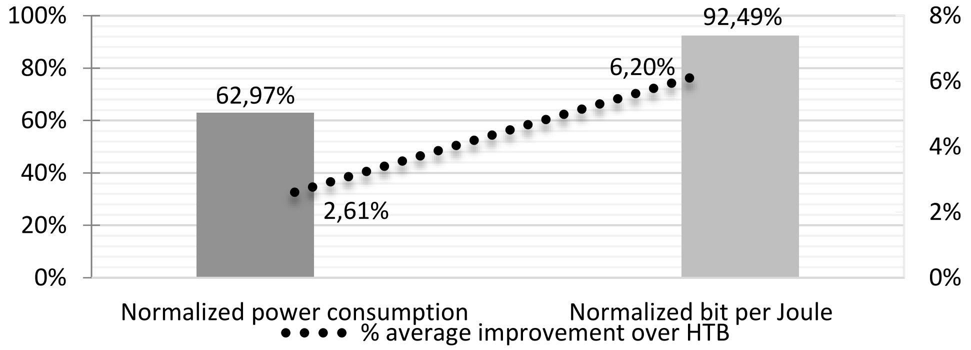


Figure 5.14: Overall normalized power consumption and bit per joule percentage improvement over FOT and over reference algorithm, based on a real daily traffic profile [7].

5.5.3.5 Comparison of Computational Performance

The computational performance of EREBOS, HTB and exhaustive algorithms is presented in Table 5.3 and Table 5.4 where the average computational time of each algorithm for calculating the optimal solution is depicted. Each column entry represents time in seconds. In Table 5.3, we present the computational time of each algorithm running on the scaled down topology depicted in Figure 5.5. EREBOS computational time performance is superior and we can easily clarify the time-consuming process of estimating the optimal solution with the exhaustive search method; for the heaviest traffic load of 15 UEs, EREBOS calculates the optimal solution in 0,54 seconds, the HTB algorithm in 0.76 seconds and exhaustive search in 244 seconds.

Table 5.3: Computational time of EREBOS, HTB and exhaustive heuristics, while each one calculates the optimal solution in the smaller topology depicted in Figure 5.5, for GBR of 500 Kbps. Time is in seconds.

Heuristic / *# UEs*	EREBOS	HTB	EXHAUSTIVE
2	0,28	0,34	115,19
5	0,36	0,46	157,66
10	0,45	0,51	244,99
15	0,54	0,76	244,01

In Table 5.4, the computational time of EREBOS and HTB algorithms is presented, on the original heterogeneous mobile topology depicted in Figure 5.4. EREBOS computational performance again is superior compared to the reference algorithm. Both heuristic schemes remain rather immune to GBR increase, but both are affected from the traffic load (number of UEs) increase. This is in accordance with the formula of computational time presented at the end of sub-section 5.4.2, which includes the number I of UEs, but not the UEs' bitrate requirements.

Table 5.4: Computational time of EREBOS and HTB heuristics in the original network topology depicted in Figure 5.4. Time is in seconds.

	GBR of 500 Kbps		GBR of 750 Kbps		GBR of 1000 Kbps	
Heuristic / *# UEs*	EREBOS	HTB	EREBOS	HTB	EREBOS	HTB
5	0,57	2,84	0,55	2,86	0,56	2,87
15	1,19	4,51	1,09	4,65	1,11	4,43
30	1,9	7,78	2,12	9,2	2,33	7,94
50	3,83	14,55	3,93	13,25	3,72	13,23

5.6 Summary

In this Chapter, we provide energy optimization heuristics for heterogeneous mobile networks, where wireless in-band backhaul framework is deployed as the data transport mean between macro BSs and operational micro BSs. The corresponding power consumption optimization problem is formulated. An exhaustive search method is applied to compare the performance of the heuristics proposed. Two different approaches were used for estimation of the most power efficient; assignment of UEs and BH associations sequentially and jointly optimization of UE assignments and BH associations. The latter approach proved to perform near optimally, especially on lower traffic load conditions. The computational time of the most energy efficient solutions among the two proposed approaches is presented, where our energy alleviation schemes produce prompt results in each scenario examined. Furthermore, wireless in-band BH transmissions inject an average ~26% extra power consumption cost, as opposed to the results in [126] where higher energy burdens were recorded on similar uniformly distributed UE scenarios running different type of backhaul technologies. Wireless in-band backhaul inflicts lower energy and CAPEX costs than other backhaul solutions but on the other hand, may have its disadvantages when dealing with high network traffic loads, since exploiting network resources for providing both backhaul and access links reduces energy efficiency, due to the increased utilization of the network resources. Finally, application of the proposed heuristics may lead to total heterogeneous network's power consumption alleviation by up to ~37% while useful information per Joule transmitted may be by up to ~92.5% increased during their daily operational cycle, compared to similar FOT networks.

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

In this PhD Dissertation, the research problem on energy efficiency in wireless communication networks has been investigated. In the introductory chapter, the research motivation, scope, objectives and anticipated impact have been discussed. Chapter 2 includes literature review and current trends in green wireless networks related works, together with the presentation of the main power consumption minimization problem we approached in our Dissertation and a high-level image of this problem's variations we examined. Chapters 3, 4 and 5 include the technical contributions of the current Dissertation. In the following subsections, the basic conclusions of our Dissertation are summarized and future research directions are presented.

6.1 Conclusions

6.1.1 General Conclusions

Environmental concerns and energy efficiency targets direct wireless communication networks to a holistic approach of their current design and operational policies. Dense heterogeneous networks are the key to cope the predicted upcoming peak hour data rates demands but are also prone to high power consumption variations during their daily operation. Higher energy efficiency can be achieved when wireless networks are designed to operate according to the traffic load variations. Energy efficiency reacts inversely proportional to the traffic load variations, while the service provided to the end users consumes lower than the traffic load but not negligible amount of energy. Backhaul can determine the overall performance and efficiency of a wireless broadband network. Backhaul implementation in modelling and designing phases of such networks will reveal more realistic figures of networks' behaviour to the researchers and operators. Finally, with careful selection of the energy efficient approach, end users QoS' relegation can be avoided and overall network's energy efficiency can be substantial improved.

6.1.2 Mobile Networks' Energy Efficiency

The energy efficiency of wireless mobile broadband networks was the epicenter of this Dissertation. From a theoretical perspective, we formulated the corresponding power minimization problems of different wireless mobile broadband system models and classified them as CFLP-SS problems, which are NP-hard. We employed low computational complexity optimization techniques to obtain an upper bound on system performance. We thoroughly investigated a variety of homogeneous and heterogeneous mobile topologies and models, which were providing a diversity of services to a different in number and distribution traffic load of mobile subscribers, and proposed energy efficient solutions capable of alleviating the power consumption in each of the wireless mobile broadband network system model examined.

More specifically, after extended review of the relevant to the energy efficiency in wireless communication networks' literature, we identified the main culprit of their power consumption. We provided low computational complexity energy efficient solutions, capable of reducing wireless networks' power consumption during a snapshot or their daily cycle operation, where each of the examined RAN, running on WCDMA or LTE RAT, was evaluated as a whole. Each energy optimization scheme derives the optimal subset of BSs necessary to serve a certain user traffic load. Common and easily retrievable data from mobile networks operators, namely BSs coordinates and their utilization percentages together with traffic loads' estimations, were utilized as inputs to our proposed energy efficient algorithms, ensuring their feasibility and applicability to any of the current or upcoming mobile broadband networking environments.

We compared the performance of our proposed heuristics against the optimum, which was acquired per snapshot by means of an exhaustive search, where all potential solutions were investigated and the most energy efficient one was selected as the optimum, and it was shown which of the proposed heuristic performs the best in each scenario evaluated. In homogeneous mobile topologies, we reduced the total energy consumption by up to 56% and 65% in WCDMA and LTE system models respectively. In heterogeneous mobile topologies, the corresponding energy reduction reached up to ~73% and in backhaul aware system models we alleviated the energy consumption by up to 82,3%.

We exploited our energy optimization schemes, by solving a large number of similar problem instances, to estimate the required number of BS and acquired BS activation probabilities of the examined topology to serve certain load level. Next, we proposed BS activation schemes, according to the BS activation percentages and minimum common BS coverage area overlap. We applied our algorithms on different grid wireless mobile broadband network deployments with various traffic loads and services, and showed that mobile networks can benefit by the introduction of our proposed BS activation schemes; energy consumption and data transmission efficiency can be greatly improved, especially on low to medium traffic load scenarios. More specifically, we could serve the daily telecommunication traffic by reducing the needed energy for running the homogeneous and heterogeneous mobile networking environments we examined by ~27,8 and ~23,2% respectively. Furthermore, we showed that the dynamic adaptation of the network dimensions to match the daily traffic variation yields a different perception on Key Performance Indicators of the network, such as throughput, handoff rate and cell residence time. Finally, we proved the applicability of our proposed schemes by proposing smooth transitions between BS activation profiles for energy efficient daily network operation in each network deployment.

6.1.3 Backhaul and Energy Efficiency

A low cost backhaul solution which can be easily applied to almost any mobile network topology, the wireless in-band backhaul, was deployed and evaluated in a heterogeneous mobile broadband environment as the data transport mean between macro BSs and operational smaller cells (more specifically micro BSs). A newly introduced power consumption minimization problem was formulated, in order to cope with the computational complexity arose from utilizing macro BSs spectrum to provide both access and backhaul transmission from and to the core network. Two different approaches were used to estimating the most energy efficient way to utilize network resources for providing both access and backhaul links; assignment of UEs and BH associations sequentially and jointly optimization of UE assignments and BH associations. The latter approach proved to perform near optimally, especially on lower traffic load conditions, and provided faster solutions in each of the scenario examined. Furthermore, wireless in-band BH transmissions injected an average ~26% extra power consumption cost to mobile networks operation, as opposed to the results in [126] where higher energy burdens were recorded on similar uniformly distributed UE scenarios running different type of backhaul technologies.

6.2 Future Research Directions

As wireless communication networks becoming denser and denser, multiple tiers of different power transmission capable APs should be investigated thoroughly, in order to identify the key directions for their prudent placement and utilization towards networks' higher energy efficiency levels. Additionally, the increased number of APs can allow a higher scale of adaptation to mobile networks' traffic load variations during their daily operation, thus, energy efficiency can be potentially improved further. Our proposed energy efficient heuristics are designed in a flexible way and can be adapted to cope the higher heterogeneity of upcoming mobile broadband networks and thus their performance can be reevaluated with newer RAT technologies and RAN models.

The higher heterogeneity achievement in wireless mobile broadband networks relies on the existence of very low power consumption capable APs, such as femto and pico cells, that can be deployed to hot spot areas providing the necessary bandwidth for higher capacity and throughput to the mobile subscribers. Harvesting energy from renewable resources and/or from radiated RF signals should be evaluated as main or optional power resources for these smaller APs. Additionally, although cooperation among MONs can result to less complicated mobile network infrastructures with lower OPEX and CAPEX, without proper energy efficient approaches this cooperation can lead to lower than anticipated energy efficiency performance. Therefore, current energy efficient schemes should be updated or new ones should be introduced for coping the complexity inserted by such complex mechanisms of wireless network access.

Furthermore, since the backhaul availability determines the feasible placements of cells, and impacts installation costs and the time needed for site acquisition and installation, backhaul solutions should be considered in every energy efficient approach. Energy efficient, low cost and installation time backhaul solutions, as the wireless in-band backhaul, should be evaluated further in order to redefine their importance in the mobile networks' market. Furthermore, comparison, coexistence and/or cooperation of wireless in-band with mmWave backhaul techniques in various deployment scenarios towards mobile network's power consumption minimization can be an additional subject of future research.

A Appendix

A. 1 Short CV

Short CV
 Mr. Georgios Kyriazis was born in Athens, Greece in 1982. He has received the Diploma and Master Degree in Digital Systems, from the University of Piraeus in 2006 and 2010, respectively. Mr Kyriazis has participated (under scholarship) in the "THALES - ENDECON" EU founded project (09/2013-02/2015), being responsible for designing and developing of energy efficient wireless mobile cognitive networks' solutions. Additionally, has worked for 3 years (2007-2010) in Siemens Hellas, as a software engineer on landline telecommunication networks. His main research focus is on energy efficient mobile networks planning and optimization.

A. 2 List of Publications

Publications in Journals	
1.	Rouskas, A., Kyriazis, G. & Komnakos, D.I., "Green Optimization Schemes for Mobile Network Design and Operation", Springer Wireless Pers Commun (2017). doi:10.1007/s11277-017-4350-9.
2.	George Kyriazis and Angelos Rouskas**, "**Towards Access and Backhaul Power Consumption Optimization in Heterogeneous Mobile Broadband Networks**",** River Publishers' Journal of Green Engineering. doi: 10.13052/jge1904-4720.641, 2017.
3.	George Kyriazis and Angelos Rouskas, "Design and Operation of Energy Efficient Heterogeneous Mobile Networks", Springer Wireless Networks. doi: 10.1007/s11276-015-1083-0, 2015.

Publications in Conferences	
1.	G. Kyriazis and A. Rouskas, "Energy efficient wireless in-band backhaul in heterogeneous networking environments," *2016 24th International Conference on Software, Telecommunications and Computer Networks (SoftCOM),* Split, Croatia, 2016, pp. 1-6. doi: 10.1109/SOFTCOM.2016.7772138.
2.	G. Kyriazis, A. Rouskas and G. T. Karetsos, "Energy-efficient base station management in heterogeneous networking environments," Computers and Communication (ISCC), 2015 IEEE Symposium on, Larnaca, Cyprus, 2015, pp. 283-288. doi: 10.1109/ISCC.2015.7405529.
3.	Kyriazis, G.; Rouskas, A., "Energy optimization schemes in heterogeneous wireless mobile networks," Computer Aided Modeling and Design of Communication Links and Networks (CAMAD), 2014 IEEE 19th International Workshop on vol., no., pp.375,379, 1-3 Dec. 2014. doi: 10.1109/CAMAD.2014.7033269.
4.	Georgios Kyriazis, Angelos Rouskas, "RBS Activation Schemes for Minimum Power Consumption in Mobile Networks", Procedia Computer Science, Volume 40, 2014, Pages 37-48, ISSN 1877-0509, http://dx.doi.org/10.1016/j.procs.2014.10.029.

A. 3 List of Abbreviations

ACRONYMS	EXPLANATION
ABR	Access Bit Rate
AMC	Adaptive Modulation and Coding
AP(S)	Access Point(s)
BBR	Backhaul Bit Rate
BBU	Base Band Unit
BH	BackHaul
BHLA	BackHaul Links Assignment
BS(S)	Base Station(s)
BSAS	Base Station Activation Scheme
BW	BandWidth
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CCIR	Comité Consultatif International des Radiocommunications
CFLP	Capacitated Facility Location Problems
CSI	Channel State Information
D2D	Device to Device
EB/NO	Energy per bit to noise power spectral density ratio
EREBOS	EneRgy Efficient Backhaul Oriented base Stations activation scheme
FOT	Full Operational Topology
GBPS	Giga Bits Per Second
GBR	Guaranteed Bit Rate
GHG	GreenHouse Gas
GHZ	GigaHertz
GO	Geographical Overlap
GTCO2E	Gigatons carbon dioxide equivalent
HENOBSS	HEterogeneous Network Optimal Base Station Subset
HOL	Head of List
HSPA	High Speed Packet Access
HTB	HTweak with wireless in-band Backhaul
HTWEAK	Heterogeneous opTimal poWer consumption schEme for rAdio access networKs
ICT	Information and Communications Technology
KBPS	Kilo Bits Per Second
KPI	Key Performance Indicator
LOS	Line of SIght
LP	Linear Programming
LTE	Long Term Evolution
MACRO (MA)	Macrocellular

MBPS	Mega Bits Per Second
MHZ	MegaHertz
MICRO (MI)	Microcellular
MMWAVE	millimeter wave
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MNO(S)	Multiple Network Operator(s)
MS	milliseconds
NLOS	Non-Line of Sight
NP	Non-deterministic Polynomial time
OBSS	Optimal Base Station Subset
OFDMA	Orthogonal Frequency Division Multiple Access
OHBSS	Optimal Heterogeneous Base Station Subset
OPEX	Operating Expense
PA	Power Amplifier
QAM	Quadrature Amplitude Modulation
QOS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RB	Resource Block
RF	Radio Frequency
RRH(S)	Remote Radio Head(s)
S-GW	Serving Gateway
SINR	Signal-to-noise ratio where noise includes both thermal noise and interference
SISO	Single-Input Single-Output
SLA	Service Level Agreements
SS	Single Sourcing
TWH	TeraWatts per hour
UE(S)	User Equipment(s)
WCDMA	Wideband Code Division Multiplexing Access

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