TOWARD GREEN HETEROGENEOUS SMALL-CELL NETWORKS

A THESIS SUBMITTED TO
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
KOCAELİ UNIVERSITY

BY

MUHAMMET HEVESLI

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
ELECTRONICS AND TELECOMMUNICATION ENGINEERING

KOCAELİ 2019

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LIST OF ACRONYMS

BS	: Base Station
BW	: Channel Bandwidth
DL	: Downlink
D2D	: Device-to-Device Communication
EARTH	: Energy Aware Radio and network technologies.
EE	: Energy Efficiency
eNB	: Evolved Node B
HetNet	: Heterogeneous cellular Network
HSPA	: High Speed Packet Access
LTE Advanced	: Long Term Evolution Advanced
MIMO	: Multi-Input Multi-Output
PA	: Power Amplifiers
QoS	: Quality of Service
SE	: Spectral Efficiency
SINR	: Signal to Interference and Noise Ratio
TDD	: Time Division Duplex
UE	: User Equipment
UMTS	: Universal Mobile Telecommunications System
Wi-Fi	: Wireless Fidelity
3GPP	: 3rd Generation Partnership Project
5G	: Fifth Generation

YEŞİL HETEROJEN KÜÇÜK HÜCRESEL AĞLARA DOĞRU

ÖZET

Giderek artan sayıda kullanıcının veri iletişimine olan yoğun talebi, kablosuz hücresel şebekelerin karşılaştığı büyük bir zorluktur. Bu sorunun olası bir çözümü, mevcut makro ağda çok sayıda küçük hücre (SC) kullanmaktır. SC yerleşimi, gelecekteki kablosuz ağlarda, düşük güç maliyetinde veri trafiği artışının üstesinden gelebilecek büyük bir role sahip olduğundan, heterojen ağ (HetNet), 5G şebekeleri için hücre kapsamasını ve ağ kapasitesini artıran, makro hücre trafik yükünü SC'lere aktaran (boşaltan) umut verici bir teknoloji olarak görülmektedir. Bununla birlikte, yoğun trafiğe sahip SBS'lerin toplam güç tüketimi ihmal edilemeyecek düzeyde olduğundan, aşırı yoğun SC'ler ve onların birbirinden ilişkisiz çalışmaları HetNet'teki makro baz istasyonunun (MBS) ve küçük baz istasyonlarının (SBS'ler) ortak güç tüketimi hakkında önemli bir soruyu ortaya çıkarmaktadır. Son zamanlarda, HetNets'te enerji tasarrufu sağlamak için SC uyutma tekniği ön plana çıkmıştır. HetNets'teki güç tüketimini en aza indirmek için, HetNet'teki kullanıcı dağılımına göre SBS'lerin çalışma modunu (aktif / uykuya (açık / kapalı)) dinamik olarak ayarlayan) ayarlayan üç algoritma önerdik. Önerilen algoritmaların temel bir tasarım ilkesi, sırasıyla konumlarına, kapsama alanlarındaki kullanıcı yoğunluklarına veya tasarruf edilebilecek en yüksek gücü temel alarak SBS'leri kademeli olarak kapatmaktır. Ardından, SC'ler arasında olan ya da MBS'den SC'ye olan trafik yükünün aktarımı sonucunda, herhangi bir SC'nin trafik yükünün, SC'nin kapasitesini aşması durumu dikkate alınarak algoritmanın matematiksel çerçevesi daha gerçekçi hale getirilmiştir. Bu tezde, veri trafiğinin gün içindeki değişiminin modellenmesinde Avrupa trafik profilininden yararlanılmıştır. SC'lerin ve MC'nin kullanıcı yoğunluklarını zamana göre değiştirilmiş ve HetNet'in güç tüketimini gün boyunca hesaplanmıştır. Simülasyon sonuçları, önerilen SC uyutma tekniği algoritmalarımızın kullanılması ile HetNet'in günlük yaklaşık % 20 güç tasarrufu sağlayabileceğini göstermektedir. Önerilen algoritmalarımızın performansları literatürde önerilmiş olan optimum algoritmanın performansına yakındır ve hesaplama karmaşıklıkları oldukça düşüktür.

Anahtar Kelimeler: Enerji Verimliliği, Heterojen Ağlar (HetNets), Küçük Hücreli Çalışma, Trafik Yükünü Boşaltma, Yeşil İletişim.

TOWARD GREEN HETEROGENOUS SMALL-CELL NETWORKS

ABSTRACT

The overwhelming demand for data by an ever-increasing number of users is a great challenge wireless cellular networks are faced with. One potential solution to this issue is deploying a massive number of small cells (SCs) in the existing macro network. As SC overlay has a big role in the future wireless networks that can overcome the data traffic upsurge at little power cost, heterogeneous network (HetNet) has been viewed as a promising technology for 5G networks that extends cell coverage, improves network capacity and offloads the network traffic from the macro cell (MC) to the SCs. However, the hyper-dense SCs and their uncorrelated operation raise an important question about the joint power consumption of the macro base station (MBS) and the small base stations (SBSs) in the HetNet since the aggregate power consumption of the dense SBSs cannot be ignored. Recently, the SC sleeping technique has become a hot topic for saving energy in HetNets. To minimize power consumption in HetNets, we propose three algorithms to dynamically adapt the operation of the SBSs to active/sleep (on/off) for non-uniform user distribution in the HetNet. We investigate the general optimal power minimization problem for HetNet that requires relatively high computational complexity. Taking into account the additional increase of the traffic load brought to the MBS, a key design principle of the proposed algorithms is to switch off the SBSs gradually based on their locations, user densities in their coverage areas or the highest power that can be saved by switching some of them off, respectively. Then, we enhance the mathematical framework to make the analysis more realistic by considering the offloading between the SCs and the MBS that occurs when the traffic load exceeds SCs' capacity. In this paper, based on the fact that user densities of SCs and MC change with time, we model the traffic on the European traffic profile and portray the power consumption of the HetNet throughout the day. Simulation results show that by applying SC sleeping and our proposed algorithms, the HetNet can save about 20% power daily. The performances of our proposed algorithms are close to that of the optimal algorithm and their computational complexities are remarkably lower.

Keywords: Energy Efficiency, Green Communications, Heterogeneous Networks (HetNets), Small-Cell Operation, Traffic Offloading.

INTRODUCTION

The biggest challenge for next generation wireless systems is transferring very high volume of data in ultra-high rate for a massive number of connected devices with ultra-low energy consumption [1-4]. In [5], the authors indicated that the mobile data traffic volume, which was 45 million TB/year in 2012, is expected to reach 623 million TB/year until 2020. To respond to this explosion in data traffic, 5G aims at gigabit scale data rate with higher capacity and also low latency. Besides meeting overwhelming traffic demands, network operators around the world agree that they have to manage their cellular networks' energy efficiently and reduce CO_2 emission. The Information and Communication Technology (ICT) sector and the mobile communication industry have been collectively estimated to represent 2% of global CO_2 emissions [6]. This figure is anticipated to increase (CO2 emission rate is expected to grow 6% by 2020 [6]) essentially with the exponential increase in data traffic and with customer demand for ubiquitous network access and wireless services. The two contradictory requirements of 5G systems, ultra-high network area throughput and low power consumption, can be jointly achieved by network hyper-densification [7-10]. The Massive Multi-Input Multi-Output (M-MIMO) technology, one of the strong candidates for 5G, can deliver high reliable user throughput in an energy-efficient way by using more than hundred antennas in the conventional Base Stations (BSs). By using M-MIMO, tens of users can be multiplexed in both Uplink (UL) and Downlink (DL) of each cell in coherent Multi-User MIMO (MU-MIMO) transmission [11-14]. Setting-up of enormous number of Small Cells (SCs) in the coverage areas of Macro Cells (MCs) also enhances the capacity effectively up to 100 times by using low-cost and low-power Small BSs (SBSs) where the user densities are high. Since the SBSs and the UEs are closer to each other, the area throughput will increase and the transmitted power will be significantly reduced at the price of increasing the circuit power consumption per km^2, due to the high number of hardware components and infrastructure, especially taking into account the fact that the population of SCs is expected to be around 100 millions to serve 7.6 billion mobile subscribers in 2020 [4, 5].

There is a performance difference between M-MIMO technology and dense small-cell deployment with respect to user-average spectral efficiency. While small-cell densification is favorable if user density is high, otherwise M-MIMO becomes more favorable than SC densification. If the performance metric is Energy Efficiency (EE), small-cell systems show higher performance than M-MIMO in all cases [15]. So, we can see that hyper-dense heterogeneous small-cell deployment is a promising candidate in 5G systems if we can control the power consumption levels in an efficient way. According to [16], 80% of data traffic in 2012 took place indoors and fewer than 10% of cells served about 90% of the traffic load. In light of these two facts, it is clear that optimizing indoor traffic will have a major impact on the network capacity. On the deployment side, the big news is that the number of small cells already deployed in 2015 is about 14 millions [17, 18] and this number attests to the mobile operators' belief that small cells are essential for the future of their networks.

Nowadays, densification with small-cell deployment attracts attention, especially for 5G. However, new problems come up when a large number of SBSs are deployed in a given area. As [19] shows that dense small-cell deployment in wireless networks is the complement to existing macro-cell networks, [20] asserts that this marriage of small and macro cells enhances the network performance.

Generally, SC sleeping algorithms assume that one MC is placed in the center of the coverage area and that the SCs are distributed in this area. The MC will not be able to sleep because of its important role in avoiding any service failure in the coverage area, managing all on/off operations of SCs and serving the users who are in the switched off or saturated SC's coverage area. To efficiently realize the hyper-dense SCs in 5G networks, [21] and [22] assume that a logical and physical architectural split of the control and user planes for SC users can achieve a significant improvement in the network performance in terms of mobility robustness, energy efficiency and service reliability. They propose that the control planes (signaling information) are provided by the Macro Base Station (MBS) in a low frequency band and the user planes (data traffic) are provided by their SBSs in a high frequency band.

Because of SC densification, the massive number of SCs do not need to be connected directly to the core side. Instead of that, the SCs can transmit their traffic to neighboring cells and so on until they access the concerned MBS using millimeter wave in backhaul links.

The typical power consumption of the SBS and MBS in many European countries are about 10W and 930W, respectively [5]. In [23], the authors introduce a ratio that is equal to the number of small cells divided by the number of users in the network and the results show that the highest EE occurs when this ratio is around 0.9 while SC sleeping strategy is active and 0.5 while it is inactive. Considering that 100 SBSs consume more power than one MBS does, if we deploy a large number of small cells in the macro-cell, their power consumption will not be negligible. As a result, it is important to take serious steps toward a joint power consumption management of the MCs and the SCs by sharing out the traffic load to achieve extra power saving in the Heterogeneous Network (HetNet). Indeed, the total HetNet power consumption changes with the traffic load since the power consumptions of MBS and SBS respond differently to their traffic loads' fluctuation. While the power consumption of MBS increases exponentially with its traffic load to serve every user with a steady rate of Quality of Service (QoS) [24], the SBS power consumption is almost flat for any load and independent of it [5, 25]. From this perspective, the traffic offloading from the MBS to the SBSs helps to decrease the MBS power consumption but surely increases the total power consumption of the SBSs because more SBSs have to be turned on. Thus, we should find the optimum number of SBSs to be turned on to decrease the total power consumption.

On the other hand, in cellular networks, there are notable fluctuations in traffic demand over space and time [5, 26] and sometimes some BSs can be under-utilized for certain periods of time and locations [13]. Under this concern, there is a prospect of saving energy by applying the technique of SC sleeping at off-peak hours. Cai et al. give a mathematical framework to decrease the total HetNet power consumption in two cases of user distribution: uniform and non-uniform [27]. The study shows that when the user density, traffic, is high, SBSs are activated gradually to serve the MBS's offloaded traffic. On the contrary, when the traffic is low, some of SBSs are turned off one by one to save the total power of the HetNet. Without considering the limitedness of the resources of the SCs, two near-optimal algorithms with polynomial complexity have been proposed to decide which SBSs will be turned off.

It is known that determining the optimal operation mode of the SBSs in a HetNet is a difficult combinatorial problem classified as an NP-hard problem and requires not only signaling overhead but also high computational complexity, such as $\mathrm{O}(2^{\mathrm{M}})$ where M is the number of SBSs in the system [25]. In our study, at first, inspired by [27], we propose three new algorithms to minimize the total power consumption in HetNet while meeting the desired QoS by investigating a dynamic adaptation of the SBSs' operation modes (on/off) according to the traffic load variation. Then, we determine the best algorithm among the three proposed algorithms by comparing them to that of [27]. By taking the limitedness of the resources of the SCs into account, we enhance the mathematical framework to make the analysis more realistic by considering the offloading between the SCs and the MBS that occurs when the traffic gets denser. Furthermore, by exploiting the traffic load variation during the day, we model the traffic in the network with European traffic profile and calculate the total HetNet power consumption in a day. We consider that the user distribution in the MC and SCs is non-uniform and we model the users' locations and the user densities in the network as uncorrelated random variables (RVs). In terms of performance evaluation, our proposed algorithms are near-optimal solutions with considerably low computational complexity compared to that of [27] which is $\mathrm{O}(\mathrm{M}^3)$. Our proposed algorithms try to give answers to the below questions:

Q1: Which SBSs should be switched on/off and when?

Q2: What are the parameters determining the switching decision?

Q3: What are the optimal/suboptimal algorithms for the switching on/off mechanism?

1. MODELS AND ASSUMPTIONS

1.1. Mobile Networks

When an area divided into many geographical coverage zones, named cells, and this cells connected with each other wirelessly through radio links and channels [28]. This kind of connection called cellular network related to the smallest structure in this network which is the cell. As we divide the mobile network logically in to theses cellular cells, we also can assert this division process physically by using BS in every cell. The BS serves its cell (or more than one cell) by means of support its coverage area with a radio band to communicate the UEs (mobile telephone or smartphone) in its cell zone each other [29]. The connection between the UE and the BS needs two radio links to be done; link from the site to the user called Downlink (DL) transmission link and in opposite way there is Uplink (UL) transmitting link to supply the connection from the UE to the BS [28]. Figure 1.1 presents a Practical mobile network.

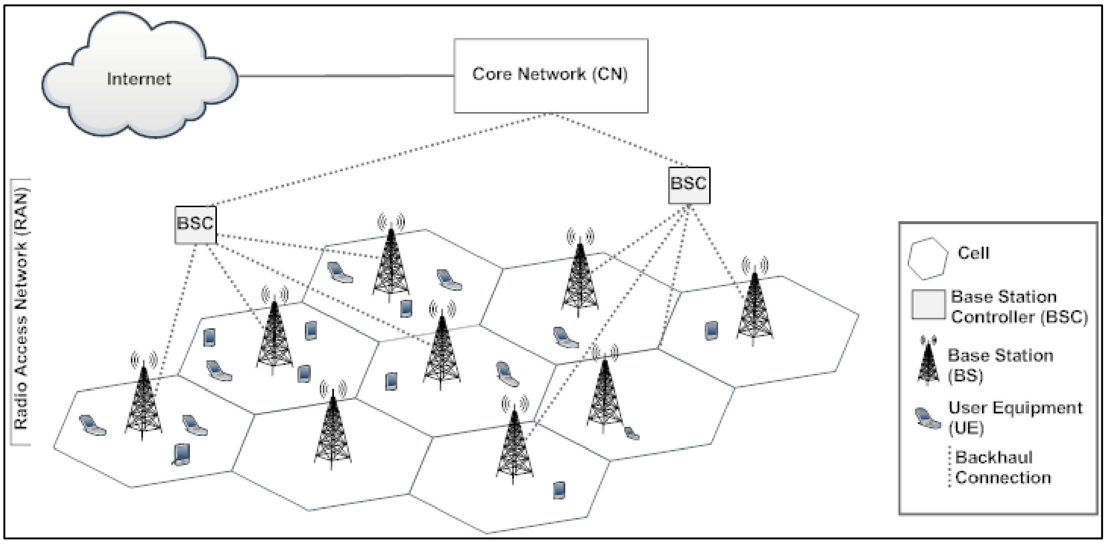


Figure 1.1. Overview of mobile network [28].

It is known that generally the geographic planning engineers in the operator network mobile company try to illustrate the coverage area in hexagonal view to study the whole network coverage easily and for many other reasons. But typically, the coverage zone can take any other shape regarding of the power that the BS can transmit with, the height of the antenna of the site and the real geographical status of the studied network [28, 29].

So, the coverage areas of the cells differ from each other and we can classify the cells from the widest coverage area to the smallest one as macrocells, microcells, picocells and femtocells. In rural areas and highways the macrocells are deployed because of their large coverage that can cover zone up to 10 kilometers. When the traffic and user get denser, the microcells are more typical to be illustrated because of the radius of this cells which is about one kilometer. Because of its small coverage, about 200 m, picocells are used in shop-malls and subways. At the last, in homes and offices the femtocell with its coverage, that is less than 100 meter, can work properly in this indoor environment.

Base Station Controller (BSC) takes the responsibility of managing some BSs and connect them to the Core Network (CN) which is serve the functionality of call process and traffic managing between other entities in the mobile network [29]. The radio channels, BSs and BSCs in a cellular network provide what we call it Radio Access Network (RAN) which can gather the traffic from the UEs and transfer it to the CN that will transmit to the public network of the studied mobile network [28].

Handoff management could be a main process that cellular networks should be supported with and using this function the network can provide its users s with mobility and support them with connectivity under satisfied QoS parameters. Thanks to handover (handoff function) for allowing the call to be up and to be continued when the UEs move through different sites in the network. When a UE established a call or a data session under the coverage of one BS and enter the coverage area of another BS the Handoff function is done to transfer this traffic to CN and to forward it to that new BS. Hand off is split into two classes, hard handoffs and soft handoffs [28]. In hard handoff, the CN delete the radio links that established with the old BS then establish a new radio channels with the new BS. But in soft handoff, throughout the handoff process, each old established resources and new ones will be used. In point of view of the RAN networks, there are also different two classes which are horizontal handoffs and vertical handoffs. When the user change between completely different coverage zones of the same RAN network, the horizontal handoff occurs

[28]. Otherwise, vertical handoff happens once a user move through two different Radio Access Networks (RANs) [28].

A lot of people think wrongly that Long Term Evolution (LTE) is an access technology used in the fourth generation networks. Although that LTE is a member of third Generation Partnership Project (3GPP) family (release 8) but also it plays an important role to fulfill the communication requirements for fourth Generation (4G) mobile networks [30]. LTE technology provide the network with data downloading in a speed of 100 Mbps at least and 50 Mbps in uploading link, less latency and also more spectrum efficiency than the other technology like HSPA+ in the third generation (3G) [30, 31]. A new radio techniques are used in LTE networks. Since in DL way Orthogonal Frequency Division Multiple Access (OFDMA) is used, the Single Carrier Frequency Division Multiple Access (SC-FDMA) in UL way [28, 31]. The architecture of the system in any LTE network is created from two different layers. The first part is Evolved UMTS Terrestrial Radio Access Networks (E-UTRAN) which can be studied as a RAN with many evolved nodeBs (eNBs) [31] that can also use a new technique to increase the capacity which called MIMO [28]. The second part is System Architecture Evolution (SAE) which is the CN node to serve IP-based services. To fulfill the necessities of International Mobile Telecommunications-Advanced (IMT- Advanced), LTE-Advanced (LTE-A) is created as the next evolution for LTE and is classified absolutely as 4G network [30]

1.2. State-of-the-art Issues of 5G Wireless Systems

At the time, when G. Marconi, an Italian discoverer, opened the trail of recent day wireless transmissions by communicating the letter “S” as magnetism waves on a distance of three kilometers as a three-dot Morse code, the new era of wireless communications has begun. When this exceptional breakthrough, wireless communication has begun to be key part of present society providing the ever-present connectivity [32]. It absolutely was less than some decades since mobile wireless communications were introduced with the primary generation (1980’s) – voice-only communication systems. Over the last few decades, the globe has witnessed gradual, however steady evolution of mobile wireless communications towards second (circuit switching systems), third (utilizing both circuit and packet switching systems), fourth and currently fifth generation (all-IP) wireless networks, that are using packet switching. Together with mentioned factors, approaches also differentiate between commissioned spectrum and unauthorized spectrum [33]. looking back to the history, all four recent generations of cellular systems are evolved over more or less 10-year crossed cycles and so, several expect that the following major evolution in wireless communications – the fifth generation – are enforced and totally deployed around 2020 and on the far side [34]. Any large real-world preparation is usually preceded by thorough analysis stage and since we, as a search society, are presently around four years before the expected roll out of next-generation 5G mobile systems, it's not stunning that 5G is that the most turbulent topic among analysis community today with many scientific articles indexed by international databases each year. The key of such extreme interest lies within the anticipated revolutionary character and high nonuniformity of the future 5G network’s design combining the aspects of emerging ultra-high-frequency spectrum access, hyper-connected vision, new application-specific needs and much more [33].

A quick inspect recent wireless network statistics reveal that international mobile traffic grew sixty three in 2016 and nearly half a billion (429 million) mobile devices and connections were added in 2016 [35]. Globally, sensible devices delineate forty six of the whole mobile devices and connections in 2016; they accounted for eighty nine of the mobile information traffic. Another fascinating finding is that smartphones represented only forty five of total mobile devices and connections in 2016, however delineate eighty one of total mobile traffic. Cisco’s Visual Networking Index (VNI) forecasts that by 2021, nearly three-quarters of all devices connected to the mobile network will be “smart” [35].

Based on the above mentioned facts, 5G is introducing a breakthrough shift, barely comparable with previous generations, supported fully new technologies and brilliant innovations that transcend our current imagination.

1.2.1. 1000x capacity gains for 5g networks

Both industry and academia have described the requirements of 5G wireless networks, which will support one thousand-fold capacity gains and connections for at least 100 billion devices with extremely low latency. Deployment of these networks is expected to commence in 2020. In particular, 5G radio access will be built upon both innovative radio access technologies and evolved existing wireless techniques (such as LTE, GSM and WiFi), and it will realize networks capable of providing zero-distance connectivity between people and machines [36].

Besides the network capacity, more diversified requirements are put forward for 5G networks, including 1) low energy and cost, 2) enhanced security and privacy, and 3) lower latency [37]. Among all those requirements, the most prominent one is the 1000x capacity gains, which will be achieved through the combined gains in three categories:
More spectrum, higher spectral efficiency and dense deployment.

As illustrated in Figure 1.2, more spectrum means larger bandwidth, which can be achieved by utilizing new spectrum or re-farming spectrum with cognitive ratio techniques. Higher spectral efficiency represents a wide range of techniques mainly refers to multiple-input multiple-output (MIMO) techniques.

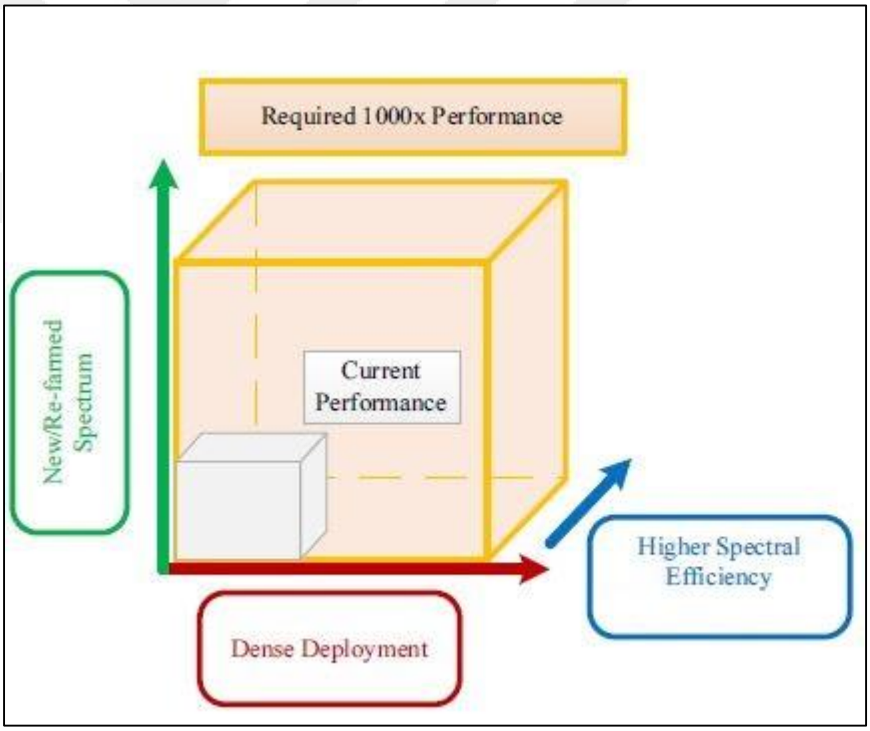


Figure 1.2. Illustration of the capacity gains from different categories [37].

Dense deployment indicates deploying more BSs for spectrum reuse gains. Throughout this thesis, we mainly focus on one aspect, which is dense deployment of the network. In the following, we will briefly introduce the concepts of MIMO Techniques and cell densification.

1.2.2. MIMO Techniques

MIMO techniques, where transmitters and receivers are equipped with multiple antennas, are a key breakthrough in wireless communications. There are three main performance gains from MIMO techniques: 1) spatial diversity, 2) interference nulling and 3) spatial multiplexing. Link reliability can be improved by spatial diversity techniques [38], which involves the processing of multiple independent copies of the same signal. Interference nulling can be achieved by sending signals in the subspace orthogonal to the channels to the undesired receiver. Spatial multiplexing involves the transmission of multiple streams across multiple transmit antennas. The streams can be data streams to a multi-antenna user or to multiple users simultaneously, or it can be the jamming noise to disturb nearby eavesdroppers. The concepts of massive MIMO [39] and full-dimension (FD) MIMO, proposed in recently years, are the applications of spatial multiplexing. For example, in very recent 3GPP standardization of FD-MIMO, a BS can support 64 antennas in a 2D array to communicate simultaneously with 32 mobile users [40].

1.2.3. Cell Densification

From 1G to 4G, the majority of capacity gains in cellular networks actually came from shrinking cell sizes. To exemplify, in the past 50 years, about a 1600x capacity increase is attributed to the smaller cell size, which is astonishing compared with the about 5x capacity increase from better modulation schemes, or about 25x from more spectrum [41]. However, to meet the capacity requirement in 5G networks, a more aggressive spectrum reuse is needed rather than continuing to shrink current macro cells, due to their high building and operating costs. In addition, the increasing demands from indoor users and indoor services require short-distance indoor access points, which usually have low-power and are called small cells. Basically, the small cells usually have lower deployment costs, smaller transmit power, and can be deployed based on the capacity demand [42].

A network consisting of various types of base stations (BSs), such as macro cells and different types of small cells, is called a heterogeneous network (HetNet). As a promising solution for 5G networks, HetNets have been stated in release 10 [43] of

3GPP standardization, as well as being under wide investigation in both industry and academia.

1.3. Small cells

To serve the UEs in HotZones (such as offices and shop-malls) with high data transmission rate, small cells are preferred to be used in HetNets enhancing the capacity and improving the efficiency of spectrum and energy. Small cells generally are the BSs with low transmit power, ranging from 100 mW to 2 W, and therefore have smaller coverage area comparing to that of macro cells There are three models of small cell according to its transmit power and the size of the coverage area that can serve; microcell, picocell and femtocell. It's known that whenever coverage area of a small cell get smaller, the SBS of this cell transmits with less power. Micro BSs have a coverage range of less than 1 km. The range size of a Pico BSs is shorter and it is about 200 m. Femto BSs have the shortest coverage range size of less than 100 m. There is also a type of solution which is called distributed antenna system (DAS) using one radio controller that can powers several antennas [44].

In indoor environment such as homes and offices a fully featured small BS (SBS) typically deployed. Using internet connections like DSL, the SBS generally connects to the CN [45, 46]. The deployment of small cell has gained wide attention not only in the cellular manufactory but also in the society of the academic researchers due to their important benefits such as capacity enhancement, coverage improvement and traffic offloading in the network [47, 48]. It is not surprising if we explore that the number of installed macrocells in the mobile networks nowadays is less than the number of small cells that already deployed [46]. A typical femtocell deployments is shown in Figure 1.3.

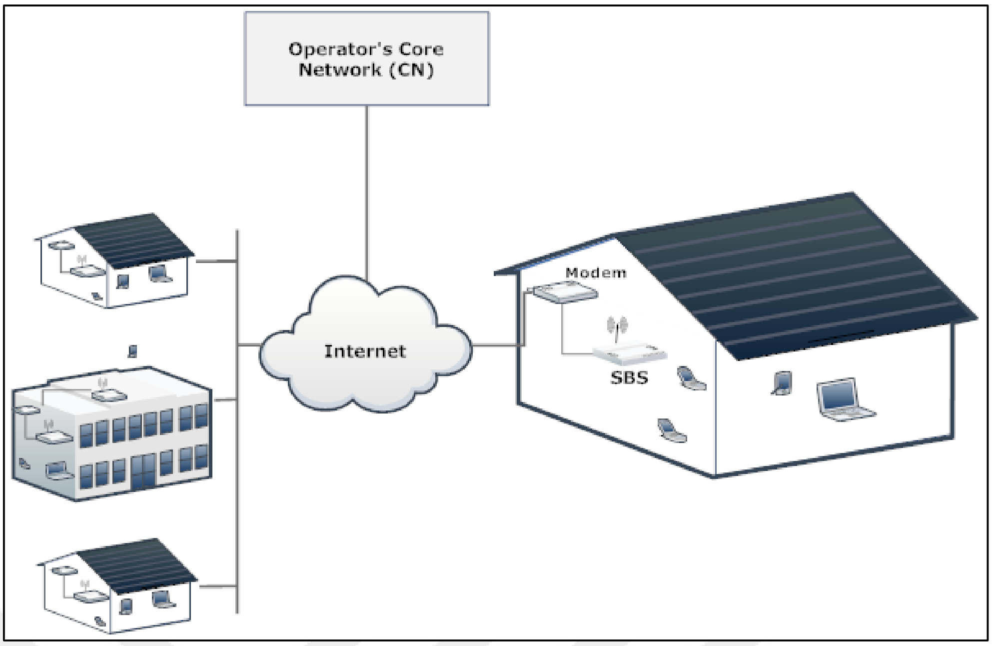


Figure 1.3. Typical femtocell deployment [45].

1.3.1. Small cell deployment methods

Small cells could be configured in many ways depending on accessibility and radio spectrum assignment [49].

- Depending on Accessibility:

Access management is one of the most important specifications of Small cells. Closed access mode, open access mode and mixed access mode are the common modes of access management of Small cells deployment [50, 51].

- Closed Access Mode: in this mode, especially for femtocells, there is a list called Access control List (ACL) which specifies the users that can be served by the small cell in a Closed Subscriber group (CSG).
- Open Access Mode: in airports, malls or hotspots any user should get the service from the small cell (especially picocell) without any restrictions. This mode additionally called as Open Subscriber group (OSG).
- Mixed Access Mode: in this mode, some of CSG users are served by already reserved resources for them and the remaining resources are available to be used by the other users in OSG.

- Depending on Radio Spectrum Assignment:

There are three aspects to share the frequency spectrum between the small cells and macrocells in HetNets [52-54].

- Dedicated approach: the macrocells and small cells will separately use completely different frequency bands in this approach
- Co-channel approach: the whole accessible spectrum bands will be shared by the macrocells and small cells.
- Partial co-channel approach: in this approach, a part of the frequency bands will be used special by macrocell and the remaining part of the frequency bands will be shared by the macrocells and small cells.

In this thesis we consider the dedicated approach to remove the possibility of frequency interference.

1.3.2. Deployment challenges

In spite of several advantages and benefits of HetNets deployment, it additionally includes its challenges and problems. These challenges and issues have to be managed for productive preparation of small cells. Some of the most relevant problems include:

- Auto configurations and Self Organization Network (SON): SBS are deployed as plug-and-play devices as a Consumer Premise Equipment (CPE), so it shall integrate itself into the cellular network without user intervention [28, 55]. Hence, different SON and auto configuration algorithms and techniques are needed.
- Frequency interference: when a lot of users deploy their small cells (such as femtocell) randomly and without planning, the mobile networks will suffer from a big challenge which is frequency interference. We can classify the frequency interference that occurs in HetNets as: co-layer interference and cross layer interference [56]. When the SBS's frequency bands interfere with that of MBS, cross-layer interference happens. Co-layer interference takes place since the SBSs interfere each other.
- Handoff management: Because of the massive number of SBS deployed in the HetNet [55] and for CSG that limits the accessibility to small cell, the handoff management (handover between SBSs, from MBS to SBS or vice versa) becomes a big challenge that need to be solved smoothly [49, 57].

- Backhaul: The RAN connects the CN in HetNet through a connection link called backhaul. Because of the various cells' needs, the backhaul access style is a serious issue that a lot of researches and studies try to overcome it [55].

1.3.3. Indoor small cells

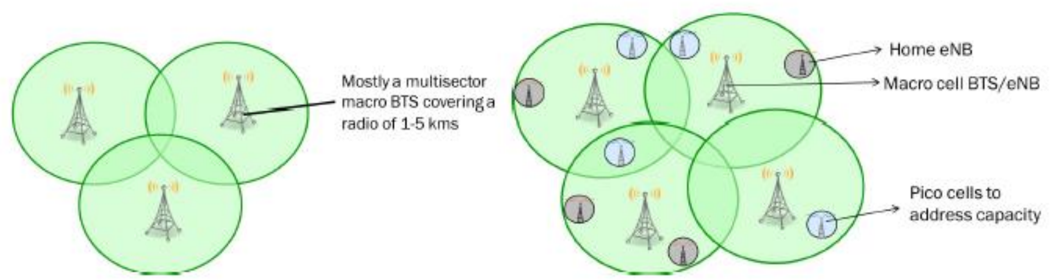
Due to loss of wall permeation, usually, indoor areas suffer from poor coverage of MBSs. In urban areas and to serve the UEs in the streets properly, the sectors of MBSs' antennas are down-tipped causing a bad coverage for UEs in the high floors of high rise residential towers. This encourages the mobile network operators to consider the small cell deployment as an effective solution in indoor areas in HetNets. In addition, according to the fact that is the top traffic demand is consumed in working-offices, train-stations and malls, the small cell deployment in those indoor areas is not an option but it will be a must.

All kinds of small cells (micro, pico and also femto) will be deployed in small cell indoor solutions. However, SBSs can also be employed in outdoor areas.

In giant workplace buildings, outlets and different jammed areas, pico BSs are often deployed on walls or within the roof. Femto BSs are more appropriate for smaller rooms and are offered as industrial home solutions. Usually, SBS supposed to be user-deployed for indoor deployment (homes, offices and subways) and connected to the CN of the operator via an internet connection (DSL, cable, etc.) [45, 46].

1.4. Heterogeneous LTE Networks

With LTE, a new term Heterogeneous Network (HetNet) was introduced. HetNets have gained significant attention for their ability to optimize the system performance, especially for uneven user and traffic distributions. LTE networks were first based on homogeneous networks consisting of macro BSs that provided basic coverage. With the involvement of pico and femto BSs, networks achieved significant improvement in terms of overall capacity and cell-edge performance. In HetNets, layers of low power pico or femto eNBs that are deployed in a less planned manner are on top of the layer of planned high power macro eNBs [58]. Cellular systems in urban areas now generally use small cells for street level transmissions at much lower power [59]. Typical 2G/3G and 4G HetNet deployments can be seen from Figure 1.4 (a) and (b), respectively.



(a) 2G/3G Typical Cellular Deployment (b) 4G HetNet Deployment

Figure 1.4. Evolution of cell deployments [58]

However, the evolution of heterogeneous networks resulted in more complicated network designs. Since, mobile users pass through small cells more quickly than a macro cell; handoffs must be processed more quickly. Moreover, location management becomes harder, as there are more cells within a given area where a user can be located [59]. Energy management is also an important issue, since activating picocells all the time may be energy inefficient. Thus, small cell eNBs should have some kind of sleep strategy.

A lot of mobile network operators have recognize that sometimes the performance improvement requires an adjustment in network topology [60]. To deliver mobile services in HetNets, a mixture of typical MBSs under laid with many SBSs is employed. HetNets shape a new model in mobile networks that provides the UEs and the networks with many benefits; enhancement in capacity and coverage, cellular data traffic offloading, and increasing the efficiency of the spectral reusing [47,54, 60]. That is the reason for considering the HetNet as the main players not only in 3GPP but also in LTE and LTE-A deployments [47, 60].

1.4.1. Spectral efficiency and energy efficiency

An important tool to investigate a network is that the Quality of Service (QoS). QoS is that the overall performance of a network, notably the performance experienced by the users of the network. To quantitatively measure QoS, many connected aspects of the network service are usually thought about, like error rates, throughput, transmission delay and noise. QoS may be considered the flexibility to produce totally different priority to different applications, users, or data flows, or to ensure a specific level of performance to a data flow. As example, a needed bit rate, delay, jitter, packet dropping chance and/or bit error rate is also secure [61]. Within the context of HetNets, we tend to think about two QoS parameters: energy efficiency that is measured in bits/J and also the average bit rate achieved by users.

To calculate the bit rate that a mobile user gets, we use the Shannon's capacity formula given by:

$$Ci = w_i \log_2 (1 + SNR_i) \tag{1.1}$$

where, w_i is the bandwidth of that user and SNR_i is the Signal to Noise Ratio of the user. SNR that a user gets can be calculated by:

$$SNR_i = P_t^{BS} PLi(di)GBSGMUPshadow /kTwi \tag{1.2}$$

where P_t^{BS} is the transmit power of the BS, $PL_i(d_i)$ is the path loss the user experiences, G_{BS} and G_{MU} are antenna gains of BS and mobile user, P_{shadow} is the shadowing with log-normal distribution, T is the temperature in Kelvin and k is the Boltzmann constant. SNR value in the receiver should be above a certain threshold for the symbols to be accurately decoded. Using these values and total consumed power, we can obtain the parameter bits per joule (bits/J), which is used as a metric for energy efficiency (EE). Bits/J is simply the ratio of the capacity to the rate of energy expenditure [62]. It is a special case of the capacity per unit cost [63]. We define EE as:

$$EE = \frac{\sum_i C_i}{P_{tot}} \text{ bits/J} \tag{1.3}$$

where the summation in the numerator is the total capacity of the network and P_{tot} is the total consumed power.

1.4.2. User distributions

We can classify the distribution of the users in the network in two ways: non-uniform (hotspot) and uniform. In hotspots, a fraction of UEs are randomly placed among the coverage space of low power cells and the remaining UEs are uniformly distributed among the macro cells but randomly [64]. On the opposite hand, uniform, UEs are randomly and uniformly distributed within the geographic coverage space of macro cells.

Since in real life mobile users are not uniformly distributed and the number of users is denser in areas such as schools, shopping malls and hospitals, hotspot is a more realistic approach than the case of uniform distribution. Depending on the time of the day, some hotspots may periodically be active or disabled. For instance, in a business center a hotspot may occur between 8am - 5pm, whereas in a shopping mall may operate between 10am - 10pm.

1.4.3. Fairness

In this study, we used equal bandwidth share that makes the users fair in terms of allocated bandwidth. Assuming that the total allocated bandwidth for the macro cell is W and the total number of users is N. Since the users are fair in terms of allocated bandwidth, each user will get a bandwidth band of W/N. To eliminate co-channel interference and to serve with better performance, all SBS are assumed to be transmitting in different frequencies [65]. Consequently, a portion of the total bandwidth is given to the SBSs to serve their users and accordingly, the bandwidth allocated to every SBS is directly proportional with the number of users within that cell.

1.4.4. Hotspot

Due to the fact that the distance between UE and the antenna of SBS is very short, the EE of the users of picocells may be sufficiently large. However, number of users in picocells may be very small; since when the users are distributed randomly, their probability of being inside a picocell is quite small. Thus, the overall effect of the picocells would not be very significant. Then, to observe the benefit of the HetNet more, we should increase the number of users in picocells. For that purpose, instead of distributing the users randomly, we should introduce a hotspot concept. The small cells serving a hotspot may require more bandwidth than a regular small cell, in order to maintain the required QoS.

In hotspot scenario, there are Nh hotspot users and $N - Nh$ random users that act like in uniform case. All hotspot users are assigned a specific picocell and work time during their creations. Then, initially, all users are again distributed randomly. When their assigned work time come, each user picks a random location from their allocated picocell and starts moving towards it. In this case, when we have taken the number of hotspot users as 1000, the maximum number of users that a picocell can get is around 10 (since we have 100 SBSs), which is a sufficient number to see the benefits of heterogeneous network as shown by simulations.

2. POWER CONSUMPTION ANALYSIS

2.1. Energy Consumption Metrics

Using the parameters that join the consumed energy with the size of studied coverage area and the amount of transferred data traffic, the energy consumption of cellular networks can be quantified clearly. Planning an energy efficient mobile network means an optimization problem which endeavors to minimize the energy consumed by the network, whereas maintaining a specific degree of quality of service (QoS). Therefore, it's necessary to think about the relationship between the metrics related to energy consumption with the parameters measuring the QoS of mobile network services. The power consumption of mobile networks (especially that of MBSs) increases when the traffic load gets larger. At the other hand, the UEs will not be satisfied with available QoS in dense environment as the interference becomes a real challenge in high traffic load (a lot of UEs) networks. In [66], the EARTH model defines two metrics, or energy consumption indices (ECIs), which are; power per area unit and energy per bit.

- Power per area unit: The power per area unit is denoted $ECI_{P/A}$. Due to the fact that the area covered by a particular deployment remains constant with varying traffic conditions, this metric is relevant for comparing different deployment scenarios. With the power supplied to the serving BSs denoted by P and the coverage area by A we can calculate as:

$$ECI_{(P/A)} = \frac{P}{A} \ [W/m^2]. \tag{2.1}$$

- Energy per bit unit: The consumed energy per transmitted bit unit is denoted $ECI_{E/B}$. Denoting the number of useful data bits transferred by the system during a time period T by B and the total consumed energy by the same time period by E, we can calculate as:

$$ECI_{(E/B)} = \frac{E}{B} \ [J/bit]. \tag{2.2}$$

In another way, we can rewrite the previous expression taking in to account that the average supplied power $P = \frac{E}{T}$ and the average bitrate $R = \frac{B}{T}$ during the time period as:

$$ECI_{(E/B)} = \frac{P}{R} \quad [\frac{W}{\frac{bit}{s}}] \qquad (2.3)$$

2.2. Base Station Power Models

The power radiated from the transmit antennas of the BS, which called transmit power, is an important metric that can affect the QoS of any wireless mobile network generally. However, to plan for a green (energy efficient) mobile network, a detailed and clear information about the amount of power that studied network consumes. Mathematically, it is clear that the BS internally consumes power for some functionality process (such as cooling or signal processing) more than what consumes in transmitter parts. A power model is a term that clarify the radiated power and the consumed power in one chart model. According to State of The Art (SoTA), part of the EARTH project, BS power model is developed to determine the energy consumption at system level. The breakdown of the power consumption of the modules in an exceedingly BS and their load dependency showed that a linear power model is extremely accurate. See [66] for additional details.

As mentioned earlier, linear power models are often employed in simulation studies of mobile network energy consumption, e.g. in [67-70] models with similar parameters as in [66] are used.

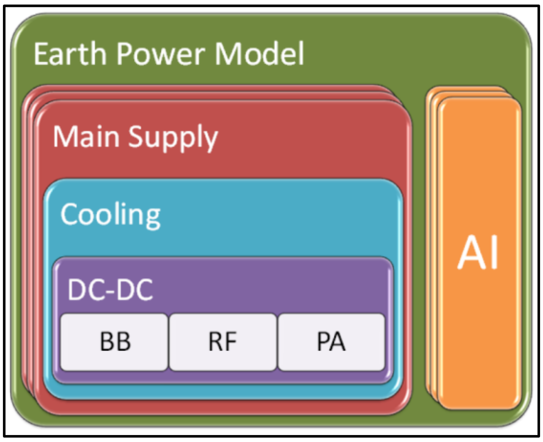


Figure 2.1. Power consuming modules in the EARTH SoTA power model [5].

Figure 2.1 portray a typical structure that is applicable to any type of BSs considered in this study. Generally, the BS consists of many transmitter and receiver (TRX) modules. The TRX module, typically, includes a main power supplier which connects the BS to the electrical power grid, cooling unit, a DC-DC power converter, an antenna a baseband (BB) module, a radio frequency (RF) module, amplifier (PA) and an antenna interface (AI) unit. The subsequent section will explain the working functionality of those modules and the way that their power consumption relies on the traffic load.

- The antenna interface: it connects the antenna with the PA. Because of different parts like feeders and filters, signals lose a little from their power. To limit the impact of feeder losses in remote radio head (RRH) units, the PA is placed near the antenna.

- The power amplifier: the PA consumes the largest part of the power in MBS because of the PA is forced to work consistently even during a non-saturated zone to avoid non-linear disfigurements resulted from the adjacent channel interference. Recently, pre-distortion technique is employed to enhance the power efficiency. Because of the PA accounts for a small part of the power consumed in SBS, commonly, there is no need to apply pre-distortion technique in SBS.

- The radio frequency module: this unit is as an analog-digital converter (ADC) for signal both in DL and UL links. The power consumption of the RF module relates to some factors like; the resolution of the ADC, the reserved bandwidth and also the permitted signal to noise and distortion ratio (SINAD).

- The baseband module: different digital operations (such as signal processing, digital up and down conversion and OFDM modulation) are accomplished in this module. It is also plays as a connection link to the backhaul network. The power consumes in this module depends on the TX/RX antennas, the algorithms applied in the processors of those antennas, and the bandwidth of signal.

2.3. Load Dependency

The power consumption of a BS is a result of the power consumed in its modules. In another word, the BS will consume much power when its resources are used totally. Figure 2.1 show the distribution of consumed power between the modules in the BS. The percentage of the power consumption in the PA module changes considerably between BS types. Since in MBS this percentage is about 75%, whereas it is just 35% in SBS. What is more, just the PA module consumes power according to traffic load. Compared to the PA, The symmetry between the power consumption and load variation in the other modules in BS is incredibly little and sometimes negligible. Consequently, the load dependency is extremely apparent in MBSs. whereas in SBS, the power consumption is approximately constant and depends on traffic load.

2.4. Network Topology

Generally, MBSs provide the underlying coverage of LTE networks and they are commonly deployed in groups of three sector-antennas in the BS site. The BSs are usually deployed in a hexagonal grid with a coverage of 120 degrees per sector. Output power of a macro BS can vary between 5 and 40 W [71]. The inter-site-distance (ISD) is the distance between adjacent sites and can range between 200 m in dense deployments and several kilometers in rural areas. Since the efficiency of mobile network links is order to meet the capacity requirements. With a sparse macro deployment, the capacity can be increased by densifying the macro deployment itself. However, with already dense macro deployments, the gains from further densification is limited [71]. Also, high demand for coverage increases in certain highly populated areas that called Hotspot areas like office areas, shopping malls and train stations. In fact, 70% of all data traffic is served to indoor users [72]. In addition, non-uniform propagation environment caused by various kinds of buildings and obstacles, that are primary made of material, will cause coverage holes wherever the signal-strength of the MBS is weak. These kinds of issues may be mitigated by deploying small cells.

2.5. Small Cell Sleep Modes

As mentioned above, and according to the power model confirmed from EARTH project, one MBS consumes power as what 100 SBS (picocell) do. The remarkable low power consumption of small cells attracts attention of mobile operator companies. Since the coverage area that a SBS can serve is typically small, the dense deployment of SBSs (to cover the whole area) will makes the total power consumed in SBS layer could not be ignored at all. However, the low power consumption of SBSs that served a dense traffic load in HotZones and indoor areas reflects as an enhancement in ‘energy per bit’ metric. As a result, the small cell deployment in HetNet will improve not only the QoS in mobile networks but also the energy efficiency especially in HotZones and high traffic load areas [67].

According to the fact that SBS consumes a fixed amount of power regardless of its traffic load, a prospect of energy saving could be achievable whenever SBS is not utilized. At this situation, we can save energy in HetNet by operate the SBS with a very low power level or switching it off completely while still maintaining the required level of QoS in the network. To implement small cell sleeping technique, a control mechanism would be applied by either central network control or by a distributed control made in SBS layer.

Usually in HetNets, small cells are deployed to get benefit in two scenarios. The first one is to enhance the QoS (especially signal strength) in areas wherever the coverage of MBS is weak and the second is to accomplish an increase in capacity efficiency in high traffic loaded areas. Distributed control is often ineffective solution for the first scenario, whereas the network may not be able to guarantee the negotiated QoS to some UEs in some SBS. Whereas, in the second scenario, a centralized decision determining the best operation mode (on/off) of the SBSs is preferable since the UEs have a coverage of the MBS at least.

A distributed algorithm could be applied keeping the SBS in idle mode for a part of time before going to sleep. But here there is an impotent question which is how and when the SBS would be switched-on again. To answer this question, there is one suggestion to employ a low-power sniffer with a specific threshold on the received signal power and when UE getting into the coverage area of the sleeping SBS, the sniffer will switch on the SBS.

2.6. Network Model

We consider a cellular network with massive number of SCs in one MC as shown in Figure 2.2. While the MBS is always active to keep large coverage (as an umbrella) and avoid any service failure, the SBSs can be active or not according to the traffic load in their coverage areas. When a SBS is active, it handles the offloaded traffic load from the MBS. Thus the traffic load of MBS can be reduced. Our scheduling scheme can also be applied in case of multiple MCs by following the same architecture design for each MC.

All of SBSs are shown as a set $\mathcal{M}$= {1, 2, 3,…, M}, and their operation modes are defined as a vector such as $\theta = [\theta_1, \theta_2, \ldots, \theta_M]$. If SBS_m is active, its operation mode θ_m equals 1, otherwise θ_m equals 0.

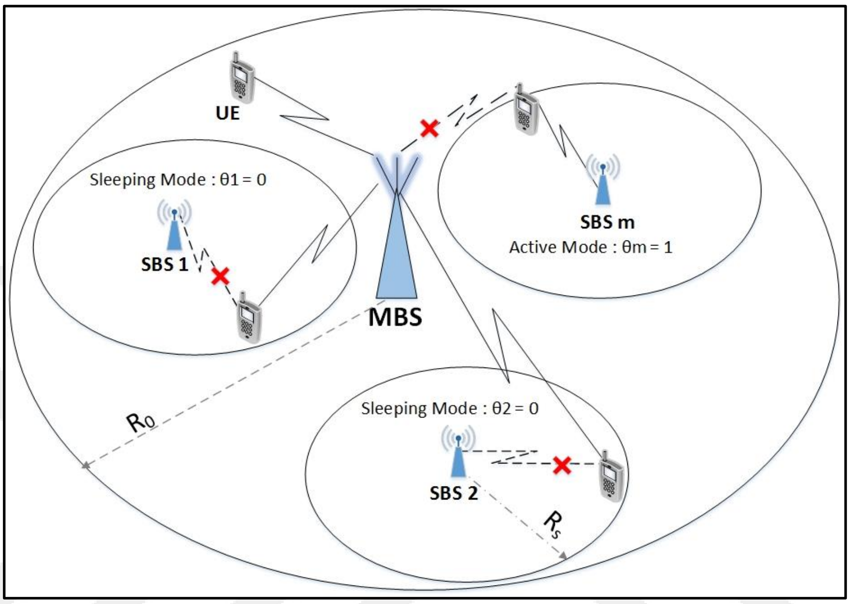


Figure 2.2. System model of the HetNet with M small cells and one macro cell.

In our system, each SC has the same radius R_s of the order of tens of meters [73, 74]. The coverage area of any SC can be calculated as $A_m = \pi R_s^2 \ \forall \, m \in \mathcal{M}$. We assume that the MBS is placed at the center point of the examined coverage area with radius R_0 (about half kilometer [74, 75]) and the SBSs are identically and independently distributed (i.i.d.) in this area. SBS_m is located at the center of its coverage area, which is entirely enclosed in the MBS's coverage area and its distance from the MBS is d_m, $\forall \, m \in \mathcal{M}$. We also define the complement area of the joint coverage of all SCs as $A_0 = \overline{\cup A_m}$, $\forall \, m \in \mathcal{M}$ We model the users' locations and the user density λ_m in the network as a Poisson Point Process (PPP), since each user is independently distributed in the HetNet and uniformly distributed within the coverage area A_m $\forall \, m \in \{0\} \cup \mathcal{M}$ [76]. The user density λ_m in the coverage area A_m is independent and different from the user density λ_n in the coverage area A_n and as in general, the user density in SBS_m is higher than that (λ_0) of MBS, forming hotspot area, $\lambda_m > \lambda_0$, $\forall \, m, n \in \mathcal{M}$. To avoid interference, it is assumed that SBSs and MBSs are operated over different spectrum bands dynamically [77] and the resulting inter-cell interference between the SBSs can be controlled well to assure the required QoS for the SBSs' users [75, 78].

2.7. Power Consumption Model

To serve small areas under high traffic load such as malls, airports, coffee shops or stadiums, the proposed solution for 5G is traffic offloading to SCs which are low-power and low-cost cells covered by SBSs. While one MBS consumes at least 712W (base power level, $\underline{P}$), the active SBS consumes only 10W if it is in active mode, and 3W when it is in inactive (sleep) mode. By using this solution, mobile operators not only serve their users with a constant QoS but also lower their costs by decreasing the MBS power consumption.

To decrease the HetNet total power consumption, the MBS offloads its traffic to the surrounding active SBSs. This will be carried out in a dynamic on/off operation scheme for the SCs to serve the offloaded traffic. When a SC goes off in this scheme, the MBS will serve not only its own users but also those within the switched off SCs' coverage area.

With respect to coverage area, location of SBSs and user density, we use different models of power consumption for both the SBSs and the MBS according to [27]. Transmit power of MBS P^t is a function of the operation modes θ of the SBS. Thus we can write the power consumption P of the MBS as:

$$P=\underline{P}+uP^t(\theta), \tag{2.4}$$

where $u > 0$ is the power utilization coefficient for the MBS. According to (1), P starts with a base level $\underline{P} > 0$ and increases linearly with the transmit power P^t according to its traffic load [5]. The power consumption of SBSs does not depend on their traffic load. For each SBS_m, the power consumption p takes two values according to the operation mode θ_m of SBS_m [5, 25]:

$$p=\begin{cases} p_1=\underline{p}+vp^t, & \text{if } \theta_m=1 \text{ (Active/on)} \\ p_0, & \text{\&if } \theta_m=0 \text{ (Sleeping/off)} \end{cases} \quad \forall\, m \in \mathcal{M} \tag{2.5}$$

where p_1 and p_0 are the SBS's power consumption in the active and sleeping modes, respectively. The power consumption of SBS_m when it is active, similar to MBS' power consumption model, starts with base level $\underline{p} > 0$ and increases linearly with its transmit power $p^t > 0$ by the utilization coefficient $v > 0$. However, unlike the MBS, the dominant power consumption component in the SBS is no longer the power amplifier [79]. Also, because of short-range communication in the SBS's region, the transmit power increases slightly with traffic load. For example, as shown in [5, 25], if the traffic load increases from 80% to 100%, the transmit power will increase only 0.07 W. Therefore, p^t in the SBS is assumed to be a traffic-independent component.

As we see in (1) and (2), the power consumption in the MBS and the SBSs is a function of θ. Therefore, if we denote the number of active SBSs as $H(\theta)$ and define $\Delta p = p_1 - p_0$, we can write the total power consumption of the HetNet as:

$$P^{Het}(\theta) = \underline{P} + uP^t(\theta) + Mp_0 + H(\theta)\Delta p \,. \tag{2.6}$$

As the MBS's transmit power $P^t(\theta)$ is related to the traffic load of the MBS and the switched off SBSs, in the following subsection we will try to transform the $P^t(\theta)$ component to an accurate mathematical expression to calculate the optimal P^{Het}.

In order to compare our algorithms with that of [37] , We assume that the MBS serves $K = \lambda_0 \pi R_0^2 - \lambda_0 M \pi R_s^2 + \sum_{\{m|\theta_m=0\}} \lambda_m \pi R_s^2$ users that are outside all active SBSs, given in the set $K = \{1, 2, \ldots, K\}$. To model the downlink wireless channel between the MBS and its users, we consider not only short-term fading but also large-scale fading. While short-term fading is modelled with Rayleigh fading coefficient h_k with unit mean, large-scale fading is modelled as distance-dependent path loss. The received power P_k^r at user k depends on the distance r_k between the user k and the MBS. When the distance is less than the reference distance r_0, the received power decreases by a fixed path loss $D > 0$. Otherwise, the received power involves an additional factor depending on the path loss exponent a, which is a property of the propagation environment. Thus we can write the received power of user k as:

$$P_k^r = \begin{cases} P_k^t \, h_k D, & \text{if } r_k < r_0 \,, \\ P_k^t \, h_k D \left(\frac{r_k}{r_0}\right)^{-a}, & \text{otherwise.} \end{cases} \tag{2.7}$$

where P_k^t is the transmit power from the MBS to user k. Although it is not realistic, for the sake of simplicity, we consider the fairness concept to serve all the users in the network with the same level of QoS by applying the equal-bandwidth-sharing scheme such that the available bandwidth for each user is W/K where $W(Hz)$ is the total spectrum bandwidth allocated to the MBS [24, 76]. For a given outage probability ε, the MBS should guarantee a QoS with bit rate no smaller than the predefined value $b > 0$ bits/sec for each user in the MBS's coverage area. According to [24], we can write the required MBS transmit power to user k that achieves supposed QoS as:

$$P_k^t = \begin{cases} \frac{\Gamma N_0 W}{-D \ln(1-\varepsilon)} \times \frac{2^{\frac{Kb}{W}}-1}{K}, & \text{if } r_k < r_0 , \\ \frac{\Gamma N_0 W}{-D \ln(1-\varepsilon)} \times \frac{2^{\frac{Kb}{W}}-1}{K} \times \left(\frac{r_k}{r_0}\right)^a, & \text{otherwise.} \end{cases} \quad (2.8)$$

In (5), $\Gamma \geq 1$ is the loss of capacity due to modulation and coding operations and N_0 is the spectral power density of the additive white Gaussian noise (AWGN). From (5) we observe that the required transmit power increases with both the distance r_k and the number of users, K, in the area defined as $A_0 \cup_{\{m|\theta_m=0\}} A_m$. K is a Poisson RV with mean $\mu=\lambda_0 \|A_0\| + \sum_{\{m|\theta_m=0\}} \lambda_m \|A_m\|$ and its probability mass function is given as $\Pr[K=n] = \frac{\mu^n}{n!} e^{-\mu}$. Likewise, r_k is an (i.i.d.) RV with probability distribution function, $f(r_k)=\frac{2\, r_k}{R^2}$, $R \geq r_k \geq 0$.

Due to the randomness of r_k and K in the network, P_k^t is also a RV and we can rewrite it as a function of K and r_k as $P_k^t(K, r_k)$. If we calculate the summation of $P_k^t(K,r_k)$ over all users in the considered coverage area and derive the expectations over K and each r_k, we can fulfill $P^t(\theta)$ as [22]:

$$P^t(\theta)= E_K \left[E_{\, r_1,\, r_2,\, \dots ,r_K} \left[\sum_{k=1}^{K} P_k^t(K,r_k)\right]\right] \triangleq E_K \left[K\, E_{r_k} \left[P_k^t(K,r_k)\right]\right]. \quad (2.9)$$

According to [30] and [37], we can obtain $P^t(\boldsymbol{\theta})$ as a product of $T(\theta)$, which gives the traffic load in the area outside all the active SBSs' coverage areas, and $Z(\theta)$, which indicates the MBS's average transmit power for an individual user:

$$P^t(\theta)= T(\theta)\, Z(\theta), \quad (2.10)$$

$$T(\theta)= \frac{\Gamma N_0 W}{-D \ln(1-\varepsilon)} \left[\exp\left[\left(2^{\frac{b}{W}}-1\right)(K)\right]-1\right], \tag{2.11}$$

$$Z(\theta)= \frac{\frac{2\pi\lambda_0}{a+2}\left(R_0^{a+2}+ \frac{ar_0^{a+2}}{2}\right) -\lambda_0 \sum_{m=1}^{M} \lambda_m \pi R_s^2 d_m^a + \sum_{\{m|\theta_m=0\}} \lambda_m \pi R_s^2 d_m^a}{r_0^a K}. \tag{2.12}$$

It is easy to see that the transmit power of the MBS, $P^t(\theta)$, increases with the traffic load served by the MBS. Consequently, to reduce its power consumption, the MBS offloads its traffic load to the surrounding active SBSs. However, the power consumption resulting from switching on a lot of SBSs cannot be ignored as well. As a result, to save the total power consumption of the HetNet, an optimal trade-off between reducing the MBS's power consumption and reducing SBSs' power consumption should be obtained by adapting the operation modes of all SBSs in the HetNet. In the following section we will reform the minimization problem of the HetNet's power consumption $P^{Het}(\theta)$ entirely by considering the general case with non-uniform user distribution in the HetNet since $\lambda_m \neq \lambda_n \ \forall\ m,n \in \{0\} \cup \mathbf{M}$.

2.8. Daily Traffic Load Profile

It is known that not all subscribers are always active and the traffic load (number of active users) varies along the day between peak and off-peak hours. Accordingly, we assume that the traffic load in the examined network changes according to the European profile [5, 26] shown in Figure 2.3, such that the daily maximum traffic load, between 20:00 and 24:00, is about 6 times higher than the minimum one, between 04:00 and 08:00.

To satisfy the desired QoS of the users in the examined network, we assume that the operating point of the system saturates when the user density of the MBS, λ_0, reaches its maximum value, $\lambda_0(\max)$, then transmit power of the MBS reaches the maximum value P^t_{max} and after that the system becomes infeasible. Accordingly, if, for any reason, the traffic load exceeds the predefined level that the system is designed to deal with, $\lambda_0 > \lambda_0(\max)$, the system applies an access control to randomly prevent a portion of users from accessing the HetNet such that the system will be able to serve the remaining users and satisfy their QoS.

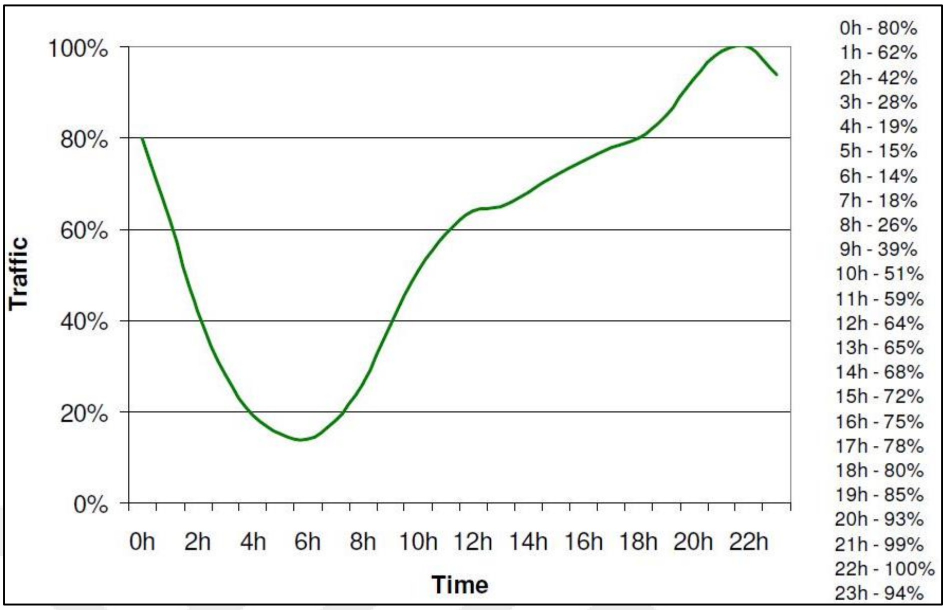


Figure 2.3. Normalized average daily data traffic profile [26].

3. SMALL CELL SLEEPING ALGORITHMS

3.1. Small Cell Scheduling

Let us assume the SCs are designed to serve different hotspot areas where λ_n , $\lambda_m > \lambda_0$ and $\lambda_m \neq \lambda_n$ $\forall$ m,n$\in$M. By substituting (8) and (9) in (7), we obtain $P^t(\theta)$. Then by substituting (7) in (3), we can find the HetNet power consumption. When the traffic load suddenly becomes too large, although all SBSs are active θ=[1, 1, …, 1], the MBS's maximum transmit power, P^t_{max}, cannot satisfy the QoS of the users and the system becomes infeasible. Therefore, to solve the (P1) problem (stated below) thoroughly for a feasible solution, we assume that the traffic load always fulfills $P^t(\theta)\big|_{\theta=[1, 1, \ldots, 1]} \leq P^t_{max}$. Taking into account the fact that the $P^t(\theta)$ of the MBS is constrained by the maximum transmit power P^t_{max} [5], it is easy to write the minimization problem of HetNet power consumption as [26]:

(P1):

$$\min_{\theta} P^{Het}(\theta) = \underline{P} + uP^t(\theta) + Mp_0 + H(\theta)\Delta p,$$

$$\text{s.t } P^t(\theta) \leq P^t_{max},$$

$$\theta_m \in \{0, 1\}, m \in \mathcal{M} \ ,$$

In the following subsections, we provide the proposed algorithms to find the optimal modes combination of the SCs that minimizes the total power consumption of the HetNet. Then, taking the limitedness of the resources of the SCs into account, we will investigate the realistic case of dense network in which offloading from saturated SCs (those operating at maximum capacity) to the MBS takes place.

3.2. Small Cell Sleeping Proposed Algorithms

To find the optimal solution for (P1), we have to go through the binary states of all SBSs with 2^M combination probabilities. For example, if the MC has just 100 SBSs in its coverage area, 1.26×10^{30} combinations should be checked! However, in this paper, we propose an efficient and appropriate way to solve this NP-hard problem by adopting three different algorithms to find the near-optimal operation modes of the SBSs in the HetNet where users are non-uniformly distributed.

3.2.1. Distance based operation algorithm

As shown in (3.8), it is easy to see that the transmit power from the MBS to user k, P_k^t, increases exponentially with the distance between the MBS and the user k. As we mentioned above, the MBS is responsible for serving the users located in the switched off SBS's region. Consequently, to decrease the power consumption of the MBS, it is preferred to switch off the SBSs that are closest to MBS. Thus we will record the SBSs in a new set $\mathcal{M}_1$ according to their distances from MBS in increasing order $\mathcal{M}_1 = \{1, 2, 3,\ldots, M\}$ such that if we have two indexes m, n and $m < n$, then $d_m < d_n$. Thus by assuming that the initial modes of all SBSs are active, we can switch off the SBSs gradually according to the order of their indexes in the set $\mathcal{M}_1$. In real SBS, transition from one state to the other requires some time (delay) and energy that we ignore for its triviality and simplicity.

By switching off SBS_m, we will decrease the power consumption of SBS_m by $\Delta p = p_1 - p_0$. On the other hand, since the MBS has to serve the users within SBS_m's coverage area, its power consumption will increase by $\Delta P_m = u\left(P^t(\acute{\theta}) - P^t(\theta)\right)$, where $P^t(\acute{\theta})$ is the MBS's transmit power after we switch off SBS_m. We can rewrite ΔP due to switching off of SBS_m as:

$$\Delta P_m = uP^t\left(\left[0_{1\times(m-1)}, \theta_m, 1_{1\times(M-m)}\right]\right)\Big|_{\theta_m=0} - uP^t\left(\left[0_{1\times(m-1)}, \theta_m, 1_{1\times(M-m)}\right]\right)\Big|_{\theta_m=1} \quad (3.1)$$

While switching off the SBSs in $\mathcal{M}_1$ gradually, the power consumption of the SBSs decreases and the power consumption of the MBS increases. Therefore, the SBSs' switching off process is constrained with the saturated level when the saved power at the SBSs' side is less than the consumed power at the MBS. So the gradual switching off of the SBSs has to stop at SBS_m if no power is saved when we switch SBS_{m+1} off (i.e., $\Delta P_m - \Delta P_{m+1} < 0$). Also, since the transmit power of the MBS cannot exceed its maximum value P_{max}^t, the SBSs deactivating process has to stop when P_{max}^t is reached. According to the pseudo-code shown below, the computational complexity of the distance based operation algorithm is $O(M)$.

Algorithm 1: Distance Based Operation Algorithm

Record all SBSs in a new set $\tilde{\mathcal{M}}$ in increasing order of $\boldsymbol{d_m}$
$\boldsymbol{\theta_s} \leftarrow \boldsymbol{1_{1xM}}$
for $\boldsymbol{all\ SBSs\ n} \in \{\boldsymbol{1}, \boldsymbol{2}, \ldots \boldsymbol{M}\}$
    $\boldsymbol{\theta_x} \leftarrow [\boldsymbol{0_{1xn}}\ \boldsymbol{1_{1x(M-n)}}]$
    if $\boldsymbol{P^{Het}}(\boldsymbol{\theta_x}) < \boldsymbol{P^{Het}}(\boldsymbol{\theta_s})$ & $\boldsymbol{P^t}(\boldsymbol{\theta_x}) \leq \boldsymbol{P^t_{max}}$
        $\boldsymbol{\theta_s} \leftarrow \boldsymbol{\theta_x}$
    end if
end for
return $\boldsymbol{\theta_s}$, $\boldsymbol{P^{Het}}(\boldsymbol{\theta_s})$

Figure 3.1. Distance based operation algorithm

3.2.2. Density based operation algorithm

In the previous algorithm, the deactivation decision was made according to the distance between the MBS and the given SBS. It may not be efficient to switch off an SBS which serves much more users than the others do, only because it is closer to the MBS than the other SBSs. Or if there are some SBSs at the same distance from the MBS, the algorithm does not tell which SBS is preferred to be switched off first.

It is observed from (3.10) that the transmit power $P^t(\theta)$ for the MBS increases with the traffic load $T(\theta)$ outside all the active SBSs. For a given network, the part $\lambda_0\pi R_0^2$- $\lambda_0 M\pi R_s^2$ of the number of users K has a fixed value. So, according to(θ), $T(\theta)$ increases as $\sum_{\{m|\theta_m=0\}}\lambda_m\pi R_s^2$, the number of users in the switched off SBSs' region, increases. Therefore, it is clear that λ_m is an important criterion in the decision for switching off SBSs. The SBSs that have the least traffic load have a higher priority to be switched off because the MBS will not consume much power to serve this small traffic load.

We record the SBSs in a new set $\tilde{\mathcal{M}}$ = {1, 2, 3… M} in the increasing order of their user densities such that if we have two indexes m, n and $m < n$, then $\lambda_m < \lambda_n$. As in the distance-based operation algorithm, by assuming that the initial modes of all SBSs are active, we can switch off the SBSs in the set $\tilde{\mathcal{M}}$ gradually according to the order of their indexes. The SBS deactivation process should be stopped when there is no more saved power or when the transmit power of the MBS is equal to its maximum value. Also we can obtain two thresholds λ_{on} and λ_{off} of the user density

λ_m in SBS$_m$ where λ_{on} is the user density threshold that if $\lambda_m > \lambda_{on}$ then SBS$_m$ should be active. In the same way, if $\lambda_m < \lambda_{off}$, SBS$_m$ is preferred to be switched off [27]. The computational complexity of the density based operation algorithm is $O(M)$.

Algorithm 2: Density Based Operation Algorithm

Record all SBSs in a new set $\boldsymbol{\mathcal{M}}$ in increasing order of $\boldsymbol{\lambda_m}$
$\boldsymbol{\theta_s} \leftarrow \boldsymbol{1_{1xM}}$
for $\boldsymbol{all\ SBSs\ n} \in \{\boldsymbol{1}, \boldsymbol{2}, \ldots \boldsymbol{M}\}$
    $\boldsymbol{\theta_x} \leftarrow [\boldsymbol{0_{1xn}}\ \boldsymbol{1_{1x(M-n)}}]$
    if $\boldsymbol{P^{Het}}(\boldsymbol{\theta_x}) < \boldsymbol{P^{Het}}(\boldsymbol{\theta_s})$ & $\boldsymbol{P^t}(\boldsymbol{\theta_x}) \leq \boldsymbol{P^t_{max}}$
        $\boldsymbol{\theta_s} \leftarrow \boldsymbol{\theta_x}$
    end if
end for
return $\boldsymbol{\theta_s}$, $\boldsymbol{P^{Het}}(\boldsymbol{\theta_s})$

Figure 3.2. Density based operation algorithm

3.2.3. Distance-density based operation algorithm

The distance based operation algorithm is applicable when the variation of the user densities of the SBSs is rather small. Otherwise, if the traffic load of the SBSs varies widely, the density based operation algorithm is a more effective solution only if the MBS's coverage area is relatively small so that all of the SBSs are close to each other and to the MBS. Taking the randomness of the user density λ_m and the distance between SBS$_m$ and MBS referred to as d_m into account, we propose in distance-density based operation algorithm an energy-efficient way of obtaining an optimal operation mode of the SBSs in the examined HetNet.

As shown in (8) and (9), the MBS is responsible for serving not only its own users in the area A_0, $\underline{L} = \lambda_0 \pi R_0^2 - \lambda_0 M \pi R_S^2$, but also the users within the deactivated SBSs' coverage areas, $L = \sum_{\{m|\theta_m=0\}} \lambda_m \pi R_S^2$, so we can divide the MBS's traffic load into two parts $\underline{L}$ and L. Since the first part $\underline{L}$ has a fixed value, we can write the power consumption of the MBS as a function of L as $P(L)$. As we see above, when we switch SBS$_m$ off, we can save its power but the MBS will consume more power to serve SBS$_m$'s traffic load. We denote the total HetNet power saving achieved by switching SBS$_m$ off as $\Delta P_{HetNet|\theta(m)=0}(L)$ and formulate it as [27]:

$$\Delta P_{HetNet|\theta(m)=0}(L) = \Delta p - \frac{u\Gamma N_0 W}{-D\ln(1-\varepsilon)r_0^{a}} \times \frac{\exp\left[\left(2^{\frac{b}{W}}-1\right)\left(\underline{L}+L\right)\right]-1}{\left(\underline{L}+L\right)} \times \lambda_m \pi R_s^2 d_m^a \qquad (3.2)$$

Algorithm 3: Distance and Density Based Operation Algorithm

```
Record all SBSs in a new set 𝓜s in increasing order of λ_m
  L̲ ← λ_0 × (A_m − M A_s)
  L ← 0
  m ← 0
  vector_max ← empty set
  θ_s ← 1_{1xM}
  θ_x ← 1_{1xM}
for all SBSs i ∈ {1, 2, ... M}
    for all SBSs j ∈ {1, 2, ... M}/{vector_max}
    ΔPHetNet(j) ← Δp − (uΓ N_0 W / (−D ln(1−ε) r_0^a)) × ((exp[(2^(b/W) − 1)(L̲+L)] − 1) / (L̲+L)) × λ_j π R_s^2 d_j^a
        Q(j) ← ΔPHetNet(j) / (λ_j π R_s^2)
    end for
    find the Index_max of max value of the vector Q
    L ← L + A_s λ_{Index_max}
    θ_x (Index_max) ← 0
    vector_max ← vector_max ∪ {Index_max}
    if P^Het(θ_x) < P^Het(θ_s) & P^t(θ_x) ≤ P^t_max & Q(Index_max) ≥ 0
        θ_s ← θ_x
    end if
end for
return θ_s , P^Het(θ_s)
```

Figure 3.3. Distance and density based operation algorithm

By considering the user density variation among the SBSs, we introduce a power saving efficiency factor, Q_m, which gives the saved power per user in the HetNet if we switch SBS$_m$ off. This factor takes high values not only when $\Delta P_{HetNet|\theta(m)=0}(L)$ increases but also when the user density λ_m of SBS$_m$ is low. Since the total power saving in the HetNet achieved by switching off SBS$_m$ is $\Delta P_{HetNet|\theta(m)=0}(L)$, we can also write Q_m as a function of L as $Q_m(L)$:

$$Q_m(L) = \frac{\Delta P_{HetNet|\theta(m)=0}(L)}{\lambda_m \pi R_s^2} \qquad (3.3)$$

Supposing that all the SBSs are sorted in increasing order in $\mathcal{M}_S$ set according to their user densities and that they are all active initially ($L = 0$), we will calculate the power saving efficiency factor for all SBSs according to (12) and then SBS_m with the highest power saving efficiency factor is preferred to be switched off. After switching SBS_m off and taking $L = \lambda_m \pi R_s^2$ into account, the power saving efficiency factor of each SBS will change. By obtaining the new values of the power saving efficiency factor for all SBSs, we will switch the SBS that now has the highest value of power saving efficiency factor off and so on.

At the first round we need to calculate the power saving efficiency factor for M SBSs, then at the second round after we switch one SBS from the set $\mathcal{M}_S$ off, we need to calculate the power saving efficiency factor for $(M-1)$ SBSs and so on, and at the n^{th} round we have to obtain the power saving efficiency factor for $(M-n)$ SBSs. As a result, the computational complexity of this calculation process is about $O(M^2)$.

3.3. The Realistic Scenario

In the previous subsection, we assume that the MBS serves $K=\lambda_0 \pi R_0^2 - \lambda_0 M \pi R_s^2 + \sum_{\{m|\theta_m=0\}} \lambda_m \pi R_s^2$ users without any limitations on the number of users that can be served by the SCs. But in real life, each femtocell can serve a limited number of users. For this reason, in this subsection, we suppose that a femtocell can serve maximum F_{max} users in its coverage area and when the users in the network get denser, the extra users in the coverage area of the saturated SBSs will be served by the MBS. Since these extra users will receive the service from the MBS, they must be included in the K equation.

Without loss of generality, the MBS should serve $\acute{K}$ users which are not only the MBS users but also the extra users from the saturated SBSs; $\acute{K}=\lambda_0 \pi R_0^2 - \lambda_0 M \pi R_s^2 + \sum_{\{m|\theta_m=0\}} \lambda_m \pi R_s^2 + \sum_{\{(m|\theta_m=1) \cap (A_m \lambda_m > F_{max})\}} (\lambda_m \pi R_s^2 - F_{max})$. For this reason in (2.8) - (2.12) and (10), K should be replaced by $\acute{K}$. However, to obtain the average transmit power for an individual user taking the extra users offloaded from the saturated SBSs to MBS into account, (2.12) should be changed to: (equation 3.4)

$$\acute{Z}(\boldsymbol{\theta})=\frac{\frac{2\pi\lambda_0}{a+2}\left(R_0^{a+2}+\frac{ar_0^{a+2}}{2}\right)-\lambda_0\sum_{m=1}^{M}\lambda_m\pi R_s^2 d_m^a+\sum_{\{m|\theta_m=0\}}\lambda_m\pi R_s^2 d_m^a+\sum_{\{(m|\theta_m=1)\cap(A_m\lambda_m>F_{max})\}}\left(\lambda_m\pi R_s^2-F_{max}\right).d_m^a}{r_0^a\,\acute{K}}.$$

Moreover, (3.2) and (3.3) include *L* value, which denotes the users within the deactivated SBSs' coverage areas, $L=\sum_{\{m|\theta_m=0\}}\lambda_m\pi R_s^2$. In the realistic case, *L* also should include the users which are offloaded to MBS from the saturated SBSs, $\acute{L}=\sum_{\{m|\theta_m=0\}}\lambda_m\pi R_s^2+\sum_{\{(m|\theta_m=1)\cap(A_m\lambda_m>F_{max})\}}\left(\lambda_m\pi R_s^2-F_{max}\right)$. Thus, (3.2) and (3.3) should be modified as;

$$\Delta\acute{P}_{HetNet|\theta(m)=0}(\acute{L})=\Delta p-\frac{u\Gamma\,N_0W}{-D\ln(1-\varepsilon)r_0{}^a}\times\frac{\exp\left[\left(2^{\frac{b}{W}}-1\right)\left(\underline{L}+\acute{L}\right)\right]-1}{\left(\underline{L}+\acute{L}\right)}\times\lambda_m\pi R_s^2 d_m^a \tag{3.5}$$

$$\acute{Q}_m(\acute{L})=\frac{\Delta\acute{P}_{HetNet|\theta(m)=0}(\acute{L})}{\lambda_m\pi R_s^2} \tag{3.6}$$

4. NUMERICAL ANALYSIS

4.1. Simulation Scenario

Our simulations consist of three parts. First, we investigate the performance of the proposed algorithms by comparing them to the optimal algorithm. Next, we study how the power consumptions of the MBS, SBSs and HetNet change with the traffic load variation with/without SC sleeping in two scenarios: that proposed in [27] and our realistic one. Finally, we evaluate the results by calculating the daily power that the network can save using the proposed SC sleeping schemes. The parameter values used in the simulation are shown in Table 4.1.

4.2. Performance of the Proposed Algorithms Compared to Optimal One

In this subsection we will calculate the total power consumption of the HetNet when the optimal SC sleeping algorithm is applied and compare it with those of the proposed algorithms. The optimal SC sleeping algorithm is a method with an exhaustive search process such that for M SBSs, taking into account that the mode of any SBS_m is either $\theta_m = 1$ or $\theta_m = 0$, we have to test 2^M probabilities to decide the optimal operation mode vector of the SBSs, $\theta^*=[\theta_1^*, \theta_2^*, \dots \theta_M^*]$, which maximizes the energy efficiency of the HetNet. Because of the exponential increase of the computational complexity with the number of SBSs in the HetNet, $O(2^M)$, in the optimal SC sleeping algorithm, we calculate the power consumption of the HetNet with $M = 20$.

Table 4.1 Reference parameters (some of these values are taken from [27].)

PARAMETER	VALUE
Macro cell radius, R_0	500 m
Small cell radius, R_s	10 m
Set $\mathcal{M}$ of SBSs, $\mathcal{M}$ = {1, 2, …., M }	200
Operation spectrum bandwidth of the macro cell, W	10 MHZ
Each user's required data rate, b	0.1 Mbit/sec

Table 4.1.(Continued) Reference parameters

Maximum allowable outage probability, ε	0.05
Reference distance in channel model, r_0	1 m
Reference path loss, D	-35 dB
Path loss exponent, a	2.5
Coverage area of SBS_m, A_m	$\pi \times 10^2$ m^2
Area outside of all small cells, A_0	$\pi \times (500^2 - 10^2)$ m^2
User density in A_0 , λ_0	$[0.1 \rightarrow 2] \times 10^{-3}$ user/m^2
User density in A_m , λ_m , $m \in \mathcal{M}$	$[50 - \sqrt{3\sigma^2} \rightarrow 50 + \sqrt{3\sigma^2}] \times \lambda_0$ user/m^2
User density variation among SBSs, σ^2	$400/3$
MBS's maximum transmit power, P_{max}^t	40 W
Base level of the MBS's power consumption, $\underline{P}$	712 W
SBS's power consumption in sleeping mode, p_0	3 W
SBS's power consumption in active mode, p_1	10 W
Capacity loss, Γ	1
Noise power, N_0	-74 dBm/Hz
Power utilization coefficient for the MBS, u	14.5

Then we calculate the power consumption of the HetNet when the proposed algorithms are applied. Because M is rather small, the user densities of the SBSs are chosen from the range $[5-\sqrt{3\sigma^2} \rightarrow 5+\sqrt{3\sigma^2}] \times \lambda_0$ since $3\sigma^2 = 15$ and λ_0 changes within the range $[0.1 \rightarrow 2] \times 10^{-3}$. Although the computational complexity of the 3^{rd} algorithm, O (M^2) , is pretty low compared to that of the optimal algorithm, $O(2^M)$, the performance of our proposed algorithm is the same as the optimal one over the range of λ_0. We also noted that the 3rd algorithm performs 1% better than that proposed in [27] over the range of λ_0 with remarkably low complexity. The computational complexity and the performance of the proposed algorithms are shown in Table 4.2. To study the performance, we take the percentage of average value of P^{Het}(optimal alg.) /P^{Het}(proposed alg.) for different values of λ_0 from the range [0.1 →2] ×10^{-3}.

We've also ran the 3rd algorithm with different input values (e.g. varying macro cell radius between $400m$ and $600m$, small cell radius between $5m$ and $30m$, bandwidth between $8MHz$ and $100MHz$, etc.) and verified that the performance of the 3rd algorithm is always the same as that of the optimal solution.

Table 4.2 Performance and complexity of our proposed algorithms

Algorithm	1st	2nd	3rd	[37]
Complexity	$O(M)$	$O(M)$	$O(M^2)$	$O(M^3)$
$\frac{P^{Het}(optimal\ alg.)}{P^{Het}(proposed\ alg.)}$ (%)	97%	99%	100%	99%

4.3. Evaluation of the Proposed Schemes

In this subsection we show the power consumption of the MBS, SBSs and total HetNet with/without SC sleeping. As shown in Figure 4.1, at low values of λ_0, $\lambda_0 < 0.2 \times 10^{-3}$, all SBSs are switched off and the power consumption of the SBSs is $p_0 \times M = 3 \times 200 = 600\ W$. When λ_0 increases, the MBS offloads its traffic load to surrounding SBSs that will be gradually switched on to serve this offloaded traffic. When $0.3 \times 10^{-3} < \lambda_0 < 1.4 \times 10^{-3}$, the power consumption of the MBS decreases and the power consumption of the SBSs increases, showing that the traffic offloading process has been successful. After that when $\lambda_0 > 1.4 \times 10^{-3}$, all SBSs are switched on, consuming $p_1 \times M = 10 \times 200 = 2000\ W$ and the MBS transmit power increases to serve this high user density until the max transmit power P^t_{max} is reached at $\lambda_0 = 1.8 \times 10^{-3}$; then the system becomes infeasible as discussed above.

We also investigated the case when the users are uniformly distributed in the SBSs, i.e. $\lambda_m = \lambda_n\ \forall\ m, n \in \mathcal{M}$ and the results show that the 1st algorithm performs the same as the 3rd algorithm does. The details of this case were omitted here for brevity.

Figure 4.2 shows the total power consumption of the HetNet according to (3) with/without SC sleeping. The results show that when $\lambda_0 < 1.4 \times 10^{-3}$, the power consumption of the HetNet with SC sleeping is clearly less than the power consumption without SC sleeping for all schemes. Because all SBSs are active when $\lambda_0 > 1.4 \times 10^{-3}$, the power consumption of the HetNet with and without SC sleeping is the same. When $\lambda_0 \geq 1.8 \times 10^{-3}$, the HetNet power consumption reaches its maximum value, that is, $P^{Het} = 712 + 14.5 \times 40 + 200 \times 10 = 3292$ W and the systems with/without SC sleeping adaptation become infeasible. As observed in Figure 4.2 in the range of offloading process, the performance of the 3rd algorithm is about 3%, 1% and 1% higher than those of the 1st algorithm, [27]'s algorithm and the 2nd algorithm, respectively.

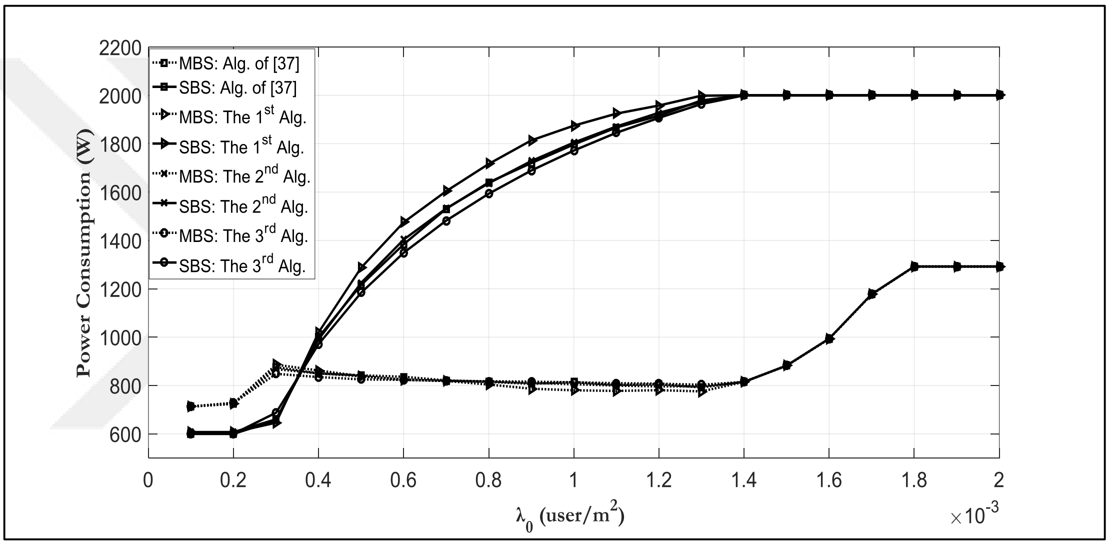


Figure 4.1. Power consumption of the SBSs and the MBS for the proposed schemes.

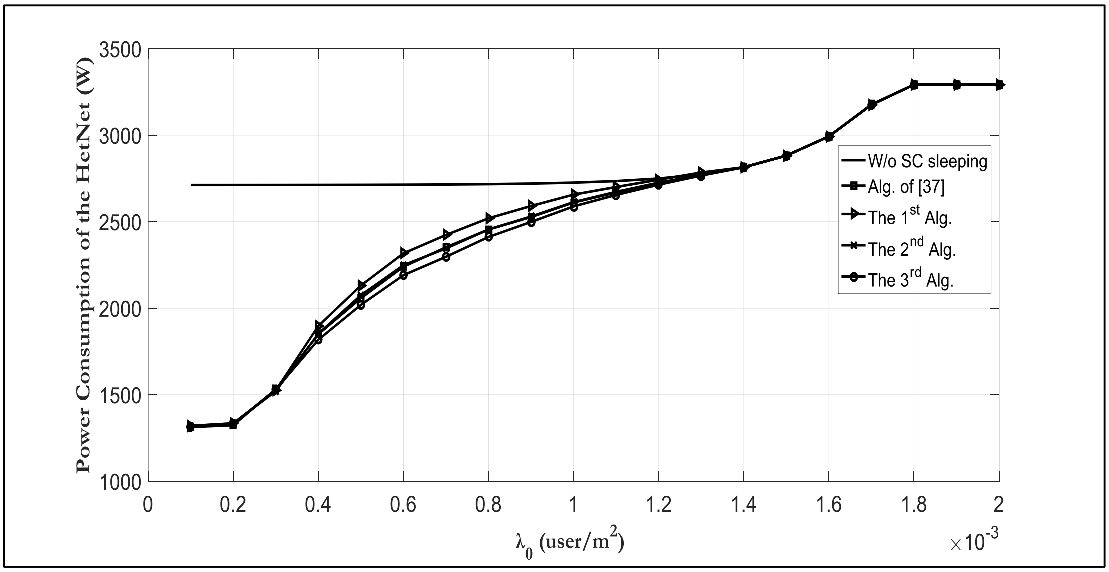


Figure 4.2. Total power consumption of the HetNet for the proposed schemes.

Figure 4.3 clarifies the effectiveness of the proposed algorithms in power saving. We compare the total network power consumption when SC sleeping is active to that of the baseline case (without SC sleeping) and show the percentage of power saving gain for the proposed algorithms. We also investigated the impact of λ_m variation on the HetNet power consumption. In Figure 4.4, the results show that the HetNet power consumption of the 3rd algorithm decreases with increasing σ^2. This means that according to the result of the 3rd algorithm, the power consumption decreases when the variation of user densities in SBSs is high.

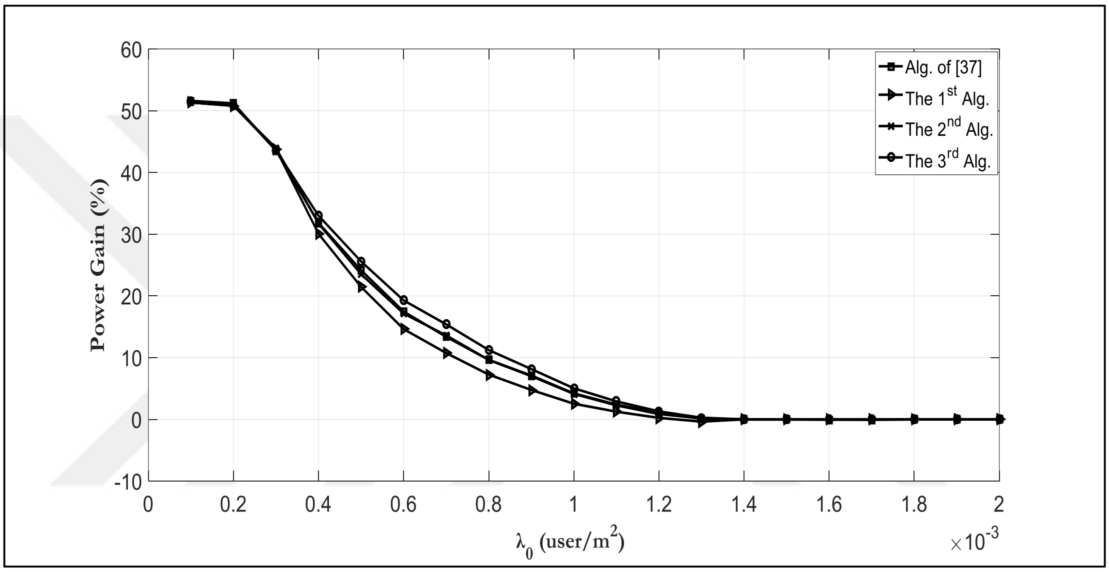


Figure 4.3. Power saving gain (%)

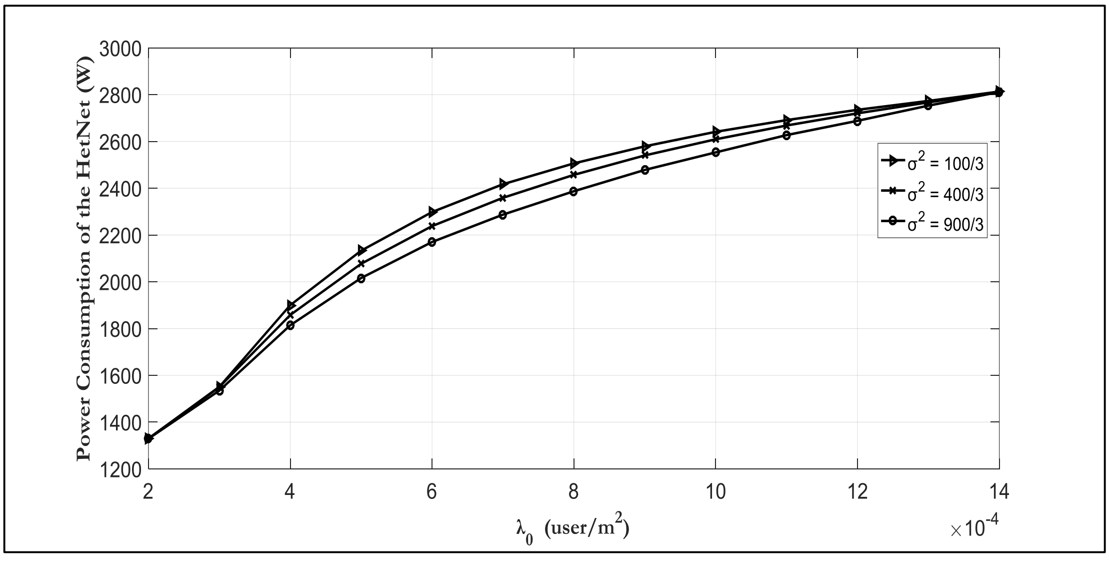


Figure 4.4. Total power consumption of the HetNet for different values of σ^2 for the 3rd scheme.

Using the same parameters of Table 4.1 and taking the SC capacity ($F_{max} = 10$) into account, we study the performance of the proposed algorithms over the range of user density in MC λ_0 as $[0.1 \rightarrow 1] \times 10^{-3}$ instead of $[0.1 \rightarrow 2] \times 10^{-3}$. Figure 4.5's smaller λ_0 range compared to that of Figure 4.1 is due to the fact that in a practical case when the traffic load in SCs increases for any reason, the extra SC users will be offloaded to the MBS and the SC activation process will increase linearly, resulting in early saturation of the system.

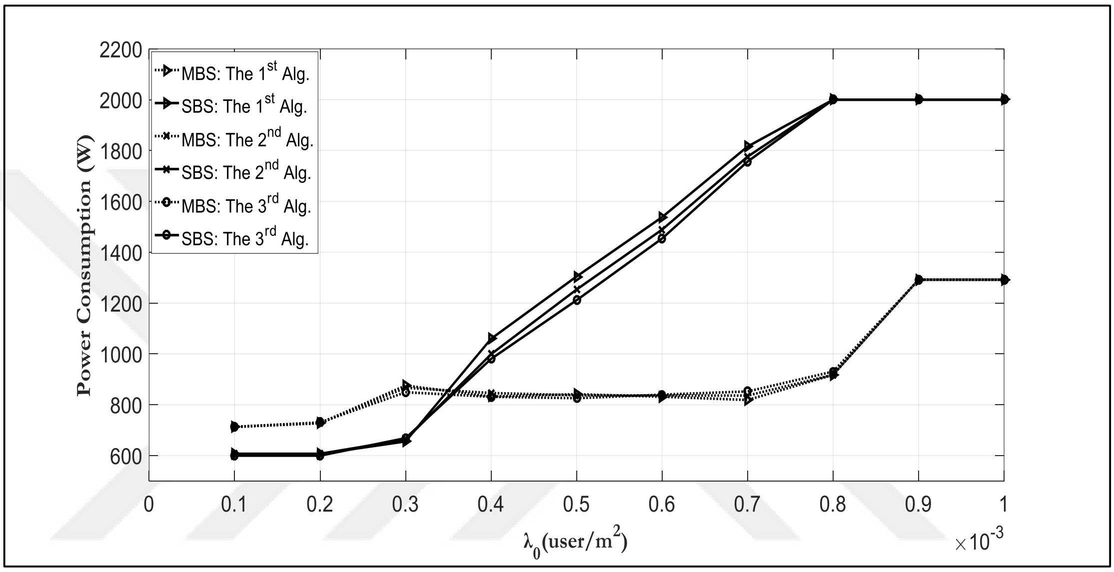


Figure 4.5. Power consumption of the SBSs and the MBS for the proposed schemes with load sharing between the saturated SCs and the MBS.

Total power consumption of the HetNet for the realistic scenario is given in Figure 4.6. There are two major points that should be noted when we compare Figure 4.6 with Figure 4.2. The first point is that the power consumption of the network without SC sleeping remains constant until $\lambda_0 = 0.7 \,.\, 10^{-3}$ in Figure 4.6 and until $\lambda_0 = 1.2 \,.\, 10^{-3}$ in Figure 4.2. The second one is that the saturation begins at $0.9 \,.\, 10^{-3}$ in Figure 4.6, while it begins at $1.8 \,.\, 10^{-3}$ in Figure 4.2. We can also see that the 3rd algorithm outperforms the other algorithms in terms of power saving.

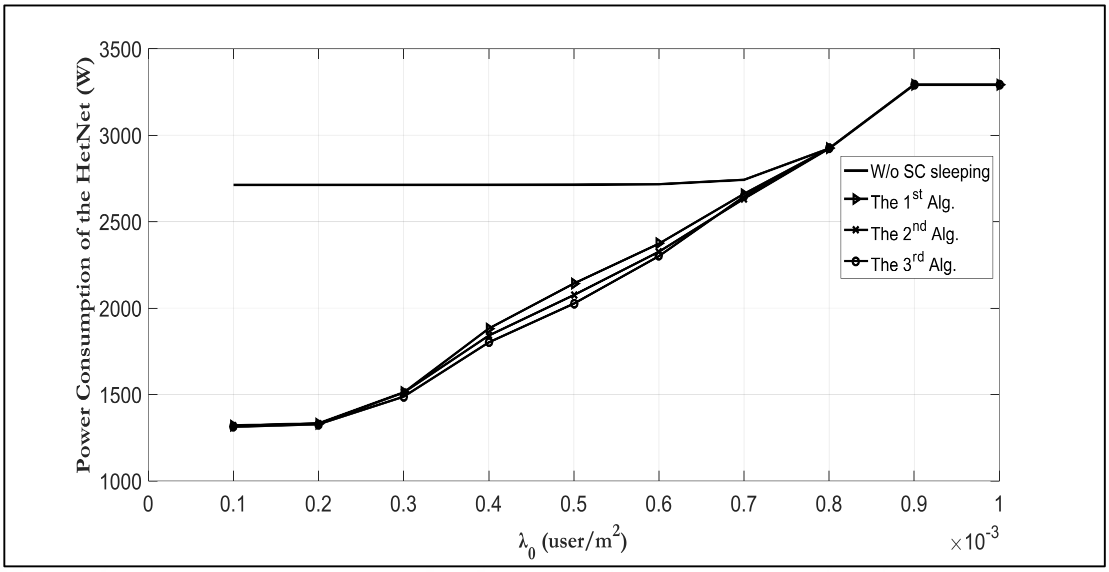


Figure 4.6. Total power consumption of the HetNet for the proposed schemes with load sharing between the saturated SCs and the MBS.

Actually, for the given HetNet defined by the parameters in Table 4.1, there is a maximum number of users ($\acute{K}$) that can be served by the MBS and if any of the parameters changes, this number will also change. For example, if we want to increase the average requested bit rate for each user, this number of users will decrease. When the traffic load in the studied HetNet is huge, this means more SCs are needed taking into account that the MBS is limited by its maximum transmit power P_{max}^{t} to serve the users with the predefined QoS. Figure 4.7 shows that when the number of SCs (M) in the HetNet increases, the total power consumption will also increase. When the 3rd algorithm is used, the saved power (shown as the difference between two plots for a certain M value) also increases, but the range of λ_0 before the saturation becomes narrower because there are more SBSs that offload their traffic to the MBS. For example, when $\lambda_0 = 0.5 \,.\, 10^{-3}$, the saved power is 500W, 600W and 700W for $M = 100$, $M = 200$ and $M = 300$, respectively.

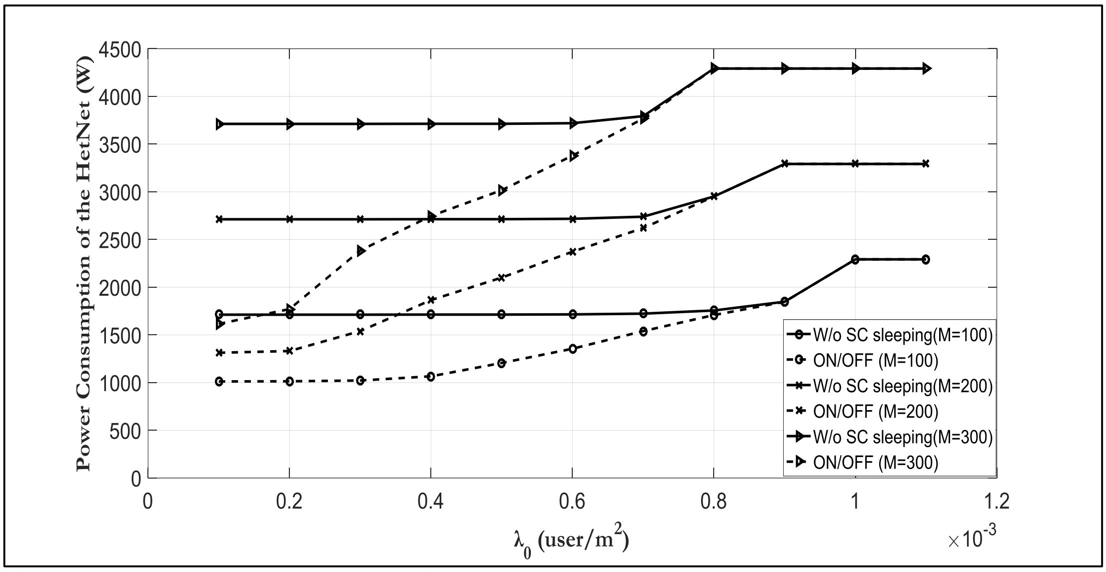


Figure 4.7. Total power consumption of the HetNet for the proposed schemes with load sharing between the saturated SCs and the MBS with different values of number of SCs (M)

4.4. Daily Power Savings Benchmarking

In this subsection we will portray the power consumption of the MBS, SBSs and HetNet during one day and show how much power we can save using each proposed scheme for the realistic case. According to the EU traffic load profile discussed in Section 2.8, Figure 4.8 shows how λ_0 changes over 24 hours between the minimum value at $\lambda_0 = 0.125 \times 10^{-3}$ and the maximum at $\lambda_0 = 0.9 \times 10^{-3}$ (case of $\mathrm{M} = 200$ shown in Figure 4.6).

Similar to Figure 4.5, Figure 4.9 shows the power consumption of the MBS and SBSs using the proposed schemes to adapt the SBSs operation mode on/off along one day. In off-peak hours between 03:00 and 08:00, the traffic load is too low ($\lambda_0 < 0.3 \times 10^{-3}$) as shown in Figure 4.8, so all the SBSs are switched off. In the same way, in peak hours from 19:00 to 23:00, all SBSs are active and the transmit power of the MBS starts to increase in order to serve the dense HetNet. Although the traffic load is high between 21:00 and 23:00, the MBS can offload a portion of its traffic load to the SBSs all of which are active. The dynamic on/off SBSs adaptation is shown over the remaining normal day hours with average traffic load since it is easy to see the traffic offloading process from the MBS to the SBSs. Accordingly, while the power consumption of the MBS between 08:00 and 19:00 decreases and that of SBSs increases, the power consumption of the MBS between 00:00 and 02:00 increases and that of SBSs decreases.

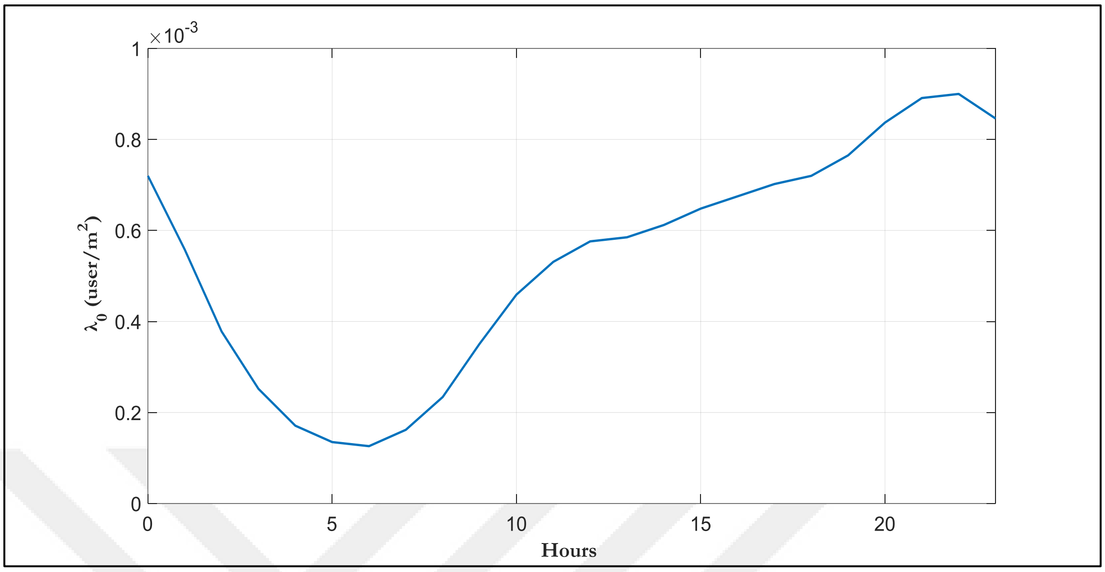


Figure 4.8. Variation of λ_0 over 24 hours.

Figure 4.10 illustrates the daily total power consumption of the HetNet with/without SC sleeping and shows the power that can be saved using our proposed schemes, which is represented by the area between the two graphs. From 00:00 to 19:00, the power consumption of the HetNet with SC sleeping scheme is clearly less than that without SC sleeping scheme. We can save daily more than 20% of the HetNet's power, about 20 KW for our system parameters, using the 3rd algorithm to adapt the operation mode of the SBSs.

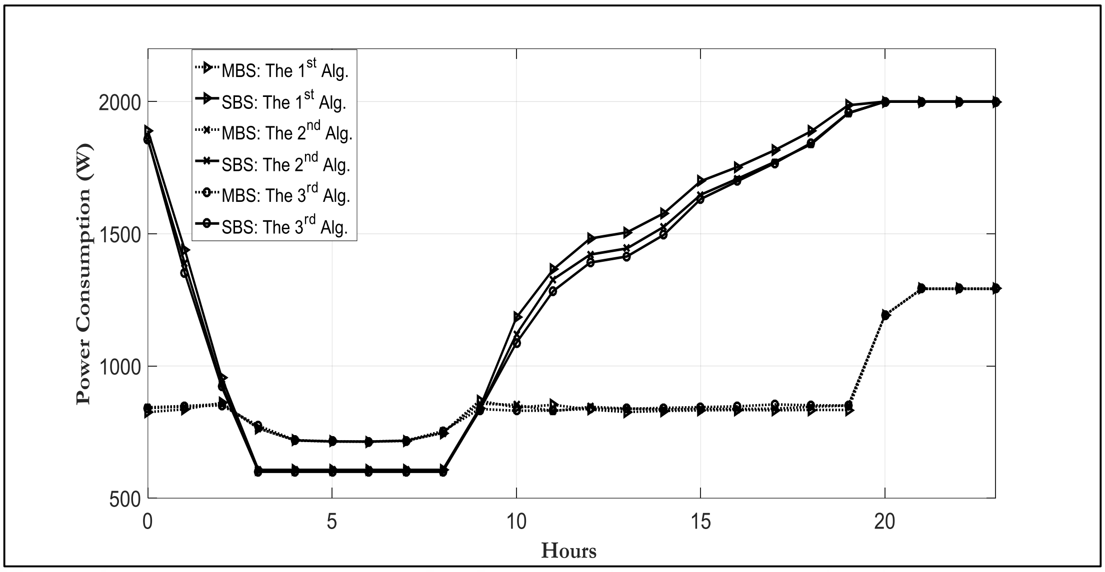


Figure 4.9. Power consumption of the SBSs and the MBS for the proposed schemes over 24 hours

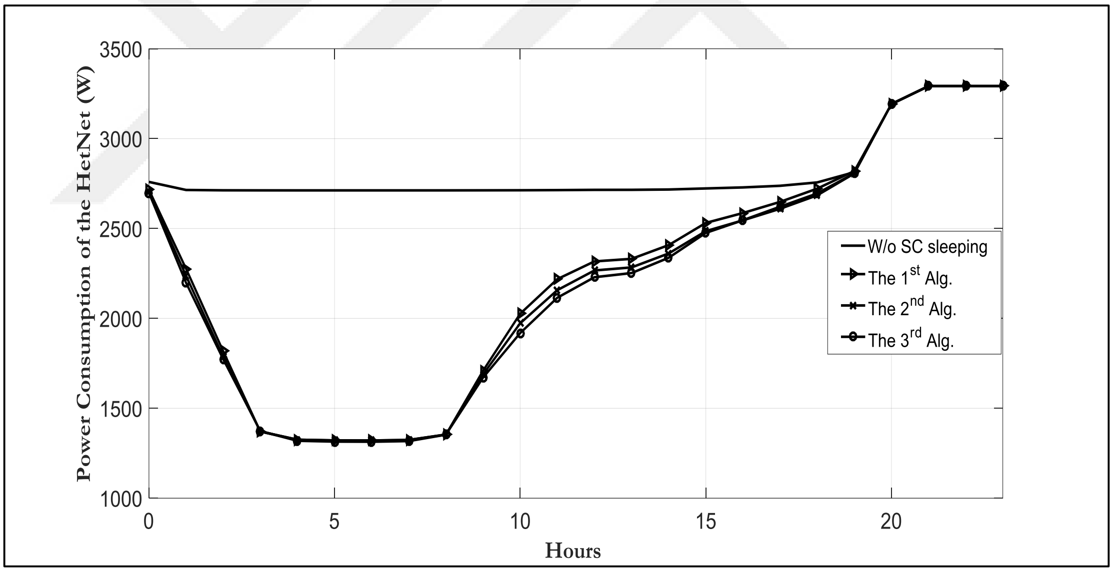


Figure 4.10. Total power consumption of the HetNet for the proposed schemes over 24 hours.

4.5. Conclusions and Future Work

In this study, we proposed three different algorithms with acceptable computational complexities to dynamically adapt the operation mode of the SBSs to minimize the HetNet power consumption when the users are non-uniformly distributed in the network. The performance of the 3^{rd} proposed algorithm is perfectly the same as that of the optimal one but has a remarkably low computational complexity. Then, to make our study more realistic, we enhanced the mathematical framework by restricting the number of users which can be served by the femtocell. So, some of users of SCs can be offloaded to the MBS. It is observed that in comparison to the unrestricted case the system saturates faster because of the new offloaded traffic from the active saturated SBSs that the MBS has to serve. We modelled the user density variation according to the European traffic model and calculated the daily total power consumption for SBSs, the MBS and the HetNet system. We showed that by applying SC sleeping technique using the 3rd proposed algorithm, we will be able to save daily more than 20% of the power that the HetNet consumes in a day without using SC sleeping.

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