Planning for Small Cells in a Cellular Network

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

In this thesis, we analyze the effect of deploying small cells on the performance of a network comprising several macro cells. We identify potential locations for low-power base-stations based on the coverage patterns of the macro cells and propose three schemes for placing the small cells. We show that by judiciously installing just two small cells for every macro base-station at these locations and allocating separate resources to all the small cells on a global level, we can increase the performance of the network significantly ($\sim 45\%$). An added benefit of our schemes is that we can switch off the macro base-stations at night (when the number of active users is low) and significantly reduce their operation cost.

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Chapter 1

Introduction

There is an overwhelming growth in data traffic in wireless networks and this trend is expected to continue in the future. Thus, there is a need to accommodate more users, increase the capacity and improve the performance of these networks. In this thesis, we focus on wireless cellular networks, which are by far among the most important and widely used types of wireless networks. Small-cell is a new concept in cellular networks which has recently drawn much attention from academia and industry. We particularly analyze the effect of deploying small cells on the performance of a cellular network. In the next section, we will briefly describe the basic concepts and the evolution of cellular networks.

1.1 Overview of Wireless Cellular Communications

The service area of a cellular network is divided into many smaller areas, called cells. Cells are the basic geographical unit of the cellular networks on which everything else is built. It is usually modeled as a hexagon, but in practice, because of the geographical features of the service area, cells are not hexagonal or of the same size. Each cell is equipped with one or several base-stations (BS) and a number of radio channels, assigned according to the channel allocation scheme. All user equipments (UE) and BSs are equipped with wireless transceivers which are used to set up a call or send and receive data over the wireless link between the UEs and the BSs. Figure 1.1 illustrates a typical hexagonal cellular network. Triangles represent base stations.

The historical evolutions of cellular networks, from the first generation to the fourth generation is shown in Table 1.1 taken from [36]. FDMA was used in the first generation

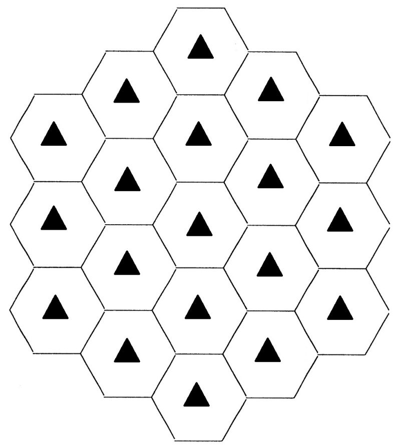


Figure 1.1: A typical hexagonal cellular network architecture

of wireless cellular systems where the system was based on analog FM and required using costly bandpass filters. Digital modulation techniques were introduced in the second generation where TDMA and CDMA were heavily used. 2G added a new cost to the system for using digital signal processors in both UEs and BSs but it was worth it because it could increase the network capacity by more than 300% [33].

The primary goal of the first two generations of wireless cellular networks was voice transmission which does not require high data rate or bandwidth. With the growing demands for internet access, new generation of cellular networks were introduced. 3G networks offered always connectivity to the internet and reduced the cost of voice call by introducing Voice-over-IP technology. 3G popularized internet applications and social networks by providing high speed data rate of megabit per seconds. Currently, there is an growing interest in internet applications, online games and multimedia-rich contents, and cellular networks require a much higher data rate (in the range of Gb/s) and better user experience. Therefore, there are numerous research studies on identifying the network limitations and the possible solutions for improving the network performance. In the next section,we present some of the these limitations.

Table 1.1: Historical evolution of mobile communication systems taken from [36]

Property	**1G**	**2G**	**3G**	**4G**
Starting Time	1985	1992	2002	2010-2012
Representative Standard	AMPS	GSM	IMT-2000	*UWB*
Radio Frequency (Hz)	400M-800M	800M-900M	1800M-2400M	2G-8G
Bandwidth(bps)	2.4K-3K	9.6K-14.4K	384K-2M	20M-100M
Multiple Access Technique	FDMA	TDMA, CDMA	WCDMA	OFDM
Switching Basis	Circuit	Circuit	Circuit,Packet	Packet
Cellular Coverage	Large area	Medium area	Small area	Mini area
Service Type	Voice	Voice Limited Data	Voice Data Limited Multimedia	Multimedia

1.2 Cellular Networks; Challenges and Limitations

Recently, Cisco has announced that, by 2015, mobile data traffic will grow to 1 billion gigabytes of data per month and by 2017 about two-third of the mobile data traffic will originate from video services [37]. This is the reason why wireless operators need to find a way to accommodate more users with large screen devices on their networks. The urgent needs of today's networks are clear. We need to find possible solutions to improve network performance and meet the growing demands of users. We can not provide a solution unless we have a good understanding of the current limitations and bottlenecks of the networks [28]. In this section, we focus on these limitations, understand the nature of the wireless medium and briefly describe solutions and techniques that can be used to overcome the limitations.

1.2.1 Limited Bandwidth Resources

Bandwidth resource is globally considered as one of the most scarce resource on the planet. The total amount of frequency spectrum is limited. Of these limited frequency spectrum, only a portion can be used due to technology limitations and possible health effects of RF signals. The bandwidth resource is not only severely limited but it is also shared by everyone and for different applications including cellular networks, sensor networks, WiFi, home appliances, etc. The frequency spectrum allocated for cellular communications is very limited, but user's interests require much higher data rate and better user experience. There are two solutions for overcoming this limitation:

Additional Spectrum: The U.S. Federal Communications Commission has recently announce that they are trying to get an additional 500 MHz of spectrum for the next decade, including 300 MHz spectrum to be added to the available spectrum in the next five years [10].

Improving Bandwidth Efficiency: Adding more spectrum is a promising solution; however, it takes time and not all spectrum is of the same quality. For now we need to improve the bandwidth efficiency; we need to get more efficient in the way we use the network resources. To improve the bandwidth efficiency, better resource management and channel assignment schemes should be designed. Most of the channel assignment schemes are based on the concept of frequency reuse. Frequency reuse is the practice of using the same frequencies and channels within a network more than once to improve the capacity and spectral efficiency; however, if two adjacent devices use the same frequency at the same time, they create interference which yields to poor user experience. To avoid any interference, wireless systems will isolate identical frequencies from each other. More information about channel assignment schemes is provided in the next section.

1.2.2 Interference

It is known as the second biggest problem of wireless networks after the limitation of the shared medium. It degrades the quality of service, and in case of a severe interference, calls might be even dropped. There is two types of interference; co-channel interference (CCI) and adjacent-channel interference (ACI).

CCI is the result of using the same channel by two or more users simultaneously and ACI is the result of using adjacent channel, without enough frequency gap. Users refer to any type of device including cellphone, laptop, base-station or even home appliance; if they are operating on the same or adjacent frequency bands, they causes interference on each other. Users at any distance may causes interference on each other; however, it is negligible if they are far enough from each other.

Although the amount of interference affects the quality of the link, it is not a link quality metric. Signal to Interference plus Noise Ratio (SINR) is used to measure the quality of wireless communication links. Signal is the power level of the desired signal, and noise and interference are the unwanted signals. In wireless cellular networks, co-channel interference is more significant than the noise and adjacent-channel interference. Interference mitigation techniques are commonly used to overcome this limitation and increase the SINR level of the users.

Interference Mitigation: To reduce the interference level of the system, channels of the same or adjacent frequency bands should not be used in neighbouring cells. Frequency reuse is the main technique for interference mitigation where the co-channel cells are placed at a minimum distance called, reuse distance.

Using directional antenna can also reduce the interference level of the system. Directional antenna is effective in only one direction, therefore, it imposes less interference on the devices located in the back of the antenna.

Moreover, ACI can be suppressed by using better bandpass filters in both transmitter and receiver. If any of them does not have a perfect bandpass filter, some of the signal from adjacent channels may leak into the system.

Power control can be an effective method to mitigate the interference only if it is not a symmetric network, where all the cells are of the same size and same shape.

1.2.3 Path Loss

Path loss is the attenuation of the signal as it travels some distances and propagates through space. In other words, path loss is the difference between the initially transmitted power of a single signal and the finally received power at the observation point. Path Loss depends on two parameters; distance and the propagation environment. Thus, it is usually represented by travelling distance and path loss exponent,(η). Path loss exponent depends on the specific environment in which the signal is propagating. In a free space model with a clear line-of sight between the sender and observation point, η is equal to 2 and a signal experiences less attenuation. In urban area, a signal is more prone to reflection and scattering, so may experience more attenuation. Thus, η in urban area is larger (up to 4).

Decreasing the cell size is a possible solution for overcoming this limitation. As the size of the cells decrease and more base stations are deployed in a specific area, users are closer to the base stations and the signal experiences less attenuation [33].

1.2.4 Fading

Fading is a significant limitation of wireless medium because this type of attenuation may vary with time or frequency. There are two types of fading; shadow fading and multi-path fading. Shadow fading refers to the significant strength reduction of the signal as it travels from source to destination through a path with large obstruction. Shadow fading is often modeled by a log-normal distribution. Multi-path fading, another common type of fading, happens when the signal travels several different paths before arriving at the receiving equipment. Therefore, the received signal is the sum of the multiple reflected signals from different directions, and it might be severely attenuated.

Decreasing the cell size, and placing the base stations at good spots with suitable height can be an effective method to overcome this limitation. For example, in dense urban areas with high-rise buildings, cells should be small and BS should be placed at the highest available spot [33].

1.3 Cellular Networks; Solutions and Improvement Techniques

In the next couple of sections, we will briefly describe some of the common techniques used to overcome the above-mentioned limitations and increase the throughput of the network.

1.3.1 Multiple Access Techniques

In order to accommodate more users in the cell, we should define a mechanism so that multiple users can access the shared medium simultaneously. This is why multiple access techniques, with a global perspective of the system, are defined. Multiple access techniques cope with two difficulties of the wireless systems; limited shared bandwidth and interference. If two or more users simultaneously transmit on the same or adjacent frequency bands, they may causes interference on each other and degrade the quality of service of all users. On the other hand, the allocated bandwidth to cellular network is limited and there can not be a large space between allocated channels of users. Multiple access techniques intelligently divide the medium and deploy smart modulation schemes so that more users can access the medium while causing no or small interference on each other. Four major multiple access techniques of cellular networks are listed here:

- **Frequency division multiple access (FDMA):** In FDMA, the shared frequency spectrum is divided into smaller bands. Each user is allowed to transmit on only one frequency band and each band can be used by only one user at a time. In this scheme, users are distinguished in the frequency domain; they can always transmit, but on only one frequency band. Implementation of FDMA is costly because it requires high quality bandpass filters. This method was used in the first generation of wireless cellular systems [33].

- **Time division multiple access (TDMA):** In TDMA, time is divided into periodic frames made of small time intervals, or time-slots (TS). Each user is allowed to transmit on only one specific TS and each TS is used by only one specific user. Thus, in TDMA, transmission would be non-continues or so called "buffer-and-burst" [33]. In this scheme, users can transmit on the entire bandwidth but not always have access to the spectrum. In Dynamic TDMA (DTMA), which is the most recent version of TDMA, unused slots can be borrowed from other users, if there is a demand on the network [22]. TDMA was used in the second generation of wireless cellular systems.

- **Code division multiple access (CDMA):** In CDMA, several users can transmit on the same band at the same time and they can still be distinguished using some uniquely assigned codewords. This codeword is obtained from a digital modulation technique known as spread-spectrum. CDMA requires a special encoding and decoding method on both sides of the link to recover the message. This was used in the second generation of wireless cellular system and an improved wideband version of it is used in the third-generation of cellular networks [33].

- **Orthogonal frequency division multiple access (OFDMA):** OFDMA is a modulation and access technique that combines both TDMA and FDMA technologies. OFDMA is based on OFDM technique. In OFDM, the allocated network bandwidth is divided into many orthogonal sub-carriers. Each user employs a parallel data stream mechanism to send the data over several orthogonal sub-carriers. [40].

1.3.2 Optimized Channel Assignment and Frequency Reuse Scheme

Radio spectrum has long been considered the most scarce resource because it has a limited availability but has been employed over a wide range of applications. Therefore, new radio resource management schemes that can increase the bandwidth efficiency and improve the overall performance of the networks have always been in dire demand. To use the radio spectrum more efficiently, it is divided into a set of radio channels and depending on the system goal, these radio channels are assigned to a number of base-stations. How the radio spectrum is divided into a number of channels and how each of these channels is assigned to a number of antennas are addressed in channel assignment schemes [23].

Investigating channel assignment schemes for cellular communication systems is not a new research topic, but it has been drawing new attention recently after the adoption of orthogonal frequency division multiple access (OFDMA) for the Long Term Evolution networks(LTE).

OFDMA is based on OFDM technique. OFDMA combat the inter-symbol interference (ISI) and gives a high flexibility in the resource allocation but has a big challenge, known as co-channel interference (CCI) [40]. CCI is the result of using the same channel for two or more users simultaneously. How severe the interference is depends on how closely the co-channel antennas are located and how powerful their signal is.

The simplest channel assignment scheme is when there is only one omnidirectional antenna in each cell and all antennas transmit on the entire bandwidth. It is called universal frequency reuse or frequency reuse factor (FRF) of 1. With FRF of 1, users suffer from a large CCI, especially near the cell edge, and can not receive the adequate service rate. With larger FRF, less CCI would be experienced by users; however, less bandwidth is available in each cell.

The trade-off between reducing the CCI and retaining the system spectrum efficiency makes it difficult to propose a new high-quality channel assignment scheme, but the huge need of todays heavily loaded cellular communications networks has made it crucial to find a better channel assignment scheme.

1.3.3 User Association Methods

The service area of a cellular network consists of many base-stations and typically contains user equipments. Because the wireless medium is broadcast, all the users receive a signal from all the base-stations but not all of them are strong enough. Therefore, there is a need for a mechanism to assign users to base-stations. This mechanism is called, user association.

User association is the set of rules by which a user selects a base station. Each base-station is responsible for service delivery to only its specified set of users. The received signal from users and base-stations other than the assigned ones is considered as interference. User association rules are defined to improve load balancing, increase the capacity of the system and offer good service to users.

The basic rule of all user association method is that there should be a feasible link between users and the assigned base-station. A link is defined by 3 elements; user, base-station and a large enough SINR. Users can decode the signal and receive the data, only if the received SINR is greater than a threshold.

1.3.4 Scheduling and Resource Allocation

Channel assignment scheme takes care of the global assignment of the channels and frequency bands to each cell. User association scheme is responsible for assigning users to the best base station. Scheduling is the way we manage the allocated resources of a cell within the cells and between the assigned users. In each cell, bandwidth and time resources are shared by all of the users assigned to that cell, which requires a mechanism to mange the resources and allow users to use the shared media. Generally, there are three common approaches: random access, scheduled access and hybrid access [33]. We briefly describe only the random access and scheduled access, because the hybrid access is just a combination of the two other methods.

Random access: It is a contention based media access. In this method, network resources are allocated to users for transmission on a random basis. It is possible that more than one device simultaneously initiate the transmission which yields to collision. Pure ALOHA is the simplest random access protocol in which there is no collision avoidance technique; user initiate the transmutation as soon as data is ready. If more than one user transmits at the same time, a collision occurs and packets will not be delivered to their destinations. After each collision, the senders wait for some time and then, re-try to send the packets. This simple scheme works well when there is only a few users in the system; however, it causes many collisions in dense networks [33]. These are not used in cellular networks.

Scheduled access: It is a contention free or controlled access method. In this method, network resources are allocated to the users for transmission, according to a schedule provided by a central scheduler. All of the transmissions happen within specified time-slots and on specified channel. Thus, users have to wait for their time to access the medium and set up a connection. Round-robin, proportional fair and max-min are the most common scheduling schemes. Round-robin is when users have equal number of time-slots for using the entire network's bandwidth. Proportional fair scheduling maximizes the sum of log-scale throughput [24] and max-min scheduler, as the name suggests, maximizes the minimum performance metric of the system ([8], [19]).

The selection of the scheduling scheme depends on the overall goal of the network. For example, a max-min scheduler is usually used when the network operator wants to maximize the minimum data rate of the cell, rather than maximizing the total throughout of the system. Implementation of scheduling is more complex than random access method but it is still the preferred method for cellular networks because base-stations can be equipped with strong processors to be the central scheduler of the cell.

1.3.5 Sectoring and Directional Antenna

Cell sectoring is a widely used technique for co-channel interference mitigation and network capacity improvement [33], [7]. In sectoring, the cell has the same size, but it is divided into several smaller areas, called sectors. Instead of using a single omnidirectional antenna, cell sectoring deploys several directional antennas at the base station where each sector is served by one of these directional antennas. With directional antenna, the RF energy is directed in one particular direction, leaving less interference on other cells and sectors compared to a single omnidirectional antenna system. Therefore, the network capacity is increased [33].

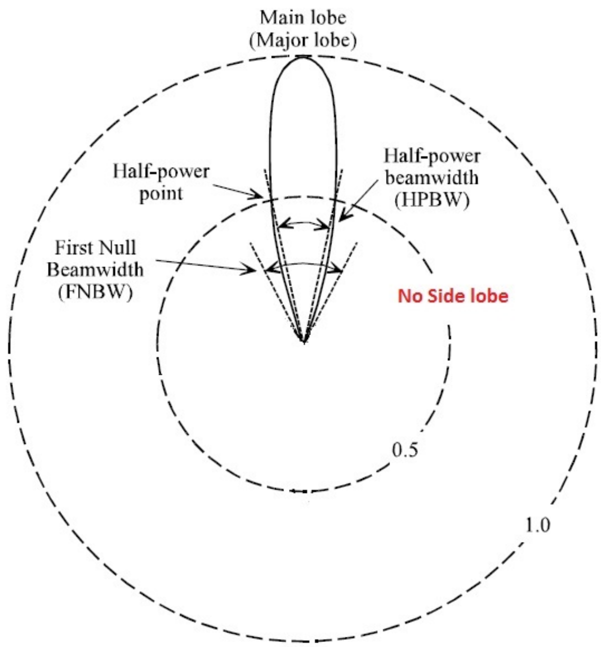
Cell sectoring is based on the use of the directional antenna. A directional antenna is an antenna designed to radiate and function more effectively in one or more directions than in others [9]. A better directional antenna results in a better sectored-cell system. Fig 1.2a illustrates the radiation pattern of an ideal directional antenna with no side lobes, but in practice the pattern of a directional antenna is similar to the one shown in Fig 1.2b adapted from [5]. Antenna with smaller side lobe is considered to be a better directional antenna.

A directional antenna does not need to be fed up with more energy. In fact, a directional antenna just focuses the same amount of energy towards a certain direction and it can even cover a larger distance than an omnidirectional antenna using the same power level.

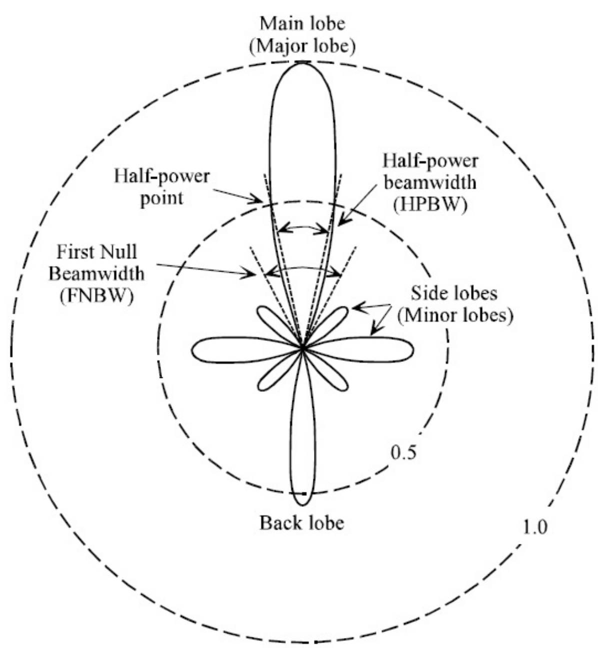
Directional antennas are often categorized by their directivity gain and 3db beamwidth. Directivity is a measure of the directionality of the antenna [5]. An Omnidirectional antenna has no effective directionality, and thus, it has the directivity gain of $0dBi$. However, a larger directivity implies a more focused or directional antenna. 3db beamwidth is the beamwidth between two points where the transmitted signal is attenuated to 50% (3 dB) of the maximum radiation power [9].

There are two mathematical models which are often used in network calculations; in [30], a bessel function of the first kind has been used to model the antenna directivity. In this model, directivity depends on the distance and angle of the receiver from the source of the signal, therefore, points with different distance or angle observe different directivity gain. This model is very accurate, but it complicates the system analysis. This was often used till 3GPP group recommended a simpler antenna model [1].

In in [1], a simpler model is presented where directivity depends on the distance and angle of the receiver only if it is imposed to the main lobe of the antenna, but it is always constant if the receiver device is imposed to the side lobe of the antenna. This model is



(a) Ideal antenna with no side lobes



(b) Practical antenna

Figure 1.2: Normalized power pattern of directional antenna adapted from [5]

not very accurate, but it simplifies the analysis and it is the recommended model by 3GPP group [1].

Typically, a cell is divided into three sectors with equal width, 120. This approach is suitable for networks with highly uniform traffic load, but in networks with non-uniformly distributed traffic, while some sectors with large traffic load may suffer high outage probability, other sectors with smaller traffic load do not efficiently utilize their allocated resources. This deficiency can be eliminated by using an adaptive cell sectoring method where cell widths are adaptively adjusted according to the traffic distribution [41].

1.3.6 Scaling the Cell size

By decreasing the cell size, the base station is moved closer to the users which results in a higher signal quality and better spatial efficiency. Moreover, in networks with smaller cells, the ratio of the number of users to that of base stations is smaller, and consequently less number of users share the limited resources of the same base station.

Reducing the cell size is a widely used technique to increase the network capacity, but it increases the infrastructure cost. This concept is the basis of two well-known architecture, applied on cellular networks at different point of time:

Cell Splitting: Cell Splitting was the technique to rapidly accommodate more users in a specific area by splitting a single congested cell into smaller ones. Using this approach, urban areas with higher density of users could be split into as many cells as necessary to provide a good quality service. In this technique, an original cell was usually divided into four smaller cells [6] , [33]. Cell sectoring is also based on the same concept with more economical advantages. In cell sectoring, multiple directional antennas are deployed on one base station and there is no need to spend extra time, money, or space to locate and install a new base station. Other advantages of cell sectoring can be found in [20].

Small Cells: This is the latest trend in cellular communications networks. After deploying the cell sectoring and improving the existing macro cell networks, now, the objective is to add extra base stations and create extra cells of very small size. These small cells are planned within the existing macro cells in order to improve the SINR value of the poorly serviced users and off-load a portion of the traffic from macro base stations (MBS).

The base stations used in these new small cells, commonly support an omnidirectional antenna. These base stations, known as pico base-station (PBS), are much smaller than original macro base-stations. PBSs weight no more than a couple of kilograms and their power output is usually less than two watts [31].

Moving the base station to the user equipments results in a higher signal quality, consequently more bits can be transmitted at the same time, which leads to a better throughput and a larger network capacity. The main advantage of small cells is better cell edge coverage; small cells provide better service to the users in the edges of the macro cells where users usually receive a slow data rate [11]. Cell edge coverage can be further improved by using the max-min scheduling method. A better cell edge coverage results in an improved quality of experience and better user satisfaction.

These additional small cells result in a heterogeneous cellular network (HCN) structure which poses some new challenges to the system design. First of all, different deployment scenarios need to be studied to find the best PBS placement scheme with maximum throughput. Furthermore, radio resources should be wisely allocated to the base stations to mitigate the interference between neighboring cells and increase the throughput of the system. It is essential to find the fraction of the spectrum that should be assigned to small cells for a throughput optimal design. Lastly, new user association rules are required. Pico base stations and other lower power base-stations may not provide as strong signal as macro base stations do. If users simply associate with the BS with the best SINR, MBSs may become overloaded. It is essential to design new user association schemes to push a portion of the users to be assigned to the PBSs.

1.4 Motivation and Contributions

According to [11], 98% of mobile operators consider the small cells as the key solution to increase the capacity of their mobile networks. Moreover, they have reported that the number of deployed small cells overtook the total number of macro cells in November 2012. Soon, the number of deployed small cells would be even larger as we are now just in the early stage of the global deployment of the small cells [11].

Location planning for small cells is one of the least investigated aspects of HCNs. It is often assumed that they are either symmetrically placed in the macro cell [16, 18] or that they are uniformly distributed in the macro cell [25] or that they are placed close to the hot spots [16, 35]. Although, placing the small cells within the interior of the macro cell seems natural, it might be more beneficial to place them at the intersections of the macro cells where the coverage is weak and the interference is strong.

In this thesis, we identify two sets of such potential locations for small cells within a homogenous cellular network and propose three different schemes of installing small cells based on these locations. Also, unlike most of the literature, we assume that the resource allocation to the small cells is done at the network level globally. We also do not consider the scenario with hot spots and assume that the users are uniformly distributed in the network.

The main contributions of this thesis are as follows.

1. Three placement schemes for small cells are proposed and it is shown that judiciously installing just two small cells for each macro cell (and allocating separate resources to the small cells on the network level) is enough to achieve a large gain ($\sim 45\%$) in the performance of the network. Unlike much of the literature, the performance of the network is evaluated from a global perspective and not just for a single macro cell.

2. It is shown that the performance of simple user association rules like best SINR and small cell first (SCF) is within 10% of the upper bound on the performance.

3. An additional benefit of our small cell placement and resource allocation schemes is that it is possible to switch off the MBSs at nights. In other words, the small cell planning and placement proposed here is enough to maintain connectivity under low traffic conditions. This is important as MBSs consume a significant amount of power for their operation.

1.5 Outline of the Thesis

This thesis is organized as follows: chapter 2 provides some background information about different type of cellular networks; homogeneous and heterogeneous networks are defined and a summary of related literature is provided.

In chapter 3, the system model including power allocation, channel model and the baseline system are described. Moreover, the three proposed schemes are described and illustrated with pictures.

In chapter 4, we mathematically formulate the problem and briefly explain how we can solve the problem. In chapter 5, numerical results are provided. These results are also presented in [34]. Chapter 6 concludes the thesis.

Chapter 2

Related Work

There is an extensive literature on various aspects of cellular networks. Researchers always try to optimize the performance of the cellular network based on a given set of performance metrics, where data rate and network capacity are the most commonly used. Cellular networks can be classified into two broad types; homogeneous and heterogeneous cellular networks.

In this thesis, we take a global perspective and analyze the effect of overlaying small cells on the performance of a cellular network, thus we need to perform a literature review on both types of the cellular networks.

2.1 Homogenous Cellular Networks

A homogeneous cellular system is defined as a "network of base stations in a planned layout and a collection of user terminals, in which all the base stations have similar transmit power levels, antenna patterns, receiver noise floors and a similar backhaul connectivity to the data network" [21].

For a long time, the architecture of the cellular network has been a homogeneous architecture. Homogeneous networks are based on deploying only one type of base-station, known as macro base stations (MBS). FRF 1 is the first scheme used in homogeneous cellular networks (Fig 2.1). In this scheme, there is only one omnidirectional antenna in each cell and all antennas transmit on the entire bandwidth. With FRF of 1, users suffer from a large CCI, especially near the cell edge, and can not receive an adequate service rate.

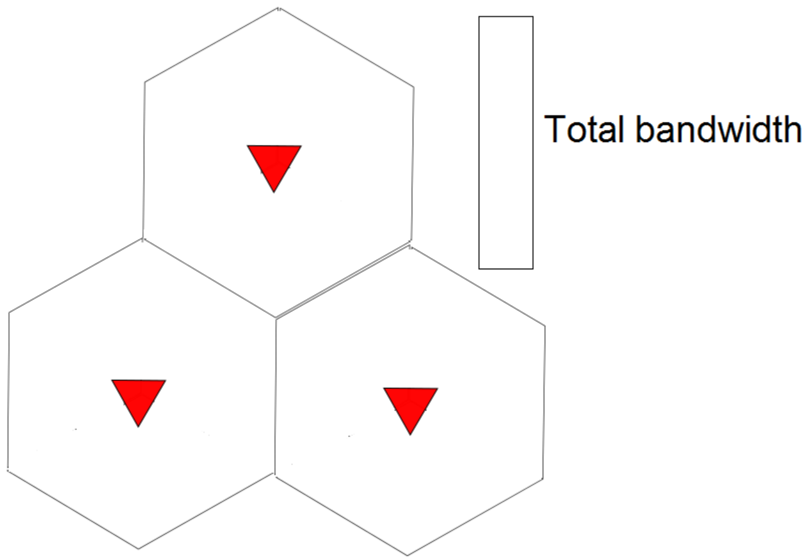


Figure 2.1: Initially purposed scheme with frequency reuse factor of 1

With a large number of deployed Macro-cells all over the world, it is resealable to first improve the performance of the homogeneous networks and maximize the throughput which we can get from these macro-cells. This has led to some better frequency reuse schemes:

FRF N**:** Later, to improve the service experience of users in the cell edges, schemes with larger FRF have been introduced(for example FRF 3 in Fig 2.2) [23]. Although schemes with larger FRF could result in better SINR curves, but smaller bandwidth are allocated to each cell.

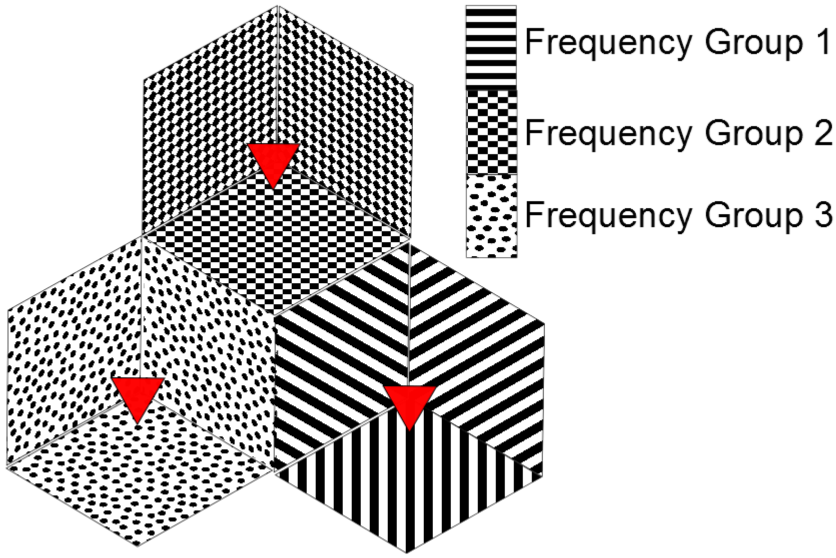


Figure 2.2: Frequency reuse factor of 3 with one omnidirectional antenna in each cell

Multi-Sectored Cell: Networks with multi-sectored cells are another well-known type of homogenous networks which are based on using directional antenna in each sector. Multi-sectored cell is economical solution to improve the network performance since there is no need to spend extra time, money, or space to locate and install a new base station. In sectoring with FRF 3 (Fig 2.3), each sector is operating in different bandwidth while FRF of 1 is still maintained in each cell. Sectoring with FRF 3 is considered as our baseline.

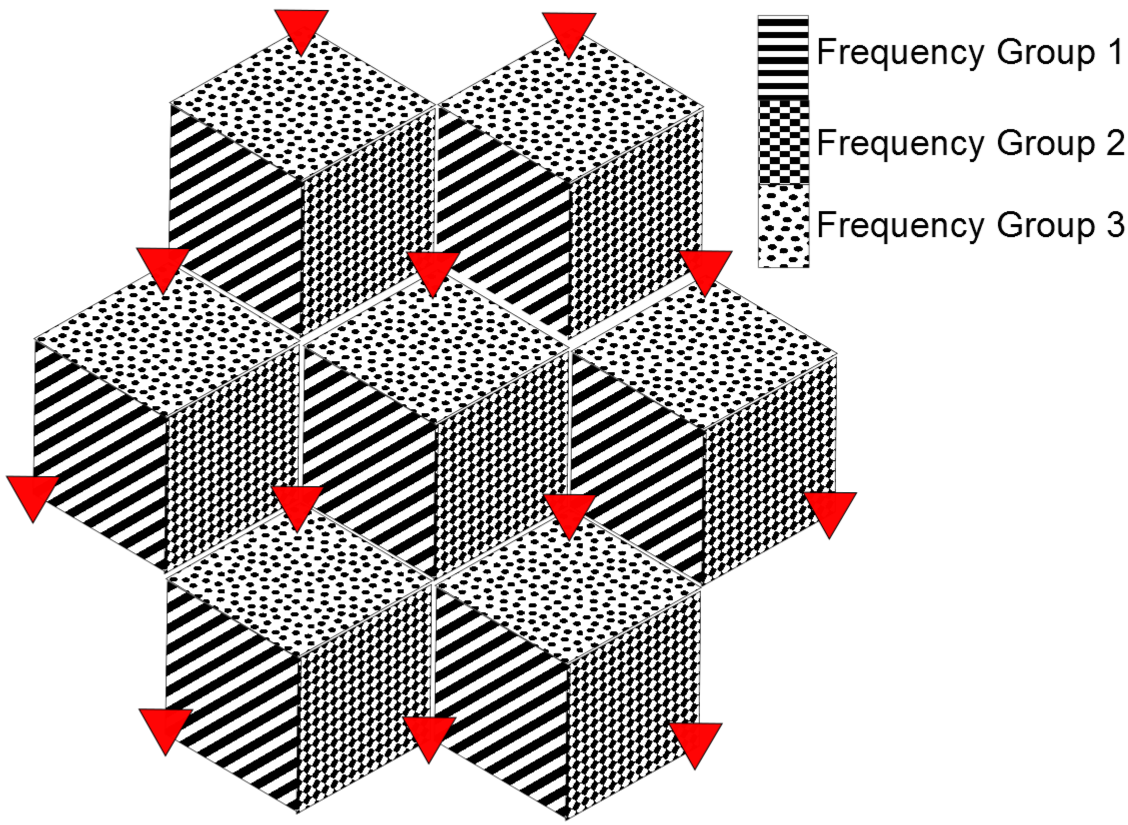


Figure 2.3: Sectoring with three directional antenna in each cell

2.2 Heterogeneous Cellular Networks

There is an extensive literature on various aspects of homogenous cellular networks; However, this approach is no longer sufficient to meet the exponentially growing demand for network throughput. Deploying additional low-power base stations (e.g., pico base-stations (PBS), femto base-stations (FBS), etc.) is one of the most promising approaches to increase the throughput of the network in a cost effective manner [12]. However, this now results in a heterogeneous cellular network (HCN) structure.

A heterogeneous cellular network employs a diverse set of base stations consisting of regular macro base stations with high transmit power of $5W$ to $40W$, pico size base-stations and femto size base-stations with a considerably lower transmit power, ranging from $100mW$ to $2W$ [21].

There has been a large research thrust on HCNs which has established that the deployment of these low-power base-stations indeed improves the throughput of cellular networks. In particular, in [3], Andrews *et al.* present an overview of the history of the femto-cells and list the key challenges of the small cell networks. They identify the interference as the most important challenge for femto-cell deployments specially when a full shared (FS) spectrum method is used between the macro-cell and small cells.

In [29], Liu *et al.* introduce femto-cell placement as a possible solution to overcome the interference challenge. The authors model the building features of a commercial building environment and based on that, they optimize the femto-cell base station (FBS) placement to increase the battery life for user equipments. However, they investigate the placement of the small cells only in a multi-storey office building with limited space and without considering the possibility of users connecting to the macro-station out side of the building.

In [15, 16, 18], it has been shown that installing low-power base stations such as pico base-stations, increases the throughput of the cellular network. In [15], Fooladivanda *et al.* identify four major factors that should be considered for designing a heterogeneous network; pico base station placement, interference management and resource allocation, user association and scheduling policy. They focus more on user association, channel allocation and reuse pattern selection, and calculate the optimum network setting according to these three factors. They also investigate two possible pico base station placements where small cells are placed either symmetrically around the MBS or close to the hot spots. However, these are investigated to get a better understanding of the user association rather than finding a good pico base station placement. Moreover, the investigated system is composed of only one macro-cell and some pico base stations.

In [18], Ghimire *et al.* presents a framework for the off-line study of heterogeneous networks. They study different combinations of resource allocation schemes, transmission coordination mechanisms and pico base station placements. They consider a single macro-cell overlaid with different number of pico base station; 2, 3, 4, and 6, and they show that adding more picos to the network, improve the performance of the network. Similar to the authors in [15], they study only a single cell and interference from the surrounding cells is not addressed in this paper.

In [25], Li *et al.* investigate resource management in heterogeneous networks. Their proposed resource management scheme is based on fractional frequency reuse (FFR). Although, FFR has been originally proposed for homogeneous networks, they optimize it for heterogeneous networks in order to minimize the interference, maximize the spectrum efficiency, and address the fairness among the UEs. They divide each cell into 3 sectors and uniformly locate 4 pico in each sector. They use proportional fairness scheduling algorithm and study different user associations. Their baseline scheme is not a homogeneous network; it is a heterogeneous network deploying full shared spectrum without power control. Moreover, their system model is not according to LTE standards, cell radius is pretty large, 2km, which is even larger than the cell radius for rural area.

In [35], Shimodaira *et al.* optimize the locations of the small cells within a macro cell. More precisely, they search for the optimum location of PBS in a network with fixed locations of hot-spots. Their baseline system is a heterogeneous network with one MBS at the center of the cell and four PBSs at the center of the hot-spots. According to the authors, this approach depends on the initial position of PBS and it is possible to find a local optimal location for PBS placement. While this paper gives us good engineering insights about placement of the PBS according to the hot-spots, small cells are deployed within only one macro cell and the interference from neighbouring cells is not considered.

HCNs have also been analyzed using stochastic geometry techniques [13,14]. There, the BSs are randomly distributed in the network area. However, these techniques do not shed any light on the best locations for the small cells. Most of the related work on cell Planning have considered only interference management, bandwidth allocation and user demands; however, the authors in [42], consider the cost as the main factor when Planning the small cell locations. In [42], Zhao *et al.* propose an optimization problem to minimize the total deployment cost of the network by choosing the best locations for MBSs and small cells from among a given set of potential locations. Potential locations of PBSs are selected with an uniform distribution in the deployment area of the network. The investigated system is composed of only one MBS, one PBS and one relay node.

In [27], Li *et al.* use a Gibbs sampling based optimization to find the best locations for small cells. In this method, the area of interest is evenly divided into many rectangular-shape small cells. Then, in each iteration, each pico base station decides whether to relocate to a neighboring small cell or remain in its current location. Relocation of PBSs is according to a probability distribution computed based on the summation of the throughputs of all users. The probability distribution is defined so that the steady state of the process is concentrated around the global optimal solution. However, their system model is an HSDPA system with 4 MBS equipped with omnidirectional antenna. Moreover, scheduling and interference management in surrounding cells are not considered and users simply associate with the pico with the strongest Received Signal Code Power (RSCP) value.

Unlike these works, in this thesis, we consider a HCN comprised of several macro cells and assume that the resource allocation to the small cells is done at the network level globally. Without using any type of optimization, based on the interference and coverage patterns, we identify potential locations for small cells in a homogenous cellular network. We show that installing small cells at these locations and allocating exclusive resources globally to the small cells significantly improves the performance of the network.

Chapter 3

System Architecture and Model

A single-hop OFDMA-based cellular system (Figure 3.1) is considered. We focus on the downlink of the system. Each cell is a predefined hexagonal area which might be partitioned in some sectors; if so, each sector is equipped with one antenna. The system has a set of T OFDM sub-channels on a given frequency band with a per sub-channel bandwidth of b.

3.1 Baseline System

The *baseline system* is an OFDM-based multi-sectored cellular network with M macro base-stations (MBS) each equipped with three directional antennas and T sub-channels, each of bandwidth b. It is a FRF 3 scheme shown in Figure 2.3 where $T/3$ sub-channels are exclusively assigned to each of the directional antennas.

Users are uniformly distributed all over the cell with density of ρ_u users per cell. Only the downlink traffic is considered and it is assumed that the BSs transmit all the time in all the channels assigned to them.

We quantify the performance of this network in terms of the geometric mean (GM) throughput of all the users in the central cell. We are interested in measuring the impact of deploying low-power BSs with omnidirectional antennas on the performance of this system.

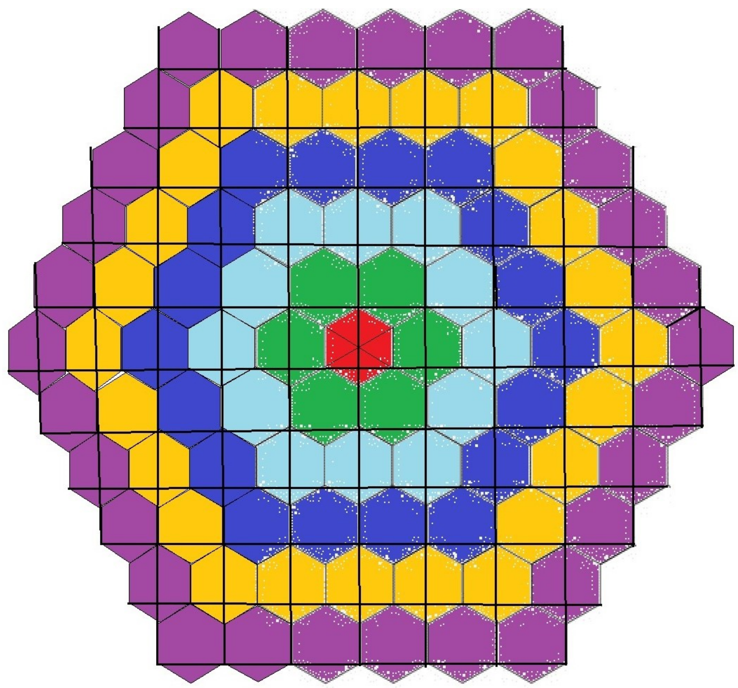


Figure 3.1: The single-hop cellular system with one cell in the center and 90 surrounding cells

3.2 Placement of Small Cells

As shown in Figure 3.2, we have identified two types of potential locations for the deployment of the small cells. At these locations, the coverage is weak (because of the longer distance from the transmitting antenna) and/or the interference can be strong (because of the smaller distance from interferer antennas).

- **Locations of type A**: At these locations, three sectors of three different bands meet. Users at these locations are farther away from the BSs. Thus the coverage is weak and the traveling signal experiences a larger path loss.
- **Locations of type B**: At locations of type B, six sectors meet such that there are two sectors from each band. Users at these locations experience a stronger interference.

Since, every point of intersection is shared by three hexagonal cells, it is easy to see that, for a large network and neglecting edge effects, there is one point of type A and one point of type B for each MBS. Depending on the type of locations chosen for the installation of the small cells, we define three different schemes.

- **Scheme A:** Install the small cells only at locations of type A.
- **Scheme B:** Install the small cells only at locations of type B.
- **Scheme C:** Install them at both locations of type A as well as type B.

Note that in Scheme A and Scheme B, we install one small cell per MBS and in Scheme C, we install two small cells per MBS. We next discuss the resource allocation used for each of these 3 schemes.

3.3 Global Resource Allocation

K channels of the total T sub-channels are assigned to the small cells and $T - K$ are assigned to the macro-base stations.

The small cells use omnidirectional antennas and utilize the frequency reuse factor of 1 but the MBS use directional antenna and utilize the frequency reuse factor of 3 on each sector. So, $(T-K)/3$ sub-channels are allocated to each directional antenna. We will play with the value of K.

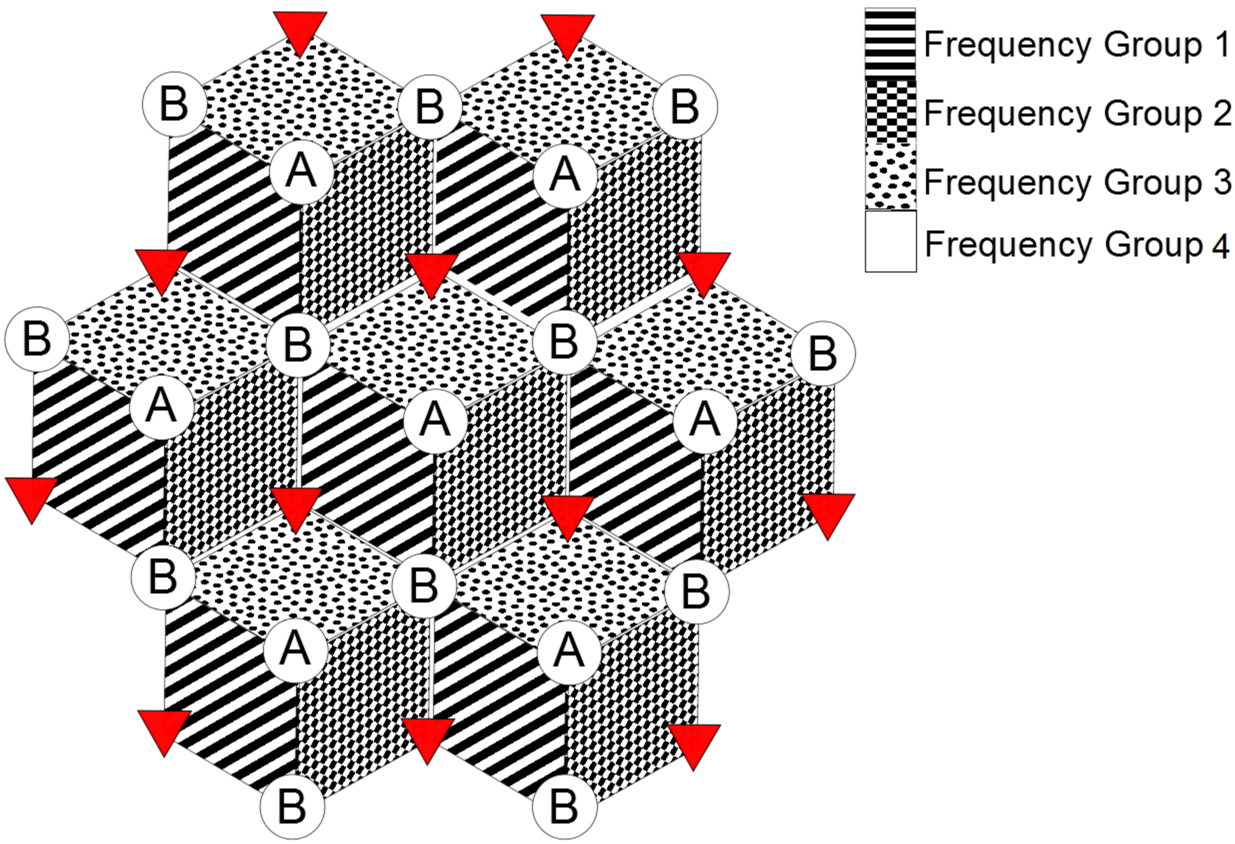


Figure 3.2: A part of the cellular network. Here locations A and B are conducive for installing small cells

Deployment of a large number of small cells across a diverse set of locations with a variety of conditions has made it a challenge to provide enough backhaul capacity. However, in this thesis we assume an infinite-capacity backhaul links.

3.4 Power Allocation

Let the transmit power of the MBS be P_{MBS} and that of a small cell BS be P_{SC}. We assume that P_{MBS} is equally divided among the three directional antennas of the MBS. The power allocation in each antenna is carried out by assigning equal power to all of the allocated sub-channels. Thus, the transmit power per sub-channel is given as follows,

$$P_i = \begin{cases} \frac{P_{\mathrm{MBS}}}{T-K} & \text{if } i \text{ is a MBS} \\ \frac{P_{\mathrm{SC}}}{K} & \text{if } i \text{ is a small cell} \end{cases} \tag{3.1}$$

This means that the interference is a function of K as will be seen in the next section.

3.5 The Channel Model

We model the channel gain, g_{ju}, between BS j and user u as, $g_{ju} = D_{ju} \times G_{ju} \times PL_{ju}$,where PL_{ju} is the path-loss, G_{ju} is the log normal shadowing, and D_{ju} is the directive gain pattern of the antenna.

For the path-loss and the directive gain pattern of the antenna, we consider the model recommended by 3GPP [1] heterogeneous networks (outdoor). According to this recommendation, the path-loss, PL_{ju}, follows the model given in Table 3.1. For the directive gain pattern of a directional antenna, they recommend $D_j(\theta) = -\min\left\{12\left(\frac{\theta}{\theta_{3\mathrm{dB}}}\right)^2, A_m\right\}$ dB, where θ is the angle made by the user position with the broadside direction of the antenna, $\theta_{3\mathrm{dB}}$ is the 3dB beamwidth ($\theta_{3\mathrm{dB}} = 70$ degrees) and $A_m = 20$ is the maximum attenuation in dB which the signal experiences in the sidelobes of the antenna. The directive gain pattern of an omnidirectional antenna is assumed to be 0 dBi for every angle.

We assume that the shadowing G_{ju} follows a log normal distribution with mean 0 and standard deviation of 8 dB.

Table 3.1: Path-loss model

Transmitter	Link (j, i)	Path-loss of the medium (ϕ_{ju}) (dB)	Antenna gain (AG_j) (dB)	Losses (ζ_j) (dB)
MBS	(j, u)	$128.1 + 37.6 \log_{10}\left(\frac{d_{ju}}{1000}\right), d_{ju} \geq 35m$	15	20
Small cell	(j, u)	$140.7 + 36.7 \log_{10}\left(\frac{d_{ju}}{1000}\right), d_{ju} \geq 10m$	5	20
Total path-loss in dB: $PL_{ju} = \phi_{ju} + \zeta_j - AG_j$				

The SINR between BS j and user u on a given channel is given as follows,

$$\gamma_{ju} = \frac{g_{ju} P_j}{N_0 + \sum_{i \in \mathcal{B}_j j \neq i} g_{iu} P_i}, \tag{3.2}$$

where P_i is the transmit power per subchannel of BS i, N_0 is the additive white Gaussian noise power and $\mathcal{B}_j$ is the set of all BSs that are transmitting on the same channels as BS j. Note that, since the transmit power P_i is a function of K (the number of sub-channels assigned to the small cells), SINR is also a function of K.

Let r_{ju} be the data rate received by user u from BS j. This is a function of the SINR received by user u from BS j, γ_{ju}, i.e., $r_{ju} = f(\gamma_{ju})$. We consider the piecewise linear function recommended by 3GPP for this rate function (see Section 5 for more details).

3.6 User Association

A user association (UA) policy determines the BS to which a given user connects with. We consider the following two simple user association (UA) rules. They are

- **Best SINR:** Users associates with the BS that provides the maximum SINR.
- **Small-cell First (SCF):** Under this rule, a user associates with the small cell that gives the maximum SINR provided that this is greater than a given threshold β. If no small cell provides SINR greater than β, it associates with the BS that provides the maximum SINR.

As $\beta \to \infty$, the SCF rule converges to best SINR rule. The SCF rule in this thesis is slightly different from the one considered in the literature [18], [16], where the user connects only to one of the macro BSs if there is no small cell that can provide a SINR greater than the given threshold.

In the next section, we give a mathematical formulation of our problem.

3.7 Scheduling

Scheduling is determining how the available resource would be allocated to each user in order to maximize the desired objective function. In this study we have implemented a proportional fairness scheduler [24], [16] on top of the interference mitigation techniques. Thus, the geometric mean (GM) throughput of all the users is the performance metric of a given network configuration (i.e., resource allocation, user association and scheduling) and we are interested in maximizing it.

Chapter 4

Problem Formulation

In this section, we first mathematically formulate the problem for a general heterogeneous cellular network as a joint optimal scheduling, resource allocation and user association problem.

Let $\mathcal{B}$ be the set of all the BSs (MBSs + small cells) in the network and $\mathcal{B}_i$ be the set of all BSs that are assigned the same set of subchannels as BS i. Let $\mathcal{N}$ be the set of all users in the network and let λ_u be the data rate received by user u. We assume that the users are greedy and are interested in maximizing their throughput. Thus, there is a need to ensure fairness in the network and we consider the proportional fair criteria [16, 24], which requires maximizing the sum of the logarithms of the throughputs.

Let x_{iu} be the user association variable which is a binary variable that is 1 if user u is associated with BS i and otherwise 0. Let α_{iu} be the fraction of time BS i transmits to user u. Clearly, $\alpha_{iu} = 0$ whenever $x_{iu} = 0$. We can compute the geometric mean throughput of a given system by solving the following optimization problem $\mathcal{P}$ and also find the corresponding user association (x_{iu}'s), the schedule (α_{iu}'s) and the number of subchannels to be assigned to the small cells (K). Note that when the given system is our baseline system, $\mathcal{B}$ consists of only the macro BSs and $K = 0$.

$$\mathcal{P}: \qquad \underset{\alpha,\mathbf{x},K}{\text{Max}} \sum_{u} \log(\lambda_u) \tag{4.1}$$

subject to

$$\lambda_u = \sum_{i\in\mathcal{B}} \alpha_{iu} r_{iu} \tag{4.2}$$

$$r_{iu} = f(\gamma_{iu}) \tag{4.3}$$

$$\gamma_{iu} = \frac{g_{iu}P_i}{N_0 + \sum_{j:j\neq i, j\in\mathcal{B}_i} g_{ju}P_j} \tag{4.4}$$

$$P_i = \begin{cases} \frac{P_{\text{MBS}}}{T-K} & \text{if } i \text{ is a MBS} \\ \frac{P_{\text{SC}}}{K} & \text{if } i \text{ is a small cell} \end{cases} \tag{4.5}$$

$$\sum_{u\in\mathcal{N}} \alpha_{iu} \leq 1 \tag{4.6}$$

$$0 \leq \alpha_{iu} \leq x_{iu} \tag{4.7}$$

$$\sum_{i\in\mathcal{B}} x_{iu} = 1 \text{ and } \quad x_{iu} \in \{0,1\} \tag{4.8}$$

Constraint (4.2) represents the total data rate received by user u. Eq. (4.3) computes the data rate between a user and a BS using the given rate function, $f(\cdot)$. Equation (4.4) computes the SINR between the BSs and the users while Eq. (4.5) computes the power per sub-channel which depends on whether the BS is a macro BS or a small cell BS. Constraint (4.6) states that the sum of the fractions of scheduling times from a given BS cannot exceed 1. Constraint (4.7) ensures that the BS allocates scheduling time to a user only if it is associated with it and constraint (4.8) ensures that a user associates with only one BS.

This optimization problem, $\mathcal{P}$, is a non-linear integer program and hence is very difficult to solve. There are three reasons for this.

1. The SINR constraint in Eq. (4.4) is non-convex (because of its dependence on K).

2. The constraint with the rate function, i.e., Eq. (4.3), is also difficult to handle. We require either a closed form expression for $f(\cdot)$ that is convex or a method to enumerate all the rates and eliminate this constraint.

3. It is an integer program and is not tractable for large problem sizes.

4.1 How to solve the optimization problem?

A typical technique used to address the issue with the SINR constraint Eq. (4.4), is to fix K, the number of channels assigned to the small cells and compute the SINRs, γ_{iu}'s, a priori. Given the SINRs and the rate function, $f(\cdot)$, we can compute the data rates available from every BS to every user and thus address the issue with the constraint in Eq. (4.3). With these two modifications in the constraints in Eq. (4.4) and Eq. (4.3) the problem transforms into a simpler non-linear integer program. However, it is still intractable in its current form. So, we relax the integer constraint on x_{iu}'s and find an *upper bound* on the GM throughput. This relaxation allows the users to be associated with multiple BSs and requires that the traffic destined to a user be split and delivered via different BSs.

We also find feasible solutions by assuming that the user association (UA) variables, x_{iu}'s, are determined by the simple UA rules given in Section 3.6 viz., best SINR and small-cell first (SCF). We define the envelope of these feasible solutions as the best feasible solution over all the considered UA rules at every K. In Section 5, we present a comparison of the upper bound with this envelope of the GM throughput of the feasible solutions versus K, which shows that there are near-optimal and within 10% for all three schemes.

For the feasible solution case, since the data rates, $\mathbf{r}$, i.e., r_{iu}'s, are computed a priori by fixing K and that the user association, $\mathbf{x}$, i.e., x_{iu}'s is given, we can compute the geometric mean throughput of the system by solving the following optimization problem $\mathcal{P}(\mathbf{r}, \mathbf{x})$.

$$\mathcal{P}(\mathbf{r}, \mathbf{x}) : \qquad \operatorname*{Max}_{\alpha} \sum_{u} \log(\lambda_u) \tag{4.9}$$

subject to

$$\lambda_u = \sum_{i \in \mathcal{B}} \alpha_{iu} r_{iu} \tag{4.10}$$

$$0 \leq \alpha_{iu} \leq x_{iu} \quad \forall i \in \mathcal{B} \quad \forall u \in \mathcal{N} \tag{4.11}$$

$$\sum_{u \in \mathcal{N}} \alpha_{iu} = 1 \tag{4.12}$$

This is a non-linear program. However, the nature of its solution is known and it can be easily computed using the following lemma, which is a specialized version of Lemma 1 in [24].

Lemma 1: Given the resource allocation parameters (the number of sub-channels allocated, the transmit power on each sub-channel and the user association) and infinite backhaul capacity, under proportional fair scheduling a BS assigns equal proportion of time to all the users associated with it.

This lemma implies that local equal time scheduling (at every BS) solves our optimization problem, $\mathcal{P}(\mathbf{r}, \mathbf{x})$ and thus we have an efficient technique to compute its optimal solution. In the next section, we present numerical results obtained by solving this problem (using the above Lemma) for a large number of random network realizations.

Chapter 5

Numerical Results

We consider a large cellular network with 91 macro cells (or 5 tiers of hexagonal cells around the central cell). We consider two different scenarios, viz., urban and rural. In the urban scenario, the inter-site distance (ISD) between the macros is 500 m while in the rural case, it is 1732 m [1]. For both these scenarios, we assume that the users are uniformly distributed with a density of $\rho_u = 25$ users per cell. Since the rural cell has 10 times larger area, its density of users per unit area is 10 times smaller than that of a urban cell. We have generated 100 random realizations of the user locations for each scenario.

The physical layer parameters used in our computations are given in Table 5.1 [1]. The typical transmit power of the MBS is 46 dBm and that of the small cell is 30 dBm.

We assume that there are a total of $T = 99$ sub-channels which can be divided among the macro and the small cells. For the rate function, we use the piecewise linear mapping

Table 5.1: Physical layer parameters

Noise Power	$-174\ \frac{\text{dBm}}{\text{Hz}}$	T_{subframe}	1 ms
P_{sc}	30 dBm	P_{macro}	46 dBm
UE Ant. Gain	0 dB	Sub-channel Bandwidth	180 KHz
Shadowing s.d.	8 dB	User Noise Figure	9 dB
Penetration Loss	20 dB	M (Number of sub-channels)	100
Macro Ant. Gain	15 dBi	Pico Ant. Gain	5 dBi
SC_{ofdm}	12	SY_{ofdm}	14

Table 5.2: Modulation and coding schemes - LTE

Threshold SINR (dB)	-6.5	-4	-2.6	-1	1	3	6.6	10	11.4	11.8	13	13.8	15.6	16.8	17.6
Efficiency (bits/symbol)	0.15	0.23	0.38	0.60	0.88	1.18	1.48	1.91	2.41	2.73	3.32	3.9	4.52	5.12	5.55

(recommended by 3GPP), which is given by

$$r_{ju} = \frac{\mathrm{SC}_{\mathrm{ofdm}}\mathrm{SY}_{\mathrm{ofdm}}}{T_{\mathrm{subframe}}} e_l \tag{5.1}$$

where e_l is the efficiency (bits/symbols) of the corresponding SINR threshold level l, $\mathrm{SC}_{\mathrm{ofdm}}$ is the number of data subcarriers per sub-channel bandwidth, $\mathrm{SY}_{\mathrm{ofdm}}$ is the number of OFDM symbols per subframe, and T_{subframe} is the subframe duration in time units. The mapping of e_l to SINR levels is given in Table 5.2.

Recall that in problem $\mathcal{P}(\mathbf{r}, \mathbf{x})$, the input rates $\mathbf{r}$ are known by fixing K and the user association, $\mathbf{x}$, is determined by either the best SINR rule or the SCF rule.

For each of the 100 random realizations in both the scenarios, we solved the problem $\mathcal{P}(\mathbf{r}, \mathbf{x})$ using Lemma 1, for all three proposed schemes and the baseline system, for every K from $K = 3$ to $K = 96$ and for both the user association rules, best SINR and SCF. $K = 3$ is when only one sub-channel is allocated to PBSs and $K = 96$ is when only one sub-channel is allocated to each sector. For the baseline system, we have used the best SINR user association rule. For SCF, we solved for 15 different β's, taken from the thresholds row in Table 5.2. Thus, we have 16 different user association rules.

In Fig. 5.1, for the urban scenario, we have plotted the upper bound on the GM throughput obtained by solving the relaxed problem versus the best GM throughput (or the envelope) due to the 16 UA rules considered, for all three schemes. We note that the performance of the best GM throughput (for each K) of our simple UA rules is within 10% of the upper bound. We also note from Fig. 5.1 that Scheme C with two small cells per MBS performs the best. When we can install only one small call per MBS, our results show that Scheme B is preferable over Scheme A.

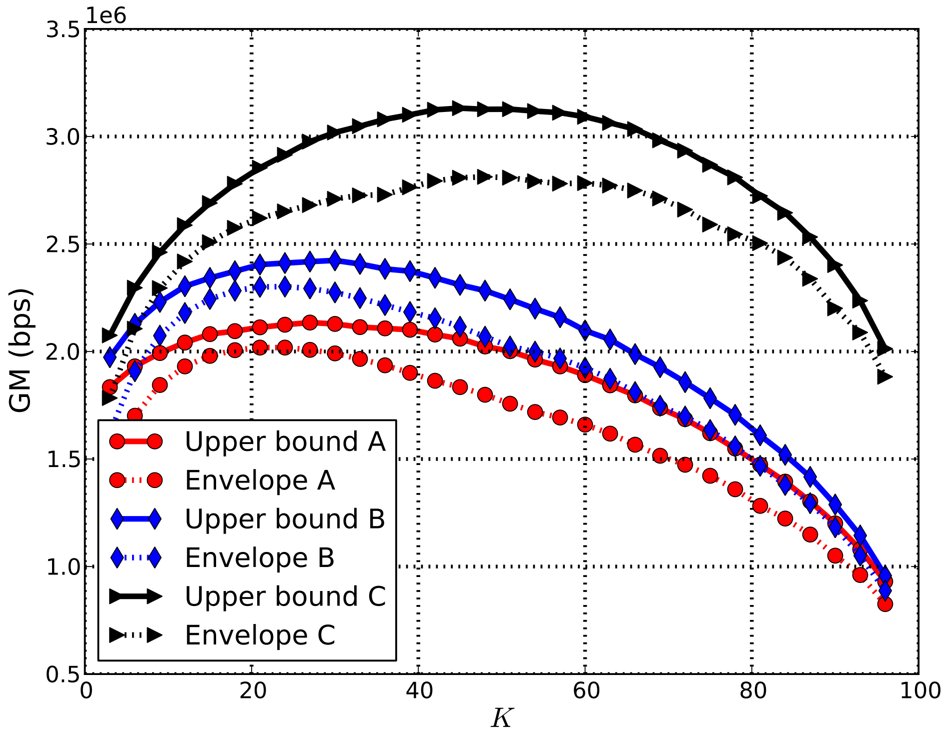
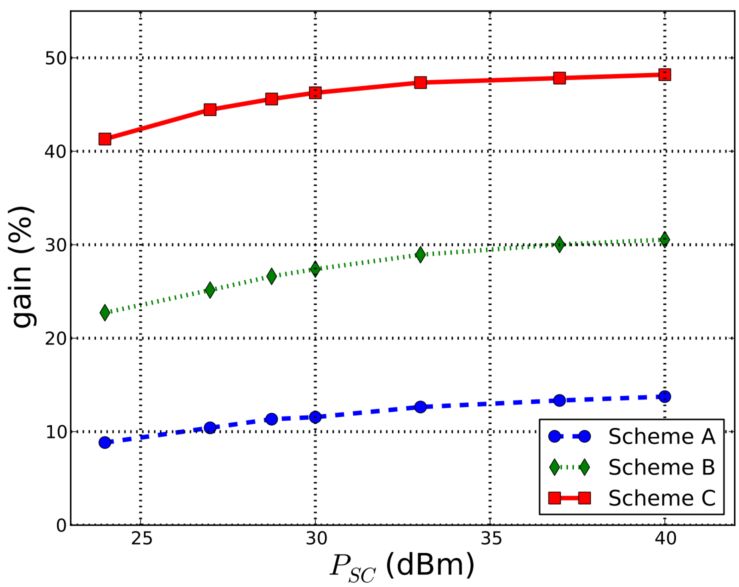


Figure 5.1: Upper bound and the best GM throughput using our UA rules (labelled as the envelope) vs K for the urban scenario, $\rho_u = 25$ and $P_{\mathrm{SC}} = 30$ dBm for all three schemes

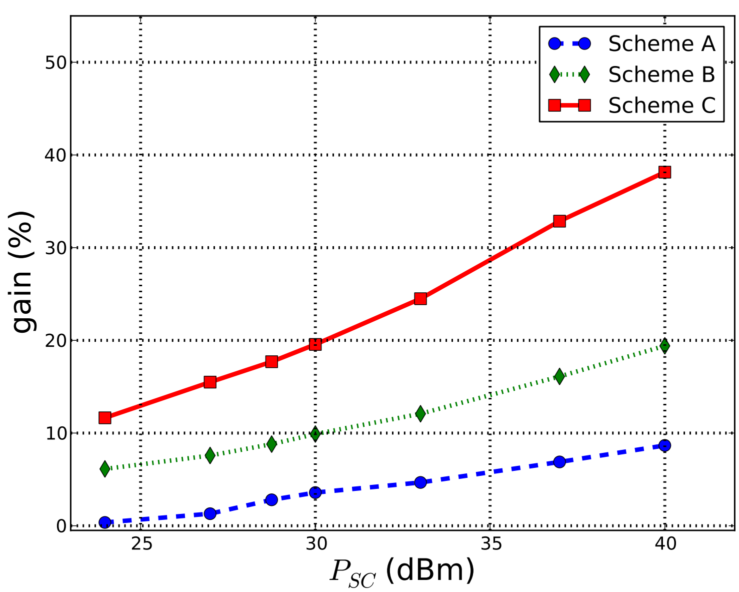
Next, we computed the percentage gain in the geometric mean (GM) throughput of every scheme with respect to the baseline GM and averaged it over the 100 random realizations (for every K and the 16 user association rules). We repeated this for 7 different transmit powers of the small cells BS. For every considered transmit power of the small cell, we have computed the best possible gain for any K and any user association rule considered and plotted it versus P_{SC} in Fig. 5.2 for both the urban and rural scenarios.

From these plots, we can infer that by judiciously installing small cells according to Scheme C, we can obtain close to 45% gain in the geometric mean throughput of the system.

We have also computed these results with a higher density of users ($\rho_u = 50$ users per cell). We observed that these results are also similar to the ones presented with a slight



(a) Urban Scenario - ISD = 500 m



(b) Rural Scenario - ISD = 1732 m

Figure 5.2: Best gains (of best SINR and 15 SCF UA rules) vs P_{SC} for the three proposed schemes of small cell placement, $\rho_u = 25$

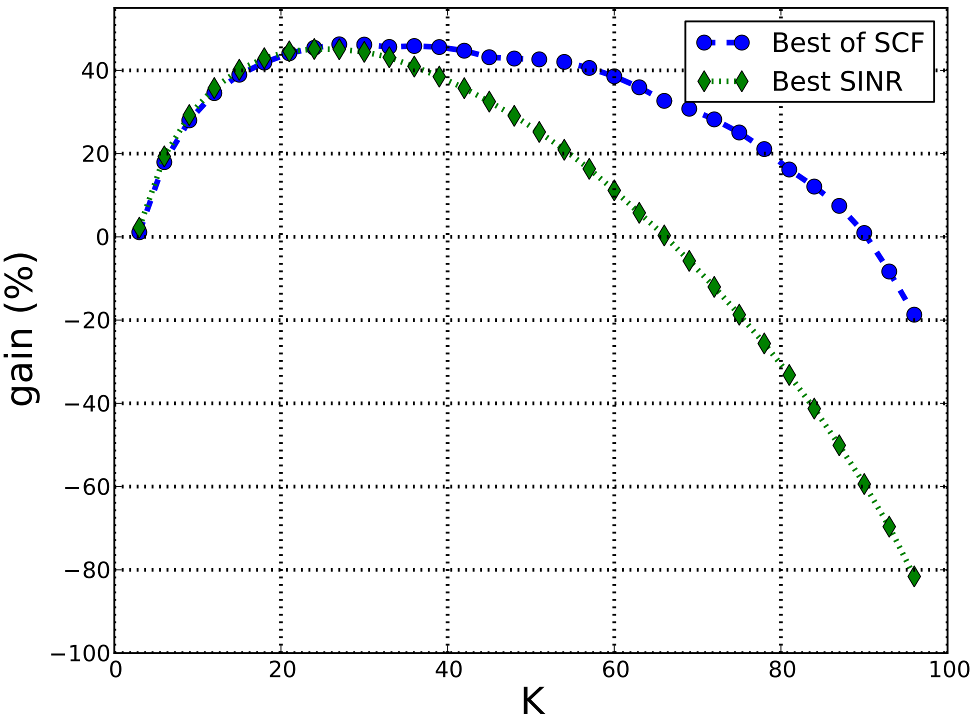


Figure 5.3: Gains due to best SINR vs the best of the SCF user associations for ISD = 500 m, $\rho_u = 25$, $P_{\mathrm{SC}} = 30$ dBm

increase in the gains.

Another important observation from these results is that in the rural scenario, the small cells have to transmit at a much higher power to obtain a significant gain in performance, while for the urban scenario, the typical small cell transmit power of 30 dBm is sufficient.

In Fig. 5.3, we show a comparison of the gains of the best SINR UA and the envelope of the best (for each K) 15 SCF user associations for the urban scenario. From this plot, we conclude that the best performance of the SINR user association rule is not far from the best performance of the SCF user associations.

MBSs have a significantly high energy cost of operation. We could substantially reduce this cost if we could afford to switch them off for a few hours every day when the number of active users is low. The proposed Scheme C provides a method to do this in an urban scenario. In Fig. 5.4, we plot the percentage of uncovered area (as a function of K,

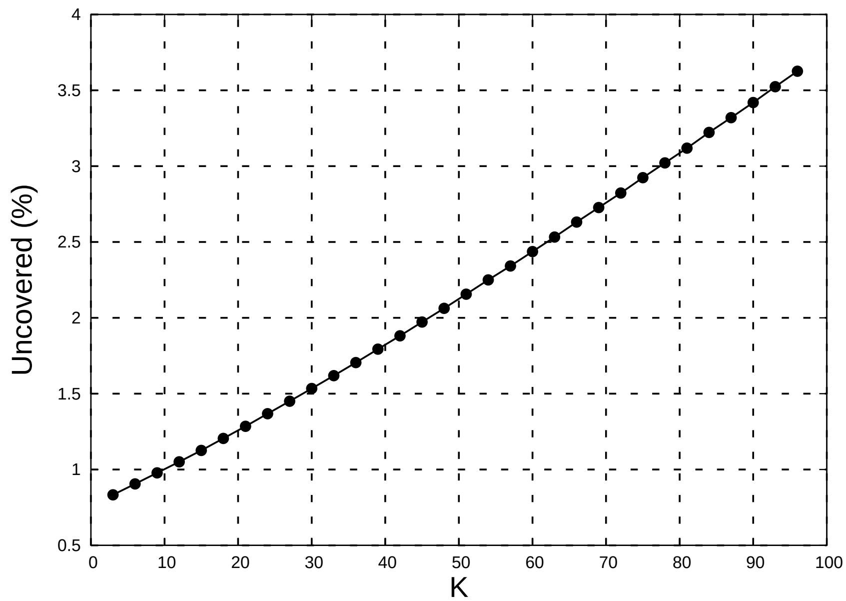


Figure 5.4: Percentage of uncovered area with just small cells in Scheme C versus K (urban scenario, $P_{\text{SC}} = 30$ dBm)

when the MBSs are switched off and the small cells are deployed according to Scheme C. First, this figure confirms that the coverage is limited by the maximum transmission power at PBS. As K increases, more sub-channels are assigned to PBSs which will result in a decrease in the per sub-channel power. Consequently, UE can be in a shorter distance from the PBS. Second, it is clear from this plot that the percentage of uncovered area is less than 2% when $K = 45$, which implies that we can afford to switch off the MBSs during night time. Thus, Scheme C provides an added benefit that results in substantial savings in terms of the overall power consumption and cost of operation.

Chapter 6

Conclusion

In this thesis, we investigated the deployment of small cells in a cellular network from the overall network point of view. Our results indicated that cell planning has a high impact on the network performance. If small cells are not placed intelligently, they may impose an extra deployment cost without any considerable improvement in the network performance.

Pico base station placement in heterogeneous networks is challenging. First of all, it is not a green field deployment. Some locations are already occupied by the MBSs. Because of the site limitations, health hazards, and severe interference, PBS should not be placed in a very close distance to MBS. Second, PBS Planning should be done according to the existing macro cell networks. Small cells are not supposed to operate as an isolated network and support the whole traffic of a large area. Small cells should be planned according to the current network limitations; to off-load some traffic from MBS and improve the network performance. This is why we claimed that in heterogeneous networks, cell planning and resource management are complex.

To propose an optimized PBS placement, it is important to consider an accurate network model which reflects the current network limitations. In this thesis, a large deployment area is considered which consists of 91 macro cells overlaid with 182 small cells. This large number of MBS and PBS gives us an accurate estimation of the network interference. Moreover, to find the effectiveness of adding small cells, we have considered an optimum OFDM-based homogeneous cellular network as our baseline system. Our baseline system is a multi-sectored network. We have measured the impact of deploying PBS on the performance of this system.

We identified two sets of potential locations for small cells within a homogenous cellular network and propose three different way to install small cells based on these locations. Potential locations are identified based on the current network limitations. At these locations, users are poorly serviced since the coverage is weak and/or the interference is strong. At locations of type A, users observe a large path loss because of the large distance between the users and the MBS. At locations of type B, six sectors meet such that there are two sectors from each frequency group. In other words, users are not only far from the MBS, they are more exposed to the interference from adjacent sectors.

We have showed that judiciously installing two small cells per macro cell at the appropriate locations is enough to achieve a surprisingly significant gain of $\sim 45\%$ in the performance of the network. We have also showed that small cells in rural area might not be as effective as in urban area because in the rural area, the small cells have to transmit at a much higher power to obtain a significant gain in performance.

Also, unlike most of the literature, we assumed that the resource allocation to the small cells is done at the network level globally. We have used simple user association rules to achieve these gains and also showed that these user association rules give a GM throughput that is within 10% of the upper bound.

We have also showed that an added benefit of our Scheme C is that we can afford to switch off the MBSs during night and reduce their operating cost in an urban scenario. In other words, the small cell planning and placement proposed here is enough to maintain connectivity under low traffic conditions. This is important as MBSs consume a significant amount of power for their operation.

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