THE REPUBLIC OF TURKEY
BAHÇEŞEHİR UNIVERSITY

ENERGY AND SPECTRAL EFFICIENT SMALL CELL DEPLOYMENT IN HETEROGENEOUS CELLULAR NETWORKS

Master's Thesis

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THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
ELECTRICAL AND ELECTRONICS ENGINEERING

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ABSTRACT

ENERGY AND SPECTRAL EFFICIENT SMALL CELL DEPLOYMENT IN HETEROGENEOUS CELLULAR NETWORKS

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Due to growing power consumption and data-rate demand in cellular networks, it is crucial to design the future networks with energy and spectral efficient strategies. Using heterogeneous networks (HetNets) is one possible way of improving spectral and energy efficiencies in cellular networks. In this thesis, under a coverage constraint, we consider deploying strategies with low power small cells in order to improve the area spectral and energy efficiencies of the conventional macrocell only cellular network. We start our analysis with accurate power consumption models for both macro and small base stations. Then, we analyze the area spectral and energy efficiencies with respect to inter-side-distance (ISD), the number and size of microcells. Finally, we formulate total power consumption of a cellular network as an optimization problem and find the optimum solution to this problem.

Keywords: Energy Efficiency, Area Spectral Efficiency, Microcell Deployment, Heterogeneous Networks, Power Optimization

ÖZET

HETEROJEN HÜCRESEL AĞLARDA ENERJİ VE SPEKTRAL VERİMLİ KÜÇÜK HÜCRE YERLEŞİMİ

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Hücresel ağlarda giderek artan enerji tüketimi ve veri hızı ihtiyacı, yeni nesil ağların enerji ve spektral verimli stratejilerle tasarlanmasını zorunlu kılmıştır. Hücresel ağlarda spektral verimliliği ve enerji verimliliğini artırmanın muhtemel bir yolu heterojen ağlar (HetNets) kullanmaktır. Bu çalışmada, bir kapsama sınırlaması altında, geleneksel makro hücreli ağların spektal ve enerji verimliliğini artırmak için alçak güçlü küçük hücre yerleşim stratejileri incelenmiştir. İnceleme için öncelikle makro ve küçük hücrelerin güç tüketimi modellenmiş, daha sonra enerji verimliliği ve spektral verimlilik hücreler arası mesafe, küçük hücre sayısı ve boyutuna göre incelenmiştir. Son olarak, hücresel ağlarda toplam güç tüketimi bir optimizasyon problemi olarak ifade edilmiş ve optimum çözüm bulunmuştur.

Anahtar Kelimeler: Enerji Verimliliği, Spektral Verimlilik, Mikro Hücre Yerleşimi, Heterojen Ağlar, Güç Optimizasyonu.

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ABBREVIATIONS

HetNet	:	Heterogeneous Network
ISD	:	Inter-Site-Distance
LOS	:	Line-of-Sight
NLOS	:	Non-Line-of-Sight
PI	:	Performanca Indicator
SINR	:	Signal-to-Interference Plus Noise Ratio

SYMBOLS

Available power for data channels	:	P_{data}
Cooling Loss	:	C_C
Dynamic Power Consumption	:	$P_{\mu,dyn}$
Hexagonal Cell Area	:	A_C
Macro Base Station Power Consumption	:	P_M
Macro Base Station Radius	:	R_M
Maximum available power budget of base station	:	$P_{\max}$
Micro Base Station Power Consumption	:	P_μ
Micro Base Station Radius	:	r_μ
Power Amplifier Efficiency	:	η_{PA}
Number of Power Amplifier per Sectors	:	N_{PA}
Number of Sectors	:	N_S
Number of Transceiver Chains	:	N_{TRX}
Path loss exponent	:	λ
Pico Base Station Power Consumption	:	P_ρ
Pico Base Station Radius	:	r_ρ
Pilot signal strength	:	P_{pilot}
Power Consumption at Zero RF Output Power	:	P_0
Power Supply Loss	:	C_{PS}
Received Signal Power	:	P_{rx}
Receiver Sensitivity	:	P_{min}
SINR at given point	:	$\gamma(r, \theta)$
Slope of the Load Dependent Power Consumption	:	Δ_P
Static Power Consumption	:	$P_{\mu,stat}$
Transmitted Signal Power	:	P_{tx}

1. INTRODUCTION

Throughput demand of cellular networks has been growing at an exponential rate. In order to satisfy this demand, power consumption of those networks is increasing rapidly. This rise in power consumption of cellular networks suggests that energy efficiency should be considered as an emerging global concern. In order to improve energy efficiency, several solutions are proposed in the literature. Detailed approach to general energy efficiency problem can be found in [Hasan et al. (2011)], [Correia et al. (2010)], [Han et al. (2011)], [Feng et al. (2013)] and [Damnjanovic et al. (2011)], and references therein.

Reference [Hasan et al. (2011)] proposed three important aspects of energy efficient networking: changes in base station hardware, heterogeneous network planning and energy efficient system design. In [Correia et al. (2010)], potential savings were divided into three groups: component level, link level and network level potentials. While first two groups are out of the scope of this study, third group includes one of the most promising solutions of energy efficiency problem of wireless cellular networks: heterogeneous deployment. In [Feng et al. (2013)], previous projects on energy efficient networks were summarized. Then, the topic was investigated under two important sections: energy-efficient radio resource management and network deployment strategies. In network deployment strategies part, several possible solutions were emphasised e.g., coordinated multi-point and cooperative communications. Reference [Damnjanovic et al. (2011)] investigated heterogeneous cellular networks from several aspects and propose technical challenges e.g, coverage problems of small cells. Then, available solutions for those challenges were referred.

The aspect that we follow, is to obtain energy efficiency through heterogeneous network planning. An idea that was proposed in [Dufkova et al. (2010)] and [Marsan et al. (2009)] for energy efficiency in cellular networks, is to shut down the under-utilized nodes in a homogeneous macrocell network. In [Niu et al. (2010)], zooming out is proposed for under-utilized nodes, instead of shutting down. However, both shutting down and zooming out a macro base station are not a very practical approach, since they could cause coverage problems. Thus, we will deal with the coverage condition delicately, not to compromise the total coverage rate.

References [Richter et al. (2009)] and [Fehske et al. (2009)] studied power consumption of a heterogeneous cellular network that consists of conventional macrocells and a varying number of low power microcells. However, they used a relatively simple model for total power consumption of base stations while comprehensive power consumption models were proposed in [Arnold et al. (2010)] and [Auer et al. (2011)]. References [Richter et al. (2009)] and [Fehske et al. (2009)] calculated the minimum transmitted power for a fixed coverage area condition with respect to ISD while employing an overlayed microcell deployment strategy. In such a case, macrocell coverage remains 100 percent regardless of microcells. Thus, microcell addition decreases energy efficiency even if it causes a better spectral efficiency.

Some literature concentrates on the energy and cost effects of small cell deployment. In [Khirallah et al. (2011)], operational and capital expenditures, and total cost of ownership were modeled for a wireless cellular network. Then, the effect of small cell deployment on possible expenditures, was investigated. Operational and capital expenditures should be considered, to investigate the sustainability of small cell deployment for mobile service operators. However, those expenditures are out of the scope of this work.

In this work, we will propose a different small cell deployment strategy: macrocell service area gets smaller with each small cell addition while keeping the coverage area the same. Then, we observe that deploying microcells or picocells, increases both energy and area spectral efficiencies at the same time.

We start our analysis by calculating the area spectral efficiency of our proposed deployment scenario. Although our primary goal is to improve energy efficiency, this should not be achieved at the expense of spectral efficiency. In spectral efficiency part, all the base stations are assumed to be working under full load condition. First we evaluate necessary pilot power levels that guarantee a coverage constraint. Then, we substract this amount from the total allowed transmitted power in order to find the available power for traffic channels. By consuming all the remaining power on data channels, we conclude that our deployment strategy improves area spectral efficiency even though the size of the macrocell got smaller.

Next, we investigate the network with respect to area power consumption. Here, we consider two different performance indicators, namely area power consumption and area power consumption per bit. We observe that area power consumption is larger for our deployment strategy with respect to a macro-only scenario. Although this performance indicator is commonly used in the literature, it does not fully reflect the joint power and spectral efficiency performance of a deployment scenario. The reason for this is that, spectral efficiency is improved drastically while power consumption increases slightly. Therefore, in the remaining part of this thesis, we consider area power consumption per bit as our performance indicator. In this case, we observe that our proposed deployment strategy performs significantly better with respect to a macro-only scenario.

Chapter 3 of this thesis contains a numerical calculation of energy and spectral efficiencies of our proposed deployment scenario under several choices of parameter values. In the final chapter, we compare the results of numerical analysis and mathematical optimization to justify our numerical results.

2. SYSTEM MODEL

In this study, we analyze energy and spectral efficiency of HetNets with a fixed coverage area. This analysis requires a propagation model, since coverage will be defined over minimum received power at the mobiles. In the following, first we introduce our propagation model, and then coverage definition.

2.1 PROPAGATION MODEL

A simplified path loss model is given in [Goldsmith (2005)] as:

$$P_{rx} = K \left(\frac{r}{r_0} \right)^{-\lambda} P_{tx} \tag{2.1}$$

where P_{rx} and P_{tx} denote the received and transmitted powers, r and r_0 denote the propagation and reference distances, λ is the pathloss exponent, and K denotes the unitless constant which depends on antenna characteristics and channel attenuation.

To investigate a radio access network, a precise path loss model is mandatory to calculate the received power. In this work, we use urban macro and urban micro path loss models for 3G, from [TSGAN (2009)]. In Table 2.1, corresponding models are summarized.

The LOS probability for macrocell in corresponding model, $\text{Pr}_{\text{M}}(\text{LOS})$ is as the follows:

$$\text{Pr}_{\text{M}}(\text{LOS}) = \min \left\{ \frac{18}{r}, 1 \right\} \left(1 - e^{-\frac{r}{63}} \right) e^{-\frac{r}{63}}, \tag{2.2}$$

and LOS probability for small cells, $\text{Pr}_{\mu}(\text{LOS})$ is as the follows:

$$\text{Pr}_{\mu}(\text{LOS}) = \min \left\{ \frac{18}{r}, 1 \right\} \left(1 - e^{-\frac{r}{36}} \right) e^{-\frac{r}{36}}. \tag{2.3}$$

Table 2.1: Urban Macro and Urban Micro Path Loss Models

Urban Macro	LOS	$PL = 22\log(d) + 28 + 20\log(f_c)$ $PL = 40\log(d_1) + 7.8 - 18\log(H'_{BS})$ $-18\log(h'_{UT}) + 2\log(f_c))$	$10 < d < d'_{BP}$ $d'_{BP} < d_1 < 5000$
	NLOS	$PL = 161.04 - 7.1\log(W) + 7.5\log(h)$ $-(24.37 - 3.7(h/h_{BS})^2)\log(h_{BS})$ $+(43.42 - 3.1\log(h_{BS}))(\log(d) - 3)$ $+20\log(f_c) - (3.2\log(11.75h_{UT})^2) - 4.97$	$10 < d < 5000$
Urban Micro	LOS	$PL = 22\log(d) + 28 + 20\log(f_c)$ $PL = 40\log(d_1) + 7.8 - 10\log(h'_{BS}$ $-18\log(h'_{UT}) + 2\log(f_c)))$	$10 < d < d'_{BP}$ $d'_{BP} < d_1 < 5000$
	NLOS	$PL = 36.7\log(d) + 22.7 + 26\log(f_c)$	$10 < d < 2000$

Reference: [TSGAN (2009)].

Using this propagation model, next we define cell coverage and spectral efficiency.

2.2 CELL COVERAGE

Given a transmitted base station power, cell coverage of that base station is the percentage of cell area that the received power at distance r, $P_{rx}(r)$, is above a certain minimum power level, $P_{\min}$. Although we consider a deterministic propagation model in this paper, in general $P_{rx}(r) - P_{\min}$ condition is probabilistic. Coverage area can be calculated by integrating the probability of this condition over the entire cell area [Goldsmith (2005)]

$$C = \frac{1}{A_C} \int_{A_C} r \Pr\left(P_{rx}(r) > P_{\min}\right) \mathrm{d}r \mathrm{d}\theta \tag{2.4}$$

where A_C denotes the hexagonal cell area. In 2G systems, minimum received power limit is chosen as $P_{\min} = -102$ dBm and in 3G systems, $P_{\min} = -120$ dBm. Our constraint in this work is that 95 percent of the hexagonal area is covered either by macro or small cells.

Our goal is to increase the energy efficiency while maintaining the 95 percent constraint. This requires us to select an energy efficiency metric in order to compare the efficiencies of two different scenarios.

2.3 AREA SPECTRAL EFFICIENCY

Area spectral efficiency is defined as the sum of achievable data rates per unit bandwidth per unit area, provided in a wireless mobile network [Alouini & Goldsmith (1999)]. Area spectral efficiency is calculated by integrating the channel capacity over the cell area.

$$S_A = \frac{1}{A_C} \int\limits_{A_C} r log_2 \left(1 + \gamma(r, \theta)\right) \mathrm{d}r \mathrm{d}\theta \tag{2.5}$$

where A_C denotes the hexagonal cell area and $\gamma(r, \theta)$ represents the *signal-to-interference-plus-noise ratio* (SINR) for the given point.

In this part, we choose a minimum required area spectral efficiency of 10 $bit/s/Hz/km^2$. Then, we will investigate how our deployment strategy affects the ISD interval, that could provide the minimum traffic demand.

2.4 AREA POWER CONSUMPTION

In order to investigate the energy efficiency of a cellular network, a valid energy efficiency metric should be considered. Several metrics have been proposed in the literature. First, we use *area power consumption* which is defined in [Hasan et al. (2011)] as the performance indicator.

Area power consumption is defined as the ratio of total power consumed by all base stations inside the region of interest to the area of that region. It is given by:

$$PI_{P/A} = \frac{\text{Total power consumed by all base stations}}{\text{Area of the region of interest}} [W/m^2]. \tag{2.6}$$

However, a performance indicator that does not consider the effects of spectral efficiency, would not reflect real performance of a wireless cellular network. Thus, we introduce a second performance indicator which takes both power consumption and spectral efficiency into account at the same time: *area power consumption per bit*. Next, we define area power consumption per bit and compare with the previous performance indicator.

2.5 AREA POWER CONSUMPTION PER BIT

Area power consumption is a convenient indicator to measure power savings. On the other hand, we need to measure more than just the power savings to investigate a wireless cellular network, since traffic demand has to be considered as another crucial parameter. Thus, we introduce another performance indicator which combines power consumption and the spectral efficiency, *area power consumption per bit*.

Area power consumption per bit is defined as the ratio of area power consumption to the total amount of achievable data rates per unit bandwidth. It is given by:

$$PI_{P/A/S} = \frac{\text{Area Power Consumption}}{\text{Spectral Efficiency}}[W/m^2/bit/s/Hz]. \tag{2.7}$$

Since area power consumption per bit could measure the joint power and spectral efficiency performance of a deployment scenario, we choose it as our prime metric to investigate the performance of heterogeneous scenarios.

In order to calculate the area power consumption and area power consumption per bit, we need to model power consumption behaviour of macro and small base stations. Accurate modeling of power consumption in a cell is crucial to this analysis and is provided in the following section.

2.6 POWER CONSUMPTION MODELS

For energy efficiency analyses, it is most important to note that the total power consumed by a base station not only includes the power transmitted to mobiles, but also powers consumed due to cooling, signal processing, etc. The more detailed this power consumption modelling is done, the more accurate our analysis will become.

Due to their different sizes and tasks, power consumption models of macro and small base stations differ. We first start with macro base station power consumption.

2.6.1 Macrocell Power Consumption Models

For macrocells, we consider three different power consumption models. A relatively simple model for macro base station total power consumption is proposed by [Richter et al. (2009)] as:

$$P_M = a_M P_{tx} + b_M \tag{2.8}$$

where P_M and P_{tx} denote consumed and transmitted power. The coefficient a_M denotes the power consumption that arises with the transmitted power, while b_M represents the offset power of the base station. The values of these parameters are given in Table 2.2.

Another model is proposed in [Arnold et al. (2010)] to determine the total power consumption of a macro base station as a function of the the transmitted power. It is given as:

$$P_M = N_s N_{PA} \left(\frac{P_{tx}}{\eta_{PA}} + P_{SP} \right) (1 + C_C)(1 + C_{PS}) \tag{2.9}$$

where P_M and P_{tx} denote the total consumed power and transmitted power, N_s and N_{PA} denote the number of sectors and the number of power amplifiers per sector, η_{PA} denotes power amplifier efficiency, P_{SP} denotes signal processing overhead, and C_C and C_{PS}

denote cooling and power supply loss, respectively. The values of these parameters are also given in Table 2.3.

Third model is given in [Auer et al. (2010)] as:

$$P_M = N_{TRX}(P_0 + \Delta_p P_{tx}), \quad 0 < P_{tx} \leq P_{max} \tag{2.10}$$

where N_{TRX}, P_0 and Δ_p represents number of transceiver chains, power consumption at zero RF output power and the slope of the load dependent power consumption, and P_{max} denotes the maximum power budget of macro base station, respectively. The values of those parameters are given in Table 2.4.

Among those three models, we use EARTH model, the third one, since it is evaluated by using State-of-the-art (SOTA) values of a commercially available BS in 2010.

2.6.2 Small Cell Power Consumption Models

For microcells, we again consider three different power consumption models. A relatively simple model for micro base station total power consumption is proposed by [Richter et al. (2009)] as:

$$P_\mu = L(a_\mu P_{tx} + b_\mu) \tag{2.11}$$

where scalar L represents the average load of a microcell. For the simulations in [Richter et al. (2009)], L is set to 1. Since microcells are smaller in size, power consumed due to traffic load is comparable to static, no-load power consumption. As a result, this simple microcell model is less accurate than its macrocell counterpart.

In [Arnold et al. (2010)], microcell power consumption is divided in two parts, namely, static and dynamic power consumption. The static part describes the power consumption of an empty base station that does not serve to any active users, where the dynamic part represents the power consumption due to the instantaneous traffic load.

$$P_\mu = P_{\mu,stat} + P_{\mu,dyn}. \tag{2.12}$$

The static power consumption contains the static signal processing power in addition to the part of the transmit power that is utilized when there are no active users in the cell.

$$P_{\mu,stat} = \left(\frac{P_{tx}}{\eta_{PA}} C_{tx} + P_{SP,stat}\right)(1 + C_{PS}) \tag{2.13}$$

where C_{tx} is the percentage of total transmit power that is utilized when there are no active users in the cell and $P_{SP,stat}$ denotes the static signal processing power. The static part of microcell power consumption is very similar to macrocell total power consumption. Because, dynamic part of macrocell power consumption is negligible with respect to its static power consumption. However, in microcell size, dynamic power consumption should be taken into consideration. We have

$$P_{\mu,dyn} = N_L \left(\frac{P_{tx}}{\eta_{PA}}(1 - C_{tx})C_{tx,N_L} + P_{SP,N_L}\right)(1 + C_{PS}) \tag{2.14}$$

where N_L denotes the number of active links, C_{tx,N_L} is the percentage of dynamic transmit power per active link, and P_{SP,N_L} denotes dynamic signal processing power per active link.

Third model for the microcell total power consumption is given in [Auer et al. (2010)] as:

$$P_\mu = N_{TRX,\mu}(P_{0,\mu} + \Delta_{p,\mu} P_{tx}), \quad 0 < P_{tx} \leq P_{max,\mu} \tag{2.15}$$

where $N_{TRX,\mu}$, $P_{0,\mu}$ and $\Delta_{p,\mu}$ represents number of transceiver chains, power consumption at zero RF output power and the slope of the load dependent power consumption, and $P_{max,\mu}$ denotes the maximum power budget of micro base station, respectively. The values of those parameters are given in Table 2.5.

Even though the EARTH model does not divide the consumption into two parts, it clearly

Table 2.2: Macrocell Parameters for [Richter et al. (2009)] Model

Parameter	Value	Parameter	Value
a_M	21.45	b_M	354.40

Reference: [Richter et al. (2009)].

Table 2.3: Macrocell Parameters for [Arnold et al. (2010)] Model

Parameter	Value	Parameter	Value
N_s	3	P_{SP}	58 W
N_{PA}	2	C_C	0.29
η_{PA}	38%	C_{PS}	0.11

Reference: [Arnold et al. (2010)].

represents the dynamic nature of microcells, since it depends on SOTA values of commercial products.

For picocells, we employ the EARTH model due to the same reasoning given above. Total power consumption of a picocell is modelled in [Auer et al. (2010)] as:

$$P_\rho = N_{TRX,\rho}(P_{0,\rho} + \Delta_{p,\rho} P_{tx}), \quad 0 < P_{tx} \leq P_{max,\rho} \tag{2.16}$$

where $N_{TRX,\rho}$, $P_{0,\rho}$ and $\Delta_{p,\rho}$ represents number of transceiver chains, power consumption at zero RF output power and the slope of the load dependent power consumption, and $P_{max,\rho}$ denotes the maximum power budget of pico base station, respectively. The values of those parameters are given in Table 2.6.

It is widely known that small cells are capable of increasing cell capacity at the cell edges. However, little is known about their capability of providing energy efficiency. In addition, if small cells are overlayed over the macrocell deployment, the total power consumption of a cellular network increases [Richter et al. (2009)]. Here, we address the energy efficiency problem with an effective small cell deployment and macrocell transmit power value. For this reason, small cell power consumption should be modeled in the most accurate way possible to evaluate the small cell effect on the energy efficiency.

Table 2.4: Macrocell Parameters for [Auer et al. (2010)] Model

Parameter	Value	Parameter	Value
N_{TRX}	6	Δ_p	4.7
P_0	130	P_{max}	20

Reference: [Auer et al. (2010)].

Table 2.5: Microcell Parameters for [Auer et al. (2010)] Model

Parameter	Value	Parameter	Value
$N_{TRX,\mu}$	2	$\Delta_{p,\mu}$	2.6
$P_{0,\mu}$	56	$P_{max,\mu}$	6.3

Reference: [Auer et al. (2010)].

2.7 CELL DEPLOYMENT

Macrocells are generally designed to cover large areas. Due to long propagation distances, they consume too much power. In contrast, microcells and picocells cover a much smaller area and due to short propagation distances, they consume much smaller power than macrocells do. In this study, we investigate the effect of adding small cell sites on the energy and spectral efficiency of conventional macrocell only deployment, while keeping the coverage constant at 95 percent of the total service area.

First we start with a macrocell only scenario with 95 percent coverage of a hexagon grid of sites represented by inter side distance. This scenario will be used as a comparison point. Then, we deploy fixed-size microcells and picocells on the edges of macrocells. With the addition of small cells, it is possible for macrocells to transmit at lower powers. Although, coverage due to macrocells will decrease, total coverage area will still be 95 percent as a result of small cell coverage. Example of macrocell only, 2 microcells per macrocell, 8 picocells per macrocell, and 20 picocells per macrocell deployments are given in Figure 2.1. In this paper when ISD is changed, distance between the centers of two neighboring hexagons (and therefore macrocells) is changed. However, the size of small cells will stay the same.

Table 2.6: Picocell Parameters for [Auer et al. (2010)] Model

Parameter	Value	Parameter	Value
$N_{TRX,\rho}$	2	$\Delta_{p,\rho}$	4.0
$P_{0,\rho}$	6.8	$P_{max,\rho}$	0.13

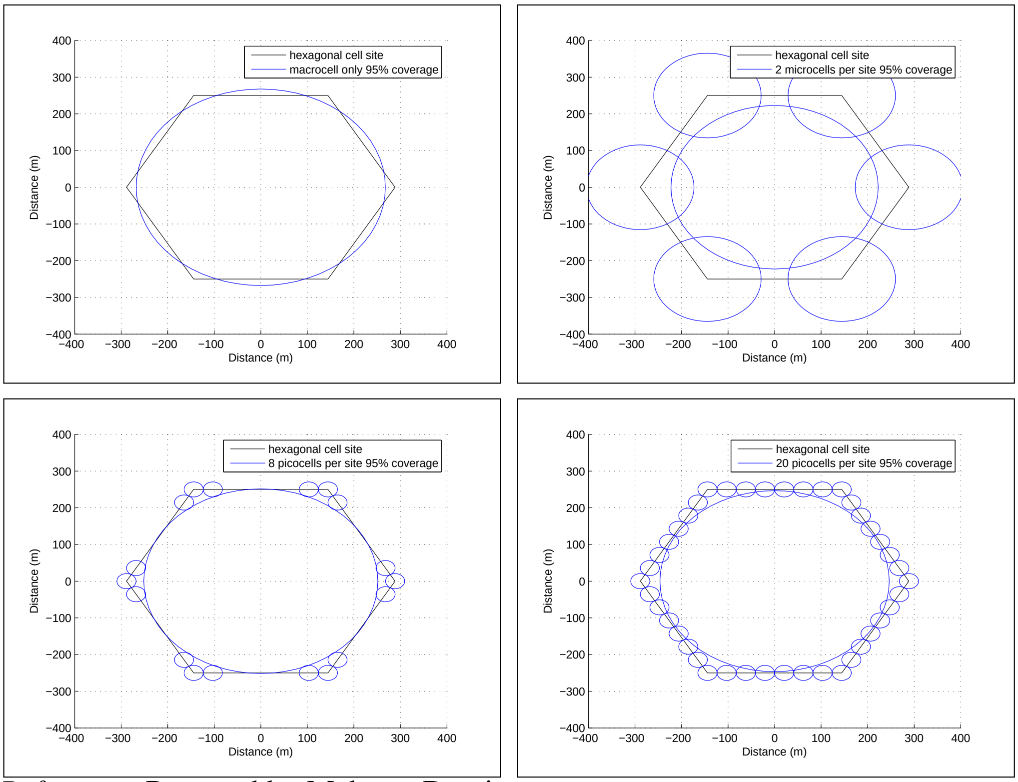
Reference: [Auer et al. (2010)].

Our model is different than [Richter et al. (2009)] and [Fehske et al. (2009)], where macrocell coverage is 100 percent regardless of the presence of microcells. In other words, microcells are overlayed over macrocell deployment. Both macro and microcells operate at full static power at all times. This makes the power consumed with macrocell/microcell combination to be larger than macrocell only deployment. This is not an issue in [Richter et al. (2009)] and [Fehske et al. (2009)], since the main goal was to analyze the effect of ISD on the energy efficiency of HetNets. However, our goal is to result in a both energy and spectral efficient strategy. Therefore, we deploy small cells to decrease the power consumption of macrocells.

For this purpose, we follow a deployment method as follows: for each small cell addition, macrocell service area shrinks while not compromising total coverage percentage. Then, total power consumption is calculated by adding small cell power consumption to this lowered macrocell power consumption.

In the following chapter, we will evaluate the necessary power levels for coverage condition, since we will use the remaining power for data channels.

Figure 2.1: An example of macrocell and small cell deployment



Reference: Prepared by Mahmut Demirtaş.

3. EFFICIENCY ANALYSIS

In this chapter, we investigate the energy and spectral efficiencies of heterogeneous cellular networks. As it is stated before, deploying low power small cells is used to boost spectral efficiency of wireless cellular networks in the literature. Since we propose a different deployment strategy, first we should analyze our model in terms of area spectral efficiency criterion. For this reason, we first evaluate the necessary transmitted power and total power consumption levels for coverage. Then, we will use the remaining power of base stations for data channels, to evaluate the area spectral efficiency under the full load condition.

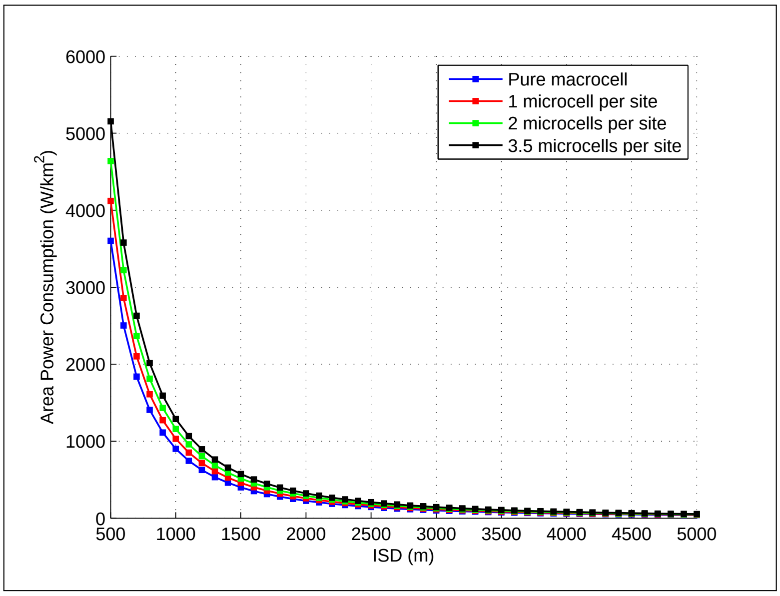
In numerical analysis, we consider an ISD range from 500 m to 5000 m. However, we should emphasise that, very large ISD values are not very practical. Thus, in mathematical optimization chapter, we will add an additional upper boundary for ISD.

3.1 TRANSMITTED POWER FOR COVERAGE

In this section, we evaluate necessary transmitted power levels for each deployment scenario to provide 95 percent coverage percentage. Besides, evaluation will be done for different microcell radius constraints and $P_{\min}$ levels of different technologies, to observe the effect of microcell radius and $P_{\min}$ on necessary transmitted power for coverage.

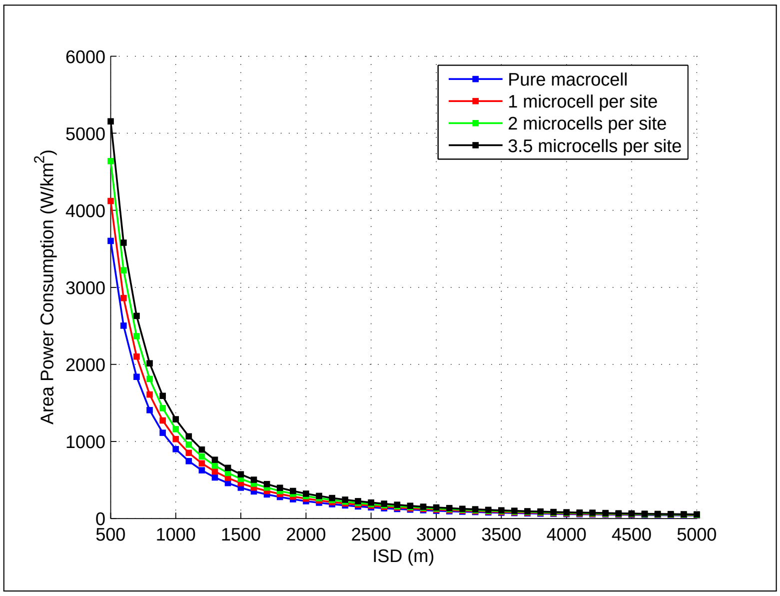
In Figure 3.1, we demonstrate the total power consumption for a 3G system, while microcell radius is fixed at 12.5 percent of ISD. As it is seen, microcell addition does not reduce the power consumption. We note that, remaining power will be used for data channels, to determine the spectral efficiency. Next, we consider different sized microcells to see the effect of microcell radius on area power consumption.

Figure 3.1: Power consumption due to the coverage for 3G systems with the first microcell radius constraint



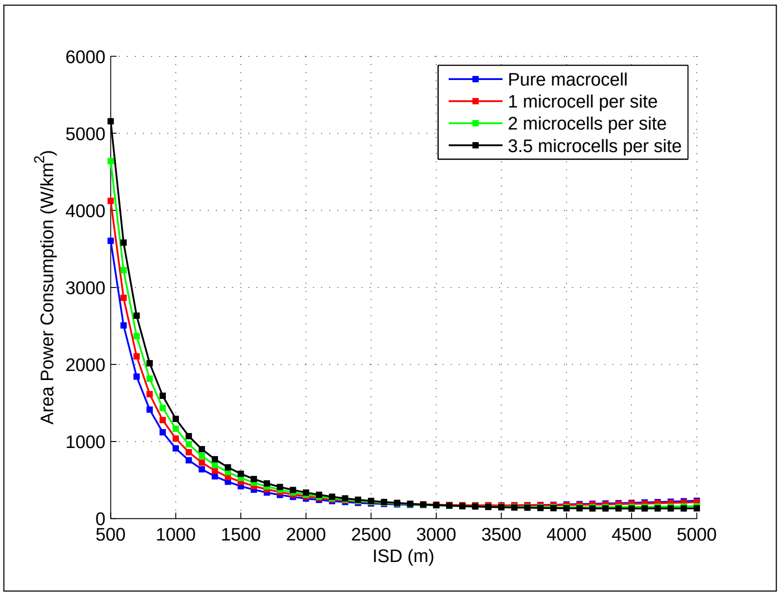
Reference: Prepared by Mahmut Demirtaş.

Figure 3.2: Power consumption due to the coverage for 3G systems with the second microcell radius constraint



Reference: Prepared by Mahmut Demirtaş.

Figure 3.3: Power consumption due to the coverage for 2G systems



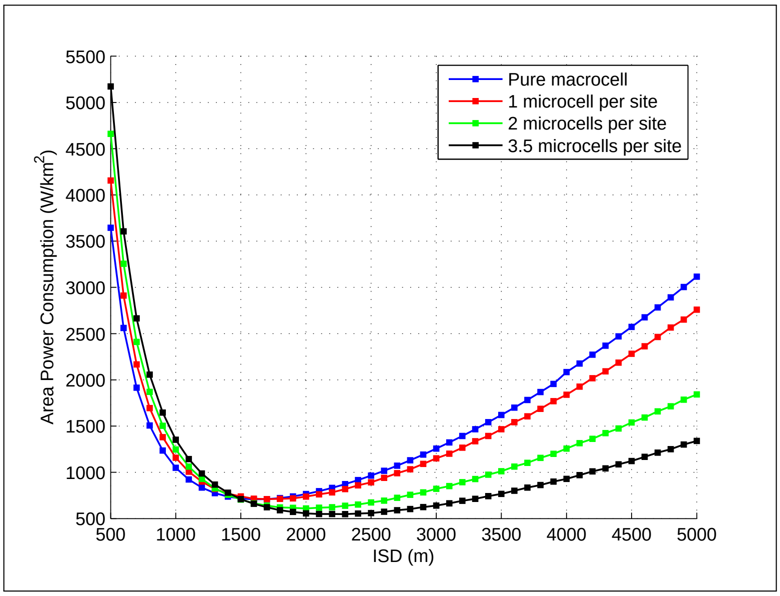
Reference: Prepared by Mahmut Demirtaş.

In Figure 3.2, we reveal the area power consumption results with the second microcell constraint: microcell radius is fixed at 20 percent of corresponding ISD. Increasing the microcell radius slightly reducing the power consumption for coverage, since larger a microcell radius results in a smaller macrocell radius. Next, same analysis will be done for 2G systems.

Figure 3.3 shows the power consumption for a 2G system, to provide 95 percent coverage. Results show that, power consumption which is used for coverage, does not significantly change for lower ISD values. However, for larger ISD values, microcell deployment is reducing the power consumption, as a result of higher minimum received power requirement. To show the effect of P_{min} on power consumption for coverage, we also do the coverage analysis for another minimum received power value: $P_{\mathrm{min}} = -90$ dBm.

In Figure 3.4, power consumption for coverage condition is given. As it is seen, for $P_{min} = -90$ dBm, consumption characteristic is completely changed. For ISD > 1500 m, microcell deployment acceleratingly improves energy efficiency with respect to macro-only network. In this work, we will use 3G receiver sensitivity, $P_{\mathrm{min}} = -120$ dBm.

Figure 3.4: Power consumption due to the coverage for $P_{\min} = -90$ dBm

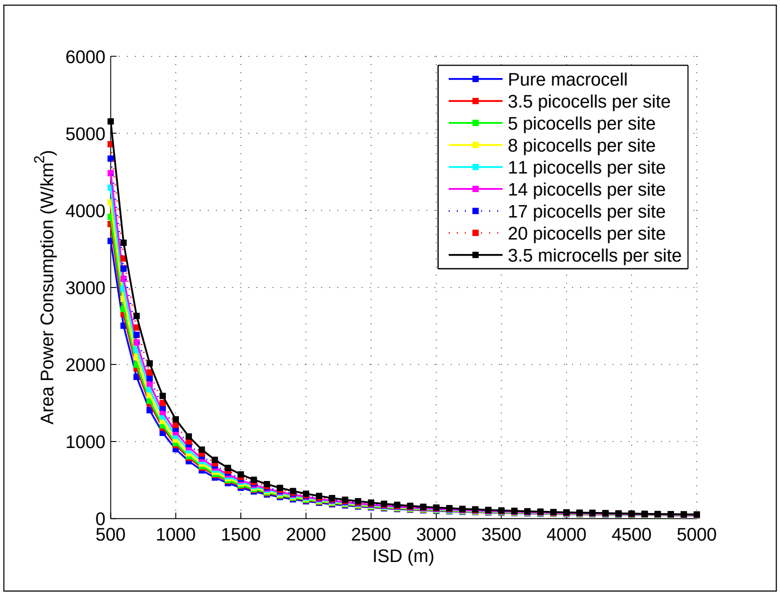


Reference: Prepared by Mahmut Demirtaş.

In addition, we do the coverage investigation for different picocell scenarios, to observe the effect of deploying a large number of picocells -instead of microcells- on the cell edges. According to the picocell power consumption model, picocells consume even less power than microcells. Due to their smaller radius constraints, deploying picocells could result in a more energy and spectral efficient scenario than microcell deployment.

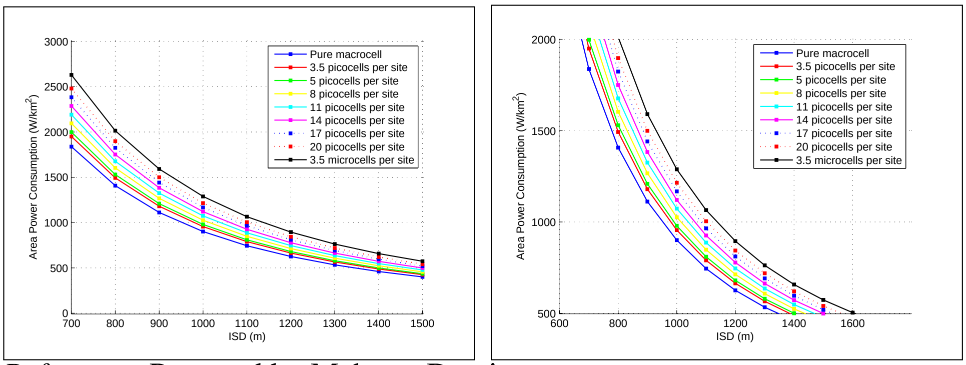
In Figures 3.5 and 3.6, power consumption levels of picocell scenarios are depicted. As it is seen, all of the picocell combinations are consuming smaller amounts of power than the 3.5 microcell per site scenario. First reason picocell scenarios are consuming less power is that smaller zero RF output power level of picocell. Tables 2.5 and 2.6 suggest that microcell zero RF output power level: $P_{0,\mu}$ is equal to 56 W, while picocell consumes only 6.8 W. Second reason is that much smaller propagation distance of picocell. Since path loss exponent is larger than 2, path loss (and therefore transmitted power) increases with a higher increment size than coverage area.

Figure 3.5: Power consumption due to the coverage for picocell scenarios



Reference: Prepared by Mahmut Demirtaş.

Figure 3.6: Zoomed in versions of picocell results



Reference: Prepared by Mahmut Demirtaş.

In the following section, we will investigate our deployment strategies with respect to area spectral efficiency and compare the results with pure macrocell deployment.

3.2 AREA SPECTRAL EFFICIENCY ANALYSIS

In this section, deployment scenarios that are considered in previous parts, will be simulated to determine the area spectral efficiency. We fix the maximum output power values of macro, micro, and pico cells as given in [Auer et al. (2010)]: $P_{\max}(macro) = 20$ W, $P_{\max}(micro) = 6.3$ W, and $P_{\max}(pico) = 0.13$ W. Remaining power after extracting the pilot signal powers that we calculated in coverage part, is available to be used as data channel power levels:

$$P_{data}(macro) = P_{max}(macro) - P_{pilot}(macro), \tag{3.1}$$

$$P_{data}(micro) = P_{max}(micro) - P_{pilot}(micro), \tag{3.2}$$

and

$$P_{data}(pico) = P_{max}(pico) - P_{pilot}(pico), \tag{3.3}$$

In this part, we use all the remaining power on data channels to investigate the maximum spectral efficiency of deployment scenarios under full load condition.

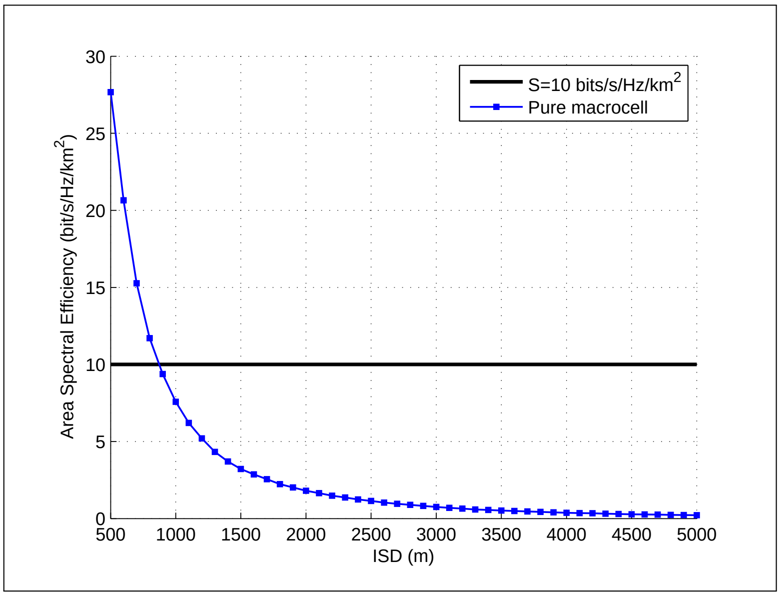
In homogeneous deployment, a reference cell and a ring of interferer neighbours are considered. Besides, it is assumed that only a single user is served in each iteration and all of the neighbouring macrocells are contributing to the interference at all times.

In heterogeneous scenarios, microcells or picocells are located at the cell edges as the previous parts and total area spectral efficiency are calculated as follows:

$$S_A = \frac{\sum_i S_i Pr(U_i > 0)}{A_C} \tag{3.4}$$

where A_C denotes the hexagonal area, S_i and $Pr(U_i > 0)$ represent the spectral efficiency

Figure 3.7: Area spectral efficiency of pure macrocell scenario



Reference: Prepared by Mahmut Demirtaş.

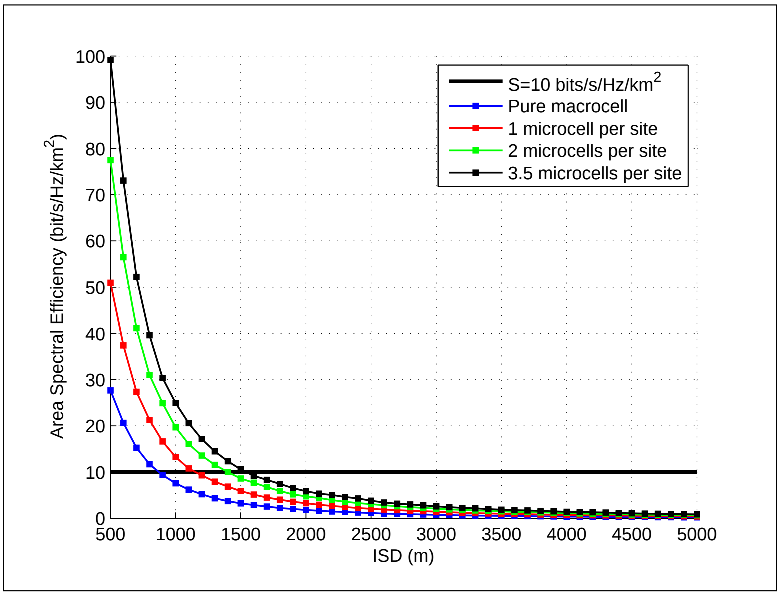
and probability of there exist at least one user in the cell coverage area, respectively.

3.2.1 Macrocell Only Deployment

In this section, we investigate the area spectral efficiency of pure macrocell scenario. For each ISD value, necessary transmitted power to provide 95 percent coverage is considered to calculate the data channel power levels and so the area spectral efficiency. In Figure 3.7, the results of spectral efficiency simulations of pure macrocell scenario are provided.

Figure 3.7 shows that area spectral efficiency is decreasing drastically with respect to ISD and after a certain level, reference macrocell could not provide the necessary data rate for the entire cell area. Next, we will investigate the heterogeneous scenarios and compare the results with pure macrocell scenario.

Figure 3.8: Area spectral efficiency of the microcell scenarios

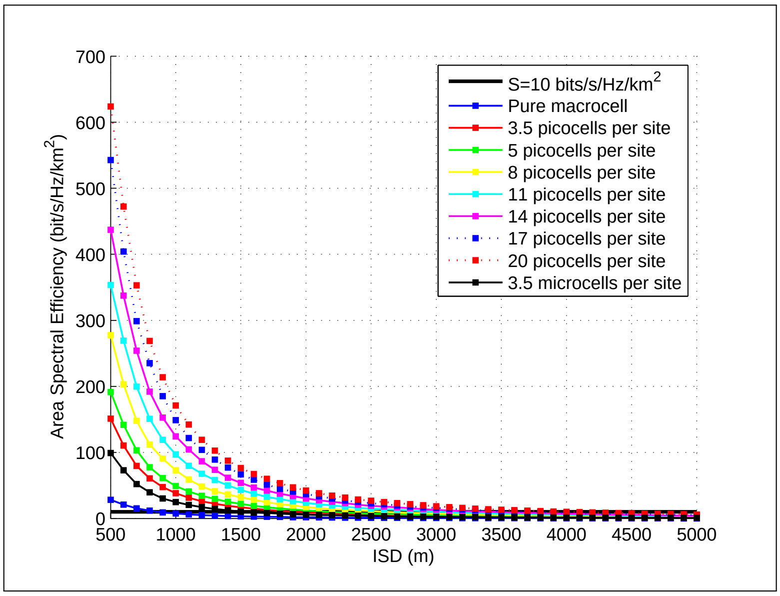


Reference: Prepared by Mahmut Demirtaş.

3.2.2 Heterogeneous Deployment

As it is mentioned before, heterogeneous deployment seems to be the most promising technique to improve energy efficiency of wireless cellular networks. In this section, we investigate the area spectral efficiency of our microcell deployment strategy to show the full potential. In Fig. 3.8, microcell radius is fixed at 20 percent of ISD. As it can be seen, deploying microcells increases area spectral efficiency for every ISD value. While pure macrocell scenario could provide required traffic demand for only small ISD values, heterogeneous scenarios have a wide ISD range to provide the same traffic demand. While pure macrocell scenario does not provide the necessary spectral efficiency for $ISD \geq 900$ m, 3.5 microcells per site scenario can provide the same data rate up to $ISD = 1500$ m. The reason for this is that microcells covers the cell edges where signal strength of macrocell is very low.

Figure 3.9: Area spectral efficiency of the picocell scenarios

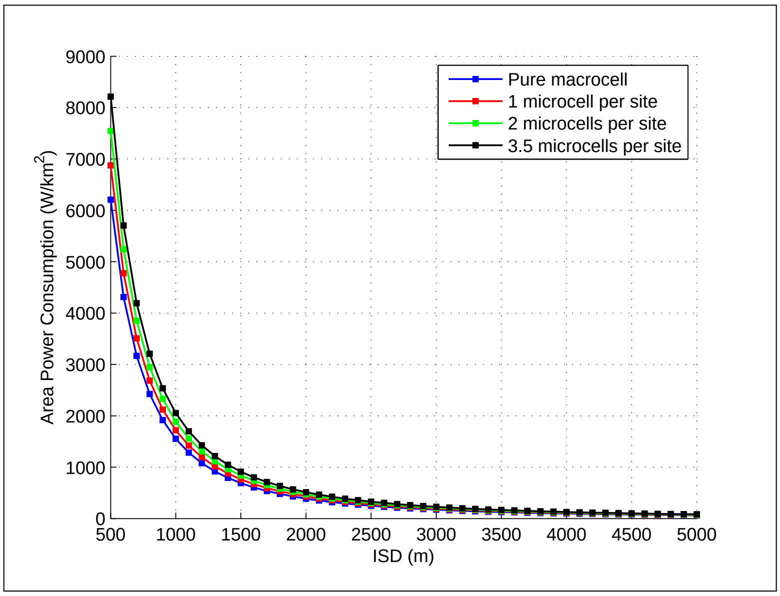


Reference: Prepared by Mahmut Demirtaş.

Then, we investigate the picocell scenarios in the same manner. In Figure 3.9, area spectral efficiency results of picocell scenarios are given. As it is seen, each picocell scenario clearly outperforms even the most spectral efficient microcell scenario. As a numerical comparison, 20 picocells per site scenario could provide the necessary spectral efficiency even for $ISD = 2000$ m while none of the microcell scenarios could not. The first reason picocell scenarios are much more spectral efficient is that the size of picocell service area. Since picocell service area is smaller than microcell service area, expected distance between picocell and the user is smaller for the picocell scenarios. As a result, user could have better channel conditions. The second reason is that, picocells have smaller pilot signal strength. Hence, the network has a smaller amount of pilot signal interference and higher SINR values.

Up to this point, we state that deploying small cells drastically increases area spectral efficiency. In the next section, we will investigate the energy efficiency of our model, to achieve a complete evaluation on heterogeneous deployment.

Figure 3.10: Area power consumption of microcell scenarios under the full load condition



Reference: Prepared by Mahmut Demirtaş.

3.3 ENERGY EFFICIENCY ANALYSIS

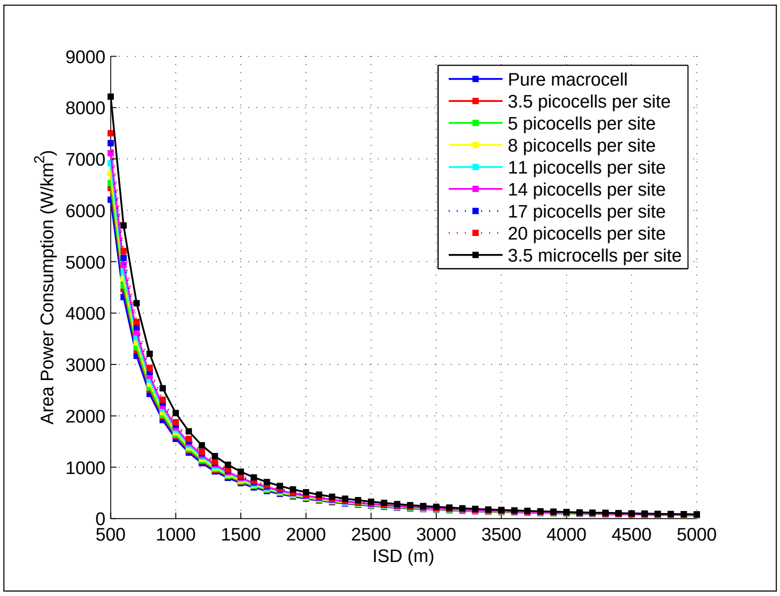
In this section, our deployment scenarios are simulated, to analyze the effect of small cell deployment on the energy efficiency of cellular networks. We investigate the scenarios in terms of area power consumption and area power consumption per bit, respectively.

3.3.1 Area Power Consumption Analysis

First, we investigate the area power consumption of our small cell deployment strategy. In the Section 3.2, we investigate the area spectral efficiencies of deployment scenarios under the full load condition. For this reason, we also should evaluate the area power consumption values under the full load condition.

Figure 3.10 shows the area power consumption results of different microcell scenarios. As it is seen, microcell deployment is not contributing much to the power efficiency in terms of area power consumption. In Figure 3.11, results of picocell scenarios are given.

Figure 3.11: Area power consumption of picocell scenarios under the full load condition



Reference: Prepared by Mahmut Demirtaş.

Even though picocell deployment is still not contributing the power efficiency, picocell scenarios are more energy efficient than microcell scenarios. We note that, those results are completely parallel with the ones that we suggest in Section 3.1, due to the same reasoning.

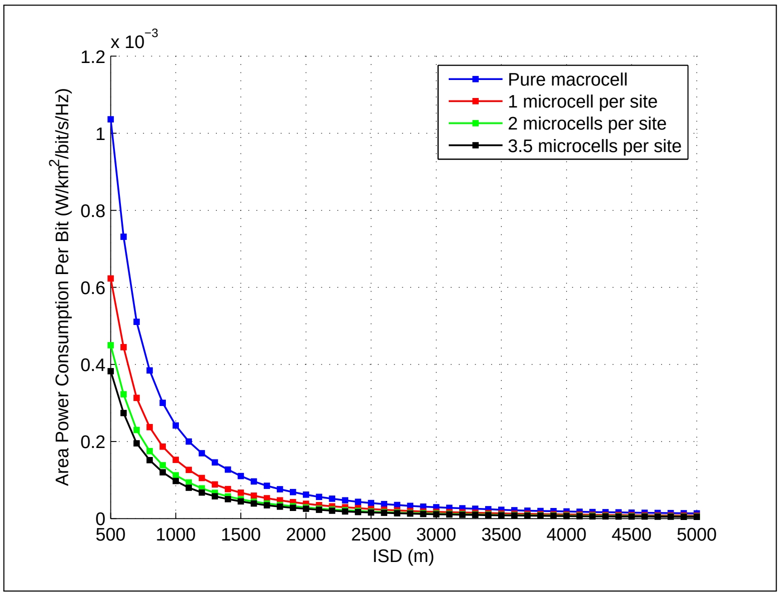
However, area power consumption is not the most accurate indicator to investigate our strategy, since it does not consider the most important requirement of a wireless cellular network: traffic demand.

In the following section, we will investigate deployment scenarios in terms of our second performance indicator: area power consumption per bit, to achieve a complete evaluation on performance of heterogeneous deployment.

3.3.2 Area Power Consumption Per Bit Analysis

In this section, we investigate deployment scenarios in terms of our second and principal performance indicator by using the power consumption and spectral efficiency values

Figure 3.12: Area power consumption per bit results of the microcell scenarios

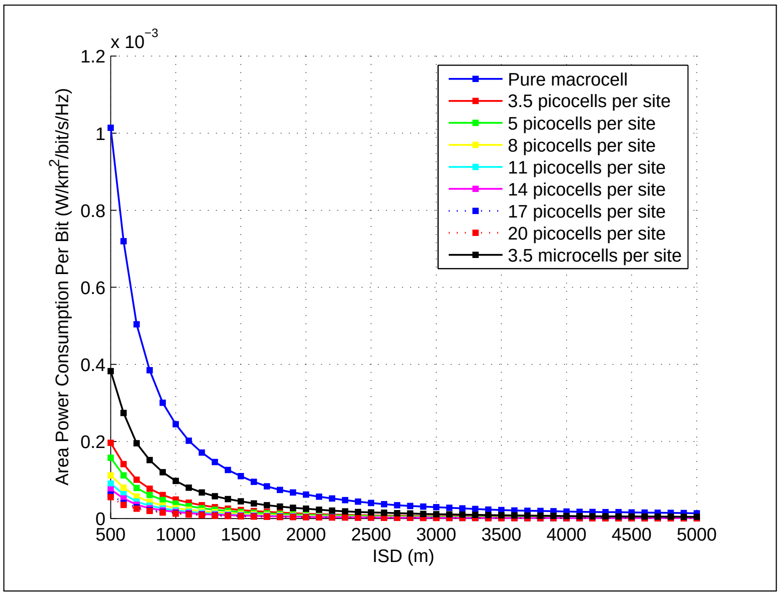


Reference: Prepared by Mahmut Demirtaş.

under the full load condition.

In Figure 3.12, it is seen that for any ISD value, deploying microcells is increasing the efficiency. Besides, microcell contribution is drastically higher for smaller ISD values. For $ISD = 500$ m, 3.5 microcells per site scenario is almost 2.5 times more efficient than the pure macrocell scenario.

Figure 3.13: Area power consumption per bit results of the picocell scenarios



Reference: Prepared by Mahmut Demirtaş.

Next, we do the same analysis for the picocell scenarios. Figure 3.13 shows that deploying picocells is again considerably outperforming microcell scenarios with respect to area power consumption per bit criteria. The reason is that, picocell scenarios have less area power consumption, while have significantly higher area spectral efficiency with respect to both macro-only and microcell scenarios

It is important to note that area power consumption per bit is a comprehensive method to evaluate the performance of a wireless cellular network. Therefore, we suggest that heterogeneous scenarios are increasing both energy and spectral efficiencies of network. Moreover, picocell scenarios are clearly more efficient than microcell scenarios, due to their small service areas (and therefore their much better propagation conditions).

Up to this point, under a certain coverage condition, we numerically investigate the energy and spectral efficiencies and conclude that deploying microcells is one of the most promising idea to increase the energy efficiency of wireless cellular networks. However, we do not mathematically optimize the power consumption. In the next chapter, we will compare the results of numerical analysis and mathematical optimization to justify our numerical results.

4. POWER CONSUMPTION OPTIMIZATION

Section 3.1 includes the numerical investigation of the effect of small cell deployment on power consumption due to the coverage criterion. In this chapter, we will transform the power consumption which is subject of Section 3.1, into an optimization problem for which an optimum solution is found. A mathematical optimization problem is defined in [Boyd & Vandenberghe (2004)] as the following:

$$\begin{aligned} &\text{minimize} \quad f_0(x) \\ &\text{subject to} \quad f_i(x) \leq b_i, \qquad i = 1, .., m \end{aligned} \tag{4.1}$$

where the function $f_0 : \mathbb{R} \rightarrow \mathbb{R}$ is the objective function, the functions $f_0 : \mathbb{R} \rightarrow \mathbb{R}$, $i = 1, ..., m$, are the constraint functions and the constants b_i, $i = 1, ..., m$, are the bounds for the constraint functions. A vector $x^\star$ is the optimal point, unless there is a smaller objective value among all vectors that satisfies the constraint functions.

Besides, a convex optimization problem is defined as an optimization problem whose objective and constraints, $f_0, ..., f_m$ are convex functions, respectively [Boyd & Vandenberghe (2004)]. Generally, a convex optimization problem is easier to handle since any local optimum of a convex problem has to be the global optimum point, too.

Under a certain coverage condition, we formulate the area power consumption of a heterogeneous wireless network as a non-convex constrained non-linear optimization problem in terms of macrocell and small cell radii, ISD and number of small cells per macrocell. Then, we minimize the objective function by using non-linear optimization methods.

4.1 POWER CONSUMPTION AS AN OPTIMIZATION PROBLEM

Initial step to optimize the area power consumption is modeling the system with the precise objective and constraint functions. In this thesis, two different optimization problems for area power consumption of microcell and picocell scenarios are written. First one is as the follows:

$$\begin{aligned}
\text{minimize} \quad & P = f(R_M, r_\mu, ISD, N_\mu) \\
\text{subject to} \quad & 0 < \text{ISD} \leq 2000 \\
& R_M \leq \text{ISD} \\
& r_\mu \leq R_M \\
& 250 \leq r_\mu \leq 500 && (4.2) \\
& 0.95 \times \text{(Cell Area)} \leq S && (4.3)
\end{aligned}$$

where R_M and r_μ denote the macrocell and microcell radius, and S represents the covered area by a macrocell plus N_μ microcells. As it is stated in Chapter 3, we choose an upper boundary for ISD in this part: ISD ≤ 2000, since larger ISD values are not practical.

Picocell scenarios should be optimized as a different case. For this reason, a second optimization problem for the picocell scenarios is written as the follows:

$$\begin{aligned}
\text{minimize} \quad & P = f(R_M, r_p, ISD, N_p) \\
\text{subject to} \quad & 0 < \text{ISD} \leq 2000 \\
& R_M \leq \text{ISD} \\
& r_p \leq R_M \\
& 0 \leq r_p \leq 250 && (4.4) \\
& 0.95 \times \text{(Cell Area)} \leq S && (4.5)
\end{aligned}$$

where r_p denote the picocell radius. As it is given above, upper boundary for the picocell radius is chosen smaller than microcell radius.

As it is stated before, power consumption due to the coverage, is formulated as a function of macrocell radius, small cell radius, ISD and number of small cells per macrocell. However, number of small cells per macrocell is a discrete parameter and will not satisfy the differentiability condition of our optimization problem. For that reason, we will solve the optimization problem for each small cell numbers that we simulate in numerical analysis part and choose the optimum solution, among all of the solutions.

Due to the equation complexity and non-convexity, we used MATLAB Global Optimization Toolbox to solve the optimization problems. In the following, we investigate the effect of coverage condition on minimum power consumption and optimum parameter values.

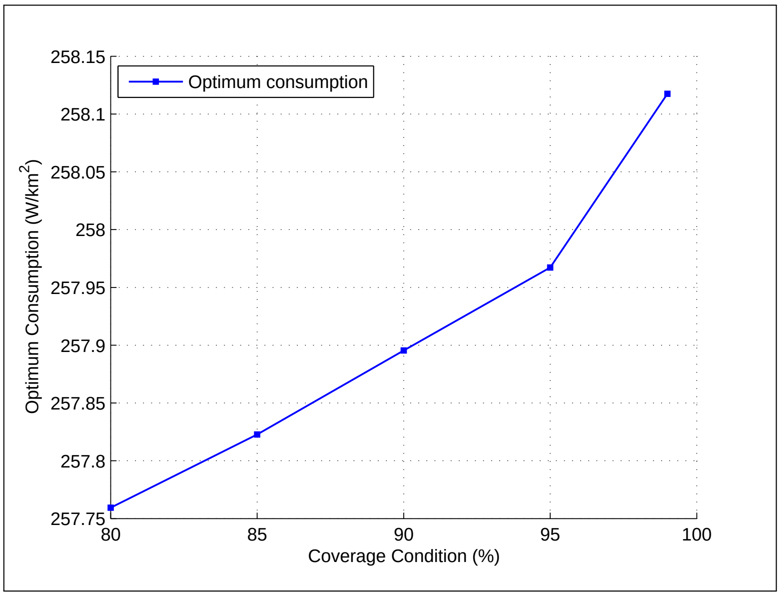
4.2 EFFECT OF COVERAGE PERCENTAGE ON OPTIMUM CONSUMPTION

In this part, both of the optimization problems are solved for different coverage conditions to investigate the relation between the coverage percentage and the minimum consumption.

First, we solve the microcell optimization problem for each microcell combinations and find out that macrocell-only scenario is consuming the least power for coverage. In addition, 1 microcell per site scenario is the most efficient microcell combination among all of the microcell scenarios. Figure 4.1 suggest that increasing the necessary coverage percentage slightly increases the optimum power consumption, since we choose an upper boundary for ISD. As we conclude in numerical part, larger ISD values result in smaller power consumption values. Hence, the toolbox solver chooses the largest ISD available for each time, so only the cell radii are changing, slightly. However, this small change in cell radius values does not result in a major change in optimum power consumption.

Next, we investigate the effect of coverage percentage on power consumption of pico-

Figure 4.1: Minimum power consumption for the microcell optimization problem



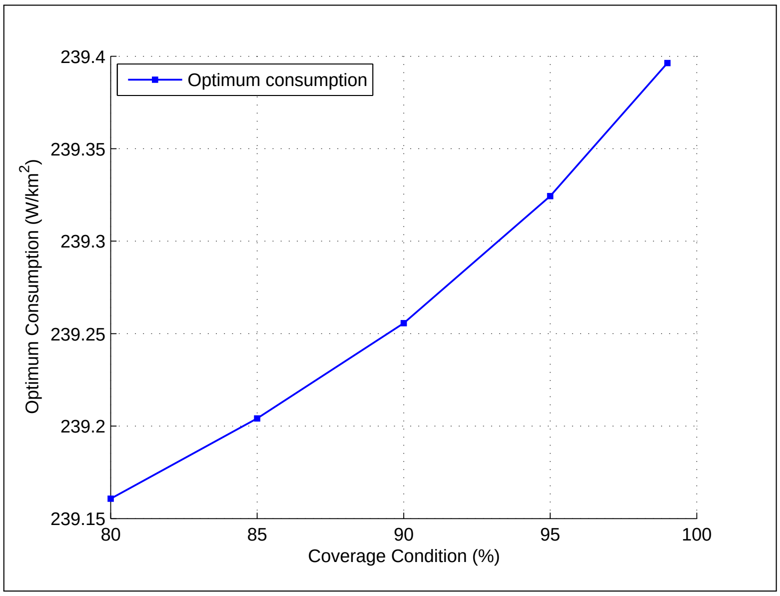
Reference: Prepared by Mahmut Demirtaş.

cell scenarios. Similarly, picocell addition is increasing power consumption with respect to macrocell-only scenario. Besides that, the smallest number of picocell scenario: 3.5 picocells per site scenario results in the lowest power consumption among all of the picocell combinations. Figure 4.2 states that increasing the necessary coverage percentage is slightly increases the optimum power consumption for picocell scenarios, too. We should also emphasise that optimum power consumption of 3.5 picocell per site scenario is also lower than the optimum solution for microcell problem. Thus, we can choose 3.5 picocell per site scenario as the most energy efficient one -according to the power consumption for coverage- among all of the small cell combinations.

After that, we investigate the effect of coverage percentage on optimum parameter values. In a similar manner, both of the optimization problems are solved for the same coverage conditions and the results are compared.

In Figure 4.3, optimum macrocell and microcell radii and ISD values are given for each coverage constraint. The toolbox solver chooses the maximum ISD value, since ISD increment reduces the area power consumption. Besides, for lower coverage percentage

Figure 4.2: Minimum power consumption for the picocell optimization problem



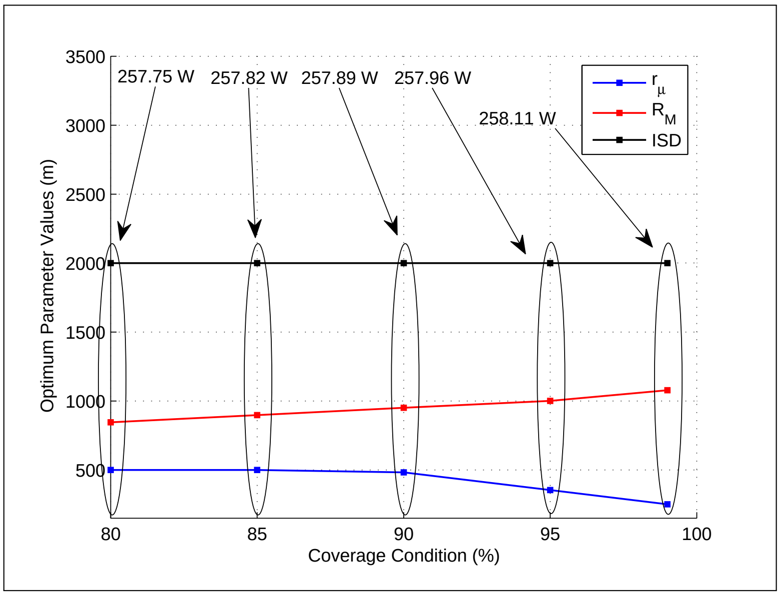
Reference: Prepared by Mahmut Demirtaş.

values, maximum microcell radius is chosen as the optimum point while microcell radius gets smaller for higher coverage conditions. To do a numerical comparison with the results in Section 3.1, area power consumption for ISD=2000 m, was calculated as 287.76 W in corresponding analysis. However, we find out that, minimum consumption with the optimum parameter choices, is reduced to 257.75 W.

Next, we will investigate the effect of coverage percentage on optimum parameter values for the picocell optimization problem. Figure 4.4 suggest that, maximum available ISD is the most energy efficient solution for picocell scenarios, too. Maximum picocell radius is also chosen as the optimum solution, and macrocell radius is changing slightly to satisfy the necessary coverage percentage. We could compare the optimum power consumption for ISD=2000 m, with the result that we calculate in Section 3.1. While the numerical evaluation results in an area power consumption of 239.38 W, mathematical optimization result is 239.15 W. It means that, we almost reach the optimum result in numerical investigation of picocell scenarios.

Up to this point, we investigate the effect of coverage percentage on optimization. How-

Figure 4.3: Optimum parameters and power consumption for the microcell optimization problem



Reference: Prepared by Mahmut Demirtaş.

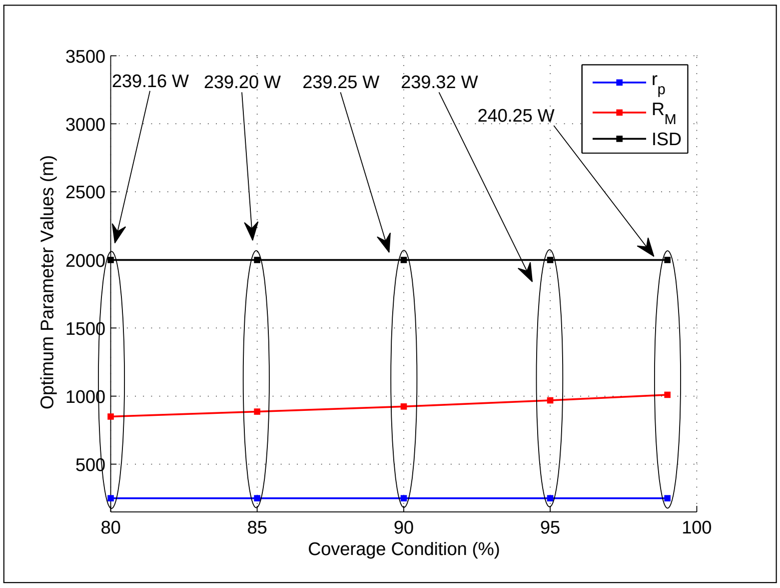
ever, number of small cells is also a highly effective parameter for optimum power consumption. For this reason, optimization results for each possible small cell combination will be given and discussed in the next section.

4.3 EFFECT OF NUMBER OF MICROCELLS

Power consumption for coverage: $P = f(R_M, r_\mu(r_p), ISD, N_\mu)$ is a function of number of microcells or picocells. However, number of small cells is an integer, and will not satisfy the differentiability condition for optimization problem. Thus, we will investigate the effect of number of small cells on optimum power consumption, discretely. We treat it as a constant and separately optimize the power consumption for each small cell scenario. Then, determine the overall optimum as the minimum of results of all separate processes. In Figure 4.5, optimum power consumption values of different microcell scenarios for the first optimization problem are given.

Figure 4.5 states that, increasing the number of microcells is not contributing much to

Figure 4.4: **Optimum parameters and power consumption for the picocell optimization problem**



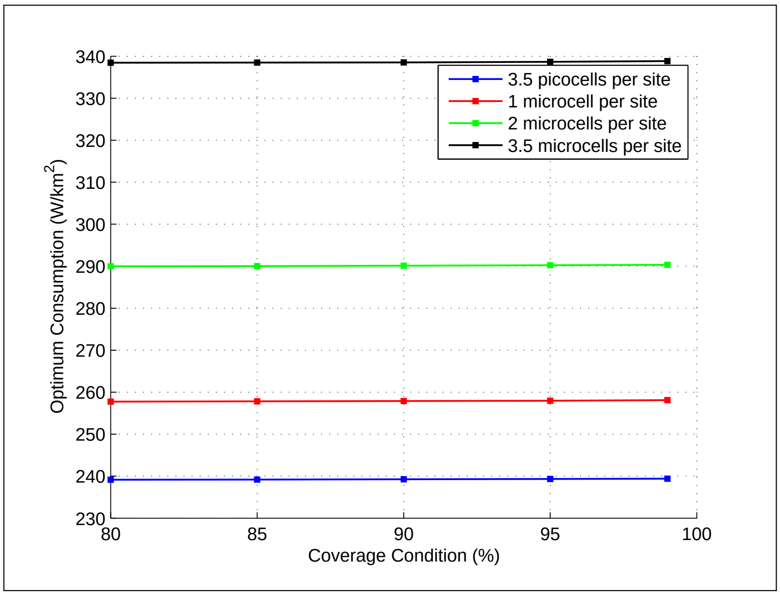
Reference: Prepared by Mahmut Demirtaş.

the optimum power consumption for coverage, as we conclude in Section 3.1. We also deduce that, 3.5 picocells per site scenario has higher energy efficiency than all of the microcell scenarios.

Next, we investigate the optimum power consumption for different picocell scenarios. Figure 4.6 shows that, adding more number of picocells is also not contributing the optimum power consumption for coverage. However, up to 8 picocells per site, picocell scenarios clearly outperforms microcell scenarios, due to the smaller zero-load consumption of picocells.

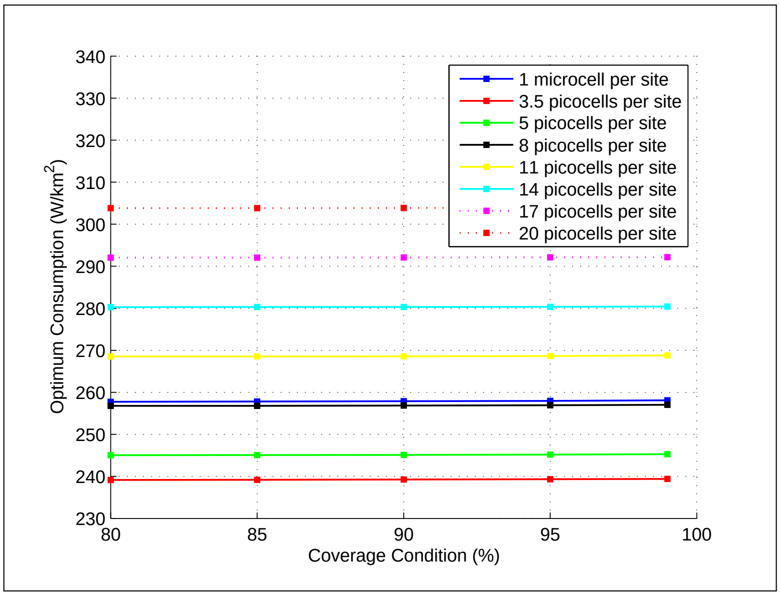
Consequently, we deduce that small cell deployment is slightly increasing the optimum power consumption of heterogeneous cellular networks. However, the power consumption which is subject to the optimization part, includes only the power that is consumed for coverage. Even though the small cell deployment is not contributing the coverage consumption, we previously conclude that it is a rewarding solution from other perspectives.

Figure 4.5: Minimum power consumption for different number of microcells for the microcell optimization problem



Reference: Prepared by Mahmut Demirtaş.

Figure 4.6: Minimum power consumption for different number of picocells for the picocell optimization problem



Reference: Prepared by Mahmut Demirtaş.

5. CONCLUSIONS

Under fixed coverage assumption, we first investigate the effect of ISD on spectral efficiency of heterogeneous cellular networks and observe that deploying small cells is increasing spectral efficiency. Later, heterogeneous scenarios are investigated with respect to area power consumption per bit metric. It is clearly seen that small cells are also improve energy efficiency of cellular networks in terms of area power consumption per bit metric.

In the final chapter, under a certain coverage constraint, we model the area power consumption as a non-linear optimization problem. We find the optimum solution to this mathematical problem. Our mathematical results verify the numerical results of the previous chapter.

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