Energy Efficiency Aspects of Base Station Deployment Strategies for Cellular Networks

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Abstract—In the strive for lessening of the environmental impact of the information and communication industry, energy consumption of communication networks has recently received increased attention. Although cellular networks account for a rather small share of energy use, lowering their energy consumption appears beneficial from an economical perspective. In this regard, the deployment of small, low power base stations, alongside conventional sites is often believed to greatly lower the energy consumption of cellular radio networks. This paper investigates on the impact of deployment strategies on the power consumption of mobile radio networks. We consider layouts featuring varying numbers of micro base stations per cell in addition to conventional macro sites. We introduce the concept of area power consumption as a system performance metric and employ simulations to evaluate potential improvements of this metric through the use of micro base stations. The results suggest, that for scenarios with full traffic load, the use of micro base stations has a rather moderate effect on the area power consumption of a cellular network.

I. INTRODUCTION

Over the last decade global warming has become an increasingly important item on the global political agenda. In this regard, information and communication technologies (ICTs) have been identified to be a major future contributor to overall green house gas emissions, having a share of more than 2% already in 2007 with a strong trend to increase [1]. In order to reduce the environmental impact of ICT, efforts to increase energy efficiency of these technologies have significantly gained momentum. As one branch of the sector, mobile radio networks account for about 0.2% of global emissions, contributing a rather small portion to the overall carbon footprint of ICT today [2], [3]. However, with rising demand for communication services in developing countries, serious challenges with respect to energy needs of mobile radio networks are expected in the future.

In addition to minimizing the environmental impact of the industry, cellular network operators are as well interested in reducing the energy consumption of their networks for economical reasons. The costs for running a network are largely affected by the energy bill and significant savings in capex and opex can be realized through reduced energy needs [4], [5].

Currently over 80% of the power in mobile telecommunications is consumed in the radio access network, more specifically the base stations. Taking this into account, there are in principle two levers to lower the energy consumption of these networks. Firstly by optimization of individual sites, e.g., through the use of more efficient and load adaptive hardware components as well as software modules. Secondly, by improved deployment strategies, effectively lowering the number of sites required in the network to fulfill certain performance metrics such as coverage and spectral efficiency. In principle, gains achieved in one area are complimentary to gains achieved in the other, i.e., if the deployment is optimized with respect to a certain coverage, additional energy saving might be realized through site optimization. Interdependencies, however, do exist if site optimization affects the link budget, for instance if the receiver sensitivity is lowered through improved RF components.

With regard to network deployment, it is often believed that topologies featuring high density deployments of small, low power base stations improve the network's energy efficiency compared to low density deployments of few high power base stations [4]. In this paper we investigate on this issue in more detail and introduce concepts to assess and optimize the energy consumption of a cellular network model consisting of a mix of regular macro sites as well as a number of smaller devices which we here refer to as micro base stations. Compared to the former, the latter cover a much smaller area but feature accordingly lower energy consumption figures. In addition, the areas covered by micro base stations generally enjoy much higher average signal to interference and noise ratios (SINRs) due to advantageous path loss conditions and shorter propagation distances.

In previous contributions deployment strategies are commonly investigated with respect to spectral efficiency, coverage, or outage probability, e.g., [6], [7]. Investigations with respect to profitability and cost structure of mixed topologies consisting of macro, micro, and pico cells are conducted in [8]. In [6] the notion of spectral efficiency per unit area is introduced to measure the performance of cellular mobile radio systems. This concept is also utilized here for frequency reuse one networks. In addition, we characterize a network's power consumption in Watts per unit area for given coverage and spectral efficiency requirements and optimize the base station density with respect to this figure of merit. We also provide simple models for the power consumption of different base station types and derive certain characteristics for micro base stations to improve the overall energy consumption figures of a network.

The remainder of the paper is organized as follows. Section II introduces the system model and network performance
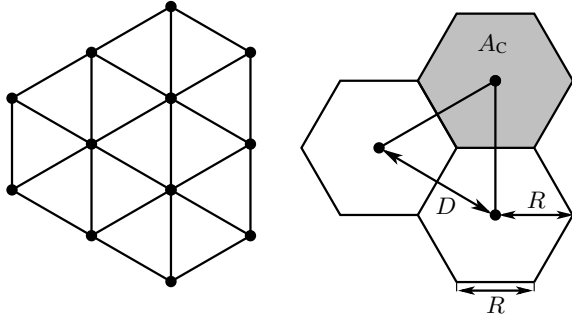
Fig. 1: Regular grid of macro sites and corresponding cell geometry with $D = \sqrt{3}R$ and $A_C = \frac{3\sqrt{3}}{2}R^2$.

metrics of interest. Section III provides the simulation setup and as well as major results. Section IV concludes the paper.

II. SYSTEM MODEL AND METRICS

We model the macro base station network as an infinite regular grid of sites characterized by the site distance D, generating equally sized hexagonal cell structures of side length $R = \frac{D}{\sqrt{3}}$ as depicted in Fig.1. In this paper we use the term *cell* to refer to the hexagonal Voronoi region of one site. Each cell might be further divided into several sectors. For given inter site distance D, the cell size A_C then calculates as $A_C = \frac{3\sqrt{3}}{2}R^2$. Throughout the paper we assume the traffic density to be uniformly distributed over the Euclidean plane.

A. Propagation Model

Commonly, deterioration of signal quality due to propagation is related to three different causes: path loss, slow fading (or shadowing), and fast (or multi path) fading. A basic signal propagation model capturing path loss as well as shadowing is formulated as [9]

$$P_{rx} = K \cdot \left(\frac{r}{r_0}\right)^{-\lambda} \cdot \Psi \cdot P_{tx} \tag{1}$$

where P_{tx}, P_{rx}, r, and λ denote transmit and receive power, propagation distance, and path loss exponent, respectively. The random variable Ψ is used to model slow fading effects and commonly follows a log-normal distribution, i.e., the variable $10 \log_{10} \Psi$ follows a normal distribution. The terms K and r_0 denote parameters to further adapt the model. While the propagation model (1) is suitable for analytical assessment, we employ propagation models presented in [10] for simulative investigations. These more realistic models incorporate path loss dependency on carrier frequency, line of sight (LOS) conditions as well as shadowing deviations. Furthermore, they also consider user terminal and base station height, where the latter differs significantly between macro and micro cells. The effective values of K, r_0, and λ, as well as the standard deviation of Ψ that were used for the simulative investigations are given in the appendix.

B. Base Station Types and Power Models

Conventional macro sites are designed to provide larger areas with a certain minimum coverage. A site's power consumption thereby depends on the size of the covered area as well as the degree of coverage required. In urban areas cell radii usually range from about 1000 m to 5000 m with coverage of more than 90%. For the relation between the average power consumption and the average radiated power per site, we employ a linear model of the form

$$P_M = a_M \cdot P_{tx} + b_M \tag{2}$$

where P_M and P_{tx} denote the average consumed and radiated power per site, respectively. The coefficient a_N accounts for power consumption that scales with the average radiated power due to amplifier and feeder losses as well as cooling of sites. The term b_M models an offset of site power which is consumed independently of the average transmit power due to signal processing, battery backup, as well as site cooling. Cooling equipment can be considered to impact both a_M and b_M, since both transmit power dependent as well as independent components contribute thermal radiation. Both a_M and b_M scale with the number of sectors and the number of antennas per sector. Note that we consider the *average* power consumption as a function of the *average* transmit power. This assumption is justified since the power consumption of currently operating macro sites is virtually independent of the instantaneous traffic load [11].

Besides conventional macro sites we consider the deployment of smaller sites, which we refer to as micro base stations. These devices feature only a single omni-directional antenna[1] and cover a much smaller area with cell radii between 100m and 250m. In turn, micro base stations feature a much smaller power consumption. In analogy to their macro counterparts the power model of micro base stations is assumed to be given by

$$P_N = L \cdot (a_N \cdot P_{tx} + b_N) . \tag{3}$$

One major advantage of micro sites is their ability to scale their power consumption with the current activity level, which is reflected in the factor L, modeling the device's average activity level. Note that scaling the overall power consumption by L constitutes a somewhat ideal case.

C. Cell Coverage

The cell coverage area is defined as the fraction of cell area where received power is above a certain level. The cell coverage C for a required minimum received power P_{min} is defined as

$$C := \frac{1}{A_C} \int_{A_C} r \cdot \mathbb{P}\big(P_{rx}(r) \geq P_{min}\big) \, dr \, d\phi \tag{4}$$

where A_C denotes the cell area as illustrated in Fig.1. In scenarios deploying macro sites with coverage C_M and additionally an average of N micro sites per cell, each supplying

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[1] The terms *site* and *base station* coincide in this case and we use them interchangeably.

an area of A_N with coverage C_N, the overall cell coverage computes as

$$C = \mu \cdot C_N + (1 - \mu) \cdot C_M \qquad (5)$$

with the area ratio $\mu := N \frac{A_N}{A_C}$. Note that the requirement $\mu \leq 1$ defines a maximum number of micro sites per cell.

D. Area Spectral Efficiency

The area spectral efficiency is defined as the mean of the achievable rates in a network per unit bandwidth per unit area, commonly measured in bit per second per Hertz per square kilometer [6]. Let $\bar{A}$ denote a sufficiently large area centered around a reference site and let M be the average number of macro and micro sites within $\bar{A}$. Let further $\gamma(r, \phi, \Psi)$ denote the SINR at (r, ϕ), which depends on the shadowing realization of Ψ. We define the area spectral efficiency as

$$\mathcal{S} := \frac{1}{A_C} \, \mathbb{E}_\Psi \left[\int_{\bar{A}} r \cdot \log_2 \left(1 + \gamma(r, \phi, \Psi) \right) \, \mathrm{d}\, r \, \mathrm{d}\, \phi \right],$$

where the shadowing variable Ψ follows an M dimensional distribution with density function $p_\Psi = \Pi_{m=1}^{M} p_{\Psi_m}$. Note that area spectral efficiency only considers the mean of the achievable rates and is not concerned with the distribution of rates around the mean, effectively ignoring any fairness aspects in the system.

E. Area Power Consumption

In general, observing the mere power consumption per site is inapt for comparing networks of differing site densities, since increasing distances generate larger coverage areas. In order to assess the power consumption of the network relative to its size, we introduce the notion of area power consumption as the average power consumed in a cell divided by the corresponding average cell area measured in Watts per square kilometer. For a given cell power consumption P_C the area power consumption is defined as

$$\mathcal{P} := \frac{P_C}{A_C} \, . \qquad (6)$$

If there is an average of N micro sites per macro site, cell power is the accumulated power consumed by macro and micro sites, i.e., $P_C = P_M + N \cdot P_N$.

Consider the propagation model (1) without shadowing, i.e., $\Psi = 1$. For fixed coverage requirements we obtain the relation $C = \frac{R_{\max}^2}{R^2}$ where $R_{\max}$ is the maximum distance from the cell center where the signal level is at least $P_{\min}$. With $D = \sqrt{3}R$ it follows

$$P_{tx} = \frac{P_{\min}}{K} \cdot R_{\max}^\lambda = \frac{P_{\min}}{K} \cdot \left(\frac{C}{3} \right)^{\frac{\lambda}{2}} \cdot D^\lambda. \qquad (7)$$

We observe from equation (7) that considering path loss only, the transmit power required for a certain coverage increases according to D^λ. If the linear relations (2) and (3) between consumed and radiated power hold we conclude that for path loss exponent $\lambda = 2$, the area power consumption is not
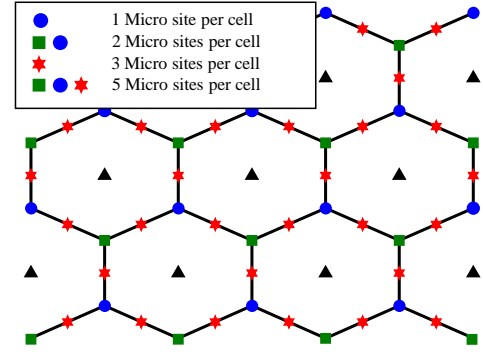

Fig. 2: Positioning of micro sites within the macro grid

affected by the site distance D, since both numerator and denominator in (6) increase with D^λ. For $\lambda > 2$ we observe

$$\lim_{D \to \infty} \mathcal{P}(D) = \infty \quad \text{as well as} \quad \lim_{D \to 0} \mathcal{P}(D) = \infty$$

where the latter relation holds due to the nonzero constant terms b_M and b_N in the power models. The latter relation simply follows from $\lambda > 2$. We conclude that for $\lambda > 2$ there exists a positive site distance D^*, which minimizes the area power consumption of the network.

III. Network Optimization

In this section we study how the area power consumption is impacted by two deployment related factors, namely the inter site distance and the average number of micro sites per cell. We employ Monte Carlo simulations for downlink scenarios to estimate area spectral efficiency and area power consumption of different deployments. We first concentrate on the area power consumption of a pure macro scenario and extend the investigations to the hybrid case with a certain number of micro sites per cell. In the second part we couple the observations with the system performance measured in terms of area spectral efficiency and investigate on the impact of the parameters b_M and b_N of the power consumption model.

A. Simulation Setup

We consider a hexagonal grid of macro sites where the site distance D ranges from 1000 m to 3500 m. Following a common procedure, we define a reference site surrounded by two tiers of interfering sites. Mobiles are placed randomly in the cell area following a uniform distribution. We consider an OFDMA system employing a frequency reuse of one, i.e., the same time and frequency resources are used for transmission in each cell. We assume no cooperation among sites or any fractional frequency reuse patterns. We further assume that in each Monte Carlo iteration, a single mobile is served by the reference cell. In case of an OFDMA system, serving multiple users per cell is equivalent to multiplying the number of Monte Carlo iterations. All sites are assumed to transmit on the maximum level. Since mobile operators typically apply network and site planning tools to optimize SINRs, we assume the inner-cell and outer-cell path loss figures to be 3 dB lower, respectively higher, than the value suggested by the propagation model. Cell coverage is required to be 99% for

each considered site distance and each base station type. Micro sites are assumed to support a circular area of radius 200 m and are positioned on the cell edges where the signal level of macro sites can be expected to be very low as depicted in Fig.2.

In our simulation we use the LTE link budget given in Tab.2 and Tab.3 in the appendix. As mentioned above, we employ the propagation models presented in [10] instead of the more simplistic model (1), since macro and micro sites can be distinguished more effectively. For completeness, the effective propagation parameters as used in the simulations are presented in Tab.1 in the appendix.

If not stated otherwise, the power model parameters are chosen as $a_M = 21.45$, $b_M = 354.44$ W, $a_N = 7.84$, and $b_N = 71.50$ W. The system load L was set to $L = 1$.

B. Network Performance Evaluation

Commonly, the inter site distance is obtained by specifying a required coverage and a base station's transmit power. Here, we follow a different approach by fixing coverage and inter site distance and calculating the respective transmit power by numerically inverting formula (4). If the deployment includes micro sites, the overall cell coverage is the weighted sum of the macro and micro coverage, and it follows from equation (5) that a macro site's transmit power reduces with increasing number of micro sites. The area power consumption for different deployments (increasing number of micro base stations per cell) is depicted in Fig.3. As explained in Section II-D, an optimal distance realizing minimal area power consumption can be seen in the plots. Although there exists an optimal inter site distance for each additional micro site, these are far from the minimum obtained by a pure macro deployment. This result is based on the fact that a macro site's power saving due to smaller area to cover does not compensate for the additional power consumption of micro sites. Of course, these results depend heavily on the parameters a_M, b_M, a_N, and b_N. Nevertheless, it is obvious that minimal area power consumption can not be the primary metric for evaluating system energy efficiency.
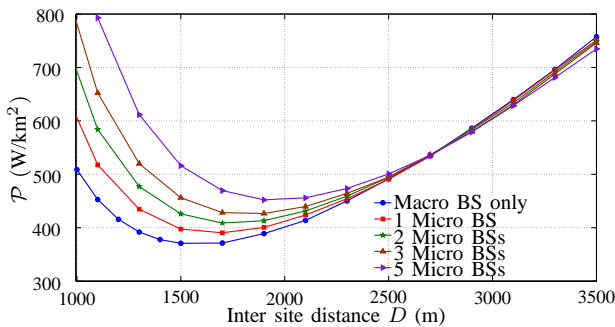

Fig. 3: Area power consumption as function of inter site distance for different deployments with $a_M = 21.45$, $b_M = 354.44$ W, $a_N = 7.84$, and $b_N = 71.50$ W

Careful deployment of micro sites is considered to primarily enhance the area spectral efficiency of a system, which is clearly visible in Fig.4. In order to find the minimum area
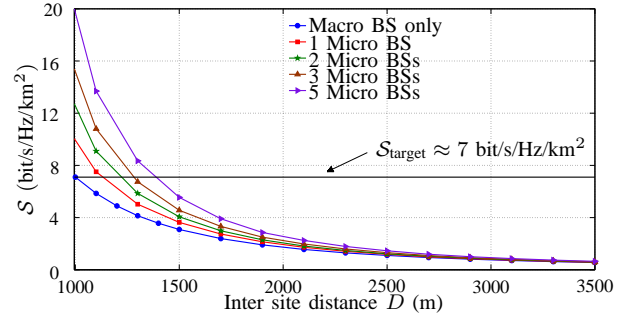

Fig. 4: Area spectral efficiency as function of inter site distance for different deployments

power consumption for a given minimum area spectral efficiency, we propose the following method. Given the spectral efficiency curves as illustrated in Fig.4 for different deployments, we set a required target area spectral efficiency, here about 7 bit/s/Hz/km^2, which needs to be achieved. We can then determine the set of inter site distances that achieve the target area spectral efficiency and find the distances that optimize the area power consumption within these sets. Following this procedure, we arrive at the curves in Fig.5. Here we still observe that micro deployment yields a rather moderate improvement in area power consumption compared to conventional deployments even if the term b_N is set to an ideal zero. Note that all setups in Fig.5 now provide the same area spectral efficiency. Consider the curves for $b_M = 0$ and $b_M = 9b_N$ in Fig.5. They depict two more extreme parameter settings, where in the first case deployment of five additional micro sites decreases power consumption compared to a pure macro scenario. In the second case pure macro deployment is superior.

Naturally, the above results depend on the sites' design parameters a_M, b_M, a_N, and b_N, as well as the average traffic load L. In this regard the question occurs, whether there is a set of optimal parameters for hybrid deployments that not only increase area spectral efficiency but ideally also decrease area power consumption. Since a_M and a_N are mainly determined by power amplifier efficiency, we focus on the dependency on b_M, b_N, and L. In Fig.6 the relation between the transmit power independent macro and micro power consumption is depicted for different deployments featuring different numbers of micro sites per cell. The curves are obtained from requiring $\mathcal{P}^0(b_M, b_N; a_M, a_N) = \mathcal{P}^N(b_M, b_N; a_M, a_N)$ for $a_M = 21.45$, $a_N = 7.84$, and $N = 1, 2, 3, 5$. Here $\mathcal{P}^0$ and $\mathcal{P}^N$ denote the minimal area power consumption for deployments without and with N micro sites per cell, respectively. For a given constant power consumption b_M of macro sites, b_N values below a curve denote constellations where employing appropriate micro sites improves area power consumption, while for b_N values above the curves a pure macro deployment is favorable, i.e., improves area power consumption. The dash-dotted curves in Fig.6 illustrate the case $L = 0.2$. Here, the range of feasible b_N values increases inversely proportional with L for each value of b_M, providing more relaxed requirements for the micro sites' average power consumption.
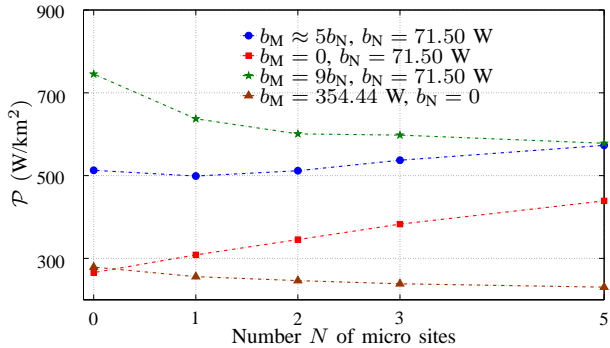
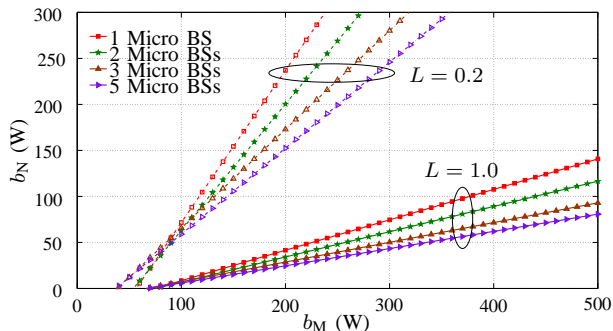Fig. 5: Area power consumption as function of number of micro sites with various b_{M} and b_{N} constellations

Fig. 6: Feasibility curve of b_{M} and b_{N} for $\mathcal{S}_{\mathrm{target}} \approx 7$ bit/s/Hz/km^2

IV. SUMMARY AND CONCLUSIONS

In this paper we investigate on the impact of deployment strategies on the power consumption of mobile radio networks. We consider layouts featuring varying numbers of micro sites per cell in addition to conventional macro sites. We introduce the concept of area power consumption as a system performance metric and employ simulations to evaluate potential improvements of this metric through the use of micro base stations. The investigations show that for the studied propagation scenarios and under the employed power consumption models, the power savings from deployment of micro base stations are moderate in full load scenarios and strongly depend on the offset power consumption of both macro and micro sites. Furthermore, the feasible offset power consumption of micro sites increases inversely proportional with the average traffic load.

APPENDIX

The effective values for the parameters in equation (1) obtained from the propagation models presented in [10] are summarized in Tab.1. The values are computed for macro and micro site antenna heights of 25 m and 10 m, respectively, a carrier frequency of 2.4 GHz, and $r_0 = 1$ m. Note that the factor K for the micro site NLOS scenario can not be formulated independently of the distance r. The shadowing variable on a logarithmic scale is denoted by $\Phi := 10 \log_{10} \Psi$.

Tab. 1: Effective propagation parameters

Urban macro cell	λ	$-10\log_{10}(K)$	σ_Φ
LOS ($r <$1152m)	2.60	32.62	4
LOS ($r \geq$1152m)	4.00	-3.55	6
NLOS	3.57	35.28	8
LOS probability	$P_{\mathrm{LOS}} = \min\left\{\frac{18}{r},1\right\}\left(1-\mathrm{e}^{-\frac{r}{63}}\right)+\mathrm{e}^{-\frac{r}{63}}$		

Urban macro cell	λ	$-10\log_{10}(K)$	σ_Φ
LOS ($r <$144m)	2.27	35.62	3
LOS ($r \geq$144m)	4.00	-2.71	3
NLOS	$2.27\ldots4.00$	$-$	4
LOS probability	$P_{\mathrm{LOS}} = \min\left\{\frac{18}{r},1\right\}\left(1-\mathrm{e}^{-\frac{r}{36}}\right)+\mathrm{e}^{-\frac{r}{36}}$		

Tab. 2: LTE-based link budget (1)

Relevant LTE system parameters	
Carrier frequency	2.4 GHz
Bandwidth	5 MHz
FFT size	512
# Subcarriers occupied	300
Subcarrier spacing	15 kHz
Fading margins	
Fast fading margin	2 dB
Inter-cell interference margin	3 dB
Mobile terminal sensitivity	
Thermal noise	-174 dBm/Hz
SNR required	0 dB
Noise per subcarrier	-132 dBm
Receiver sensitivity	-120 dBm

Tab. 3: LTE-based link budget (2)

Parameter	Macro BS	Micro BS	MS
# Antennas (per sector)	2	1	1
# Sectors	3	1	–
Antenna gain	15 dBi	2 dBi	-1 dBi
Noise figure	4 dB	4 dB	7 dB

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