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Energy Efficiency Improvements through Micro Sites in Cellular Mobile Radio Networks

Albrecht J. Fehske, Fred Richter, and Gerhard P. Fettweis
Vodafone Stiftungslehrstuhl, Technische Universität Dresden
Email: {albrecht.fehske, fred.richter, fettweis}@ifn.et.tu-dresden.de

***Abstract*—Efforts to increase the energy efficiency of information and communication systems in general and cellular mobile radio networks in particular has recently gained momentum. Besides positive environmental effects, lowering the energy consumption of mobile radio systems 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 mobile radio networks. In this paper we investigate that matter in more detail from a deployment perspective. We evaluate potential improvements of the area power consumption achievable with network layouts featuring varying numbers of micro sites in addition to conventional macro sites for given system performance targets under full load conditions.**

I. Introduction

The use and production of information and communication technologies contributes an increasing share to global green house gas emissions accounting for over 2% already in 2007 [1]. Within the communications sector a trend towards increasing the energy efficiency of key technologies can be observed. Although mobile radio networks are only a minor producer of green house gas emissions today [2], [3], significant challenges can be expected in the future. Over the past years, mobile telecommunication networks have shown exponentially increasing energy consumption figures, doubling almost every 4 years. Moreover, establishing western standards in communication services on a world wide scale would consume about 40% of today’s global electrical power generation capabilities [3].

Besides reducing the carbon footprint of the industry, there is a strong economical incentive for network operators to reduce the energy consumption of their systems. Currently over 80% of the power in mobile telecommunications is consumed in the radio access network, more specifically the base stations [3]. Improvements can in principle be achieved in two ways. 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.

With respect to energy needs, it is often believed that network topologies featuring high density deployments of small, low power base stations yield strong improvements compared to low density deployments of few high power base stations [3]. This paper investigates on this issue in more detail. Using the notion of area power consumption we assess the energy need of heterogeneous mobile radio networks featuring conventional macro sites as well as additional smaller micro sites. 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.

While in previous contributions deployment strategies are commonly investigated with respect to spectral efficiency and coverage, e.g., [4], [5], we utilize the additional metric of area power consumption to evaluate different topologies. In this regard, we are specifically concerned with quantifying the energy savings through deployment of micro sites alongside conventional macro sites.

Similar investigations with respect to profitability and cost structure of mixed topologies are conducted in [6]. In [4] the notion of mean spectral efficiency per unit area is introduced to measure the performance of cellular mobile radio systems. This concept is extended here to a quantile based notion of area spectral efficiency and utilized for networks employing frequency reuse of one. Similar to the investigations in [5], which focus on the relation between base station density and outage probability, we study the effect of base station density on area power consumption. Complementing the investigations in [7], we investigate on area power consumption figures for deployments with increasing numbers of micro sites and compare achievable gains for minimum spectral efficiency targets. 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 mobile radio network.

The remainder of the paper is organized as follows. In Section II we introduce the system model, define relevant performance measures. In Section III we study the performance of different deployments based on computer simulations. Section IV concludes the paper.

In the following we use the operators $\mathbb{P}$, $\mathbb{E}$, and Q^α to denote the probability, the expectation, and the α-quantile operator, respectively.

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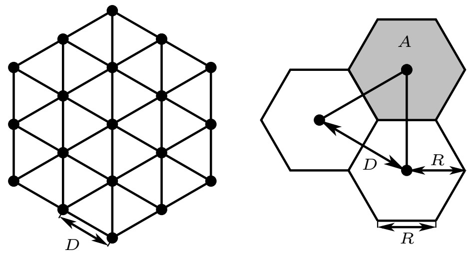

Fig. 1: Regular grid of macro sites and corresponding cell geometry with $D = \sqrt{3}R$ and $A = \frac{3\cdot\sqrt{3}}{2}R^2$.

II. System Model and Performance Metrics

In this paper the macro base station network is modeled as a 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 served by accordingly many co-located macro base stations. For given inter site distance D, the cell size A calculates as $A = \frac{3\sqrt{3}}{2}R^2$.

A. Propagation Model

Deterioration of signal quality is commonly assumed to be due to three different causes: path loss, slow fading, also referred to as shadowing, and fast fading. In this work we concentrate on the effects of path loss and shadowing and include the effects of fast fading as a margin in the link budget. We employ a signal propagation model as follows

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

where P_{tx}, P_{rx}, r, and λ denote transmit and receive power, propagation distance, and path loss exponent, respectively. The parameter r_0 specifies a reference distance where signal strength is known. The random variable Ψ is used to model shadowing effects and follows a log-normal distribution such that the variable $10\log_{10}\Psi$ follows a zero mean Gaussian distribution. We assume the parameter K to be composed of three factors, i.e.,

$$K = K(r,\phi) = U \cdot V \cdot W(r,\phi). \tag{2}$$

Factor U incorporates the impact of user terminal and base station antenna heights, carrier frequency, and propagation environment. Fractional propagation loss due to outdoor-to-indoor propagation is captured in the factor V. The antenna pattern depending on the relative location of transmitter and receiver is modeled by the term $W(r,\phi)$. For simulative investigations, we employ the propagation parameter values specified in [8], again presented in the appendix for convenience.

B. Base Station Types and Power Models

Conventional macro sites are designed to provide larger areas with a certain minimum coverage. A site's average 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 500 m to 2500 m with coverage of more than 90%. Besides conventional macro base stations we consider the additional deployment of smaller base stations, which we refer to as micro base stations. We consider micro sites that are not sectorized[1] and cover a much smaller area with cell radii typically around 100 m. In turn, micro base stations feature a much smaller average power consumption.

We model the relation between the average power consumption and the average radiated power per site in a linear fashion by

$$P_{\text{ma}} = a_{\text{ma}} \cdot P_{\text{tx}} + b_{\text{ma}} \;, \tag{3}$$

$$P_{\text{mi}} = a_{\text{mi}} \cdot P_{\text{tx}} + b_{\text{mi}} \;, \tag{4}$$

where P_{ma}, P_{mi} and P_{tx} denote the average consumed power per macro and micro site and the radiated power per site, respectively. The coefficients a_{ma} and a_{mi} account for the power consumption that scales with the average radiated power due to amplifier and feeder losses as well as cooling of sites. The terms b_{ma} and b_{mi} denote power offsets which are consumed independently of the average transmit power. These offsets are, amongst others, due to signal processing, battery backup, as well as site cooling[2]. Both a_{ma} and b_{ma} increase with the number of sectors per macro site and the number of antennas per sector. The power consumption of macro sites is virtually independent of traffic load [9]. In contrast, the ability to scale their power consumption with the current activity level is considered one major benefit of micro sites. Consequently, the parameters a_{mi} and b_{mi} should depend on the traffic load. Since we assume full load in our analysis, this aspect is disregarded here.

C. Cell Coverage

We define cell coverage $\mathcal{C}$ as the fraction of cell area where received power is above a given level P_{min}, i.e.,

$$\mathcal{C} := \frac{1}{A}\int_A r \cdot \mathbb{P}\big[P_{\text{rx}}(r,\phi) \geq P_{\text{min}}\big]\,\mathrm{d}r\,\mathrm{d}\phi \tag{5}$$

where A denotes the cell area as illustrated in Fig.1. In this work we consider the micro cells as "overlapping" in the sense that micro sites do not contribute to the macro cell coverage.

D. Traffic Dependent Spectral Efficiency

Let $\mathcal{A}$ denote the reference cell area of size A. Let further all macro and micro base stations be indexed and let $\mathcal{I}$ be a set containing all indices. We define the area $\mathcal{A}_i \subseteq \mathcal{A}$ served by base station i as the set of all points where micro or macro base station i provides the highest average receive power, i.e.,

$$\mathcal{A}_i := \left\{x \in \mathcal{A} \,\middle|\, \mathbb{E}_\Psi\left[P_{\text{rx}\,i}(x)\right] \geq \mathbb{E}_\Psi\left[P_{\text{rx}\,j}(x)\right] \text{ for all } j \neq i\right\}$$

[1] We use the terms *micro site* and *micro base station* interchangeably here.

[2] Cooling equipment can be considered to impact both, the transmit power dependent as well as the offset power consumption, since both, transmit power dependent as well as independent components, contribute thermal radiation.

where $\mathbb{E}_\Psi\left[P_{\mathrm{rx}j}\right] = K_j \cdot \left(\frac{r_j}{r_0}\right)^{-\lambda_j} \cdot \mathbb{E}[\Psi_j]$ and r_j is the distance from point $x \in A_i$ to base station j. For $x \in \mathcal{A}_i$ we define the corresponding average SINR and average spectral efficiency as

$$\gamma_i(x) := \frac{\mathbb{E}_\Psi\left[P_{\mathrm{rx}i}(x)\right]}{\sum_{j\in\mathcal{I}\setminus\{i\}} \mathbb{E}_\Psi\left[P_{\mathrm{rx}j}(x)\right] + \sigma^2} \quad \text{and} \tag{6}$$

$$S_i(x) := \min\left[\log_2\left(1+\gamma_i(x)\right),\ S_{\mathrm{max}}\right], \tag{7}$$

respectively. Constraining the SINR to be less or equal S_{max} models the use of a modulation scheme of finite size in practice.

We now define a traffic dependent notion of spectral efficiency as follows. Consider a random point process, generating a random number of coordinates (user positions) in the reference area $\mathcal{A}$. Let the random variable N_i denote the number of points occurring in the area $\mathcal{A}_i$ and let further X_i denote a random variable with realizations being the coordinates of a single user position within $\mathcal{A}_i$ as generated by the random point process. The distribution of user positions according to X_i induces a distribution of the spectral efficiency values $S_i(X_i)$ according to (6) and (7) in each $\mathcal{A}_i$. We define the overall spectral efficiency in the reference cell area $\mathcal{A}$ as the sum of the spectral efficiencies in the sub areas $\mathcal{A}_i$ weighted by the probability that at least one user is present in the area, i.e.,

$$S := \sum_{i\in\mathcal{I}} S_i(X_i) \cdot \mathbb{P}[N_i > 0]. \tag{8}$$

Equation (8) implies that the distribution of the overall spectral efficiency is obtained as the weighted convolution of the individual spectral efficiency densities generated by all base stations covering part of the reference area. Note that by this definition we implicitly assume that a users always request data and that all resources, i.e., subcarriers and power, of a base station can be utilized by a single user.

E. Area Spectral Efficiency

In [4], [7] the notion of area spectral efficiency is defined as the mean of the overall spectral efficiency in the reference cell divided by the cell size, commonly measured in bit per second per Hertz per square kilometer, i.e.,

$$\mathcal{S} := \frac{\mathbb{E}[S]}{A}. \tag{9}$$

The above definition only considers the expectation of the achievable rates per unit bandwidth but is not concerned with the distribution of rates around the mean, effectively ignoring fairness in the distribution of rates in the system. In order to incorporate a fairness aspect into the notion of area spectral efficiency we extend the ideas of [4], [7] and define area spectral efficiency as the α-quantile of the overall spectral efficiency in the reference cell divided by the cell size, i.e.,

$$\mathcal{S}^\alpha := \frac{Q^\alpha[S]}{A}. \tag{10}$$

In this work we focus our investigations on the quantile based definition (10). As a more practical relevant measure we utilize the notion of area throughput per subcarrier by scaling area spectral efficiency with the subcarrier bandwidth B_{sc}, i.e.,

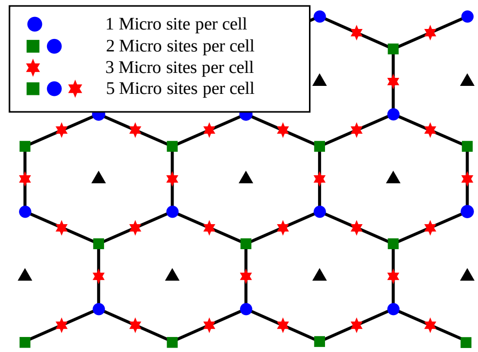

Fig. 2: Positioning of micro sites within the macro grid

$$\mathcal{T}^\alpha := \mathcal{S}^\alpha \cdot B_{\mathrm{sc}}. \tag{11}$$

F. 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 reference cell divided by the corresponding cell size measured in Watts per square kilometer. With an average of N micro sites in a reference cell of size A, the area power consumption is defined as

$$\mathcal{P} := \frac{P_{\mathrm{ma}} + N \cdot P_{\mathrm{mi}}}{A}, \tag{12}$$

where P_{ma} and P_{mi} are the average power consumed by macro and micro sites, respectively.

III. Performance Evaluation of Different Deployment Strategies

In this section we study the relation of inter site distance, the number of micro sites per cell, the area throughput as well as the minimum area power consumption of different deployments by means of computer simulations. We also investigate the impact of the offset powers b_{ma} and b_{mi} on the results.

A. Simulation Setup

The simulation setup consists of a reference macro site with two tiers of interfering macro sites placed on a hexagonal grid as depicted in Figure 1 with an inter site distance D ranging from 500 m to 2500 m. Mobile terminals are assumed to be uniformly distributed within the cell. 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 also assume no cooperation among sites. The transmit power of each site is calculated by numerically inverting formula (5) based on a cell coverage requirement of $\mathcal{C} = 95\%$ for macro as well as micro cells. Micro sites are assumed to support a circular area of radius 100 m and are positioned on the cell edges where the signal level from macro

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Tab. 1: Typical power consumption values

Macro site (3 sec. / 2 ant.)	P_{tx}	10 W	20 W	40 W	
	P_{ma}	638 W	865 W	1317 W	
Micro site (1 sec. / 1 ant.)	P_{tx}	100 mW	500 mW	2 W	5 W
	P_{mi}	32 W	35 W	43 W	60 W

sites can be expected to be very low. The positioning of micro sites relative to macro sites is depicted in Fig.2.

We utilize an LTE-based link budget given in Tab.3 and Tab.4 in the Appendix. Furthermore, we employ the propagation models presented in [8] for urban macro and micro cells. The effective propagation parameters as used in the simulations are presented in the appendix. We choose $S_{\text{max}} = 6$ bit/s/Hz for the computation of the spectral efficiency according to (7).

Values of the power model coefficients are selected based on the power consumption data given in Tab.1 for macro sites with three sectors and two antennas per sector and micro sites with a single sector with one omni-directional antenna. These data are obtained from comparing data of several existing base station types as well as operator's experience and reflect an average of power consumption figures occurring in practice. The concrete parameter values are obtained as

$$a_{\text{ma}} = 22.6 \qquad b_{\text{ma}} = 412.4 \text{ W}$$
$$a_{\text{mi}} = 5.5 \qquad b_{\text{mi}} = 32.0 \text{ W}.$$

We calculate a 10-percentile based area throughput $\mathcal{T}^{10}$ based on equations (8), (10), and (11), where we use $\mathbb{P}[N_i > 0] \approx 1$ to reflect high traffic load conditions.

B. Network Performance Evaluation

a) Area Power Consumption: In order to evaluate the area power consumption of different deployments we compute the average power required for a coverage of $\mathcal{C} = 95\%$ for increasing site distances D. Since increasing cell sizes require increasing power for fixed coverage, there exists a fundamental tradeoff between an increase of the covered area and an increase in power consumption. This tradeoff is captured in the definition of area power consumption and depicted in Fig.3. We observe a strong increase of the area power consumption for small site distances as well as the existence of a minimum area power consumption for deployments with $k = 1, 2, \ldots$ micro sites at increasing optimum inter site distances D_k^*. Both effects are due to the distance-independent power terms in the definition of the area power consumption (12) and the affine power models (3) and (4) [7]. Note that we assume the power consumption of micro sites, P_{mi}, to be independent of the inter site distance here.

b) Area Throughput: Deployment of micro sites does not directly lead to a reduction in power consumption by relaxing the coverage requirements, however, it provides significant gains in spectral efficiency in high load scenarios. Clearly, small base stations are intended to increase throughput locally by exploiting good propagation conditions. This effect is visible in Fig.4 where the 10-percentile based area throughput per subcarrier, $\mathcal{T}^{10}$, is depicted for layouts with up to five

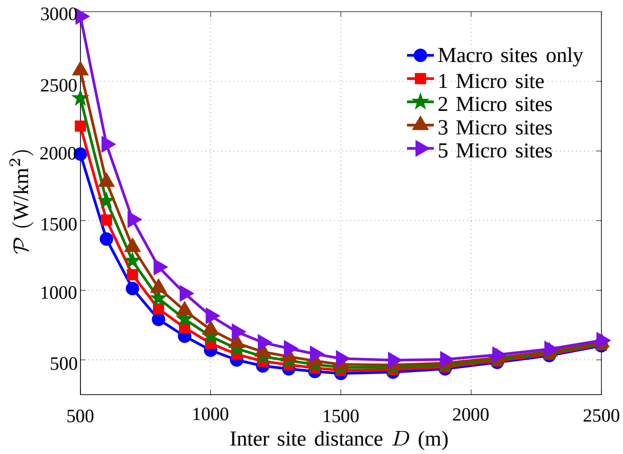

Fig. 3: Area power consumption as function of inter site distance for different deployments

micro sites per macro site for increasing macro site distances.

c) Optimal Site Distances: We suggest the following simple approach to determine minimal power consumption deployments achieving certain target area throughputs. For a given $\mathcal{T}^{10}_{\text{target}}$ and for different numbers of micro cells $k = 0, 1, 2, \ldots$ we determine the respective maximum inter site distances $\hat{D}_k$ achieving at least $\mathcal{T}^{10}_{\text{target}}$ from Fig.4. Note in particular that the curves are strictly monotonically decreasing and thus all $D_k \leq \hat{D}_k$ are feasible for $\mathcal{T}^{10}_{\text{target}}$. In order to obtain a deployment with an optimal inter site distance we search for distances $D_k \leq \hat{D}_k$ that minimize the area power consumption by examining the relation depicted in Fig.3. Due to the monotonicity properties of these curves there are two cases possible. In case $\hat{D}_k \geq D_k^*$, the inter site distance providing minimal area power consumption and area throughput of at least $\mathcal{T}^{10}_{\text{target}}$ is given by D_k^*. Otherwise the optimal site distance providing at least $\mathcal{T}^{10}_{\text{target}}$ is given by $\hat{D}_k$. The minimal area power consumption figures $\mathcal{P}^*$ for $\mathcal{T}^{10}_{\text{target}} = 100$ kbit/s/km^2 are depicted in Fig.5.

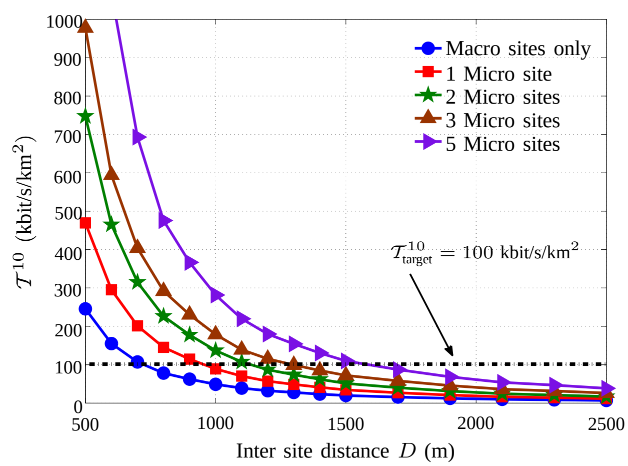

Fig. 4: 10-percentile area throughput per subcarrier as function of inter site distance for different deployments

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A similar approach is suggested in [7] considering the mean area spectral efficiency (9).

d) Dependency on Offset Power Consumption: In this last paragraph we examine the dependency of the previous result on the offset powers b_{ma} and b_{mi} of the linear power models. Note that since commonly micro sites are made of low cost components, the transmit power dependent loss per antenna is almost 50% higher for micro sites, i.e., $a_{\text{mi}} \approx 1.47 \cdot \frac{a_{\text{ma}}}{6}$. Hence the main advantage of micro sites lies in a low offset power per antenna, which is about 55% lower, i.e., $b_{\text{mi}} \approx 0.47 \cdot b_{\text{ma}}$. Fig.5 shows dependency of the minimal area power consumption for different deployments on the ratio $\frac{b_{\text{mi}}}{b_{\text{ma}}}$. Here we observe that the spectral efficiency gains in the high load scenario considered here are significant. The deployment of at least on micro site decreases the area power consumption even if the power offset per antenna is for micro sites is about 3 times that of macro sites, i.e., $b_{\text{mi}} \approx 0.5 b_{\text{ma}} = 3 \cdot \frac{b_{\text{ma}}}{6}$.

IV. Summary and Conclusions

In this paper we provided a framework to evaluate and optimize cellular network deployments with respect to the average number of micro sites per macro cell as well as the macro cell size. We introduced the concepts of area power consumption and quantile based area throughput. The simulation results show that deployment of micro sites allows to significantly decrease the area power consumption in the network while still achieving certain area throughput targets.

Appendix

The effective values for the parameters in equation (1) obtained from the propagation models presented in [8] are summarized in Tab.2. 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. Outdoor-indoor penetration loss is assumed to be 20 dB [8]. We further assume 50% of the cell area to be indoor, which yields an average penetration loss of $V = 17$ dB for a uniform distribution of users.

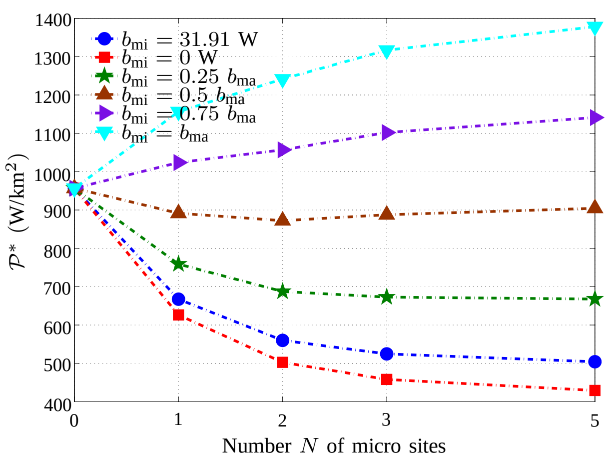

Fig. 5: Minimal area power consumption as function of number of micro sites for $\mathcal{T}^{10}_{\text{target}} = 100$ kbit/s/km^2

Tab. 2: Effective propagation parameters based on [8]

Urban macro cell	λ	$-10\log_{10}(U)$	$\sigma_{10\log_{10}\Psi}$
LOS (r <384 m)	2.20	35.60	4
LOS (r ≥384 m)	4.00	−10.90	4
NLOS	3.91	17.40	6
LOS probability	$P_{\text{LOS}} = \min\left\{\frac{18}{r}, 1\right\}\left(1 - e^{-\frac{r}{63}}\right) + e^{-\frac{r}{63}}$		
Urban micro cell	λ	$-10\log_{10}(U)$	$\sigma_{10\log_{10}\Psi}$
LOS (r <144 m)	2.20	35.60	3
LOS (r ≥144 m)	4.00	-3.20	3
NLOS	3.67	32.60	4
LOS probability	$P_{\text{LOS}} = \min\left\{\frac{18}{r}, 1\right\}\left(1 - e^{-\frac{r}{36}}\right) + e^{-\frac{r}{36}}$		

Tab. 3: 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 B_{sc}	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 per subcarrier	-120 dBm

Tab. 4: LTE-based link budget (2)

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

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