This document is a preprint of: F. Richter and G. Fettweis, “Cellular Mobile Network Densification Utilizing Micro Base Stations,” in Proceedings of IEEE International Conference on Communications (ICC 2010), Cape Town, South Africa, May 2010. DOI:10.1109/ICC.2010.5502299

Cellular Mobile Network Densification Utilizing Micro Base Stations

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

***Abstract*—Energy efficiency in information and communications technology, and in cellular mobile radio networks in particular, is gaining in importance not only with regard to the ecological assessment. Reducing the power consumption of mobile radio systems has recently attracted attention of network operators as energy costs make up a vast portion of today's operational expenditure. In this regard, it is often talked of deploying small, low power base stations to significantly increase energy efficiency of cellular radio networks. In this paper we study the efficiency of deployment layouts featuring micro base stations in comparison with conventional pure macro systems by means of area power consumption and system throughput. We further introduce the notion of measuring energy efficiency by evaluating the ratio of achievable system throughput to power spent in the network.**

I. Introduction

Already in 2007, information and communications technology has a share of 2% of the global greenhouse gas emissions, increasing with each year [1]. Moreover, expanding western standards in mobile telecommunications on a world wide scale would lead to a power consumption of about 40% of today's capabilities in electrical power generation world wide [2]. Examining past decades, a doubling of power consumption figures of mobile communications almost every 4 years can be asserted. Nevertheless, mobile communications is responsible for 0.2% of the global emissions only, meaning a rather small fraction of today's total ICT carbon footprint. Further, it can be recognized that energy efficiency plays already an increasing role in key communications technologies [2], [3], where significant challenges can be expected in the future.

Besides environmental aspects, there is a strong economical motivation for network operators to reduce power consumption of their systems. The major contribution of about 80% in mobile communications originates from the radio access network, more precisely the base stations [2]. Increasing energy efficiency of a network can therefore be achieved in at least two different but complimentary ways. On the one hand, energy efficiency of the individual sites in a network can be optimized by utilizing more efficient hardware components, e.g., power amplifier, and software modules. Load-adaptivity of the components would further contribute to a lower power consumption. On the other hand, improved deployment strategies which incorporate energy aspects in addition to conventional system performance metrics such as coverage and spectral efficiency, can be expected to reduce the number of required sites.

With regard to a network's energy balance optimization, it is commonly expected that a sufficiently dense network deployment consisting of small, low power base stations would yield strong enhancements compared to conventional low density topologies featuring few high power base stations. This paper addresses the problem in more detail. More specifically, we investigate on the impact of down-scaling the macro cells of a network on the system's power consumption and throughput compared to the deployment of micro sites only, meaning a further densification of the system. The analysis is complemented by considering heterogeneous networks consisting of both macro and micro sites. In this context, micro sites are supposed to exhibit much smaller power consumption figures than their counterparts due to advantageous path loss conditions and smaller area of coverage.

The bigger part of contributions concerning cellular network deployment strategies are typically addressing a system's performance with respect to common metrics such as spectral efficiency, degree of coverage, or outage probability, cf. [4]. By applying the metric of area power consumption introduced in [5], we are able to evaluate different network topologies with regard of their energy efficiency. In this context, we are specifically interested in quantifying energy saving capabilities of pure macro and pure micro deployments as well as hybrid scenarios. Heterogeneous systems consisting of macro, micro, and pico cells are studied in [6], where the focus is on cost structures and profitability. In [5] and [7] the notion of area spectral efficiency, both mean and quantile based, is introduced for homogeneous as well as heterogeneous deployments. In this paper we extend the investigations on pure micro networks. We introduce the quotient of area spectral efficiency and area power consumption as an ordering relation on similar deployment strategies.

The remainder of the paper is organized as follows. In Section II we introduce the system model and define relevant performance measures. In Section III we study the performance of different deployment strategies. Section IV concludes the paper.

In the following we use the notations $\mathbb{P}$, $\mathbb{E}$, $\mathbb{1}_{\mathcal{A}}$, and $\mathcal{N}_{\mu,\sigma^2}$ to denote the probability and expectation operator, the indicator function on the set $\mathcal{A}$, and the Gaussian distribution with mean μ and variance σ^2, respectively.

[1]This work was supported by the German Federal State of Saxony as part of the ”Cool Cellular” project under grant 14056/2367.

This document is a preprint of: F. Richter and G. Fettweis, “Cellular Mobile Network Densification Utilizing Micro Base Stations,” in Proceedings of IEEE International Conference on Communications (ICC 2010), Cape Town, South Africa, May 2010. DOI:10.1109/ICC.2010.5502299

II. System Model and Performance Metrics

The focus of the paper is on homogeneous and heterogeneous networks composed of macro or micro sites, respectively. Homogeneous networks are modeled as infinite regular grid characterized by the inter site distance $D \in \mathbb{R}_{++}$, yielding cell structures of equal size $|\mathcal{A}|$ as illustrated in Fig.1, where the three-fold sectorized cell structure corresponds to macro networks and the hexagonal layout to micro layouts. In this paper we use the notion *cell site*, or shortly *site*, to refer to the geometrical location of a base station's radio equipment and its antennas. Further, the notion *cell* is referred to as the area covered by a cell site.

Heterogeneous networks are modeled as homogeneous macro systems as described above, where a certain number of micro base stations are placed within the network. The inter site distance refers then to the distance of neighboring macro base stations. In the heterogeneous case, the definition of a cell is more complicated. For our purpose, a cell in a heterogeneous network describes the area covered by a macro site plus the area covered by micro sites which are located within the corresponding macro cell.

A. Propagation Model

It is commonly assumed that deterioration of a radio signal's quality is due to three different effects: path loss, shadowing or large-scale fading, and multipath or small-scale fading. In our simulations we consider all of them, whereas the latter effect is modeled as a margin in the link budget. The basic propagation model we use for our analysis is given by

$$P_{\text{rx}} = K d^{-\lambda} \Psi P_{\text{tx}} \ , \tag{1}$$

where P_{tx}, P_{rx}, d, and λ denote transmit and receive power, propagation distance, and path loss exponent, respectively. Ψ denotes a random variable with $10\log_{10}\Psi \sim \mathcal{N}_{0,\sigma^2_{10\log_{10}\Psi}}$, modeling the shadowing process. Further, we assume the parameter K to be factorized as

$$K = UVW \ . \tag{2}$$

The impact of base station and mobile terminal antenna heights, carrier frequency, propagation conditions, and reference distance are incorporated in factor U. The penetration loss due to transmission from outdoor to indoor is captured in the term V. The parameter W models the antenna pattern, which depends on the mobile's location relative to the base station.

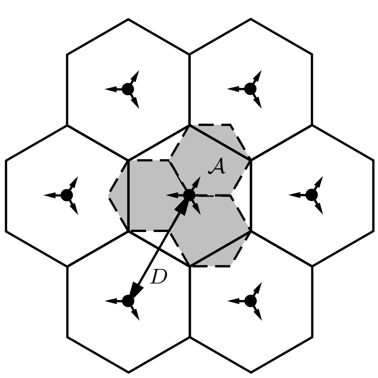

Fig. 1: Regular grid of base stations and corresponding cell geometry with inter site distance D and cell area $|\mathcal{A}|$.

B. Base Station Types and Power Models

Today's cellular networks mainly consist of powerful macro base stations, employed in rural, suburban, and urban areas, where in the latter they cover cell radii of about 500 m up to 2500 m with a degree of coverage of at least 90%. Typical antenna heights are well above roof level. In the course of the LTE rollout, a densification of the network will take place. Hence, macro site distances of less than 500 m might not be unusual. A macro site's average power consumption is thereby determined by the cell size and degree of coverage. Further, macro cells are commonly sectorized.

In contrast to this, we consider deploying smaller base stations, which we refer to as micro base stations. These micro sites are designed to cover much smaller areas, typically around 100 m cell radius, while consuming only a fraction of the power of a macro site. Moreover, they are predominately installed below rooftop and are not as powerful as their counterparts, meaning there is no sectorization and no comparable transmit power possible due to the design size.

The relation between average radiated power P_{tx} and a site's power consumption is taken from [8], where it is linearly modeled for both macro and micro sites by

$$P_{\text{ma}} = N_{\text{sec}} N_{\text{ant}} \left(a_{\text{ma}} P_{\text{tx,ma}} + b_{\text{ma}} \right) \quad \text{and} \tag{3}$$

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

where N_{sec} and N_{ant} denote the macro cell's number of sectors and the number of antennas per sector, respectively. The coefficients a_{ma} and a_{mi} account for the power consumption that scale with the average radiated power. While a_{ma} computes from power amplifier efficiency, feeder loss, and site cooling as well as power supply and battery backup, only the power amplifier and power supply is taken into account for a_{mi}. The transmit power independent power offsets b_{ma} and b_{mi} are both mainly impacted by the power spent for signal processing, whereas in the case of macro sites it is also impacted by site cooling due to hardware components contributing to thermal radiation regardless of the transmit power. Micro base stations are typically able to scale their power consumption to traffic load conditions which is disregarded here since we concentrate on full load scenarios. In contrast, macro sites are assumed to have a power consumption almost independent of traffic load [9]. From manufactural perspective, hardware components of micro base stations can be expected to be of less quality, e.g., power amplifiers can be assumed less efficient.

C. System Spectral Efficiency

As described in [7], the spectral efficiency in a cell (which is served by one macro site plus one or more micro sites in the heterogeneous case) corresponds to the weighted sum of the spectral efficiencies in the individual sectors. More precisely, let $\mathcal{I}_{\mathcal{A}}$ denote the index set of sectors belonging to the typical cell $\mathcal{A}$ of size $|\mathcal{A}|$. In this context, affiliation to a sector corresponds to highest expected receive power from the corresponding base station. Consider now a point pattern which generates a random number of users within $\mathcal{A}$. For any sector $\mathcal{A}_i$ with $i \in \mathcal{I}_{\mathcal{A}}$ let N_i denote the number of users located within $\mathcal{A}_i$. Here, we proceed on the fact that the cell $\mathcal{A}$ is partitioned into the sectors $\mathcal{A}_i$, i.e., it holds $\mathcal{A} = \bigcup_{i\in\mathcal{I}_{\mathcal{A}}} \mathcal{A}_i$ with $\mathcal{A}_i \cap \mathcal{A}_j = \emptyset$ for all $i \neq j$. Let further X_i denote the coordinates of a single user within $\mathcal{A}_i$ according to the point pattern. The spectral efficiency S_i is calculated based on

$$S_i(X_i = x) := \min\Big[\log_2\big(1+\gamma_i(x)\big),\ S_{\text{max}}\Big]\ , \qquad (5)$$

where γ_i denotes the average SINR with respect to sector i. The term S_{max} contributes to practical aspects of finite modulation schemes. The distribution of X_i induces a distribution of S_i, which thus provides the distribution of the overall system spectral efficiency S with

$$S = \sum\nolimits_{i\in\mathcal{I}_{\mathcal{A}}} S_i(X_i) \cdot \mathbb{P}\big[N_i > 0\big]\ ,$$

where the weights $\mathbb{P}\big[N_i > 0\big]$ constitute the probability of sector $\mathcal{A}_i$ being nonempty. This approach is motivated by the spatial reuse since the same resources are allocated in each sector. It is also assumed that all resources are utilized provided there is at least one mobile terminal requesting data.

The average SINR γ_i in (5) computes based on the assumption of uncorrelated shadowing in a simplified manner (with regard to the computation) as

$$\gamma_i(x) := \frac{\mathbb{E}\big[P_{\text{rx},i}\big]}{\sum_{j\in\mathcal{I}\setminus\{i\}} \mathbb{E}\big[P_{\text{rx},j}\big] + \sigma^2}\ , \qquad (6)$$

which constitutes a lower bound to the non-simplified average SINR, where the latter calculates as the expectation of the fraction in (6). Note that the expectation is due to the shadowing process. Further, the SINR corresponds to a maximal interference scenario, where a mobile terminal receives power from each base station in the network. In (6) the set $\mathcal{I}$ is referred to as the index set of all sectors in the network.

As a more practical measure we use the terminology of system throughput per subcarrier, defined by scaling the system spectral efficiency by means of the subcarrier bandwidth B_{sc} (see Tab.2), i.e.,

$$T := B_{\text{sc}} \cdot S\ . \qquad (7)$$

D. Area Power Consumption

Since we want to compare networks with differing site densities, we need to normalize the mere power consumption. This can be done by assessing the power consumption of the network relative to its expansion, leading to the notion of area power consumption, which is typically measured in watt per square kilometer. The area power consumption of a network is calculated based on

$$\mathcal{P} := \frac{1}{|\mathcal{A}|} \sum\nolimits_{i\in\mathcal{I}_{\mathcal{A}}} P_i\ , \qquad (8)$$

where the power consumption portion P_i of the site serving sector $\mathcal{A}_i$ is determined by means of (3) and (4) according to

$$P_i = \begin{cases} \frac{1}{N_{\text{sec}}} P_{\text{ma}} & \text{if } \mathcal{A}_i \text{ is a macro sector,} \\ P_{\text{mi}} & \text{if } \mathcal{A}_i \text{ is a micro sector.} \end{cases} \qquad (9)$$

Note that in (8) only the power consumption figures P_i of sites serving the sectors belonging to the reference cell are considered, in the same way as the area $|\mathcal{A}|$ corresponds to this reference cell.

E. Spectral Efficiency per Power Consumption

A mobile network operator is interested in optimal spectral efficiency figures in conjunction with minimal power consumption. These are obviously two different design goals for planning cellular networks. For instance, achieving a high spectral efficiency in a network comes along with a sufficiently dense placement of base stations equipped with high-grade signal processing technologies, which in turn is responsible for a huge amount of power spent in the network. Hence, optimizing a network with regard to energy efficiency and spectral efficiency is a multi-objective programming problem which is not easily solved. One way to circumvent the problem of maximizing spectral efficiency while minimizing power consumption is to optimize the quotient thereof,

$$Q := \frac{\mathcal{S}}{|\mathcal{A}|\mathcal{P}}\ , \qquad (10)$$

where $\mathcal{S} = \mathbb{E}[S]$ is the mean spectral efficiency or $\mathcal{S} = F_S^{-1}(\alpha)$ the α-quantile of the spectral efficiency with F_S denoting the cumulative distribution function of S. The ratio (10) is measured in bit per second per watt. Of course, the quotient can by adapted to a more general case, e.g., by weighting numerator or denominator. Moreover, in the following section we will make use of the scaled version $B_{\text{sc}}{\cdot}Q$ corresponding to the system throughput per subcarrier.

III. Numerical Results

A. Simulation Setup

The simulation setup for homogeneous networks consists in each case of one reference cell and two tiers of interfering sites, placed on a hexagonal grid as depicted in Fig.1. Inter site distances of interest range from 300 m to 1730 m for macro deployments and from 50 m to 350 m for micro scenarios. In the heterogeneous case, the macro sites exhibit distances ranging from 1000 m to 1730 m, where also two tiers of interfering sites are considered. Within each macro cell, 3, 6, and 9 micro sites are uniformly distributed in proximity of the border, all with equal distance to the macro base station. We assume a Poisson point pattern implicating a uniform distribution of mobiles within the reference cell. Our focus is on the downlink of an OFDMA system where in each sector the same resources are allocated.

The transmit powers of the individual sites are calculated by setting a coverage degree of $\mathcal{C} = 95\%$. The coverage is referred to exceeding a minimal receive power threshold defined by the receiver sensitivity (see Tab.2). This coverage

This document is a preprint of: F. Richter and G. Fettweis, "Cellular Mobile Network Densification Utilizing Micro Base Stations," in Proceedings of IEEE International Conference on Communications (ICC 2010), Cape Town, South Africa, May 2010. DOI:10.1109/ICC.2010.5502299

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

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

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

Relevant LTE system parameters	
Carrier frequency	2.0 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

degree is applied with the relation between coverage and transmit power provided in [7], considering an additional path loss due to an outdoor-to-indoor penetration loss of $V = 20$ dB and applying a typical horizontal three-sector antenna pattern for macro sites (cf. [10]) via

$$W(\phi) = -\min\left(12\left(\frac{\phi}{70°}\right)^2 \text{dB},\ 30\ \text{dB}\right),\ \ \phi \in (-\pi, \pi]$$

with a 3 dB beamwidth of 70° and a maximal attenuation of 30 dB. The parameter ϕ denotes the angle between mobile terminal and boresight direction of the major lobe. Micro base stations are assumed to be equipped with one omni-directional antenna. In heterogeneous scenarios, the micro site's radiated power calculates with regard to a circular area of coverage of radius 100 m. Further, the calculations are based on a LTE link budget provided in Tab.1 and Tab.2 as well as on propagation models taken from [10] which are summarized in Tab.4 for a carrier frequency of 2 GHz and for macro and micro base station antenna heights of 25 m and 10 m, respectively.

The computed transmit power figures of macro and micro base stations in homogeneous networks are summarized in Tab.3. The transmit powers of macro base stations in heterogeneous networks correspond to the ones calculated for homogeneous scenarios, whereas the transmit powers of the micro sites are found out to be 2.3 W for each network size.

Although the transmit powers are designed such that indoor areas are covered to a certain degree, the following results are based on users located outdoors only. For evaluating the spectral efficiency figures we apply $S_{\text{max}} = 6$ bit/s/Hz according to (5). Further, we study full load scenarios only, i.e., each sector contains at least one mobile requesting data, with all resources allocated. For applying the introduced power model, we make use of the values derived in [8], that is,

$$a_{\text{ma}} = 3.8,\ b_{\text{ma}} = 68.8\ \text{W},\ a_{\text{mi}} = 5.5,\ b_{\text{mi}} = 32.0\ \text{W}\ .$$

Tab. 3: Transmit power figures in homogeneous networks

D	300 m	500 m	1000 m	1500 m	1730 m
$P_{\text{tx,ma}}$	40 mW	310 mW	4.7 W	23.9 W	40.0 W
D	50 m	100 m	200 m	300 m	350 m
$P_{\text{tx,mi}}$	5 mW	210 mW	4.1 W	19.1 W	34.5 W

B. Network Performance Evaluation

a) Area Power Consumption: In Fig.2, the area power consumption figures for the different deployment strategies are depicted. As observed in [5] and [7], there is an area power consumption minimizing inter site distance for each strategy. It can be observed that homogeneous micro networks have a much larger power consumption per area compared to homogeneous macro and heterogeneous networks with typical inter site distances. This simply results from the dense micro network topology, where the reduced transmit powers and, thus, reduced power consumption figures can not compensate for the multiple of base stations compared to macro deployments with sufficiently large inter site distance.

By having a closer look at Tab.3, we see that the required transmit powers for micro sites with inter site distance of 200 m and larger are not feasible subject to the design space of micro base stations. From area power consumption perspective, such networks are not worth of further considerations anyway. We also observe that a densification of homogeneous macro deployments beyond 1000 m inter site distance yields a considerable increase in power consumption in the network, which should only be put up with for a significant gain in spectral efficiency.

We conclude that a homogeneous network densification, even with micro base stations with their comparably low power consumption figures, comes along with a significant increase in area power consumption. This leaves the question what gain in spectral efficiency can be achieved by employing dense networks and, hence, allowing larger power consumption figures.

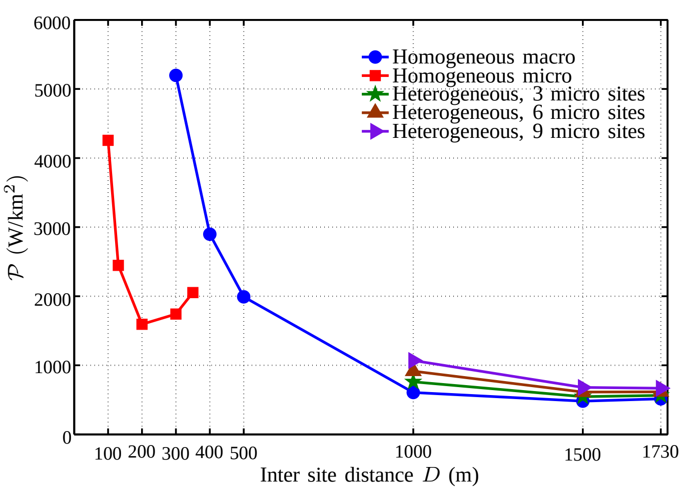

Fig. 2: Area power consumption as function of inter site distance for different deployments.

b) System Spectral Efficiency: The cumulative distribution functions of the system throughput per subcarrier are depicted in Fig.3 for homogeneous macro and heterogeneous deployments. The arrows indicate increasing inter site distances according to our simulation setup. In each scenario the spectral efficiency can be improved by decreasing inter site distance. This is a consequence of enhanced propagation conditions due to smaller distances between base station and mobile terminal. Introducing micro base stations within a macro network further enhances system throughput, where the higher the number of micro sites the higher the gain. Moreover, not only the mean throughput increases but also any quantile of it. Of course, due to geographical limits, there is a specific number of micro sites (depending on the layout) above which deploying further micro sites will decrease the system throughput, an effect which can be observed for sufficiently dense pure micro networks. We also see that the more micro sites, the larger the variance in the throughput, although the difference is relatively small.

In contrast to that consider the system throughput figures illustrated in Fig.4 for homogeneous micro networks. Here we can clearly observe that a network densification beyond a certain size does not necessarily provide higher system throughput capabilities. In our example we have an increase of low quantile-based throughput figures for decreasing inter site distance. On the other hand, the peak throughput decreases noticeably. This follows from two facts: firstly, the nearer the base stations, the higher the probability of line of sight between mobile and its associated base station. Secondly, the same holds for line of sight between mobile and interfering base stations. Hence, the SINR at a mobile is getting worse the smaller the base stations' distance due to an increasing number of base stations generating significantly high interference power. Obviously, there is a maximal peak throughput realizing inter site distance, which corresponds to about 200 m in our example. We further take from the results that the degree of fairness gets higher for more dense networks. This simply follows from the fact that for mobiles located near the cell border, the increase in receive power compensates for the increase in interference power for decreasing cell sizes due to the nonlinearity of the propagation conditions.

Tab. 4: Effective propagation parameters based on [10]

Urban macro cell	$\boldsymbol{\lambda}$	$\boldsymbol{-10\log_{10}(U)}$	$\boldsymbol{\sigma_{10\log_{10}\Psi}}$
LOS (d <320 m)	2.20	34.0	4
LOS (d ≥320 m)	4.00	−11.0	4
NLOS	3.91	15.8	6
LOS probability	$P_{\text{LOS}} = \min\left\{\frac{18}{d}, 1\right\}\left(1 - \mathrm{e}^{-\frac{d}{63}}\right) + \mathrm{e}^{-\frac{d}{63}}$		
Urban micro cell	$\boldsymbol{\lambda}$	$\boldsymbol{-10\log_{10}(U)}$	$\boldsymbol{\sigma_{10\log_{10}\Psi}}$
LOS (d <120 m)	2.20	34.0	3
LOS (d ≥120 m)	4.00	-3.4	3
NLOS	3.67	30.5	4
LOS probability	$P_{\text{LOS}} = \min\left\{\frac{18}{d}, 1\right\}\left(1 - \mathrm{e}^{-\frac{d}{36}}\right) + \mathrm{e}^{-\frac{d}{36}}$		

c) Spectral Efficiency per Power Consumption: In Fig.5, the ratio $B_{\text{sc}} \cdot Q$ of mean system throughput per subcarrier to power consumption in the network is depicted. We already observed the comparatively high power consumption in pure micro networks due to the high number of sites. Regarding the metric Q, we can conclude that the higher amount of power spent in a dense micro network can be easily compensated for by the significant increase in mean area system throughput. This is also true for any quantile of the system throughput in case of very small inter site distances (in our scenario about 50 m to 130 m) due to the high fairness in such networks. This conclusion is reasonable since although the throughput in pure macro and hybrid networks is larger due to the higher spatial reuse within the cells, the area throughput in pure micro networks is much higher due to significantly smaller cell sizes.

The notion area throughput or area spectral efficiency, especially of heterogeneous networks, was introduced in [5] and [7] for mean and quantile-based throughput considerations, respectively. With this, the measure (10) can also be written as the ratio of area spectral efficiency or area throughput to area power consumption. Hence, we end up with much better

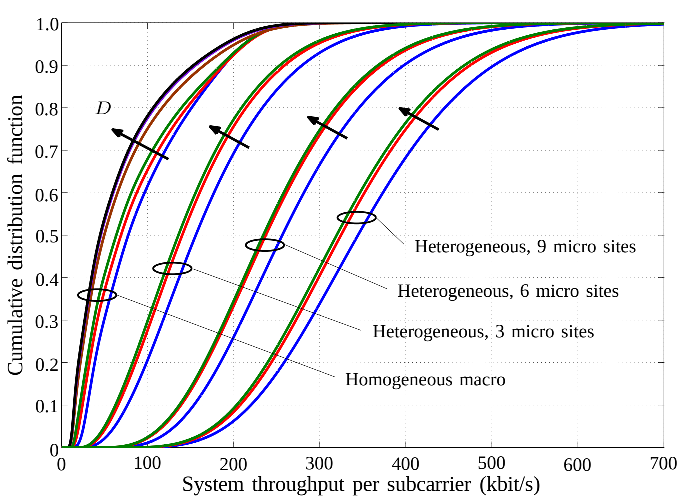

Fig. 3: Distribution of the system throughput per subcarrier for homogeneous macro and heterogeneous deployment strategies.

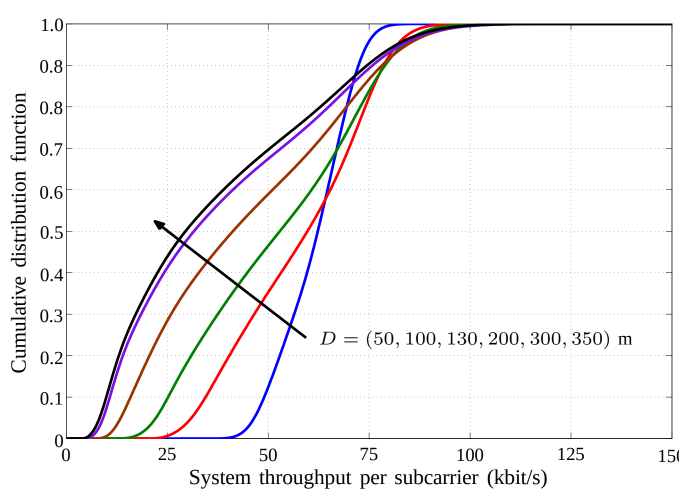

Fig. 4: Distribution of the system throughput per subcarrier for homogeneous micro deployment strategies.

This document is a preprint of: F. Richter and G. Fettweis, “Cellular Mobile Network Densification Utilizing Micro Base Stations,” in Proceedings of IEEE International Conference on Communications (ICC 2010), Cape Town, South Africa, May 2010. DOI:10.1109/ICC.2010.5502299

performance of pure micro networks compared to pure macro deployments with regard to the ratio of area throughput and area power consumption. High performance regarding (10) is also achieved by heterogeneous deployments due to their significant increase of system throughput and comparably low increase in power consumption due to the manageable number of additional low power consuming micro sites. Eventually, we can state that a high spatial reuse contributes significantly to a small cost-benefit ratio described by (10) for cellular networks.

A comparison of pure macro and heterogeneous scenarios yields that the introduction of micro sites in a macro network is beneficial since the increase in system throughput is larger than the increase in power consumption. Our example provides further that this gain gets smaller with each additional micro site.

However, a fair comparison using this metric should be based on deployment strategies having some performance indicators in common, e.g., power consumption figures feasible subject to some maximal power consumption specifications or a system throughput in a predefined domain. Clearly, the scenarios studied in this paper vary significantly regarding both throughput and power consumption capabilities. Hence, they should not be evaluated on the same level with respect to the metric Q. For instance, the smaller the inter site distance, the smaller the number of users requesting data within a cell and, thus, the higher the number of resources available for the users. Indeed, users are not capable of processing data rates larger than a certain threshold or users are not interested in them at all. That is, a high throughput can be provided but is not called on in total, resulting in an inefficiently working network.

Note that the metric (10) itself is not sufficient for evaluating a network’s performance. Since it is the ratio of throughput and power consumption, it provides no information about actually achievable throughput and power consumption figures. Nevertheless, it can be applied as an objective for power consumption minimization problems under throughput constraints.

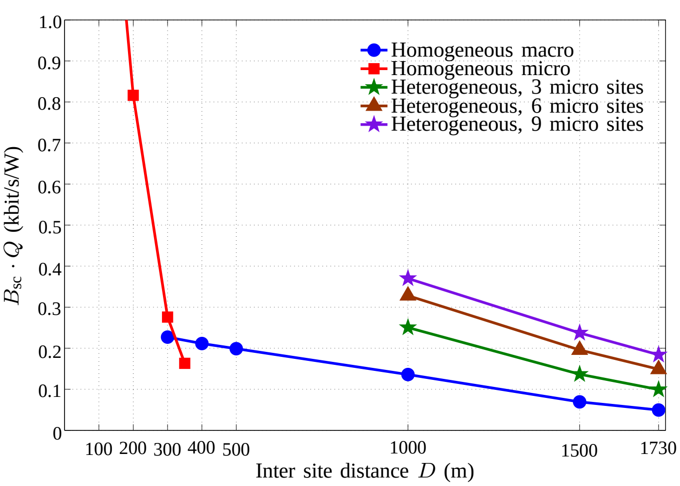

Fig. 5: System throughput per subcarrier per consumed power.

IV. Summary and Conclusions

In this paper the densification of cellular networks with respect to different deployment strategies including pure micro and macro as well as heterogeneous networks was investigated. Concerning system throughput figures, a densification to a certain degree is beneficial, whereas homogeneous micro deployments can be regarded to be superior. From energy perspective, deploying simply micro sites results in significantly higher area power consumption figures, thus being not of much interest.

We also introduced the measure of system throughput achievable per power spent in the network, which is highest for homogeneous micro networks, followed by heterogeneous networks’ throughput figures. As a conclusion, a network densification using both macro and micro base stations is in each sense to be preferred compared to homogeneous deployment strategies due to several reasons. Among them, the allocation of suitable locations for micro base stations, which might proof difficult for sufficiently many micro sites to be placed in a network.

The presented results are based on full load conditions for each network regardless the individual cell sizes. More meaningful results should be obtained when considering the different networks under varying traffic conditions, e.g., using different user densities. In praxis, the irregular shape, e.g., of urban areas, prevents from deploying hexagonal-like networks. Hence, the simple models and concepts presented in this paper should be translated to real scenarios, e.g., the downtown of a typical European city.

References

[1] McKinsey & Company, “The impact of ICT on global emissions,” on behalf of the Global eSustainability Initiative (GeSI), Tech. Rep., November 2007.

[2] G. P. Fettweis and E. Zimmermann, “ICT energy consumption - trends and challenges,” in *Proceedings of the 11th International Symposium on Wireless Personal Multimedia Communications*, Lapland, Finland, September 2008.

[3] Ericsson, “Sustainable energy use in mobile communications,” August 2007, White paper.

[4] S. Hanly and R. Mathar, “On the optimal base-station density for CDMA cellular networks,” *IEEE Trans. Commun.*, vol. 50, no. 8, pp. 1274–1281, Aug. 2002.

[5] F. Richter, A. J. Fehske, and G. P. Fettweis, “Energy efficiency aspects of base station deployment strategies in cellular networks,” in *Proceedings of the 70th Vehicular Technology Conference (VTC Fall)*, Anchorage, USA, September 2009.

[6] K. Johansson, “Cost effective deployment strategies for heterogeneous wireless networks,” Ph.D. dissertation, KTH Information and Communication Technology, Stockholm, Sweden, November 2007.

[7] A. J. Fehske, F. Richter, and G. P. Fettweis, “Energy efficiency improvements through micro sites in cellular mobile radio networks,” in *Proceedings of the 2nd International Workshop on Green Communications*, Honolulu, USA, Dezember 2009.

[8] O. Arnold, F. Richter, G. Fettweis, and O. Blume, “Power consumption modeling of different base station types in heterogeneous cellular networks,” in *Proc. of 19th Future Network & MobileSummit 2010*, Florence, Italy, June 2010, submitted.

[9] A. Corliano and M. Hufschmid, “Energieverbrauch der mobilen kommunikation,” Bundesamt für Energie, Ittigen, Switzerland, Tech. Rep., February 2008, in German.

[10] Technical Specification Group Radio Access Network, “TR 36.814 - Further Advancements for E-UTRA: Physical Layer Aspects (Release 9),” 3rd Generation Partnership Project, Tech. Rep., 2009.