Energy Efficiency Gains in Interference-limited Heterogeneous Cellular Mobile Radio Networks with Random Micro Site Deployment

Henrik Klessig, Albrecht J. Fehske, and Gerhard P. Fettweis
Vodafone Stiftungslehrstuhl, Technische Universität Dresden
Email: {henrik.klessig, albrecht.fehske, fettweis}@ifn.et.tu-dresden.de

***Abstract*—Energy efficiency considerations recently gained attention due to ecological aspects, that is to say lowering CO_2 emissions and reducing energy consumption. Furthermore, it is important to assess energy efficiency improvements from an operator's point of view, since energy costs are increasing and providing ubiquitous high speed mobile access may scale up the operators' operational expenditure. One of two promising approaches to enhance a network's operation regarding energy efficiency is to utilize smaller micro cells within one large macro cell. Another approach is to regard macro base stations as coverage providers for areas in between micro cells, while reducing their maximum transmit powers to a minimum. In this paper we investigate on the energy efficiency of a heterogeneous OFDM-based mobile network in the downlink taking into account the co-channel interference based on varying traffic demand per area. Furthermore, we carry out an assessment of potential energy savings of the two approaches mentioned above. For a sufficiently large traffic demand, increasing deployment densitiy through additional micro sites may maximize a network's energy efficiency. In that case the network operates at a load of less than 50 %. Moreover, a further gain of energy efficiency of about 20 % can be achieved due to macro site transmit power reduction while still providing coverage.**

I. Introduction

Over the last few years a significant change in the use of the internet could be recognized. It not only provides information but also serves as a main medium for communication, i. e., instant messaging, email, voice over internet protocol (VoIP), video streams and video calls. The consumers' mobility and further technical improvements lead to an annual increase of the amount of transferred data in mobile communications systems of about 400 % to 800 % [1]. This induces an increase in energy consumption of mobile communications systems of about 16 % to 20 % per year, which corresponds to a doubling every four or five years [2]. 80 % of electricity consumption of a mobile radio communication network originates in its radio access network, i. e., its base stations (BS); the consumption by base stations and its backhaul networks amounts to 60 billion kWh corresponding to 60 million households [2].

In conjunction with high consumption of energy also a large amount of CO_2 emissions can be observed. ICT systems had a share of 2 % of global CO_2 emissions already in 2007, which is equivalent to the total CO_2 emissions caused by the international air traffic [2]. Due to these aspects it is important to address the mobile systems' energy efficiency.

Since the largest part of power consumed by a network can be attributed to the base stations, one approach is to optimize its hardware components and radio interface techniques in order to enhance energy efficiency. Another way is regarding the whole network, e. g. deployment strategies like cell mixes or relays, network management algorithms, or radio resource management. In terms of cell mixes, i. e., heterogeneous networks, in [3] and [4] analyses with a certain number of micro sites at the macro cells' edges were made while assuming full buffer traffic models and scaling the deployment density by varying the inter site distance.

In this paper we extend these models by a random placement of a varying amount of micro sites within a macro cell leading to a specific deployment density at a constant inter site distance. Furthermore, we introduce a traffic model that allows to investigate on the network energy efficiency of non-full load scenarios and hot spot scenarios as well. Analyzing hierarchial cellular network structures in [5] it has been stated that large macro overlay cells cause strong interference due to their large transmit power. In this paper we also investigate on this issue in more detail by analyzing the impact of macro site transmit power reduction on energy efficiency and spectral efficiency as well.

The remainder of the paper is organized as follows. In section II system, traffic, and base station models are introduced. Section III presents receiving conditions and energy efficiency metrics based on the traffic model. In section IV increased deployment density and macro site power reduction are evaluated and section V concludes the paper.

In the following the notations $\mathbb{E}$ and $\cup$ are used to denote the expectation and union operator, respectively.

II. System Model

A. Topology

We assume the network to be modeled as a regular grid of macro sites with inter site distance D leading to a hexagonal macro cell layout as depicted in Fig. 1. We consider the macro sites to be three-fold sectorized. Due to symmetry of the network model, we restrict our evaluation to a reference area corresponding to the serving area of one macro site, illustrated as the grey shaded area $\mathcal{A}$ in Fig. 1. Its size can be calculated by

$$|\mathcal{A}| = \frac{\sqrt{3}}{2} \cdot D^2. \tag{1}$$

978-1-61284-680-4/11/$26.00 ©2011 IEEE

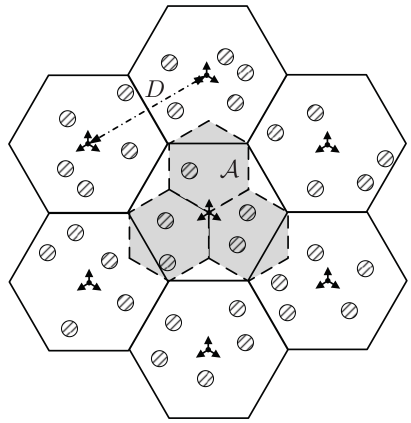

Fig. 1. Hexagonal macro cell layout with inter site distance D, cell area $|\mathcal{A}|$, and five additional randomly placed micro sites within each macro cell.

TABLE I
OVERVIEW OF 3GPP PATH LOSS MODELS [6] AND ADDITIONAL LOSSES

Path Loss Model	**σ [dB]**	**$\hat{\Psi}$ [dB]**
UMa, LOS	4	1.84
UMa, NLOS	6	4.15
UMi, LOS	3	1.04
UMi, NLOS	4	1.84
Line of Sight Probabilities for UMa and UMi		
$p_{\text{los, UMa}} = \min\left\{\frac{18}{d}, 1\right\} \cdot \left(1 - e^{-d/63}\right) + e^{-d/63}$		
$p_{\text{los, UMi}} = \min\left\{\frac{18}{d}, 1\right\} \cdot \left(1 - e^{-d/36}\right) + e^{-d/36}$		
Other Losses		**[dB]**
Indoor penetration loss [7]		20
Intra site interference margin [7]		−3
Rayleigh fading margin [7]		2
Base station noise figure [8]		5
User equipment noise figure [8]		9
Diversity gain through multiple antennas [7]		−3

To further obtain a heterogeneous network we randomly place a certain number of micro sites N_{mi} within each macro site cell area. According to [6], the minimum distance between macro and micro sites is determined to be 75 m and among micro sites 40 m. Since a mobile can only be served by one BS, macro and micro cell areas are disjoint and the overall cell area can be written as

$$\mathcal{A} = \left(\bigcup_{i=1}^{3} \mathcal{A}_{\text{ma},i}\right) \cup \left(\bigcup_{i=1}^{N_{\text{mi}}} \mathcal{A}_{\text{mi},i}\right), \tag{2}$$

where $\mathcal{A}_{\text{ma},i}$ and $\mathcal{A}_{\text{mi},i}$ denote the macro sector and micro cell areas, respectively.

B. Propagation Model

The link budget describes the amount of all losses between the transceiver of a BS and the receiver of a mobile, or more generally of the user equipment (UE). Let P_{tx} and P_{rx} denote transmit and receive power in dBm, respectively. Their relation is given by

$$P_{\text{rx}} = P_{\text{tx}} - A_{\text{ant}} - \bar{L} - \bar{\Psi} - B, \tag{3}$$

where A_{ant}, $\bar{L}$, $\bar{\Psi}$, and B denote losses due to antenna characteristics, mean path loss, mean shadow fading loss, and other losses in dB, respectively.
The model of the macro sites' directional antennas is assumed to be a two-dimensional horizontal pattern. Its analytical description can be found in [6]. In contrast to directional macro site antennas, micro sites are characterized by omnidirectional antennas with a gain of 5 dBi [6].
In general, different path loss models are provided to distinguish between macro and micro cell propagation conditions due to their different antenna heights, coverage ranges, shadow fading processes, and line of sight (LOS) probabilities. For system level simulations 3GPP path loss models are used, as provided in [6]. Table I gives an overview of the models, standard deviations σ of the lognormal shadowing processes, and LOS probabilities depending on the distance d between the BS's and UE's antennas. LOS and non-line of sight (NLOS) path losses are weighted by their probabilites according to Eq. (4) to obtain a path loss that is independent of a LOS random process. Simulation results show that this is a good approximation of averaging over many LOS realizations.

$$\bar{L}(d) = -10 \cdot \log_{10}\left(p_{\text{los}}(d) \cdot 10^{\frac{-L_{\text{los}}}{10}} + p_{\text{nlos}}(d) \cdot 10^{\frac{-L_{\text{nlos}}}{10}}\right) \tag{4}$$

The probability of NLOS is given by $p_{\text{nlos}}(d) = (1 - p_{\text{los}}(d))$. Since the standard deviation σ of the lognormal shadowing process is known, its expected attenuation in dB can be calculated by

$$\hat{\Psi} = \mathbb{E}\left[\Psi\right] = 10 \cdot \log_{10}\left(e^{\frac{\left(\frac{\ln 10}{10} \cdot \sigma\right)^2}{2}}\right). \tag{5}$$

A distance dependent mean of the shadow fading can be approximated similarly to Eq. (4) by

$$\bar{\Psi}(d) = -10 \cdot \log_{10}\left(p_{\text{los}}(d) \cdot 10^{\frac{-\hat{\Psi}_{\text{los}}}{10}} + p_{\text{nlos}}(d) \cdot 10^{\frac{-\hat{\Psi}_{\text{nlos}}}{10}}\right). \tag{6}$$

All other additional losses are also listed in Table I.

C. Traffic Model and Sector Load Estimation

The aim of assessing the load of a sector in terms of utilized resources is to provide an estimation of the co-channel interference by surrounding BSs. Therefore, the following assumptions are made. For a specific snapshot we consider a fixed reference traffic demand generated in the overall cell area $\mathcal{A}$ denoted by T. Furthermore, we assume all the sectors, especially micro cells, to have the same traffic demand, which, in addition, is equally distributed over the area of the individual sectors. The traffic demand per sector in bps is then modeled both for macro sectors and micro cells by

$$T_{\text{sec}} = \frac{T}{3 + N_{\text{mi}}}. \tag{7}$$

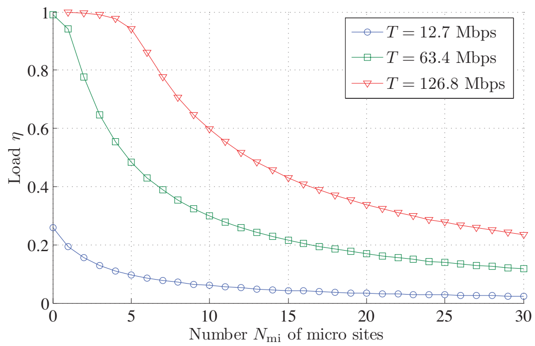

Fig. 2. Load η of the base stations as a function of deployment density given by N_{mi} for varying mean traffic density $\frac{T}{|\mathcal{A}|}$ and fixed $D = 1$ km.

It is important to note that we model the average traffic load to be equal for macro and micro BSs. Since the coverage area of micro BSs is much smaller than that of macro BSs, this implies inhomogeneous spatial distribution of traffic with higher densities around the micro sites.
Based on a Long Term Evolution (LTE) 5 MHz system according to [9] we assume m physical resource blocks (PRBs) to be the available schedulable units per transmission time interval (TTI) of 1 ms. We further define the traffic demand in PRBs for every sector as

$$A = \frac{T_{\text{sec}}}{T_{\text{max}}} \cdot m, \tag{8}$$

where T_{max} denotes the maximum achievable data rate at a fixed mean modulation and coding scheme. By assuming the arrival and allocation of PRBs to be characterized as a Poisson process, the actual number of utilized PRBs is Erlang distributed. The probability of exactly κ PRBs scheduled amounts to

$$p_{\text{Erl}}(\kappa) = \frac{\frac{A^\kappa}{\kappa!}}{\sum_{i=0}^{m} \frac{A^i}{i!}}. \tag{9}$$

Its expectation value normalized to the total number m of PRBs is then defined as the load of the sector

$$\eta = \frac{A}{m} \cdot (1 - p_{\text{Erl}}(m)) \ , \quad \eta \in [0, 1] \, . \tag{10}$$

Note that the load η is a function of inter site distance D, deployment density characterized by N_{mi}, and mean traffic density $\frac{T}{|\mathcal{A}|}$. Fig. 2 depicts the load as a function of deployment density for varying traffic demand.
It is important to mention that scheduling of PRBs is performed according to the mean modulation and coding scheme and the traffic demand. The actual throughput calculation according to the signal to interference and noise ratio (SINR) is described in section III.

D. Base Station Power Models

To assess the energy efficiency of the network the energy consumption of each BS has to be evaluated. Therefore, power models are needed, that characterize each type of BS individually. Since micro sites are utilized to cover only small areas with radii of around 100 m, their transmit power is only a fraction of the macro sites'. In [10] appropriate power models are provided, that we use here in a modified version. They can be described by

$$P_{\text{ma}}(\eta) = 3 \cdot N_{\text{ant}} \cdot (\eta \cdot a_{\text{ma}} \cdot P_{\text{tx,ma}} + b_{\text{ma}}) \quad \text{and} \tag{11}$$

$$P_{\text{mi}}(\eta) = \eta \cdot a_{\text{mi}} \cdot P_{\text{tx,mi}} + b_{\text{mi}} + \eta \cdot c_{\text{mi}}. \tag{12}$$

The variables N_{ant}, $P_{\text{tx,ma}}$, and $P_{\text{tx,mi}}$ denote the number of transmit antennas of a macro sector's BS and the maximum transmit powers of macro and micro BSs, respectively. a_{ma} models the maximum transmit power dependent energy consumption of the power amplifier, cooling, feeder losses, and power supply, b_{ma} summarizes transmit power independent components such as signal processing, battery backup, and also parts of the cooling unit. a_{mi} and b_{mi} are modeled according to the macro site's parameters, except that cooling is omitted [10]. Furthermore, c_{mi} models additional components, the power consumption of which scales with the actual load. In contrast to [10] we model the macro BS power consumption to be linearly dependent on the load η. Table II gives a more precise insight into the parameters. The total power consumption of all the BSs within the overall cell area $\mathcal{A}$ can then be calculated by

$$P(\eta) = P_{\text{ma}}(\eta) + N_{\text{mi}} \cdot P_{\text{mi}}(\eta). \tag{13}$$

TABLE II
BASE STATION POWER MODEL PARAMETERS

Macro Site		**Micro Site**	
a_{ma}	3.77	a_{mi}	1.11
b_{ma}	68.73 W	b_{mi}	26.59 W
N_{ant}	2	c_{mi}	15.26 W
$P_{\text{tx, ma}}$	20 W or variable	$P_{\text{tx, mi}}$	2 W

III. Energy Efficiency Evaluation

A. Receiving and Coverage Conditions

In the following we provide an estimate of the signal to interference and noise ratio (SINR) seen by the mobile at a certain position $(x, y) \in \mathcal{A}$ with respect to a BS indicated by i. For this purpose we introduce the random vector $\mathbf{H} = (H_1, \cdots, H_j, \cdots, H_n)^T$, the elements H_j of which have the value one if another BS indicated by j causes interference on a specific resource, i. e., PRB, used by the mobile and BS i for data transmission. Otherwise, the vector elements have the value zero. The SINR is then given by

$$\gamma_i(x, y, \mathbf{H}) = \frac{P_{\text{rx},i}(x, y)}{\sum_{j \neq i} P_{\text{rx},j}(x, y) \cdot H_j + N_0}. \tag{14}$$

Moreover, we assume that scheduling of users is based on a Round Robin algorithm and scheduling of PRBs is done randomly, i. e., each PRB has the same probability of being scheduled. Yet every sector is supposed to have the same load the expectation values of the random variables H_j are equivalent to the load, i. e., $\mathbb{E}(H_j) = \eta$, $\forall j$. By the concavity

TABLE III
LTE SPECIFICATIONS

LTE system parameters	
Carrier frequency	2.0 GHz
Bandwidth	5 MHz
Subcarrier spacing B_{sc}	15 kHz
# Subcarriers N_{sc}	300
# Total physical resource blocks m	25
User equipment parameters	
Thermal noise	-174 dBm/Hz
Receiver sensitivity per subcarrier	-120 dBm

of the function $\gamma_i(x, y, \mathbf{H})$ in $\mathbf{H}$ and Jensen's inequality it can be shown that there is a lower bound for the expected SINR [11], i. e.,

$$\mathbb{E}_{\mathbf{H}}\left(\gamma_i(x,y,\mathbf{H})\right) \geq \frac{P_{\text{rx},i}(x,y)}{\eta \cdot \sum\limits_{j \neq i} P_{\text{rx},j}(x,y) + N_0} =: \check{\gamma}_i(x,y,\eta). \tag{15}$$

In the following we will use the lower bound $\check{\gamma}_i(x, y, \eta)$ for further evaluation of the system performance. We define the area where a UE is served as

$$\mathcal{A}_{\text{c}} := \left\{(x,y) \,|P_{\text{rx}}(x,y) \geq P_{\text{rx,min}} \wedge \check{\gamma}_i(x,y,\eta) \geq 1\right\}, \tag{16}$$

i. e., a minimum receive power $P_{\text{rx,min}}$ based on the UEs' receiver sensitivity given in table III and a minimum SINR are required to detect the signal and to provide a minimum quality of service, respectively. The coverage is then given by $C = \frac{|\mathcal{A}_{\text{c}}|}{|\mathcal{A}|}$.

It can be shown by simulation that there is a maximum load $\eta < 1$ where coverage of 95 % can barely be achieved due to too much interference caused by surrounding BSs. Since the load is increasing with a higher inter site distance, higher traffic demand, and smaller deployment densities there are constellations of the variables D, T, and N_{mi} where the coverage condition cannot be fulfilled. This will be investigated in section IV as well.

B. Energy Efficiency Metrics

To analyze the network in terms of energy efficiency at least one appropriate metric has to be defined. Based on the lower bound of the SINR seen by a UE at the location (x, y) and Shannon's law the spectral efficiency is given by

$$\check{S}(x,y,\eta) = \min\left\{\log_2\left(1 + \check{\gamma}(x,y,\eta)\right),\ 6\right\}. \tag{17}$$

Similarly to Eq. (15) it can be shown that this is a lower bound for the expected value of the spectral efficiency as a function of the random vector $\mathbf{H}$ instead of η [11]. The upper bound of six bits per second per Hertz is given by LTE's highest modulation scheme 64-QAM (quadrature amplitude modulation).

With the assumptions made in section II-C we are able to calculate the actual throughput of the reference area $\mathcal{A}$ by the sum of the rates achieved in the individual sectors

$$T_{\text{eff}} = \eta \cdot B_{\text{sc}} \cdot N_{\text{sc}} \cdot \left(\sum_{i=1}^{3} \bar{S}_{\mathcal{A}_{\text{ma},i}} + \sum_{i=1}^{N_{\text{mi}}} \bar{S}_{\mathcal{A}_{\text{mi},i}}\right), \tag{18}$$

where B_{sc}, N_{sc}, $\bar{S}_{\mathcal{A}_{\text{ma},i}}$, and $\bar{S}_{\mathcal{A}_{\text{mi},i}}$ denote the subcarrier bandwidth spacing, the total number of subcarriers, and the spectral efficiencies averaged over the macro sector and micro cell areas, respectively.

Finally, we define the energy efficiency as the ratio of cell throughput and total power consumption, also referred to as information per energy metric, by

$$E = \frac{T_{\text{eff}}}{P}. \tag{19}$$

The energy efficiency metric is measured in bits per Joule.

IV. NUMERICAL RESULTS

A. Simulation Setup

For system level simulations we apply a reference macro cell with two tiers of surrounding macro sites leading to 57 macro sectors. We keep the inter site distance constant at $D = 1$ km, thus the deployment density is only scaled by the number of micro sites placed, which is set to a value between one and sixty. Due to the random placement an averaging of the overall energy efficiency has to be performed. 100 micro site placement realizations are averaged to obtain reproducible results. We further consider three different values for the reference cell traffic demand $T \in \{12.7, 63.4, 126.8\}$ Mbps representing low, medium, and high traffic demand. In every case a minimum coverage of 95 % is intented to be achieved. We consider two ways of adjusting the maximum macro BS transmit power. In the first case it is kept constant at $P_{\text{tx,ma}} = 20$ W, in the second it is incrementally increased with an upper limit of 20 W until the coverage condition is fulfilled. Network energy efficiency both with constant and variable maximum transmit power at the macro sites' BSs is investigated in the following.

B. Load Compensation by Higher Deployment Density

Energy efficiency curves for varying traffic demand are depicted in Fig. 3. For high traffic demand and low deployment density the network operates at very low energy efficiency due to a load η of approx. one (see Fig. 2) resulting in a coverage less than 90 %. Adding micro sites increases capacity and, therefore, more of the traffic demand can be satisfied, thus energy efficiency increases almost linearly. The coverage condition is fulfilled for a load less than 60 % or $N_{\text{mi}} \geq 3$ and $N_{\text{mi}} \geq 10$ for medium and high traffic demand, respectively. An additional increase in efficiency can be observed by adding more micro sites leading to a maximum. This is due to an improvement of spectral efficiency by a more equal spatial distribution of the load, which means that increasing deployment density and, therefore, reducing the load of the individual base stations improves the SINR conditions within the reference cell area although there are more interferers. Fig. 4 illustrates these gains for high traffic demand. Nevertheless, for higher deployment densities energy efficiency decreases because the gain in spectral efficiency does not compensate for the additional power consumed.

In other words, switching off micro sites and, therefore,

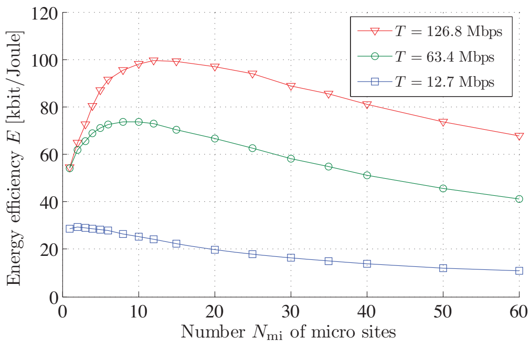

Fig. 3. Network energy efficiency E as a function of deployment density given by N_{mi} for varying traffic demand T.

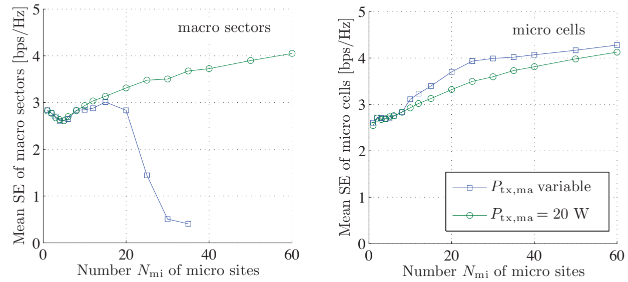

Fig. 4. Comparison of mean spectral efficiencies of macro sectors and micro cells both for constant and varying macro BS transmit power $P_{\mathrm{tx,ma}}$ for high traffic demand $T = 126.8$ Mbps.

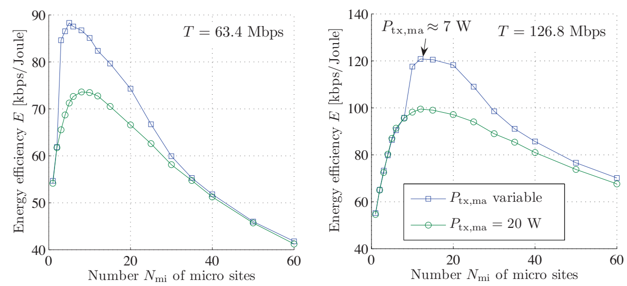

Fig. 5. Comparison of network energy efficiency with and without macro BS transmit power reduction both for medium and high traffic demand T.

shifting the load to other base stations only improves network energy efficiency if the resulting load of the residual base stations does not exceed a certain value, in our cases 30 % and 50 % for medium and high traffic demand, respectively. Otherwise, it would cause a degradation in spectral efficiency and coverage leading to worse energy efficiency.
Furthermore, for low traffic situations only a slight load compensation can be achieved through additional micro sites; therefore, energy efficiency gains can hardly be recognized.

C. Macro Site Transmit Power Reduction

The comparison of the network energy efficiencies in Fig. 5 reveals that both for medium and high traffic demand an energy efficiency gain of approx. 20 % can be achieved adopting the coverage adaptive transmit power adjustment at the macro site. In that case the power is reduced to approx. $P_{\text{tx, ma}} \approx 7$ W at the energy efficiency maximums and is being reduced incrementally to less than 2 W for $N_{\mathrm{mi}} > 30$. From that point on the macro BS acts like a micro BS in terms of radiated power and its sectors are completely displaced by micro cells for higher deployment densities.
The tradeoff here is that the transmit power reduction leads to a better spectral efficiency within the micro cells due to less interference but this implies that the micro sites cause more interference within the area served by the macro site, which can be seen in Fig. 4. It is also worth mentioning that compared to the static transmit power approach the network efficiency maximum is shifted to a lower deployment densitiy for medium traffic.
Regarding the overall system performance, an increase in reference area throughput can be observed, although the macro sectors' mean spectral efficiency drastically degradates when reducing the macro BSs' transmit power. The reason is that for high micro site densities most traffic is generated in the micro cells, which exhibit increased mean spectral efficiencies. In fact, the macro site then acts as a coverage provider in the areas in between micro cells with reduced spectral efficiency; nevertheless, the whole network operates more efficiently.

V. Conclusions

We investigated on the impact of random micro site deployment with varying density on the energy efficiency of cellular radio networks. We further introduced a traffic model that allows to take into account the co-channel interference and non-full load scenarios. It could be observed that for high traffic demand twelve micro sites double the network energy efficiency by enhancing the area spectral efficiency. We also considered to adjust the macro site transmit power to fulfill the coverage condition of 95 %. This leads to a significant efficiency gain of about 20 %, however, the macro site then only serves as a low data rate coverage provider in the areas in between micro cells.

Acknowledgment

This work was supported in part by European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 247733.

References

[1] I. Howard, "The mobile internet transformation," December 2008.
[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, Finnland, September 2008.
[3] F. Richter, A. J. Fehske, and G. P. Fettweis, "Energy efficiency aspects of base station deployment strategies for cellular networks," in *Proc. IEEE 70th Vehicular Technology Conf. Fall (VTC 2009-Fall)*, 2009, pp. 1–5.
[4] F. Richter and G. Fettweis, "Cellular mobile network densification utilizing micro base stations," in *Proc. IEEE Int Communications (ICC) Conf*, 2010, pp. 1–6.

[5] Y. Liang, A. Goldsmith, G. Foschini, R. Valenzuela, and D. Chizhik, "Evolution of base stations in cellular networks: Denser deployment versus coordination," in *Proc. IEEE Int. Conf. Communications ICC '08*, 2008, pp. 4128–4132.

[6] Technical Specification Group Radio Access Network, "TR 36.814 v9.0.0 - Evolved Universal Terrestrial Radio Access (E-UTRA) - Further advancements for E-UTRA: Physical layer aspects," 3rd Generation Partnership Project, Tech. Rep., 2010.

[7] A. J. Fehske, F. Richter, and G. P. Fettweis, "Energy efficiency improvements through micro sites in cellular mobile radio networks," in *Proc. IEEE GLOBECOM Workshops*, 2009, pp. 1–5.

[8] Technical Specification Group Radio Access Network, "TR 36.942 v9.0.1 - Evolved Universal Terrestrial Radio Access (E-UTRA) - Radio frequency (RF) system scenarios," 3rd Generation Partnership Project, Tech. Rep., 2010.

[9] ——, "TS 36.211 v9.1.0 - Evolved Universal Terrestrial Radio Access (E-UTRA) - Physical channels and modulation," 3rd Generation Partnership Project, Tech. Rep., 2010.

[10] F. Richter, A. J. Fehske, P. Marsch, and G. P. Fettweis, "Traffic demand and energy efficiency in heterogeneous cellular mobile radio networks," in *Proc. IEEE 71st Vehicular Technology Conf. (VTC 2010-Spring)*, 2010, pp. 1–6.

[11] H. Klessig, "Untersuchungen des einflusses von standortdichten und 6-fach sektorisierung auf energieeffizienz von mobilfunknetzen." Student thesis, November 2010.