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Power Consumption Modeling of Different Base Station Types in Heterogeneous Cellular Networks

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Abstract: In wireless communications micro cells are potentially more energy efficient than conventional macro cells due to the high path loss exponent. Also, heterogeneous deployments of both cell types can be used to optimize the energy efficiency. Energy efficiency of any deployment is impacted by the power consumption of each individual network element and the dependency of transmit power and load. In this paper we developed such power models for macro and micro base stations relying on data sheets of several GSM and UMTS base stations with focus on component level, e.g., power amplifier and cooling equipment. In a first application of the model a traditional macro cell deployment and a heterogeneous deployment are compared.

Keywords: Power consumption, power model, power amplifier, heterogeneous networks, energy efficiency, area power consumption, micro base station, macro base station

1. Introduction

The global information and communication technology (ICT) industry is a fast growing contributor to the world wide greenhouse gas emissions, currently it has a footprint of about 2% [1]. Within ICT, the mobile communications sector today has a rather small share [2], but a significant increase can be expected in the near future. An increase of the global number of mobile subscribers will increase the energy consumption of the networks. Further, it can be expected that new technologies for mobile internet access such as netbooks and laptops with mobile broadband card will transfer fixed internet traffic to mobile radio networks. An increase in world wide mobile data and internet traffic per month from 70 petabytes in 2008 to 1250 petabytes in 2012 is forecast [3].

Only recently, the European Union Commission called on ICT industry to intensify their ambitions to reduce its carbon footprint by about 20% already by 2015 and to improve energy efficiency of the networks. The main contributor to greenhouse gas emissions caused by radio networks originates from the radio access network, more precisely from the base stations. There are in principal two way to reduce energy wasting: by energy aware components in the base stations and by energy aware network deployment strategies, effectively minimizing idle capacity of base stations. In order to quantify gains achieved by employing energy aware techniques in network planning, an

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appropriate energy efficiency metric must be defined. One important figure of merit is the energy consumption of a network. In this work the electrical input power of macro and micro base stations in cellular mobile radio networks is characterized and quantified in dependence of the load level. The model parameters are derived according to values found in literature and by interviewing experts. With this, the power consumption of heterogeneous systems can be determined with different mixes of macro and micro base stations.

The remainder of the paper is organized as follows. In Section 2 some general remarks, assumptions, and insights are given. The power consumption model for macro base stations is introduced, followed by the power consumption model for micro base stations. In Section 3 the parameters of the two power models are qualified. In Section 4 some applications of the power models are provided. Section 5 concludes the paper.

2. Power Model

The main goal of the power consumption model we describe in this paper is to make realistic input parameters available for the simulation of total network power consumption in mobile communication networks and to compare different heterogeneous cell deployments. In Table 1 the main parameters are summarized. It can be seen that this set of parameters determines the input values for a network architecture only, i.e., further parameters are required. These additional parameters are fixed for each simulation and are determined by the technology, environmental conditions which are important for cooling, etc..

The power consumption of a base station consists of two parts, modeled concurrently. The first part describes the static power consumption, a power figure which is consumed already in an empty base station. Depending on the load situation, a dynamic power consumption part adds to the static power.

In this paper we derive a power model for typical base stations as deployed today. These provide a relative small dynamic contribution to power consumption and the optimum cell size is strongly affected by the static part. We will compare the result to today's macro cell deployment.

In the future, base stations will become more energy efficient. The items with the highest impact on a base station's power consumption are the following: utilization of remote radio heads or ordinary power amplifiers with corresponding feeder losses, different kinds of cooling (air conditioning, air circulation, or free cooling), site sharing (especially regarding infrastructure), and number of carrier frequencies. It can be expected that the average power consumption requirement per bit decreases in the following years due to new technologies. For instance, the introduction of the gallium nitride power amplifier at the end of 2010 is expected.

2.1 Assumptions

The power consumption of a base station varies over time. Several modes can be distinguished. Therefore, the power consumption depends on the mode of the base station (finite state machine). A base station can be in an operational or in a non-operational state. Furthermore, in an operational state different conditions can be distinguished, e.g., a low traffic and a peak traffic mode are available. Between all states a transition time is needed to reach the new state, e.g., the power-on of a base station needs a dedicated amount of time and energy. If the accumulated time in a

Table 1: Linear power model parameters

Parameter	Description	Parameter	Description
N_{Sector}	# sectors	N_{PApSec}	# PAs per sector
P_{TX}	Tx power	μ_{PA}	PA efficiency
P_{SP}	Signal processing overhead	C_{C}	Cooling loss
C_{PSBB}	Battery backup and power supply loss		

dedicated mode is larger than all transition times, which we assume for our modeling, then these transition times can be disregarded. For ease of modeling all transition states are omitted. The timing behavior of a base station is illustrated in Figure 1.

In all scenarios the backhaul requirements are considered to be similar and to scale with the user density, where the backhaul is assumed to be power neutral among the scenarios. We are aware that the backhaul is interesting from the OPEX point of view (rental, wired vs. wireless). Nevertheless, the backhaul aspect is not considered in this evaluation due to the focus on the technical aspect.

2.2 *Components*

Power Amplifier The power amplifier (PA) is expected to work in a state in which the peak value of the signal corresponds with the possible peak power of the PA. Thus, the efficiency can be maximized. Doherty and Gallium nitride (GaN) PAs have the potential to improve the efficiency. They are especially suited for LTE with its high crest factor compared to GSM, where a constant envelope modulation technique is employed (Gaussian Minimum Shift Keying: GMSK). In the following we refer to the ratio of transmit power to direct current input power when speaking of power amplifier efficiency.

Signal Processing UMTS signals are much more complex than GSM signals regarding the signal processing on transmitter and receiver side, whereas LTE signals are even more complex. Thus, the signal processing per link is substantially increased.

A/D Converter An A/D converter consumes less than 5% of a macro base station's input power. Thus, it is not regarded and assumed to be included in the signal processing part.

Antenna The Antenna gain is included in the link budget. It is not explicitly modeled in this section.

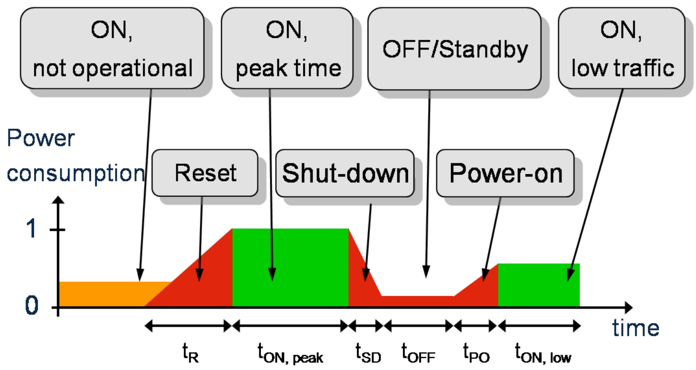

Figure 1: Timing behavior of base stations

Feeder The feeder loss is about 3 dB in a macro base station. It is included in the link budget as well. Thus, it will not be regarded in the power consumption model.

Power Supply and Battery Backup The loss within these two components is typically between 10% and 15% and depends mainly on the employed technology. By using 10%, an optimistic value is assumed.

Cooling As stated before, cooling mainly depends on environmental conditions. Values between zero (free cooling) and 40% can be found.

2.3 *Macro Base Station Power Model*

In [4] measurements regarding the power consumption of deployed GSM and UMTS base stations are shown. The measurements were taken over a period of several days. It can be seen that the power consumption varies about 3% for a UMTS and 2% for a GSM base station over time. In contrast to that, the data traffic varies between no load and a peak load level. Due to the negligible amount of dynamic power, the power model of today's typical macro base station can be reduced to the static part. Base stations with dynamic power saving features have appeared only very recently [5] and are not yet wide spread in the networks.

The efficiency of a power amplifier on the input side is mainly determined by the applied modulation schemes and by its crest factor. For modeling the power consumption, the following formula is used:

$$P_{\text{BS,Macro}} = N_{\text{Sector}} \cdot N_{\text{PApSec}} \cdot \left(\frac{P_{\text{TX}}}{\mu_{\text{PA}}} + P_{\text{SP}} \right) \cdot (1 + C_{\text{C}}) \cdot (1 + C_{\text{PSBB}}) \ . \tag{1}$$

2.4 *Micro Base Station Power Model*

A micro base station is considered to consist of one sector containing one PA. The load varies between no load and full load, represented by 0 and 1, respectively. The power amplifier has a decreased efficiency compared to the PA of a macro base station. No pre-distortion is applied. A PA efficiency of 20% is assumed. Nevertheless, in comparison to the macro base station the absolute power consumption is reduced due to the smaller coverage area and thus much smaller transmit power requirement. The power consumption is of more dynamic nature, because for a small cell the number of users is statistically varying stronger and this makes it attractive to adapt the PA during a time period with lower load.

$$P_{\text{BS,Micro}} = P_{\text{static,Micro}} + P_{\text{dynamic,Micro}} \ . \tag{2}$$

It is assumed that the digital part scales according to the number of active links. Thus, the number of frequency and time slots will impact the power consumption of this part. In [6] a mobile WiMAX base station is described. It is stated, that the baseband card consumes 28% of the total power in typical cases and 32% in peak cases. The increase between typical and peak power consumption of the baseband card is 100%.

The digital baseband is the main contributor to the dynamic part of the power consumption of a micro base station. This is regarded in the power model by varying the power consumption according to the load. No battery backup is typically needed for micro base stations. The power supply loss is approximately 10% and depends on the technology. Air condition is not required for a micro base station. The several

Table 2: Micro base station power model parameters

Parameter	Description	Parameter	Description
$P_{\text{static,Micro}}$	Stat. power consumption	$P_{\text{dynamic,Micro}}$	Dyn. power consumption
P_{TX}	Max. tx power per PA	μ_{PA}	PA efficiency
N_{L}	# active links	$C_{\text{TX,static}}$	Stat. tx power
$C_{\text{TX,NL}}$	Dyn. tx power per link	$P_{\text{SP,static}}$	Stat. signal processing
$P_{\text{SP,NL}}$	Dyn. signal processing per link	C_{PS}	Power supply loss

parameters are listed in Table 2. Summarizing the properties of a micro base station, we can derive the formula for the static power consumption as

$$P_{\text{static,Micro}} = \left(\frac{P_{\text{TX}}}{\mu_{\text{PA}}} C_{\text{TX,static}} + P_{\text{SP,static}} \right) \cdot (1 + C_{\text{PS}}) \tag{3}$$

and for the dynamic power consumption by

$$P_{\text{dynamic,Micro}} = \left(\frac{P_{\text{TX}}}{\mu_{\text{PA}}} (1 - C_{\text{TX,static}}) \cdot C_{\text{TX,NL}} + P_{\text{SP,NL}} \right) \cdot N_{\text{L}} \cdot (1 + C_{\text{PS}}) \ . \tag{4}$$

3. Results

In [7] the power consumption figures on component level of UMTS and GSM base stations are compared, where each base station is considered to consist of three sectors. Firstly, a high capacity (six carrier frequencies per sector, GSM1) and a medium capacity (two carrier frequencies per sector, GSM2) GSM macro base station are compared. A power amplifier efficiency of 35% is given. Secondly, an UMTS base station with one carrier frequency per sector (UMTS1) and a power amplifier efficiency of 15% is considered. Another UMTS base station type is described in [8] with focus on component level. Three sectors are employed, each containing two carrier frequencies (UMTS2). Unfortunately, there is no statement about cooling. Thus, cooling is assumed to be 20%. By using the given values, an adaptation to the power model is possible. In Table 3 the parameter subset for the considered macro base stations are summarized.

In the application scenario LTE macro and micro base stations are used. The macro base station consists of three sectors, each containing two power amplifiers. The power amplifiers' efficiency is set to 38%. Considering the high crest factors of LTE, these PAs are assumed to work near their peak output values. For signal processing $P_{\text{SP}} = 58$ watt are assumed. Thus, signal processing is expected to be efficient. Cooling accounts for 20 percent ($C_{\text{C}} = 0.29$), power supply and battery backup amount to 10% ($C_{\text{PSBB}} = 0.11$). The transmit power is adapted to the required base station's coverage area. For instance, for macro cells with inter site distance of 1500 m the required transmit power is about 24 watt, yielding a total power of about 950 watt.

For the LTE micro base station one sector and one power amplifier is used. The PA has an efficiency of 20%. For the number of active links a maximum of 25 is assumed, which corresponds to employing a 5 MHz bandwidth LTE system with a FFT size of 512, resulting in 300 subcarriers and, thus, 25 resource blocks of 12 subcarriers each. Further values are: $C_{\text{TX,static}} = 0.8$, $C_{\text{TX,NL}} = 0.04$, $P_{\text{SP,static}} = 15$ watt, $P_{\text{SP,NL}} = 0.55$ watt, and $C_{\text{PS}} = 0.11$. Note that these figures are used in the following section.

Table 3: Macro base station power model parameters, adapted from [7] and [8]

	P_{BS}	N_{Sector}	N_{PApSec}	P_{TX}	μ_{PA}	P_{SP}	C_{C}	C_{PSBB}
GSM1	3700 W	3	6	40 W	35%	36.4 W	0.23	0.11
GSM2	1430 W	3	2	40 W	35%	54.8 W	0.27	0.11
UMTS1	1450 W	3	1	40 W	15%	73.5 W	0.28	0.11
UMTS2	1568 W	3	2	20 W	40%	127.7 W	0.29	0.14

As in the case of macro base stations, the transmit power is adapted to the base station's coverage area. For a cell size of 100 m a transmit power of about 2 watt is sufficient.

4. Application Scenarios

Considering transmit power figures only is not a suitable approach when the focus is on energy efficiency, especially for heterogeneous networks. It is obvious that any energy efficiency metric on radio network level should comprise a network's power consumption, which in turn depends on the transmit powers of each individual base station within the network. Now, the power models developed in this work allow for computing the total power consumption heterogeneous networks simply by summation of the power consumption figures of each macro and micro base station in the network, where the latter dynamically adjusts to the current traffic demand.

When an operator wants to provide services in a given area, the question arises how many base stations he should deploy in order to minimize the total power consumption, i.e., what is the optimal compromise between larger inter site distances, hence, less base stations with larger transmit powers, and shorter inter site distances yielding more base stations with smaller transmit power figures. In [9] the notion of area power consumption of a cellular network was introduced. It was shown that for a hexagonal deployment the area power consumption metric yields an optimal inter site distance. The proof is based on the fact that the path loss (and thus the transmit power) increases faster with the inter site distance (power of the the coefficient is larger than 2) than the covered area (power coefficient of 2). For small cells the static part of the power becomes dominant and this leads to a minimum in total network power consumption.

For visualization purposes consider a cellular network with macro base stations located on a hexagonal grid with a specific inter site distance. Further, let a micro base station be placed on each corner of the Voronoi region according to the hexagonal grid. In Table 4 the features of the two base stations and a typical mobile terminal are summarized. In this regard, the micro base stations are considered to overlay the macro network, hence do not contribute to the coverage, but to capacity. Further, we employ a transmit power of about 2 watt for the micro base stations, which yields a cell size of about 100 m according to the macro base station's transmit power. Based on propagation models taken from [10], we compute the necessary transmit power as described in [9], where we define coverage by a minimal receive signal level (per subcarrier) of about -120 dBm according to the link budget provided there. Results for the two considered deployments, pure macro network and macro network with micro base stations within, are depicted in Figure 2. We can observe a minimum at 1500 m inter site distance for the homogeneous macro scenario which matches the typical value of coverage oriented macro cell deployments. This confirms the used power model. For

Table 4: Base station configuration

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

the heterogeneous deployment the micro cells act as energy efficient coverage extension and shift the minimum to about about 1600 m.

However, the static power term of the additional micro base stations obviously adds to the macro deployment, thus the heterogeneous area power consumption is always higher than for the pure macro deployment. It is obvious that the area power consumption figure can not be the exclusive metric describing energy efficiency since it does not take into account the provided additional network capacity and higher system spectral efficiency. Nevertheless, this metric makes it possible to evaluate different network topologies with similar performance figures with regard to energy efficiency.

5. Conclusions and Outlook

In this paper we have developed a power consumption model for macro base stations which comprises of a static power consumption part only. In contrast to that, a power consumption model for micro base stations additionally consisting of a dynamic power consumption part was derived. Based on data sheets of several GSM and UMTS base stations we were able to qualify the various model describing parameters, providing a tool for simulative investigations from an energy efficiency perspective. We have applied this power consumption model and could show that for conventional macro base station deployments the widely used inter site distance of 1500 m is most energy efficient. An overlay of micro base stations at the cell edge allows to shift the optimum inter site distance to slightly larger values.

The investigations and results at hand are currently being further developed and dealt with in more detail within the consortium of the FP7 project "**E**nergy **A**ware **R**adio and Ne**T**work Tec**H**nologies (**EARTH**)". The main focus of the project is on the important issue of energy efficiency of mobile broadband systems with special emphasis on energy efficient deployment strategies and network architectures. The proposed

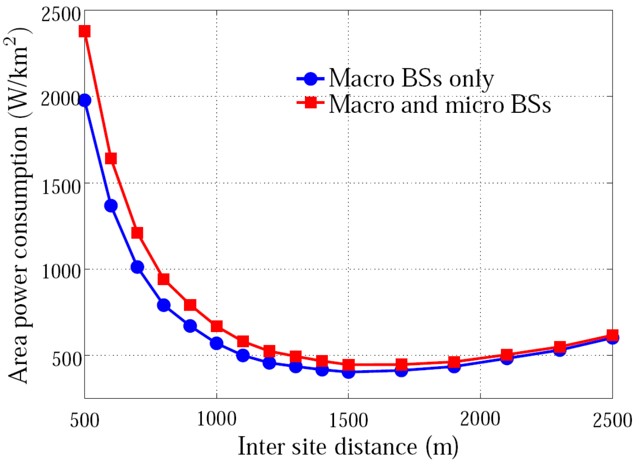

Figure 2: Area power consumption as function of inter site distance for different deployments

power consumption model for macro and micro base stations is a first step towards evaluating energy efficiency of heterogeneous deployments, which is a most promising strategy for improving a system's capacity while reducing a cellular network's energy demand. Within EARTH, we will adapt the power model to future base stations which are designed to have higher power consumption dependency on the load situation. Moreover, new metrics regarding coverage and capacity will be defined. They are applied to analyze which base station deployment strategies provide the best energy efficiency for these metrics.

The technological basis for a massive energy efficiency increase in the ICT sector, e.g., green communications and energy efficient cellular and sensor networks, is also the aim of the Spitzencluster "Cool Silicon", funded by the German government.

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