Cellular Energy Efficiency Evaluation Framework

(Invited Paper)

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***Abstract*—In order to quantify the energy savings in wireless networks, the power consumption of the entire system needs to be captured and an appropriate energy efficiency evaluation framework must be defined. In this paper, the necessary enhancements over existing performance evaluation frameworks are discussed, such that the energy efficiency of the entire network comprising component, node and network level contributions can be quantified. The most important addendums over existing frameworks include a sophisticated power model for various base station (BS) types, which maps the RF output power radiated at the antenna elements to the total supply power of a BS site. We also consider an approach to quantify the energy efficiency of large geographical areas by using the existing small scale deployment models along with long term traffic models. Finally, the proposed evaluation framework is applied to quantify the energy efficiency of the downlink of a 3GPP LTE radio access network.**

***Index Terms*—energy efficiency, green radio, power & traffic model, system level energy efficiency simulations, energy aware radio and network technologies (EARTH)**

I. Introduction

The global mobile communication industry is growing rapidly. Today there are already more than 4 billion mobile phone subscribers worldwide [1], more than half the entire population of the planet. Obviously, this growth is accompanied by an increased energy consumption of mobile networks. Global warming and heightened concerns for the environment of the planet require a special focus on the energy efficiency of these systems [2–4]. The EARTH[1] project [3, 5] is a concerted effort to achieve this goal and as part of its objectives, a holistic framework is developed to evaluate and compare the energy efficiency of several design approaches of wireless cellular communication networks.

For the quantification of energy savings in wireless networks, the power consumption of the entire system needs to be captured and an appropriate energy efficiency evaluation framework (E^3F) is to be defined. The EARTH E^3F presented in Section 2 provides the key levers to facilitate the assessment of the overall energy efficiency of cellular networks over a whole country. The E^3F primarily builds on well-established methodology for radio network performance evaluation developed in 3GPP; the most important addendums, introduced in Sections 3 and 4, are to add a sophisticated power model of the base stations (BSs) as well as a large-scale long-term traffic model extension to existing 3GPP traffic scenarios. Then, in Section 5 the E^3F is applied in order to provide an assessment of the BS energy efficiency of a 3GPP LTE network deployed within an average European country.

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II. Energy Efficiency Evaluation Framework (E^3F)

The widely accepted state-of-the-art to evaluate the performance of a wireless network is to simulate the relevant aspects of the radio access network (RAN) at system level. The computed results are, e.g. the system throughput measured in bit/s, quality of service (QoS) metrics, and fairness in terms of cell-edge user throughput. In order to ensure that the results generated by different RAN system simulation tools are comparable, well defined reference systems and scenarios are specified. This is an outcome of extensive consensus work from standardization bodies, such as 3GPP [6], and international research projects, such as the EU project Wireless World Initiative New Radio (WINNER) [7], with partners from academia as well as from industry. The most recent example is the global effort in ITU to evaluate system proposals for compliance with IMT-Advanced requirements [8]. In that direction, the EARTH E^3F builds on the 3GPP evaluation framework for LTE [6].

Fig. 1 shows the necessary enhancements over existing performance evaluation frameworks, such that the energy efficiency of the entire network, comprising component, node and network level, over an extended time frame can be quantified. The EARTH E^3F illustrated in Fig. 1, identifies the essential building blocks that are necessary for an accurate holistic assessment of energy efficiency enhancements. Although the specific realization of a system level simulation tool largely

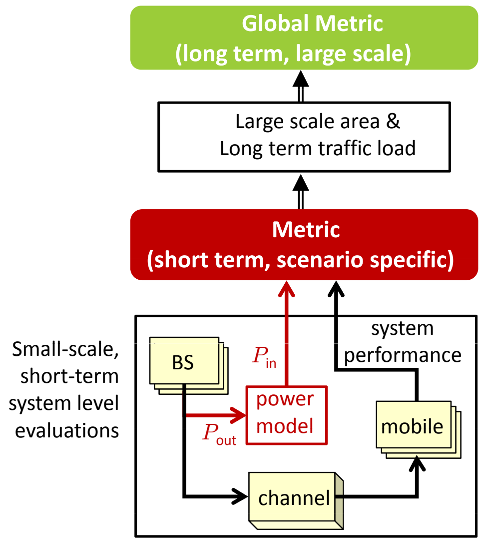

Fig. 1. EARTH Energy efficiency evaluation framework (E^{3}F).

depends on the specific problem at hand, as well as the chosen software implementation, it is envisaged that for the assessment of combinations of energy efficiency enhancements integrated into one holistic system concept, the E^{3}F should capture the following aspects:

- A sophisticated power model (specified in Section 3), that maps the RF output power radiated at the antenna elements to the total supply power of a BS site. The power model maps the gains on the component level (e.g. an improvement of the energy efficiency of the power amplifiers) to energy savings on the entire network.
- Long-term traffic models (established in Section 4), that describe load fluctuations over a day and complement the statistical short-term traffic models.
- Large-scale deployment models (developed in Section 4) of large geographical areas are considered to extend the existing small-scale deployment scenarios.

A. *Small-Scale, Short-Term System Level Evaluations*

Statistical traffic models (e.g. FTP file download or VoIP calls), specific small-scale deployment scenarios (e.g. urban macro-cell consisting of 57 hexagonal cells with uniformly distributed users), and power models that quantify the power consumption of components within a node, constitute small-scale, short-term system level evaluations (bottom block in Fig. 1). The small-scale, short-term system level evaluations are carried out by a system level simulation platform, augmented by a model capturing the BS power consumption.

B. *Global E^{3}F*

In order to extend small-scale, short-term evaluations to a global scale, covering countrywide geographical areas and ranging over a full day or week, long-term traffic models and large-scale deployment maps are to be integrated into the E^{3}F, as illustrated in Fig. 1. The global assessment of network energy efficiency comprises the following steps:

1) Small-scale, short-term evaluations are conducted for all scenarios (dense urban, urban, suburban and rural) and for a representative set of traffic loads, which captures the range between the minimum and the maximum load observed in a certain deployment.
2) The system level evaluations provide energy consumption and other performance metrics (e.g. throughput, QoS) for each small-scale deployment and a certain traffic load.
3) Given the daily/weekly traffic profile of each deployment, the power consumption over a day/week is generated by weighted summing of the short-term evaluations.
4) Finally, the mix of deployment scenarios that quantify the area covered by cities, suburbs, highways and villages, yield the global set of the large-scale system energy consumption.

III. Power Model

This section provides a power model for various types of LTE Base Stations. The power model constitutes the interface between component and system level, which allows quantifying how energy savings on specific components enhance the energy efficiency at the node and network level.

A. *Base Station Power Consumption Breakdown*

A BS site consists of multiple transceivers (TRXs). A TRX comprises an Antenna Interface (AI), a Power Amplifier (PA), a Radio Frequency (RF) small-signal transceiver section, a baseband (BB) interface including a receiver (uplink) and transmitter (downlink) section, a DC-DC power supply, an active cooling system, and an AC-DC unit (mains supply) for connection to the electrical power grid. In the following the various TRX parts are analyzed.

Antenna Interface (AI): The influence of the antenna type on power efficiency is modeled by a certain amount of losses, including the feeder (where relevant), antenna bandpass filters, duplexers, and matching components.

Power Amplifier (PA): Typically, the most efficient PA operating point is close to the maximum output power (near saturation). Unfortunately, non-linear effects and OFDM modulation with non-constant envelope signals force the power amplifier to operate in a more linear region, i.e., 6 to 12 dB below saturation [9]. This prevents Adjacent Channel Interference (ACI) due to non-linear distortions, and therefore avoids performance degradation at the receiver. However, this high operating back-off gives rise to poor power efficiency, which translates to a high power consumption P_{PA}. Digital techniques such as clipping and digital pre-distortion [10, 11] in combination with Doherty PAs [9] improve the power efficiency and linearizes the PA, while keeping ACI under control, but require an extra feedback for pre-distortion and significant additional signal processing [11]. While these techniques are necessary in macro and micro BSs, they are not used in smaller BSs, as the PA power consumption accounts for a smaller percentage of the power breakdown, allowing for a higher operating back-off.

The *Small-Signal RF Transceiver (RF-TRX)* comprises a receiver and a transmitter for uplink (UL) and downlink (DL) communication. The linearity and blocking requirements of the RF-TRX may differ significantly depending on the BS type, and so its architecture. Typically, low-IF (Intermediate-Frequency) or super-heterodyne architectures are the preferred choice for macro/micro BSs, whereas a simpler zero-IF architecture are sufficient for pico/femto BSs [12]. Parameters with highest impact on the RF-TRX energy consumption, P_{RF}, are the required bandwidth, the allowable Signal-to-Noise And Distortion ratio (SiNAD), the resolution of the analogue-to-digital conversion, and the number of antenna elements for transmission and/or reception.

Baseband (BB) Interface: The baseband engine (performing digital signal processing) carries out digital up/down-conversion, including filtering, FFT/IFFT for OFDM, modulation/demodulation, digital-pre-distortion (only in DL and for large BSs), signal detection (synchronization, channel estimation, equalization, compensation of RF non-idealities), and channel coding/decoding. For large BSs the digital baseband also includes the power consumed by the serial link to the backbone network. Finally, platform control and MAC operation add a further power consumer (control processor).

The silicon technology significantly affects the power consumption P_{BB} of the BB interface. This technology scaling is incorporated into the power model by extrapolating on the International Technology Roadmap for Semiconductors (ITRS). The ITRS anticipates that silicon technology is replaced by a new generation every 2 years, each time doubling the active power efficiency but multiplying by 3 the leakage [13]. The increasing leakage puts a limit on the power reduction that can be achieved through technology scaling. Apart from the technology, the main parameters that affect the BB power consumption are related to the signal bandwidth, number of antennas and the applied signal processing algorithms. While the consumed power scales linearly with the bandwidth; MIMO signal detection scales more than linearly with the number of antennas.

Power Supply and Cooling: Losses incurred by DC-DC power supply, mains supply and active cooling scale linearly with the power consumption of the other components, and may be approximated by the loss factors σ_{DC}, σ_{MS}, and σ_{cool}, respectively. Note that active cooling is only applicable to macro BSs, and is omitted in smaller BS types.

The breakdown of the BS power consumption at maximum load, $P_{\mathrm{out}}{=}P_{\mathrm{max}}$, may be expressed as

$$P_{\mathrm{in}} = N_{\mathrm{TRX}} \cdot \frac{P_{\mathrm{PA}} + P_{\mathrm{RF}} + P_{\mathrm{BB}}}{(1{-}\sigma_{\mathrm{DC}})(1{-}\sigma_{\mathrm{MS}})(1{-}\sigma_{\mathrm{cool}})} \qquad (1)$$

where N_{TRX} denotes the number of TRX chains of the considered BS type. Table I summarizes the state of the art power consumption of various LTE BS types as of 2010.

TABLE I
LTE Base Station Power Consumption at Maximum Load for Different BS Types as of 2010.

			Macro	**Micro**	**Pico**	**Femto**
PA	P_{max}	[dBm]	46.0	38.0	21.0	17.0
		[W]	40.0	6.3	0.13	0.05
	Back-off	[dB]	8.0	8.0	12.0	12.0
	PA Efficiency	[%]	31.1	22.8	6.7	4.4
	Total PA, P_{PA}	[W]	**128.2**	**27.7**	**1.9**	**1.1**
RF	P_{TX}	[W]	6.8	3.4	0.4	0.2
	P_{RX}	[W]	6.1	3.1	0.4	0.3
	Total RF, P_{RF}	[W]	**13.0**	**6.5**	**1.0**	**0.6**
BB	Radio (inner Rx/Tx)	[W]	10.8	9.1	1.2	1.0
	Turbo code (outer Rx/Tx)	[W]	8.8	8.1	1.4	1.2
	Processors	[W]	10.0	10.0	0.4	0.3
	Total BB, P_{BB}	[W]	**29.5**	**27.3**	**3.0**	**2.5**
DC-DC, σ_{DC}		[%]	7.5	7.5	9.0	9.0
Cooling, σ_{cool}		[%]	10.0	0.0	0.0	0.0
Mains Supply, σ_{MS}		[%]	9.0	9.0	11.0	11.0
Total per TRX chain		[W]	**225.0**	**72.3**	**7.3**	**5.2**
# Sectors		#	3	1	1	1
# Antennas		#	2	2	2	2
# Carriers		#	1	1	1	1
Total N_{TRX} chains, P_{in}		[W]	**1350.0**	**144.6**	**14.7**	**10.4**

B. BS Power Consumption at Variable Load

In a conventional BS, the power consumption depends on the traffic load; it is mainly the PA power consumption that scales down due to reduced traffic load. This mainly happens when, e.g., the number of occupied subcarriers is reduced in idle mode operation, and/or there are subframes not carrying data. Naturally this scaling over signal load largely depends on the BS type; for macro BSs the PA accounts for 55–60% of the overall power consumption at full load, whereas for low power nodes the PA power consumption amounts to less than 30% of the total.

Fig. 2 shows BS power consumption curves for a LTE system with 10 MHz bandwidth and 2×2 MIMO configuration. Three sectors are considered for macro BSs, whereas omni-directional antennas are used for the smaller BS types. While the power consumption P_{in} is load dependent for macro BSs, and to a lesser extent for micro BSs, there is a negligible load dependency for pico and femto BSs. The reason is that for low power BSs, the impact of the PA is diminishing. Other components hardly scale with the load in a state of the art implementation; although some more innovative designs could lead to an improved power scaling at low loads. As can be seen in Fig. 2, the relations between relative RF output power P_{out} and BS power consumption P_{in} are nearly linear. Hence, a linear approximation of the power model is justified:

$$P_{\mathrm{in}} = N_{\mathrm{TRX}} \cdot \left(P_0 + \Delta_{\mathrm{p}}\, P_{\mathrm{out}}\right) , \quad 0{\le}P_{\mathrm{out}}{\le}P_{\mathrm{max}} \qquad (2)$$

where P_{max} denotes the maximum RF output power at maximum load, P_0 is the power consumption calculated at the minimum possible output power, assumed to be 1% of P_{max}, and Δ_{p} is the slope of the load dependent power consumption. Table II lists the parameters for the different BS types.

TABLE II
Power model parameters for different BS types

BS type	N_{TRX}	P_{max} [W]	P_0 [W]	Δ_{p}
Macro	6	40.0	118.7	2.66
Micro	2	6.3	53.0	3.1
Pico	2	0.13	6.8	4.0
Femto	2	0.05	4.8	7.5

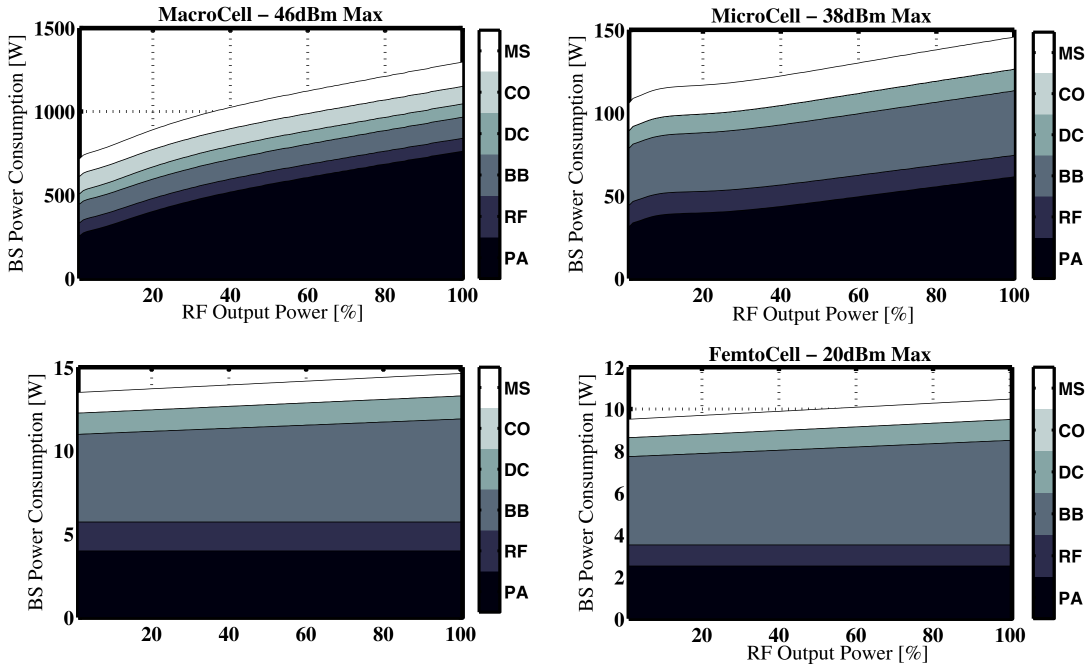

Fig. 2. Power consumption for various BS types as a function of the RF output power. An LTE system with 10 MHz system bandwidth and 2×2 MIMO configuration is considered. Macro BSs employ 3 sectors per site. Legend: PA: power amplifier, RF: small signal RF transceiver, BB: baseband processor, DC: DC-DC converters, CO: active cooling (only applicable to macro BS), MS: mains power supply.

IV. Traffic Model

In order to provide a realistic analysis of the energy efficiency of wireless networks, it is essential to know the traffic demand to be served by the network. Thus, it is important to identify the spatial and temporal variation of the traffic demand both on large- and small-scale.

A. Deployment Areas of Europe

The average population density for different deployment areas in Europe is shown in Table III. Ratio of different deployment areas hardly depends on the particular countries of Europe; however, the Nordic countries (Finland, Norway and Sweden) and Russia make a big difference compared to the averages. We therefore choose to give the European average excluding the Nordic countries and Russia. Note that in central districts of a metropolis, the population density can exceed even 20,000 citizen/km^2, but due to their negligible covered area these are omitted from the presented model.

According to the current situation in Europe (see, e.g., [14]), the coverage of the latest mobile technologies is focusing on the population and not on the amount of area covered. That is, 2G area coverage is almost 100%, while 3G coverage is below 40%. This implies that the sparsely populated areas and the wilderness are only served by 2G networks. For instance, German regulation forces to serve "only" 90% of the population with wideband access [15], which practically allows to skip scarcely populated areas also for LTE deployment.

TABLE III
Deployment Areas in Europe (Excluding Nordic and Russia)

Deployment	**Population density** [citizen/km^2]	**Covered area** [%]	**Normalized mean peak traffic load**
Dense urban	3000	1%	100%
Urban	1000	2%	33.3%
Suburban	500	4%	16.7%
Rural	100	36%	3.3%
Sparsely populated & wilderness	25	57%	–

B. Long-Term Large-scale Traffic Models

The objective for the long-term large-scale traffic models is to determine the average served traffic on a certain time of day in a given deployment scenario. Abstracting the models from the current cell planning maps of Europe, the following methodology allows to deduce the daily traffic variations as the actual traffic demand of a given area:

1) define the average served data rates per subscriber;
2) determine the percentage of active subscribers;
3) given the population densities for the respective deployments, the scenario specific peak data rates per area unit in [Mbps/km^2] can be derived;
4) finally, with the aid of a daily traffic profile the deployment specific data rates per area unit for a certain time of day is obtained.

1) Data rates per subscriber: The user generated data volume is tightly connected to operator policies and data subscriptions plans. Since the amount of traffic varies from country to country, we propose to define three traffic profiles, where the average traffic demand per subscriber is set to:

- *high traffic profile* sufficient to provide, e.g., HDTV for all active users, corresponding to 2 Mbps/user;
- *medium traffic profile* sufficient to provide, e.g., SDTV for all active users, corresponding to 0.5 Mbps/user;

TABLE IV
DATA TRAFFIC PEAKS IN THE RESPECTIVE DEPLOYMENT AREAS

Deployment	Traffic profile [Mbps/km^2]		
	high	mid	low
Dense urban	120.0	30.0	6.0
Urban	40.0	10.0	2.0
Suburban	20.0	5.0	1.0
Rural	4.0	1.0	0.2

- *low traffic profile* sufficient to provide, e.g., HQ Internet Radio with ~100 kbps/user, which represents intense data usage in current 3G networks.

We note that the above figures represent average traffic demands; typically strong temporal and geographical deviations with respect to these average values are experienced, e.g., one or two so-called heavy users may fully utilize a cell even for extended time periods.

2) Active subscribers: In today's networks 10–30% of the data subscribers are active in the busy/peak hours. According to the expectations towards wireless Internet services, the ratio of broadband data subscribers of the whole population will increase from year to year and in the most mature European markets may reach 25% by 2014; however, conservative expectations calculate with 10% as European average.[2] The recommended aggregate reference values are as follows:

- the ratio of broadband data subscribers is 10% of the whole population;
- the number of active users in the busy/peak hours is 20% of the subscribers.

As a consequence, the number of active subscribers amounts to 2% of the whole population in the busy/peak hours, which roughly corresponds, e.g., to 10 users with active data connection in a typical urban cell.

3) Peak traffic demand per area: As the data volume per subscriber does not depend on the deployment scenario, the normalized traffic values in Table III are proportional to the population density. Given the population densities (see Table III), the traffic demand per subscriber (high, mid or low), and the number of active subscribers, the peak traffic demand per km^2 of the considered deployment scenarios are listed in Table IV.

4) Served data traffic over time: Fig. 3 illustrates the typical daily variation in Europe (based on internal sources on traffic data and the Sandvine report [16]). The daily traffic variation are plotted relative to the peak traffic demand of a given deployment in Table IV. The same normalized traffic profile is assumed for all deployments.

The EARTH project found that the daily variation of the number of active users scales with the daily variation of the traffic. We therefore assume that the number of active users is scaled to match the traffic variations in Fig. 3, while the average rates per active user remain fixed.

[2]The amount of broadband subscribers correspond to subscriptions of at least 1 GB monthly cap, which are typically personal computer (PC) related today. However, smartphones and other mobile equipment could generate additional 10–25% traffic in Europe; and even more in North America, due to much lower mobile PC traffic compared to Europe.

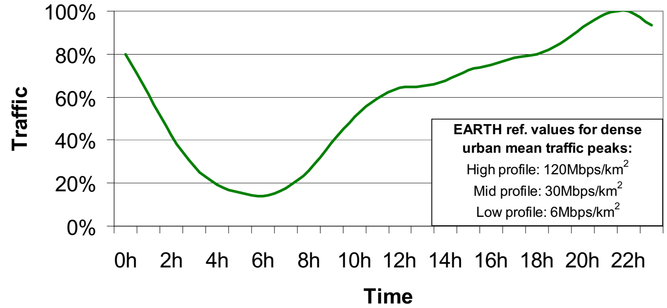

Fig. 3. Typical average daily data traffic profile in Europe.

Aggregating the traffic demands per active user over a whole month amounts to a traffic volume per subscriber of about 68, 17 and 3 GB/month/subscriber for the high, mid and low traffic profile, respectively. Note that these traffic demands are higher than that of current 3G networks, but should be considered as expectations for well-established mobile broadband markets beyond 2014. For instance, in today's mature markets a data volume of 1–3 GB/month/subscriber accounts as very intensive data usage [17–19].

C. Statistical Short-Term Traffic Models

In order to model the fluctuation of the traffic in short-time scale, the packet distribution generated by the different type of applications is modeled statistically. Since the same short-term traffic models per active user should be applied in all deployment areas, the traffic demands in different deployments are derived from the differences in the corresponding user density figures. A detailed description of the traffic models can be found in [6].

V. CASE STUDY: ENERGY EFFICIENCY OF LTE

For short-term, small-scale evaluations a macro-cellular network with regular hexagonal cell layout is implemented. 19 sites, each with 3 sectors, 10 MHz bandwidth operating at 2.1 GHz carrier frequency is assumed. Moreover, 2×2 MIMO transmission with adaptive rank adaption is assumed. The inter-site distance (ISD) for the dense urban and urban environments is set to 500 m, whereas the ISD for suburban and rural areas is set to 1732 m. The users are uniformly distributed, with population densities corresponding to the respective deployment scenarios. The simulation parameters are taken from 3GPP specifications [6].

The power per area unit P/A, expressed in [kW/km^2], is depicted in Fig. 4. The power consumption increases with the served traffic in the network. In an urban scenario (see Fig. 4 (top)), with an ISD of 500 m corresponding to a coverage area of 0.2165 km^2 per site, the power per area unit is around 4.15 kW/km^2 at low loads, whereas it approaches 5.1 kW/km^2 at high loads. For comparison, an empty network when only control channels are transmitted, but no user data, the power consumption equals 885 W per site, which corresponds to a power per area unit of 4.1 kW/km^2. In the (hypothetical) extreme case, when nothing at all is transmitted (i.e., no data and no control channels) so that the RF output power

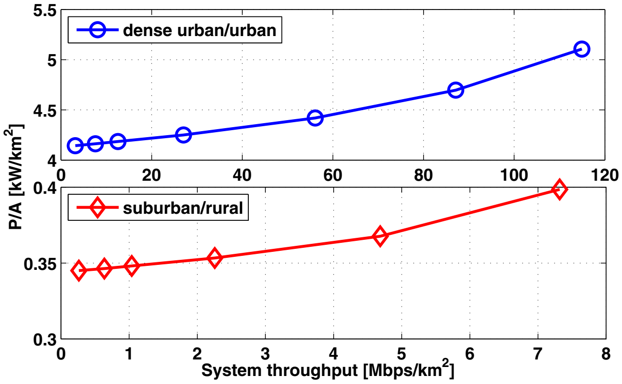

Fig. 4. Power per area unit, P/A, versus system throughput in dense urban/urban (top) and suburban/rural (bottom) scenarios. Notice the different scales in both x and y-axis.

is 0 W, we obtain P/A=3.3 kW/km^2. The power consumption per area unit for suburban and rural areas, shown in Fig. 4 (bottom), is substantially lower, which is due to the increased ISD of 1732 m, which corresponds to a coverage area of 2.6 km^2. However, the system throughput per area unit decreases accordingly, due to the increased site coverage area.

In order to assess the expected performance of a country-wide area over a day, short-term, small-scale evaluations are combined with the long-term traffic models and the geographical distribution presented in Section 4. It is assumed that no coverage is provided in the sparsely populated and wilderness areas and hence, these areas are not included in the analysis. Moreover, the global traffic model in Section 4 is for the entire user population, whereas the short-term, small-scale evaluations are performed for a single carrier, which is served by a single operator. It is here assumed that the market share of the studied operator is 30 % and that this operator also carries 30 % of the total data traffic.

The outcome of the aggregation indicates that with the models and assumptions used in this evaluation, the average power per area unit is about 0.6 kW/km^2. This value is almost independent of whether high, medium, or low traffic density is assumed, i.e., the power consumption is mostly insensitive to the traffic load. One reason for this is that given the traffic and deployment models used here, the network typically operates in the very low load regime, where transmissions of control signals dominate over data. These evaluations highlight the fact that on average cellular networks are primarily providing coverage, and therefore mainly operate at low traffic loads.

VI. Conclusions

In order to identify the key levers for energy savings the power consumption of mobile communication systems needs to be quantified. This includes sophisticated power models that map the radiated RF power to the supply power of a BS site, as well as traffic and deployment models that extend short-term small-scale evaluations to the country wide power consumption of a network over a whole day or week. Numerical results reveal that for current network design and operation, the power consumption is mostly independent of the traffic load. This highlights the vast potential for energy savings by improving the energy efficiency of BSs at low load.

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