HOW MUCH ENERGY IS NEEDED TO RUN A WIRELESS NETWORK?

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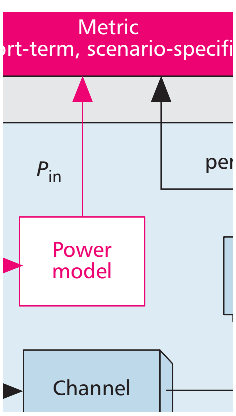

In order to quantify the energy efficiency of a wireless network, the power consumption of the entire system needs to be captured. The authors discuss the necessary extensions with respect to existing performance evaluation frameworks.

ABSTRACT

In order to quantify the energy efficiency of a wireless network, the power consumption of the entire system needs to be captured. In this article, the necessary extensions with respect to existing performance evaluation frameworks are discussed. The most important addenda of the proposed energy efficiency evaluation framework (E^3F) are a sophisticated power model for various base station types, as well as large-scale long-term traffic models. The BS power model maps the RF output power radiated at the antenna elements to the total supply power of a BS site. The proposed traffic model emulates the spatial distribution of the traffic demands over large geographical regions, including urban and rural areas, as well as temporal variations between peak and off-peak hours. Finally, the E^3F is applied to quantify the energy efficiency of the downlink of a 3GPP LTE radio access network.

INTRODUCTION

The global mobile communication industry is growing rapidly. Today the global number of mobile phone subscribers approaches 6 billion, so virtually every human being on this planet makes use of mobile communications. Obviously, this growth is accompanied by increased energy consumption of mobile networks. Global warming and heightened concerns for the environment require a special focus on the energy efficiency of these systems. The EARTH[1] project [1] is a concerted effort to achieve this goal, and as part of its objectives, a holistic framework is developed to quantify the energy efficiency for the operation of a radio access network.

Recent surveys on the energy consumption of cellular networks, including base stations (BSs), mobile terminals, and the core network, reveal that around 80 percent of the energy required for the operation of a cellular network is consumed at BS sites [2]. The EARTH energy efficiency evaluation framework (E^3F) presented in this work therefore focuses on the BS power consumption. The E^3F primarily builds on the radio network assessment methodology developed in the Third Generation Partnership Project (3GPP); the most important addenda are a sophisticated power model for various BS types, as well as a large-scale long-term traffic model that allows for a holistic energy efficiency analysis over large geographical areas and extended periods of time. Then the E^3F is applied in order to provide an assessment of the BS energy efficiency of a 3GPP Long Term Evolution (LTE) network deployed within a representative European country. The calculated energy efficiency of LTE is compared to that of already deployed networks.

One of the key findings of the EARTH energy efficiency analysis is that on average the vast majority of the resources are idle, a fact that has been verified recently by measurements on a real 3G network in a major European city [3]. Unfortunately, it is at low loads where the energy efficiency of contemporary systems such as LTE is particularly poor. This highlights the need to reduce the BS power consumption particularly at low network loads.

1 EU funded research project Energy Aware Radio and Network Technologies (EARTH), FP7-ICT-2009-4-247733-EARTH, January 2010 to June 2012: https://www.ict-earth.eu

Energy Efficiency Evaluation Framework

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 the system level. The computed results are, for example, system throughput, quality of service (QoS) metrics, and fairness in terms of cell edge user throughput. In order to ensure that 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. In that direction, the EARTH E^3F builds on the 3GPP evaluation framework for LTE [4].

The EARTH E^3F, illustrated in Fig. 1, identifies the essential building blocks for a holistic energy efficiency assessment. The principal enhancements with respect to existing performance evaluation frameworks are:

- A sophisticated power model that maps the RF output power radiated at the antenna elements, P_{out}, to the total supply power of a BS site, P_{in}. The power model defines the interface between the component and system levels.
- Long-term traffic models that describe load fluctuations over a day and complement statistical short-term traffic models.
- Large-scale deployment models that extend existing small-scale deployment scenarios to large geographical areas.

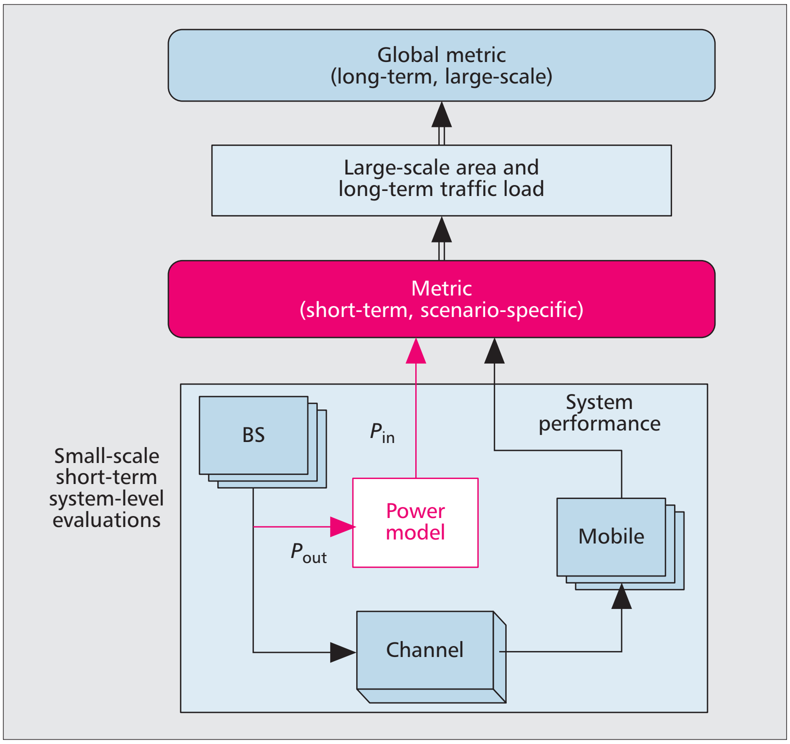

Figure 1. *EARTH energy efficiency evaluation framework (E^3F).*

Small-Scale Short-Term System-Level Evaluations

Statistical traffic models (e.g., FTP file download or voice over IP [VoIP] calls), as well as specific small-scale deployment scenarios (e.g., urban macrocell consisting of 57 hexagonal cells with uniformly distributed users), constitute small-scale short-term system-level evaluations (bottom block in Fig. 1). These evaluations are carried out by a system-level simulation platform, augmented by a model capturing the BS power consumption.

Global E^3F

In order to extend small-scale short-term evaluations to 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^3F. The global assessment of network energy efficiency as sketched in Fig. 1 comprises the following steps:

- Small-scale short-term evaluations are conducted for all deployment scenarios, capturing cities, suburbs, and villages, as well as for a representative set of network loads. The gathered figures of merit (e.g., energy consumption, throughput, QoS) capture the range between minimum and maximum load observed in a certain deployment.
- Given the daily/weekly traffic profile of each deployment, performance metrics over a day/week are aggregated by weighted summing of the short-term evaluation results.
- Finally, weighted summing over the considered mix of deployment scenarios yield the global figures of merit.

Power Model

The BS power model constitutes the interface between the component and system levels, which allows the quantification of how energy savings on specific components enhance the energy efficiency at the network level. The characteristics of the implemented components largely depend on the BS type, due to constraints in output power, size, and cost. These heterogeneous characteristics mandate a power model that is tailored to a specific BS type.

Base Station Power Consumption Breakdown

Figure 2 shows a simplified block diagram of a complete BS that can be generalized to all BS types, including macro, micro, pico and femto BSs. A BS consists of multiple transceivers (TRXs), each of which serves one transmit antenna element.

A TRX comprises a power amplifier (PA), a radio frequency (RF) small-signal TRX module, a baseband engine 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: The influence of the antenna type on the power efficiency is modeled by a certain amount of losses, including the feeder, antenna bandpass filters, duplexers, and matching components. Since macro BS sites are often

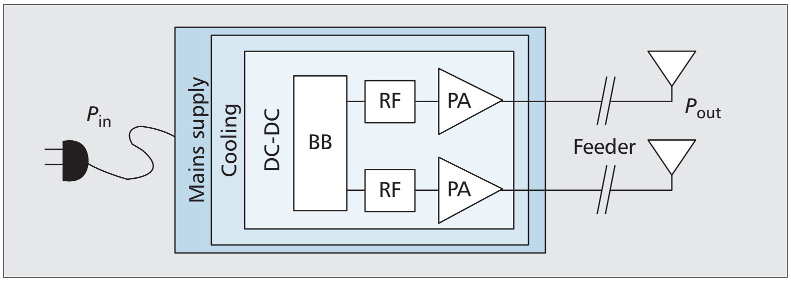

Figure 2. *Block diagram of a base station transceiver.*

situated at different physical locations than the antennas, a feeder loss of about $\sigma_{feed} = -3$ dB needs to be added. The feeder loss of a macro BS may be mitigated by introducing a remote radio head (RRH), where the PA is mounted at the same physical location as the transmit antenna. Likewise, feeder losses for smaller BS types are typically negligible.

Power amplifier (PA): Typically, the most efficient PA operating point is close to the maximum output power (near saturation). Unfortunately, nonlinear effects and orthogonal frequency-division multiplexing (OFDM) modulation with non-constant envelope signals force the power amplifier to operate in a more linear region (i.e., 6–12 dB below saturation) [5]. This prevents adjacent channel interference (ACI) due to nonlinear distortions, and therefore avoids performance degradation at the receiver. However, this high operating back-off gives rise to poor power efficiency η_{PA}, which translates to ian ncreased PA power consumption

$$P_{PA} = \frac{P_{out}}{\eta_{PA} \cdot (1 - \sigma_{feed})}.$$

Digital techniques such as clipping and digital pre-distortion [6] in combination with Doherty PAs [5] improve the power efficiency and linearize the PA, while keeping ACI under control. The required extra feedback for pre-distortion and additional signal processing [6] are deemed necessary in macro and micro BSs. In smaller BS types, on the other hand, such advanced PA architectures are omitted, at the expense of an increased operating back-off; the fact that the PA accounts for a smaller percentage of the total BS power consumption justifies a lower PA efficiency.

The *small-signal RF transceiver* comprises a receiver and a transmitter for uplink and downlink communication. The linearity and blocking requirements of the RF module may differ significantly depending on the BS type, which impacts the RF architecture: low-intermediate frequency (IF) or super-heterodyne architectures are the preferred choice for macro/micro BSs, whereas a simpler zero-IF architecture is sufficient for pico/femto BSs [7]. Parameters with highest impact on the RF energy consumption, P_{RF}, are the required bandwidth, the allowable signal-to-noise-and-distortion ratio (SiNAD), and the resolution of the analog-to-digital conversion.

Baseband (BB) unit: The BB engine (performing digital signal processing) carries out digital up/downconversion, including filtering, modulation/demodulation, digital pre-distortion (only for large BS types), signal detection (synchronization, channel estimation, equalization, compensation of RF non-idealities), and channel coding/decoding. For large BSs the digital BB also includes the power consumed by the serial link to the backbone network. Finally, platform control and medium access control (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 two years, each time doubling the active power efficiency, but multiplying by three the leakage [8]. The increasing leakage puts a limit on the power reduction that can be achieved through technology scaling.

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. Moreover, for RRHs active cooling is also obsolete, since the PA is cooled by natural air circulation.

Assuming that the BS power consumption grows proportionally with the number of transceiver chains N_{TRX}, the breakdown of the BS power consumption at maximum load, where $P_{out} = P_{max}$, yields

$$P_{in} = N_{TRX} \cdot \frac{\frac{P_{out}}{\eta_{PA} \cdot (1 - \sigma_{feed})} + P_{RF} + P_{BB}}{(1 - \sigma_{DC})(1 - \sigma_{MS})(1 - \sigma_{cool})}.$$

The *efficiency* is defined by $\eta = P_{out}/P_{in}$, whereas the loss factor is defined by $\sigma = 1 - \eta$. Note that the RF output power per transmit antenna, P_{out}, is measured at the input of the antenna element, so that losses due to the antenna interface (other than feeder losses) are not included in the power breakdown. It is seen that the supply power P_{in} scales linearly to the number of TRX chains N_{TRX} (i.e. transmit/receive antennas per site).

Table 1 summarizes the state-of-the-art power consumption of various LTE BS types as of 2010. Three sectors are considered for macro BSs, whereas omnidirectional antennas are used for the smaller BS types. By introducing RRHs in macro BS sites, where the PA is mounted close to the transmit antenna, feeder losses σ_{feed} and active cooling are avoided, so power savings exceed 40 percent.

BS Power Consumption at Variable Load

In an LTE downlink the BS load, defined by P_{out}/P_{max}, is proportional to the amount of utilized resources, comprising both data and control signals. More generally, the BS load also depends on power control settings in terms of the transmitted spectral power density, which is applicable, for example, to an LTE uplink.

			Macro	RRH	Micro	Pico	Femto
BS	Max Tx power (average) P_{max}	[dBm] [W]	43.0 20.0	43.0 20.0	38.0 6.3	21.0 0.13	17.0 0.05
	Feeder loss σ_{feed}	[dB]	–3	0	0	0	0
PA	Back-off	[dB]	8.0	8.0	8.0	12.0	12.0
	Max PA out (peak)	[dBm]	54.0	51.0	46.0	33.0	29.0
	PA eff. η_{PA}	[%]	31.1	31.1	22.8	6.7	4.4
	Total PA, $\dfrac{P_{max}}{\eta_{PA} \cdot (1 - \sigma_{feed})}$	**[W]**	**128.2**	**64.4**	**27.7**	**1.9**	**1.1**
RF	P_{TX}	[W]	6.8	6.8	3.4	0.4	0.2
	P_{RX}	[W]	6.1	6.1	3.1	0.4	0.3
	Total RF, P_{RF}	**[W]**	**12.9**	**12.9**	**6.5**	**1.0**	**0.6**
BB	Radio (inner Rx/Tx)	[W]	10.8	10.8	9.1	1.2	1.0
	Turbo code (outer Rx/Tx)	[W]	8.8	8.8	8.1	1.4	1.2
	Processors	[W]	10.0	10.0	10.0	0.4	0.3
	Total BB, P_{BB}	**[W]**	**29.6**	**29.6**	**27.3**	**3.0**	**2.5**
DC-DC, σ_{DC}		[%]	7.5	7.5	7.5	9.0	9.0
Cooling, σ_{cool}		[%]	10.0	0.0	0.0	0.0	0.0
Mains supply, σ_{MS}		[%]	9.0	9.0	9.0	11.0	11.0
Total per TRX chain		**[W]**	**225.0**	**125.8**	**72.3**	**7.3**	**5.2**
# Sectors		#	3	3	1	1	1
# Antennas		#	2	2	2	2	2
# Carriers		#	1	1	1	1	1
Total N_{TRX} **chains,** P_{in}		**[W]**	**1350**	**754.8**	**144.6**	**14.7**	**10.4**

Table 1. *Base station power consumption at maximum load for different BS types as of 2010. An LTE system with 10MHz bandwidth and 2 × 2 MIMO configuration is assumed.*

The BS power model constitutes the interface between the component and system levels, which allows the quantification of how energy savings on specific components enhance the energy efficiency at the network level.

Figure 3 shows the BS power consumption for LTE with 10 MHz bandwidth and 2 × 2 MIMO configuration. Examination of the BS power consumption as a function of its load reveals that mainly the PA scales with the BS load. However, this scaling over signal load largely depends on the BS type. While the power consumption P_{in} is load-dependent for macro BSs, and to a lesser extent for micro BSs, the load dependency of pico and femto BSs is negligible. The reason is that for low power nodes the PA accounts for less than 30 percent of the overall power consumption, whereas for macro BSs the PA power consumption amounts to 55–60 percent of the total, which mandates more sophisticated PA architectures for the latter. Other components hardly scale with the load in contemporary implementations. However, in future systems some more innovative designs are envisaged to improve power scaling at low loads [7]. As can be seen in Fig. 3, the relations between relative RF output power P_{out} and BS power consumption P_{in} are nearly linear. Hence, a linear approximation of the BS power model appears justified:

$$P_{in} = \begin{cases} N_{TRX} \cdot P_0 + \Delta_p P_{out}, & 0 < P_{out} \le P_{max} \\ N_{TRX} \cdot P_{sleep}, & P_{out} = 0 \end{cases} \quad (1)$$

where P_0 is the power consumption at the minimum non-zero output power, and Δ_p is the slope of the load-dependent power consumption. The parameters of the linear power model of Eq. 1 for the considered BS types are obtained by least squares curve fitting and are listed in Table 2.

Also indicated in Fig. 3 and Table 2 is a sleep mode power consumption, P_{sleep}. Fast deactivation of components (i.e., to put them into sleep when there is nothing to transmit) is believed to be an important solution to save energy [3]. While state-of-the-art implementations mostly lack sleep capabilities, $P_{sleep} < P_0$ is introduced here to capture sleep modes for future BS.

Traffic Model

In order to realistically analyze the energy efficiency of wireless networks, it is essential to identify the spatial and temporal variation of the mobile subscribers and their associated traffic

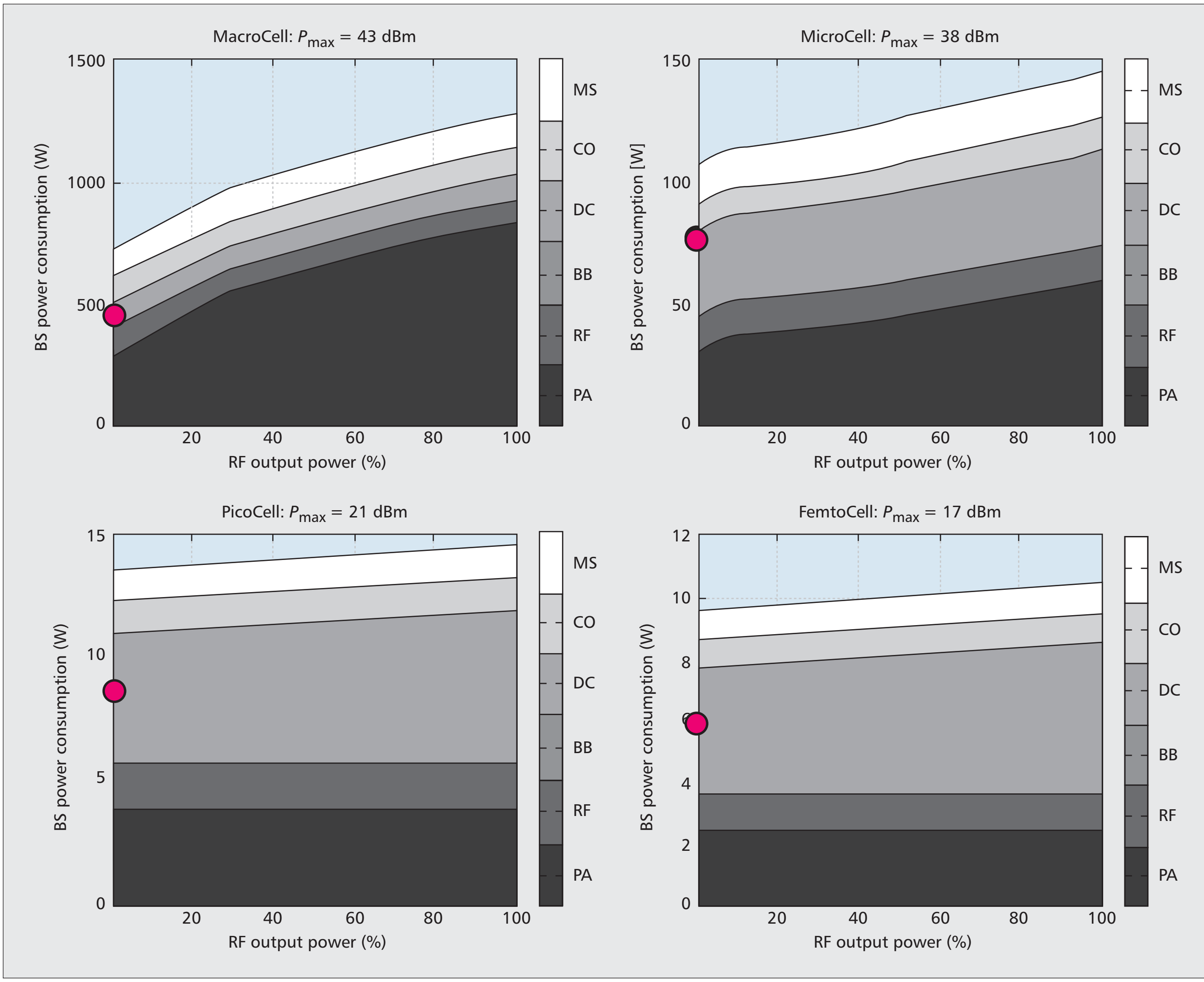

Figure 3. *Power consumption for various BS types as a function of the load,* P_{out}/P_{max}. *An LTE system with 10 MHz system bandwidth and 2 × 2 MIMO configuration is considered. Macro BSs employ three sectors per site. Legend: PA: power amplifier, RF: small signal RF transceiver, BB: baseband processor,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

demands. The traffic model presented in this section is based on the UMTS Forum's mobile traffic forecast [10].

Deployment Areas of Europe

The deployment areas of a given country or region may be classified into dense urban, urban, suburban, and rural areas. The ratio of different deployment areas in Europe and their associated population densities, depicted in Figs. 4a and 4b, hardly depends on the particular countries. However, the Nordic countries (Finland, Norway, and Sweden) and Russia are substantially less densely populated than the European average and are therefore omitted from Fig. 4. Note that in central districts of a metropolis, the population density can exceed even 20,000 citizens/km^2, but due to their negligible covered area, these are omitted from the presented model.

According to the current situation in Europe, the coverage of mobile broadband is focusing on the population and not on the amount of area covered [9]. That is, second-generation (2G) area coverage approaches 100 percent, while 3G coverage is below 40 percent. This implies that sparsely populated areas are exclusively served by 2G networks, which practically allows us to skip sparsely populated areas also for LTE deployment.

Long-Term Large-Scale Traffic Models

The following methodology captures the long-term and large-scale variations of traffic demand:
- Define the average served data rates r_k for a given terminal type k.
- Identify the fraction of subscribers s_k from the entire population.
- From the subscriber base, determine the percentage of *active* subscribers $\alpha(t)$ over time t.
- Given the population densities for the respective deployments, the scenario specific average data rates per area unit in megabits per square kilometer can be derived.

Terminal and Subscriber Mixes — Emerging terminal types such as tablets and smartphones complement PC generated mobile broadband traffic, and stimulate additional traffic demand already today. As a consequence, the expected traffic volume to be served by future wireless networks is increasingly dominated by mobile broadband subscribers. Due to the diminishing share of voice traffic, voice subscribers are not included in our model. We emphasize that user generated data volume is tightly connected to operator policies and data subscriptions plans. Moreover, strong temporal and geographical deviations of the traffic demands per active subscriber are experienced; for example, one or two so-called *heavy users* may fully utilize a cell even for extended time periods.

The projected terminal and subscriber mixes for 2015 are as follows:

- A large portion of the population will be mobile data subscribers: s_{PC} = 20 percent, s_{tab} = 5 percent, and s_{fon} = 50 percent of the population are (mobile) PC, tablet, and smartphone users, respectively.
- Heavy users request the following data rates r_k: PC, tablet, and smartphone users demand an average data rate of 2 Mb/s, 1 Mb/s, and 250 kb/s, respectively. These rates represent a range from high-definition video streaming with a display resolutions of 1280 × 720 pixels (720p HD) to intensive web browsing, which accumulates to a data volume of 900 Mbytes/h and 112.5 Mbytes/h, respectively.
- Ordinary users demand 1/8 of the respective heavy user rates.

By adjusting the ratio of heavy users, different scenarios can be constructed that reflect the expected share of mobile broadband subscribers:

- *Scenario #1*: 20 percent of the subscribers are classified as heavy users. This means that the 20 percent most demanding users consume 2/3 of the network resources. According to [10], this is the most relevant European scenario for 2015.
- *Scenario #2*: 50 percent of the subscribers are classified as heavy users. This scenario serves as an upper bound on the anticipated traffic for 2015.
- *Scenario #3*: All subscribers are classified as heavy users. This scenario serves as an extremity for very high data usage in future networks.

Daily Traffic Variations — Clearly, not all subscribers are always active; rather, the number of active subscribers changes between busy and quiet hours. In today's networks 10–30 percent of the data subscribers are active in the busy/peak hours. As a European average we assume that 16 percent of mobile broadband subscribers are active in peak hours.

Based on internal surveys on operator traffic data within the EARTH project and the Sandvine report [11], the average traffic demand follows the daily variation $\alpha(t)$ as illustrated in Fig. 4c. Furthermore, the temporal variation of active subscribers in Fig. 4c is valid for all deployments in a country-wide average.

Aggregating the traffic demands per active PC user over a whole month amounts to a traffic volume of about 64 and 8 Gbytes per month for heavy and ordinary users, respectively.

Note that these traffic demands should be considered as expectations for well established mobile broadband markets beyond 2015. For comparison, in today's mature markets a data volume of 1–3 Gbytes per month counts as very intensive data usage [12–14].

BS type	N_{TRX}	P_{max} [W]	P_0 [W]	Δ_p	P_{sleep} [W]
Macro	6	20.0	130.0	4.7	75.0
RRH	6	20.0	84.0	2.8	56.0
Micro	2	6.3	56.0	2.6	39.0
Pico	2	0.13	6.8	4.0	4.3
Femto	2	0.05	4.8	8.0	2.9

Table 2. *Power model parameters for different BS types.*

Areal Traffic Demand — As the data volume per subscriber does not depend on the deployment scenario, the generated network traffic is proportional to the population density p. Considering a country that is served by N_{op} operators, each operator carrying $1/N_{op}$ of the total traffic, the areal traffic demand for a given deployment is determined by

$$R(t) = \frac{p}{N_{op}} \alpha(t) \sum_k r_k s_k \quad \text{in [Mb/s/}km^2\text{]}, \tag{2}$$

where r_k and s_k denote the average data rate demand and the ratio of subscribers for terminal type k. Note that r_k should be calculated as the weighted average of heavy and ordinary subscribers. For instance, the PC traffic demand for scenario #1 amounts to $r_{PC} = 2 \cdot (0.2 + 0.8/8) = 0.6$ Mb/s. For a country that is served by 3 operators, the average areal traffic demand per operator in dense urban areas at peak hours yields 27.6 Mb/s/km^2 for scenario #1, 51.75 Mb/s/km^2 for scenario #2, and 92 Mb/s/km^2 for scenario #3. The figures for other deployment areas are obtained by substituting the respective population densities in Eq. 2.

Statistical Short-Term Traffic Models

In order to model the fluctuation of the traffic on a short timescale, the traffic distribution in terms of packet arrivals at the BS is modeled statistically. Since the same short-term traffic models per active user are applied in all deployment areas, the traffic demands in a given deployment are derived from the corresponding user density figures. A detailed description of the short-term traffic models can be found in [4].

Energy Efficiency of LTE

Short-term small-scale evaluations are conducted for a macrocellular network with regular hexagonal cell layout. Nineteen sites, each with 3 sectors and 10 MHz bandwidth operating at 2.1 GHz carrier frequency, are assumed. Moreover, for 2 × 2 MIMO transmission, cross-polarized antennas are employed at both BS and user ter-

Since rural areas dominate on a country-wide average, the network operates in a low load regime most of the time, in which case transmissions of control signals dominate over data.

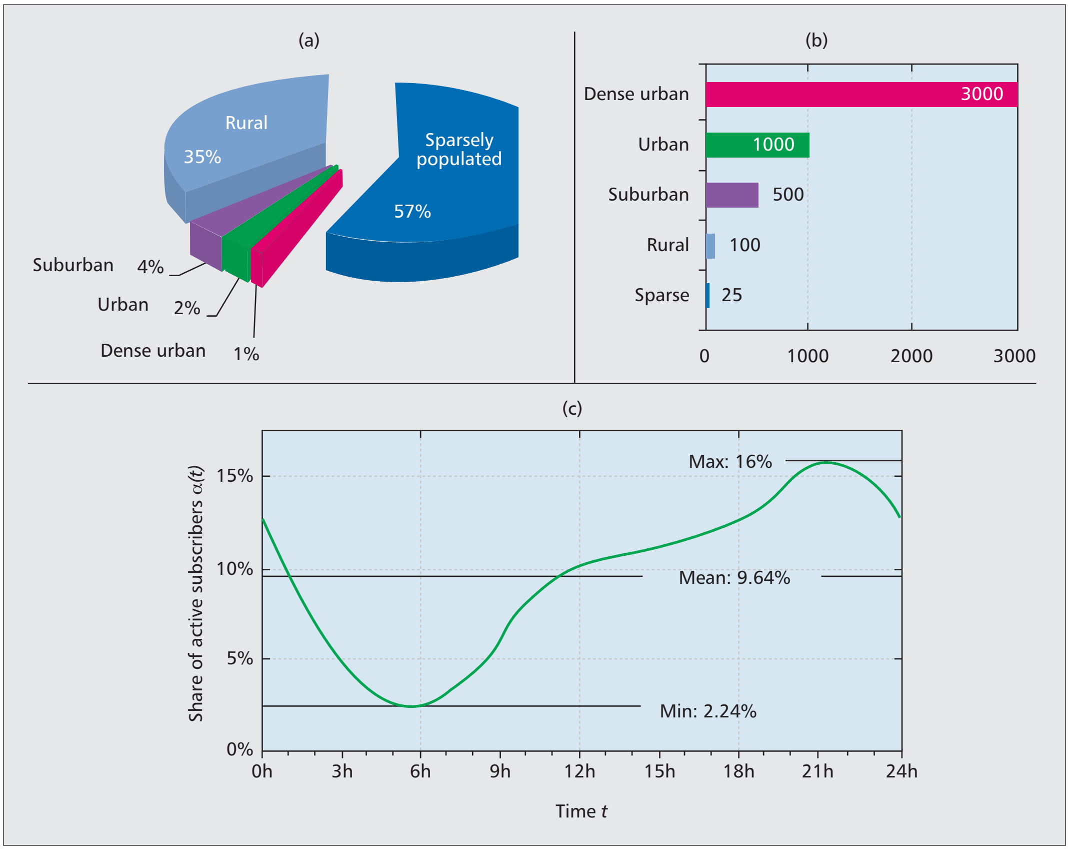

Figure 4. *a) Classification of an average European country into different deployment areas (excluding Nordic countries and Russia); b) their respective population densities; c) average daily data traffic profile taken as a reference for a European country.*

minal. The transmitter utilizes adaptive precoder selection with rank adaptation, whereas the two receive antennas perform minimum mean square error (MMSE) combining for interference suppression. The intersite distance (ISD) for the dense urban and urban environments is set to 500 m, whereas the ISD for suburban and rural areas is 1732 m. In all deployments users are uniformly distributed and move at a velocity of 3 km/h. The simulation parameters are taken from 3GPP specifications [4].

Users arrive in the network according to a Poisson process, and each user downloads a single file of 0.5 Mbytes, referred to as the FTP file download model in [4]. To model different levels of (average) traffic load, system-level simulations are conducted for different user arrival rates. Results are recorded for *stable operational points* only, that is, for operational conditions in which packets, on average, enter and leave the system at the same rate.

Two cases are simulated:
- BSs without sleep mode
- BSs with micro sleep capability during idle transmit intervals [3]

When neither data nor control signals (broadcast channels, scheduling information, synchronization and reference signals, etc.) are to be transmitted, so $P_{out} = 0$ in Eq. 1, a base station may go into micro sleep with reduced power consumption at zero load, $P_{sleep} < P_0$.

Figure 5 shows the power per area unit, P/A, as a function of the traffic load. As can be seen, the power consumption increases with the served network traffic. In an urban scenario, with an ISD of 500 m corresponding to a coverage area of 0.22 km^2/site, the power per area unit is around 4.4 kW/km^2 at low loads, whereas it approaches 5.7 kW/km^2 at high loads. For the network with micro sleep capable BSs, the areal power reduces to 3.55 kW/km^2 at low loads, whereas energy savings are diminished at high loads. The power consumption per area unit for suburban and rural areas is substantially lower, which is due to the increased ISD of 1732 m, corresponding 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 long-term large-scale traffic models. Following the methodology laid out in the preceding section, the aggregated areal power consumption for a representative European country is obtained as follows:
- Determine the traffic demand per area $R(t)$ in Eq. 2 for a certain deployment at a given hour of day.
- Extract the power consumption P/A for that traffic load from Fig. 5.
- Aggregate the P/A values to the global scale by weighted summing over all deployments and over a full day.

In line with the traffic model discussion, no coverage is provided in the sparsely populated areas, and a country served by three operators is considered. Applying the traffic demands for the envisaged scenarios #1 to #3, it turns out that the considered LTE network is unable to always serve the peak traffic demands anticipated for scenario #3, where all subscribers are heavy users. These extreme traffic demands may be satisfied by increasing the bandwidth (20 MHz instead of 10 MHz), adding more sites (effectively reducing the ISD), and/or complementary deployment of low-power BSs in hotspot areas. Since any of these measures affects the power consumption of the considered network, scenario #3 is omitted in the further analysis.

The aggregation to a country-wide average for scenarios #1 and #2, where 20 and 50 percent of the subscribers are classified as heavy users, yields an average areal power consumption of about 0.6 kW/km^2. By introducing micro-sleep-capable BSs, the areal power consumption is reduced to about 0.5 kW/km^2, resulting in energy savings of 15–20 percent. These values are almost independent of whether scenario #1 or #2 is assumed; the power consumption is mostly insensitive to the traffic load. One reason for this is that although at peak hours in dense areas the network is fairly loaded, in rural areas at off-peak hours cells are virtually empty. Since rural areas dominate a country-wide average, the network operates in a low load regime most of the time, in which case transmissions of control signals dominate over data. These evaluations highlight that on average, cellular networks are primarily providing coverage, and therefore mainly operate at low traffic loads.

Energy Efficiency in Real Deployments

The E^{3}F-based system-level simulations output an LTE energy consumption of 0.6 kW/km^2, which translates to an annual energy consumption per subscriber of about 49 kWh/year. In the following the E^{3}F is compared to an approach based on statistical analysis of *real* networks [2], where historical data gathered over the last 15 years is used to project the energy efficiency of cellular network operation until 2020. According to [2], the global number of sites is expected to increase from 3.3 million in 2007 to more than 11 million in 2020. This means that the global BS power consumption may grow from 49 TWh in 2007 to 98 TWh in 2020. Taking into account predictions on the number of mobile subscriptions between 2007 and 2020, the annual BS power per subscription is expected to decrease from about 16.6 kWh/year to 13 kWh/year during the considered period.

The above figures indicate that the LTE energy consumption per subscriber as assessed by the E^{3}F exceeds the current global average and future predictions of [2] by more than a factor of three. This rather large deviation highlights the need to examine some critical assumptions for the system-level evaluations conducted in the previous section. One crucial parameter is the number of BS sites, which vastly impacts the network energy efficiency through the high load-independent power consumption P_0 of the BS power model of Eq. 1. If accompanied with the allocation of lower carrier frequencies, the number of deployed sites may be reduced by extending the ISD. For instance, in Europe the 800 MHz band is allocated for LTE, which practically allows for ISDs of up to 10 km in areas where the traffic demand is sufficiently low. Moreover, allowing operators to share a radio access network, so only one instead of three networks is deployed in quiet areas, may also result in substantial energy savings. Together with the energy efficiency improvements envisaged in [1], it can be concluded that LTE will be able to sustain the current market trends reported in [2].

It must be emphasized, however, that the simulation-based E^{3}F presented in this work exclusively considers LTE and a rather specific mix of propagation conditions and traffic scenarios. In contrast, current and future cellular networks feature a mix of different cell sizes and standards. Despite these obvious differences, a comparison of E^{3}F-based system-level evaluations with real-world data provides valuable insight into the principal effects of LTE deployment on cellular network efficiency. The E^{3}F presented in this work is an enabler to verify enhanced technologies and energy efficiency improvements for commercial viability of a large-scale LTE rollout.

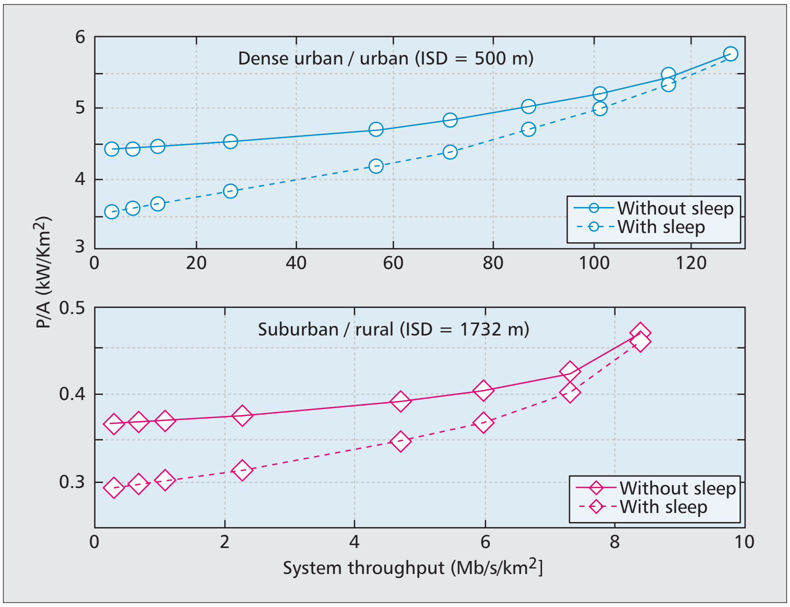

Figure 5. *Power per area unit,* P/A*, of the downlink of a LTE radio access network as a function of the system load. Notice the different scales in both x and y-axis.*

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 aggregate short-term small-scale evaluation results 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

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