Energy Aware Radio and neTwork tecHnologies

SEVENTH FRAMEWORK PROGRAMME

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Energy efficiency analysis of the reference systems, areas of improvements and target breakdown

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Abstract: In order to quantify the energy savings in wireless networks, a holistic view of the power consumption of the entire system needs to be captured. This requires an appropriate energy efficiency evaluation framework. In this deliverable, we present the necessary enhancements over existing performance evaluation frameworks for the wireless networks. The main objective is to capture the factors affecting the energy efficiency at component, node and network level. The most important additions to the existing frameworks include: (1) a sophisticated power model for various BS types, that maps the RF output power radiated at the antenna elements to the total supply power necessary to operate the network; (2) 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; (3) a suitable set of metrics that allows quantifying the amount of energy savings capturing the most important trade-offs between energy savings and maintaining the system capacity, network coverage and quality of service parameters. After presenting the framework and necessary components of the framework, the proposed evaluation framework is applied to quantify the base station energy efficiency of 3GPP LTE. The overall promise of energy efficiency improvement is further investigated qualitatively for different possible areas of improvement in the system and some fundamental technology potential limits are also identified.

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Executive Summary

The document provides the main outline and requirements for the evaluation framework along with the other useful components that will enable overall evaluation of the energy efficiency like the traffic and deployment models, power model for the base station and the suitable metrics to be used for such evaluations. It then provides an example of using the framework to evaluate the performance of a baseline system and also highlights the important areas for the improvement in energy efficiency.

Evaluation Framework

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 framework comprises methodologies and metrics that allow for a fair comparison between different networks, e.g. between the EARTH baseline system [EARTH-D2.2] and a system with (individual or combination of several) integrated EARTH innovations. This framework is the first effort that allows assessing EE at system level and is intended to become a widely accepted tool in the mobile-broadband industry and in the associated scientific community.

Traffic Model and Deployment

We provide realistic models for the deployment mix within Europe (relative ratio of different types of deployment areas), along with long-term and short-term traffic models and reasonable assumptions that enable meaningful estimates of the energy efficiency of a typical deployment of cellular infrastructure in Europe.

Power Model for LTE Baseline System

To evaluate the benefits of the EARTH solutions it is very important that we employ an appropriate power model for all types of LTE Base Stations. In [EARTH-D2.2] a baseline configuration for a macro BS (i.e. for a BS used in macro-cell network deployment) is given as well as configurations for micro, pico and femto BSs. Here, the power consumption models of all these BS scenarios are derived. The main focus is given to the radio hardware, which is the major contributor on the overall BS energy consumption.

Metrics and System Level Evaluation

In a situation where not only the spectrum utilization and the user QoS, but also the network energy (or equivalently power) consumption, is of importance, the analysis must be extended such that the energy utilization is considered as well. In this report the evaluations are mainly performed assuming a file download service, in which each user downloads a single packet of a given size. To capture the energy consumption perspective in the analysis, in addition to the traditional quality performance metrics, we employ the *Power per area unit* and the *Energy per bit* energy consumption metrics.

Evaluation of Reference System

To demonstrate the handling of the energy efficiency evaluation framework we provide a downlink evaluation of the reference system as described in [EARTH-D2.2]. More specifically, we provide a small-scale, short-term evaluation in three scenarios. The derived LTE baseline system power model is used in order to monitor the energy consumption of the network and the appropriate performance metrics are adopted. According to the data statistics obtained from the traffic model and deployment analysis, the aggregation to global scale is provided.

Breakdown of Potential Improvement Areas

The EARTH project aims to improve the energy efficiency of wireless systems at component, node and system level. A considerable potential for energy saving is expected from advances in BS components; the energy utilisation of a single BS multiplied by the total large number of BSs in the network leads to extensive total energy consumption. The power consumed by the BS consists of a fixed and a variable part. One important target of the EARTH project is to reduce both parts by improved component design, carefully planned algorithms and sophisticated methodology. Furthermore, the investigation and optimisation of the power consumption of various BS types, tailored to work in different environments, will help to decrease the overall system energy consumption. In addition, deployment, management and cooperation of BSs may offer saving potential on system level. In that direction, the areas for potential improvement in energy consumption are introduced and an estimation of their contribution in conserving energy is presented.

Fundamental Challenges and Outlook of Future Potential

Finally, a closer analysis on the challenges and the possibilities for the research area of network energy efficiency is provided. Traditionally, radio access research both in the academy and the industry focuses on the challenge to achieve as high data rates as possible for a given maximum transmission power. Closer analyzing the challenges and the possibilities for the research area of network energy efficiency it is found that there is a second challenge, which is still not widely addressed or even accepted in the community; that is the power consumption of the system when it is not transmitting any data. The EARTH-reference scenario simulations of a network covering the dense urban, the urban and the sub-urban areas of a country or region, yield that more than 98% of the subframes do not contain any transmitted data. The number of subframes not used for data transmission can be seen as a form of theoretical limit for how large the potential is for the second challenge in addition to the power reduction achievable by features addressing subframes that are utilized for data transmissions. Moreover, an overview is provided for the areas that the project explores for potential savings in energy consumption of cellular network. Analysis of all tracks is currently ongoing and first results are presented in the EARTH deliverables [EARTH-D3.1] and [EARTH-D4.1]. Eventually, the evaluation framework will be used to compare the different approaches and to select the most promising tracks for deeper analysis and validation of potential savings during the second half of the project.

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Acronyms and Abbreviations

3GPP	3rd Generation Partnership Project
ACI	Adjacent Channel Interference
ACLR	Adjacent Channel Leakage power Ratio
ADC	Analogue-to-Digital Converter
AMC	Adaptive Modulation and Coding
ARQ	Automatic Repeat Request
BB	Baseband
BLER	Block Error Rate
BLS	Baseline System
BS	Base Station
BW	Bandwidth
cdf	Cumulative distribution function
CoMP	Coordinated Multi-Point
CQI	Channel Quality Indicator
CRS	Cell Reference Signals
DAC	Digital-to-Analogue Converter
DC	Direct Current
DL	Downlink
DSP	Digital Signal Processing
DTX	Discontinuous Transmission
E-UTRAN	Evolved UTRAN
EARTH	Energy Aware Radio and neTwork technologies
EE	Energy Efficiency
EESM	Effective Exponential SIR Mapping
eNB	E-UTRAN NodeB
EPRE	Energy Per Resource Element
FTP	File Transfer Protocol
GPRS	General Packet Radio Service
GSM	Global System for Mobile communications
HARQ	Hybrid ARQ
HetNet	Heterogeneous Network
HSPA	High-Speed Packet Access
HW	Hardware
IF	Intermediate-Frequency
IP	Internet Protocol
ITU	International Telecommunications Union
LTE	Long Term Evolution
L2S	Link-to-System level
LO	Local Oscillator
MAP	Maximum *A Posteriori*
MCI	Max C/I per chunk
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input Multiple-Output
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OPA PA	PA with Operating Point Adjustment
PA	Power Amplifier

PAPR	Peak-to-Average Power Ratio
PBCH	Physical Broadcast Channel
PCFICH	Physical Control Format Indicator Channel
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PHY	Physical Layer
PRB	Physical Resource Block
PON	Passive Optical Networks
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
PSS	Primary Synchronization Signal
RAN	Radio Access Network
RAT	Radio Access Technology
RF	Radio Frequency
RE	Resource Element
RLC	Radio Link Control
ROADM	Reconfigurable Add/Drop Multiplexers
RRH	Remote Radio Head
RRM	Radio Resource Management
RS	Reference Signal
RX	Receiver
SD PA	PA with Stage Deactivation
SiNAD	Signal-to-Noise And Distortion ratio
SID	Silence Insertion Descriptor
SIR	Signal-to-Interference Ratio
SINR	Signal-to-Interference plus Noise Ratio
SNR	Signal-to-Noise Ratio
SON	Self-Organizing Network
SOTA	State-Of-The-Art
SSS	Secondary Synchronization Signal
TCP	Transmission Control Protocol
TRX	Transceiver
TX	Transmitter
UDP	User Datagram Protocol
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
UL	Uplink
UTRAN	UMTS Terrestrial RAN
VAF	Voice Activity Factor
VGA	Variable Gain Amplifier
VoIP	Voice over IP
WP	Work Package

1. INTRODUCTION

The ICT sector in general and mobile communication in particular has a considerable potential to decrease CO_2 footprint of other sectors, e.g. the transport sector. This ability and will of the ICT industry has recently been manifested through the joint Guadalajara ICT declaration [ICT-Cop16] presented at the UN Climate Change conference COP16 which has been signed by more than 40 ICT companies. In order to be credible, it is most essential for ICT and mobile industry to show that we are actively working on our own CO_2 footprint and energy efficiency. It is also a way for the industry to lead by example and at the same time gain valuable insight in how to improve energy efficiency from own experience. An added advantage will be a lower running cost for the operators of the system improving the viability of the business and future services on wireless communication networks. EARTH project is a concerted effort to achieve this goal and as part of its objectives, aims to develop a holistic framework to evaluate and compare the energy efficiency of several design approaches of wireless cellular communication network. This document aims at outlining this framework and the rest of the document is organised as follows.

In Chapter 2, a suitable energy efficiency evaluation framework is defined to capture the overall system power consumption. Ultimately, this global E^3F, by encompassing methodologies, models and metrics which allow for a reasonable comparison between different strategies and networks, shall enable the quantification of the potential energy savings in wireless systems. The essential building blocks with the required level of detail are identified and analysed in this report. In Chapter 3, realistic long-term traffic models along with large-scale models for the deployment mix in Europe are provided, complementing the existing short-term and small-scale scenarios in order to enable a holistic evaluation of the energy efficiency. In Chapter 4, an appropriate and sophisticated power consumption model describing each Base Station type (from LTE baseline system) is developed. The scope of the power model is to constitute the interface between component and system level, allowing to quantify how energy savings on specific components enhance the energy efficiency at the node and network level. In order to quantify the possible benefits of different technology solutions, well-defined and relevant performance metrics are adopted and presented in Chapter 5. The quality performance metrics, recommended by 3GPP, along with the *Power per area unit* and the *Energy per bit* energy consumption metrics are employed to provide the assessment of the overall performance and the *overall energy savings* at network level. Chapter 6 demonstrates the handling of the energy efficiency evaluation framework and provides an example which identifies the necessary steps leading to the overall system evaluation. The reference system evaluations will also deliver the reference results for comparison with the innovative EARTH tracks, and they will provide guidance for the selection of the most promising tracks. In Chapter 7, the areas for potential improvement on energy efficiency over the reference system are introduced. The range of these promising approaches at component, node and system level is described highlighting the important areas for improvement and, as an example of estimated energy savings, we show results of assessment and synergy gain in case of different packet scheduler and power amplifier alliances. Finally, Chapter 8 concludes this document and provides an overview of the fundamental challenges and the future potential of the areas the EARTH project explores for improvements of energy efficiency.

2. 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 system level. The computed results, e.g. the system or user throughput measured in bit/s, are usually represented by a cumulative distribution function (cdf). In order to ensure that results generated by different RAN system simulation tools are comparable, well defined reference systems and scenarios are to be specified. This is the result of extensive consensus work from standardization bodies, such as 3GPP [TR36.814R9], and international research projects, such as the EU project Wireless World Initiative New Radio (WINNER) [WINNER-D6.13.7], 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. In that direction, the EARTH reference system and scenarios [EARTH-D2.2] build on the 3GPP evaluation framework for LTE [TR36.814R9].

However, to assess the system energy efficiency, contemporary RAN performance evaluation frameworks, such as the one used in 3GPP for LTE [TR36.814R9], exhibit several major shortcomings:

- The system performance is optimized for capacity and evaluated at full load, which, in the context of energy efficiency evaluations, implies that the system is poorly configured for the very important low load and no load scenarios.
- Performance evaluation is limited to a small geographic area, e.g. 57 hexagonal cells as specified in [TR36.814R9].
- The performance evaluation is considering only the RF-transmission power, taken as output power at the antennas. A proper modelling of nodes and components that contribute to the overall power consumption of the entire radio access network is absent.
- Performance metrics that accurately measure the energy efficiency are missing.

2.1. EARTH E^3F OVERVIEW

In this section, 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, over an extended time frame can be quantified.

The EARTH E^3F identifies the essential building blocks and the required level of detail that are necessary for an accurate holistic assessment of energy efficiency enhancements. The EARTH E^3F primarily builds on well-established methodology for radio network performance evaluation developed in 3GPP; the most important addendums are to add a sophisticated power model of the BSs, as well as a large-scale long-term traffic model extension to existing 3GPP traffic scenarios. Although the specific realization of a system level simulation tool largely depends on the specific problem at hand, as well as the chosen software implementation, it is envisaged that for the assessment of the EARTH innovations integrated into one holistic system concept, the EARTH E^3F, in general, captures the following aspects:

- A sophisticated power model (specified in Chapter 4), that maps the RF output power radiated at the antenna elements to the total supply power necessary to run a BS site, is developed. 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 Chapter 3), that describe load fluctuations over a day, are introduced to complement the statistical short-term traffic models.
- Large-scale deployment models (developed in Chapter 3) of large geographical areas are considered to extend the existing small-scale deployment scenarios.
- Improvements on node level for energy efficient radio transmission techniques that translate into savings for the entire network. This includes multiple antenna systems, link adaptation and HARQ protocols. The framework must also take into account the required energy for the associated baseband signal processing operations.
- Energy efficient radio resource management (RRM), comprising e.g.
    - energy efficient power and resource allocation, possibly coordinated over neighbouring BSs;
    - discontinuous transmission (DTX) and reception (DRX), where micro-sleep is utilized for energy savings on an OFDM symbol, sub-frame or (multi) frame level;
    - bandwidth adaptation dependent on the BS load.
- Deployments deviating from the classical macro-cellular topology. This includes heterogeneous networks, where the classical macro-cellular topology is complemented by low power nodes, such as micro-, pico- or femto-cells, as well as relays. Here, also the energy consumption of the backhaul needs to be captured. Extensions to multi-hop ad-hoc networks, where user terminals transfer and/or relay information to other users without a network infrastructure, should also be covered.
- Sophisticated energy efficiency metrics are defined in Chapter 5.

Ideally, the E^3F should allow for arbitrary combinations of the above features. In practice, however, owing to the prohibitive complexity to implement a comprehensive simulator that captures all the above features, it may be difficult to cover all of the above combinations with a unique simulation tool; rather, specific embodiments of a system level simulation tool are typically tailored to examine certain techniques, and may not cover all features of the E^3F.

2.2. GLOBAL E^3F

In order to extend the existing small-scale, short-term evaluation frameworks 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 (see Chapter 3) are to be integrated into the E^3F. The principle of the holistic EARTH E^3F is shown in FIGURE 1.

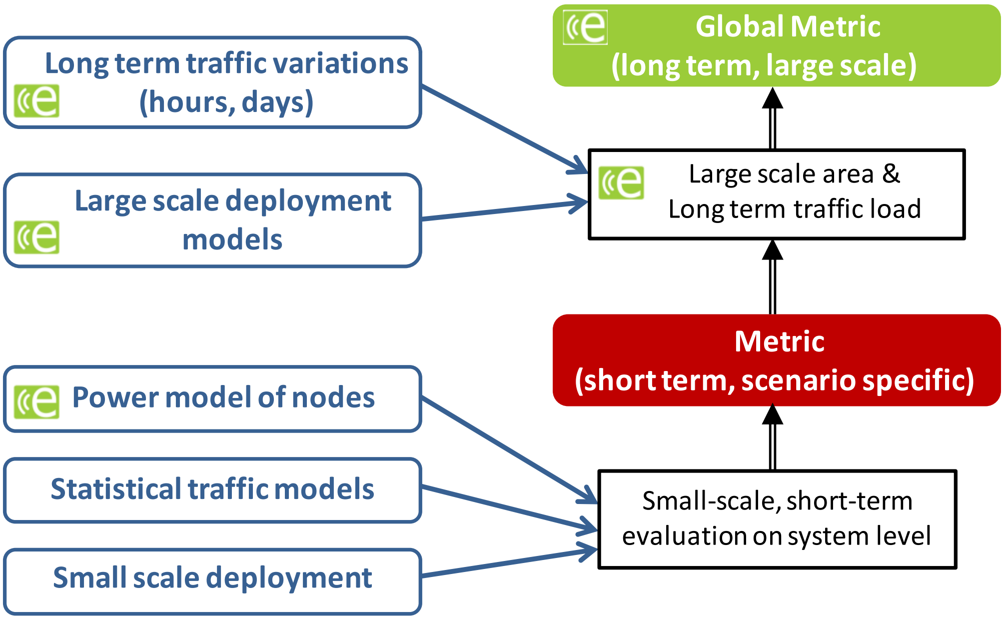


FIGURE 1. Global energy efficiency evaluation framework (E^3F)

The 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, as further described in Section 2.3. These evaluations are conducted for all scenarios (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 (see Chapter 3). The system level evaluations provide energy consumption and other performance (e.g. throughput, QoS) assessment for each small-scale deployment in reliance on the traffic load (see Chapter 3). This allows computing the energy efficiency metrics for each scenario, as defined in Chapter 5.

These small-scale, short-term evaluations fail to capture the energy efficiency of the entire network which typically comprises:

- Networks include rural areas and densely populated areas, with different small-scale deployments for each of these areas.
- The load situation of a network varies radically over the time of a day and a week; network Management may dynamically reconfigure the network to the observed traffic variations, in order to always operate in an energy efficient mode.

As shown in FIGURE 1, for a global assessment of network energy efficiency, these aspects need to be included by weighted summing of all the small-scale energy consumption evaluations. Long-term traffic variations specify the traffic load *x* over time, for a given scenario, as shown in FIGURE 5. In that manner, the long-term performance for a certain scenario is determined. Finally, the mix of deployment scenarios that quantify the area covered by cities, suburbs, highways and villages, as depicted in FIGURE 4, yield the global set of the large-scale system energy consumption and performance evaluations. Using these outputs from the E^3F, the energy consumption index and other system metrics, discussed in Chapter 5, can be computed.

2.3. SMALL-SCALE, SHORT-TERM SYSTEM LEVEL EVALUATIONS

The small-scale, short-term system level evaluations (right bottom block in FIGURE 1) are carried out by a RAN system level simulation platform, augmented by a model capturing the power consumption of RAN components. The specific simulator implementation and the necessary level of detail largely depends on the particular problem at hand, so that further abstractions may often be justified, resulting in simplified simulation tools which should be used with care (see Section 2.3.1). Nevertheless, an accurate assessment of integrated solutions as a whole does essentially require a *dynamic system level simulator,* where time variations of the served traffic, the radio resource management (RRM) and the PHY are modelled on an OFDM symbol basis.

The block diagram of a generic dynamic system level simulation tool is illustrated in FIGURE 2.

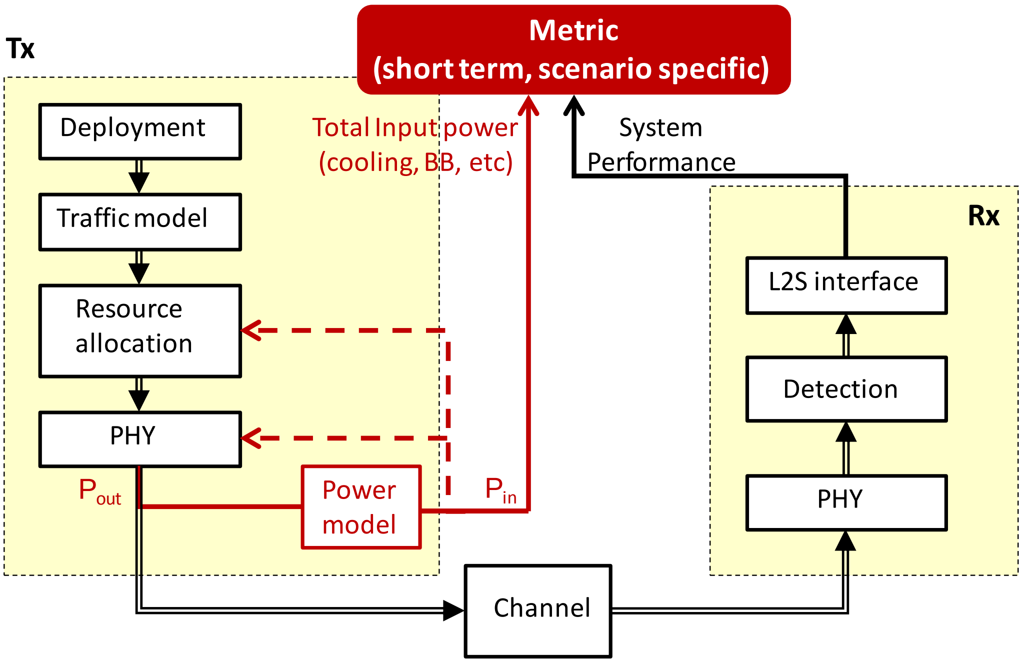


FIGURE 2. Placement of the power model in a RAN system level simulation platform extended for EARTH EE evaluations. In DL transmission the Tx-block is the BS and the Rx-block is denoting the mobile device.

The prohibitive complexity of today's wireless networks makes a certain level of idealisation unavoidable; yet the dynamic system level simulation tools available today, utilized e.g. for the standardization of LTE within 3GPP, are able to assess the performance of a "real" network with reasonable accuracy. While the basic structure of the simulator in FIGURE 2 essentially resembles the state-of-the-art in the performance evaluation of wireless networks, the important added value developed within the EARTH project is the integration of a sophisticated power model, as introduced in Chapter 4, into the simulator (drawn with red in FIGURE 2 so as to highlight the novel EARTH contribution). 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. The detailed implementation between different embodiments of a system level simulator may substantially differ; however, there are a number of important properties regarding the power model, mandated by the holistic EARTH approach that calls for the assessment of the *overall* energy savings of improvements on component, node and network level:

- For comprehensive performance analysis, an *instantaneous power model* is required to capture the dynamics and transient behaviour of the power amplifier to changes in its operation mode, e.g. powering on from micro-sleep mode and vice versa. The same also applies to the other components of a network node responsible for power consumption.
- The simulator must be able to capture approaches where the resource utilization and/or the radio transmission part (block PHY in FIGURE 2) are operating in an energy aware way, i.e. resource allocation and modulation scheme are optimized with respect to the required input power of the node, P_{in}, as opposed to the transmitted RF output power P_{out} at the antenna elements (this adaption is marked by the dashed lines in FIGURE 2). The time scale for such adaptations may be as short as one OFDM symbol and smaller.

It is fully acknowledged that various approaches to enhance energy efficiency can be accurately assessed in simulators that incorporate further abstractions and idealizations, as further elaborated in Section 2.3.1. As long as the underlying assumptions are justified, a reliable performance evaluation at significantly reduced complexity and run-time is maintained. On the other hand, the assessment of the overall energy savings that are attained by the combination of the most promising tracks, e.g. by a combination of an energy efficient scheduler with a heterogeneous deployment, in general, requires dynamic system level simulations (along the lines shown in FIGURE 1 and FIGURE 2).

The basic building blocks of a dynamic system level simulator, as shown in FIGURE 2, are briefly described in the following.

- **Deployment**: specifies the deployment scenario (e.g. dense urban), the BS specification (antenna configuration, maximum transmission power, etc.) and the BS site locations, e.g. hexagonal macro-cellular layout consisting of 19 sites, with 3 sectors per site. Mobile users are randomly dropped, following a uniform distribution, or clustered non-uniform distribution to resemble hot spots [EARTH-D2.2]. This block includes the association of mobile users to their serving BS, typically the BS with the lowest path-loss (including log-normal shadowing).
- **Traffic model**: instantaneous traffic variations per mobile user, described by statistical traffic models, e.g. FTP file download or VoIP calls [EARTH-D2.2].
- **Resource allocation**: the assignment of physical resource blocks (PRBs) to mobile users in time, frequency and space, to be generated for all BS sites in the network.
- **PHY**: includes the framing/deframing operation at the transmitter/receiver, inserting control information and reference signals (pilots) to facilitate channel estimation. Furthermore, MIMO processing and modulation are performed. The PHY is typically subject to abstractions so as to avoid the complexity of detailed baseband processing (e.g. channel coding, channel estimation, etc.).
- **Power model**: defines the interface between component and node/network level. The power model maps the consumed input power, P_{in}, to achieve a certain RF output power, P_{out}, at the antenna, as is elaborated in detail in Chapter 4.
- **Channel**: comprises all transmitter-to-receiver links (in the downlink all BSs to all mobile links) in the network. This includes the intended links, as well as the interference between adjacent cells. The channel of one link is composed of distance dependent path-loss, log-normal shadowing and time-variant frequency-selective fading. For signals that penetrate into buildings, wall penetration losses

are to be added. In case of MIMO transmission, one channel realization is to be generated between each transmit and receive antenna element.

- **Detection**: the signal to interference plus noise ratio (SINR) for each transmitted symbol is determined.
- **L2S interface**: given the SINR per symbol per user, the desired figures of merit are determined, e.g. user throughput, block error rates (BLER), delay, etc. Different mappings between the input (SINR) and the output, and their respective accuracy, are discussed in [BAS+2005].
- **Metrics**: Together with the power consumption, system and user throughputs, as well as other QoS figures are gathered to calculate the associated metrics defined in Chapter 5.

2.3.1. Implementations of System Level Evaluations

Energy efficiency analysis based on dynamic system level simulations with the full modelling depth of MAC and PHY as described above is quite demanding on calculation power and in many cases is overloading. Thus, it may have limited capabilities to analyse the huge parameter space and to model all relevant aspects (e.g. effects on below symbol level time granularity or the performance of advanced iterative receiver algorithms).

A modelling approach which is tailored to the object of investigation may yield better insight into fundamental limits and trade-offs and will allow investigating the vast number of combinations of different tracks to identify the best integrated solutions. Different tailored implementations of the E^3F will be used for the analysis of the different tracks in EARTH.

As an example, in the case where improvements of the power efficiency of node hardware do not change the link transmission performance, further simulator abstractions are feasible. Instead of re-computing the simulator performance with different power models, those can be applied successively to the simulator output of the baseline system to evaluate the effect of hardware improvements. This requires dynamic system simulations to provide the scheduled resource utilisation level per OFDM symbol duration as output, modelling the actual interface between baseband processing and power amplifier. Such output from the simulator can further be used to generate test signals for a test bed setup, so that, within the framework, the simulation results of energy savings can be compared to actual measurement results of the hardware components developed by EARTH.

In many cases, energy savings achieved on the node level are assessed by means of link-level simulations; these are relevant for parameter optimization and testing with reasonable runtime. Comparison with a conventional solution does then allow getting a coarse understanding of the potential gains that may be achieved. On the other hand, contemporary cellular networks are operated with an *aggressive frequency reuse* of the available resources, meaning that the attainable performance of today's networks is critically dependent on *inter-cell interference*. To this end, impressive gains observed at the link level might diminish when evaluating the performance at system level. Hence, it is necessary to validate link-level results by selected simulations on system level.

Examples of such cases regard energy saving approaches like DTX duty cycles of the transmission, adaptation of the bandwidth or changes of the antenna configuration. Based on well selected dynamic system simulations, the relative energy saving effect of these measures can be calculated using an abstracted model of the resource allocation or channel performance. However, higher order effects may impact the energy consumption, e.g. caused by a reduction of the dynamic channel diversity gains. In these cases, it may be necessary to validate the trends and trade-offs by selected simulations with higher modelling depth.

2.3.2. Visualisation of the System Level Evaluations

The results of EARTH including the understanding of trade-offs and of interdependencies of approaches can be utilised to provide a visualisation tool that demonstrates the effects of energy saving approaches and their combination researched in EARTH.

This requires a bibliotheca of system level evaluations of small-scale scenarios with evaluations on radio interface (PHY), component or node level, which comprise the base line system, single track improvements and scenarios with combined improvements of EARTH tracks. The impact of hardware improvements, of variations in large scale deployments and of energy aware network management can be then directly calculated by applying the global E^3F framework on this bibliotheca.

3. TRAFFIC MODEL AND DEPLOYMENT

In order to provide a realistic analysis of the energy efficiency of a mobile system, it is essential to know what kind of traffic demands should be served by the network. Thus, it is important to identify and define the spatial and temporal variation of the traffic demands both on large-scale and small-scale.

This chapter is organized as follows. First, the deployment related structure of the European countries is introduced by presenting the population density in different areas of the countries and identifying the ratio in these countries that corresponds to each specific area. The relevant areas identified by the EARTH project are dense urban, urban, rural and suburban areas.

After that, we introduce long-term, large-scale traffic models by:

- describing the amount of data traffic one can expect in the different deployment areas;
- presenting how active the subscribers are;
- describing the amount of voice traffic the subscribers generate.

Finally, we introduce short-term, small-scale traffic models by describing reference applications to be used when modelling the fluctuation of the traffic in short timescale.

Note that the usage of the traffic and deployment models in the global E^3F framework is presented in Section 6.2, where the short-term, small-scale evaluation of the reference system is aggregated to a global level.

3.1. DEPLOYMENT AREAS OF EUROPE

Population density in different deployment areas of Europe[1] is shown in FIGURE 3. The reference values for EARTH are also provided in the same figure. According to this, we can identify five deployment area categories with the following population densities[2]:

- dense urban areas with 3000 citizen/km^2 on average;
- urban areas with 1000 citizen/km^2 on average;
- suburban areas with 500 citizen/km^2 on average;
- rural areas with 100 citizen/km^2 on average;
- sparsely populated & wilderness with 25 citizen/km^2 on average.

[1] The figures were derived based on the reports of national statistics agencies of Europe from 2007-2008.

[2] The numbers represents Europe excluding Russia, Norway, Sweden and Finland. These four countries have very low population density compared to other parts of Europe because of their relatively large sparsely populated and wilderness areas.

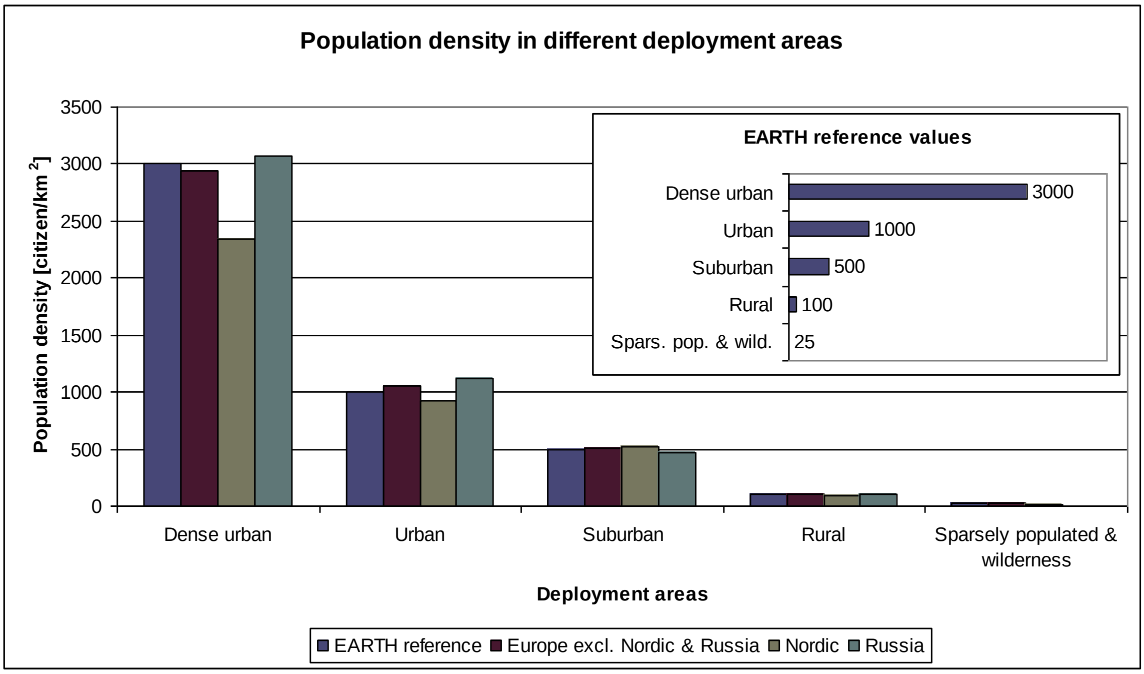


FIGURE 3. Population densities in different deployment areas of Europe

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. FIGURE 4 shows the ratio of different deployment areas in Europe. The reference values for EARTH are also provided in the same figure.

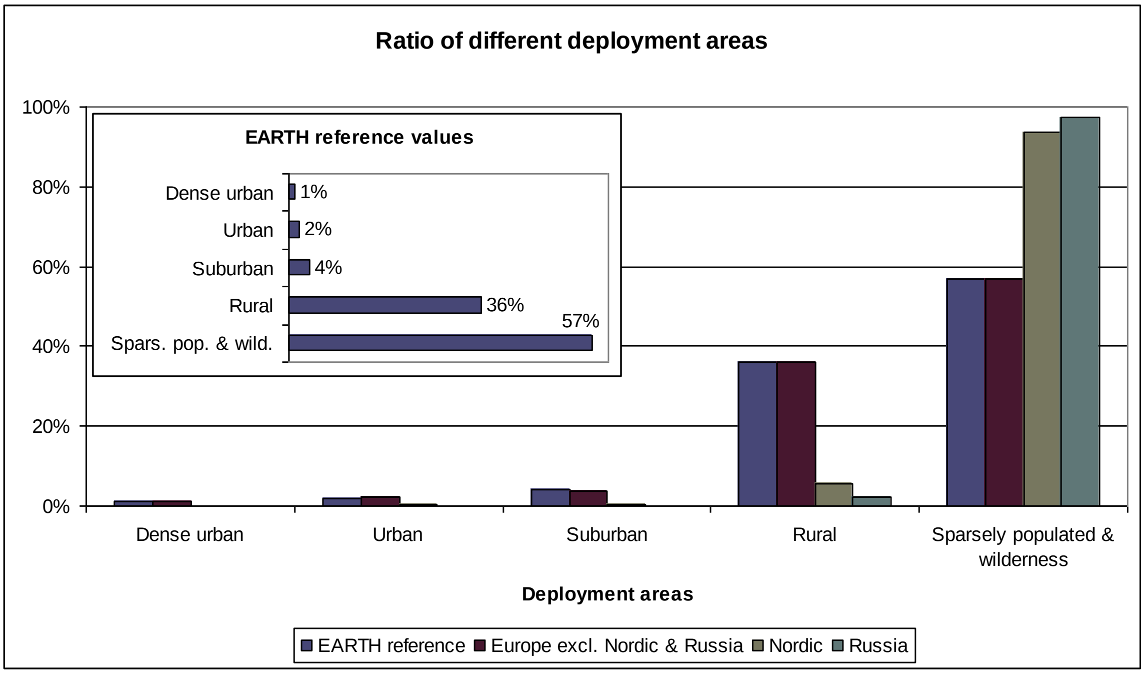


FIGURE 4. Ratio of different deployment areas in Europe

According to the current situation in Europe (see, e.g., [NMIA2010]), the coverage of the newest mobile technologies is focusing on the population and not on the amount of the area. That is, while 2G area coverage is almost 100%, the 3G coverage is hardly 40%. This reflects that the sparsely populated areas and the wilderness are served on the minimum service level defined by national telecommunication authorities, i.e., voice (2G) and low speed data connection (GPRS).

The question is whether LTE will continue this trend or LTE will be used for providing "broadband for everyone" even in sparsely populated areas. In any case, since the deployments of LTE are and will be launched in line with current 3G deployment plans, the EARTH project focuses on dense urban, urban, suburban and rural areas in its traffic models. The question of sparsely populated and wilderness might be addressed later during the project[3].

3.2. LONG-TERM LARGE-SCALE TRAFFIC MODELS

During the optimal planning of the network deployment setup and the management of the networks, the long-scale traffic models are of extreme importance. The long-scale traffic models have three parts and presented in the following order: data user activity, the data traffic model, the voice/VoIP traffic model. The traffic model presented in this section is based on the UMTS forum's mobile traffic forecast [UMTSforum2011].

Note that the macro/micro/pico/femto scenarios are not the basis of the models, but controversially the traffic models together with the model of the deployment areas determine whether a macro cell or a micro cell can serve the actual traffic demand of a given region. In other words, the energy efficiency optimization solutions will determine whether, e.g., a macro or a micro cell would be the better choice to serve the given traffic.

3.2.1. Data User Activity Model

Beyond the volume of the traffic, it is also important to know how many users are active in a given region. The project has found that a) the daily variation of the number of active users is analogous to the daily variation of the traffic (see FIGURE 5), and b) 10-30% of the data subscribers are active in the busy/peak hours in today's networks. Similarly to the traffic of particular cells, in case of active users one can also see significant differences compared to the averages, e.g. one or two "heavy" users can fully utilize a cell even for longer time periods. According to the expectations towards wireless Internet services, the ratio of mobile PC users of the whole population will increase from year to year and in the most mature European markets may reach 25% by 2014. As European average, we calculate with 20% mobile PC users and also include the emerging terminal types such as smartphones and tablets. These terminals further stimulate traffic demands and boost the expected number of mobile broadband subscribers. In sum, the reference values to be used in EARTH are as follows:

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

- A large portion of the population will be mobile data subscribers: 20%, 5% and 50% of the population are (mobile) PC, tablet and smartphone users, respectively.
- Heavy users request the following data rates: PC, tablet and smartphone users demand an hourly average data rate of 2 Mbps, 1 Mbps and 250 kbps, respectively. These rates represent a range from

[3] For example, German regulation forces to deploy LTE 800 to serve 90% of population with wideband access. This would allow skipping the scarcely populated areas which host 12% of the population according to the data provided in this section. In [BundesTelekom2009] - sections 4.4.4 and 4.4.5, it is stated that the operator has to cover 25% of users by 2014 and 50% by 2016, but 90% of users in a list of cities by 2016. At first, cities with up to 5,000 inhabitants are addressed and only after 90% of the users are covered, cities with 5,000 - 20,000 are allowed to be addressed.

high-definition video streaming with a display resolutions of 1,280x720 pixels (720p HD) to intensive web browsing, which accumulates to a data volume of 900 MB/hour and 112.5 MB/hour, respectively.

- Ordinary users demand for 1/8 of the respective heavy user rates.
- The number of active users in the busy/peak hours is 16% of the subscribers. On average over a day, the activity level is 9.64 %

3.2.2. Data Traffic Model

Abstracting the models from the current cell planning maps of Europe, we present the daily traffic variation of the traffic as the actual traffic demand of a given area, i.e., how many kbps should be delivered per square kilometre. Note that the range of daily variation is quite connected to operator policies and data buckets of subscriptions, i.e., the daily maximums are 2-10 times higher than the daily minimums. FIGURE 5 illustrates the typical daily variation α(*t*) in Europe, and provides the reference values for traffic peaks (based on which the actual values of the profiles can be calculated). We use two user categories: heavy user and ordinary user. A heavy user consumes 900MB/hour and the ordinary user consumes 112.5MB/hour. By adjusting the ratio of heavy users, different scenarios can be constructed that reflect the expected share of mobile broadband subscribers:

- *Scenario #1*: 20% of the subscribers are classified as heavy users. This means that the 20% 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% 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.
- *Scenario #4:* serves as reference scenario for the contemporary traffic demand, where 10% of the population are reference PC users in 2010, of which 10% are classfied as heavy users with rates 125 kbps. The remaining 90% of ordinary users consume a data rate of 31 kbps.

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 $1/N_{\mathrm{op}}$ of the total traffic, the areal traffic demand for a given deployment is determined by

$$R(t) = \frac{p}{N_{op}} \alpha(t) \sum\nolimits_k r_k s_k \quad in\, [\mathrm{Mbps/km^2}] \qquad \text{(3-1)}$$

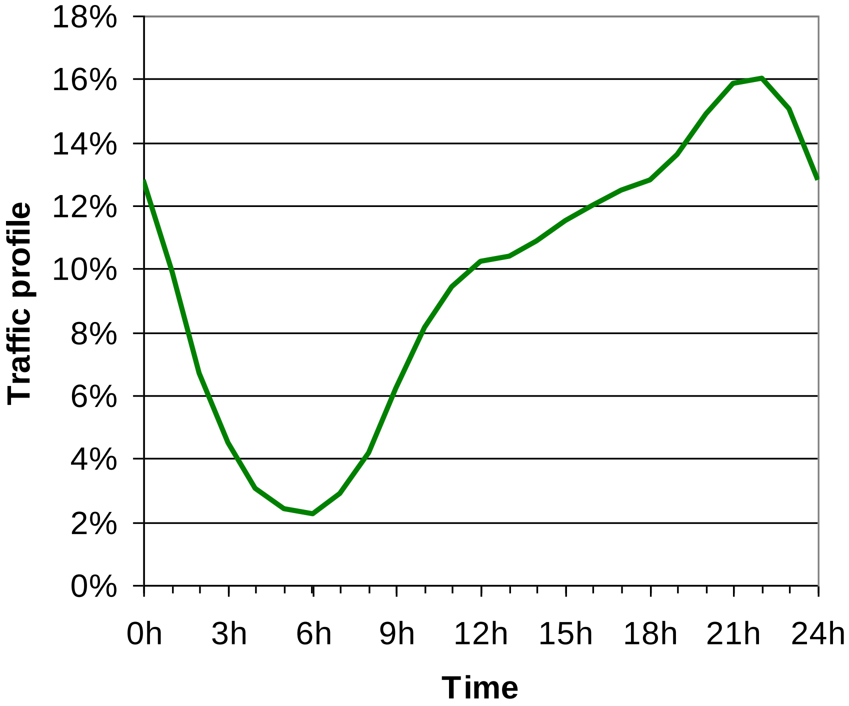
where r_k and s_k denote the average data rate demand and the ratio of subscribers for terminal type k. Note that r_k should be calculated as the weighted average of heavy and ordinary subscribers. For instance, the PC traffic demand for scenario $\#1$ amounts to $r_{\mathrm{PC}} = 2\cdot(0.2+0.8/8)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

Aggregating the traffic demands per active PC user over a whole month amounts to a traffic volume of about 64 and 8 GB/month for heavy and ordinary users, respectively. Please note that the above numbers are higher than what one can see in 3G networks in 2010, but should be considered as a projection for the future of Europe with well-established mobile broadband networks for beyond 2015; e.g., in today mature markets 1-3 GByte data traffic per month per subscriber accounts as very intensive data traffic usage (see [Akamai2010], [NMIA2010b] and [SPTA2010]).

TABLE 1 shows the peak area throughput and number of active users per cell at peak traffic served by 3 operators for dense urban environment with 3000 citizen/km^2 and 500 m inter-site distance between base stations.

TABLE 1. Estimated area throughput and number of active users at busy hours served by 3 operators in a dense urban cell in Europe of 2015

Scenarios	**Ratio of heavy users**	**Peak area throughput**		**Active users** per cell per operator
		total [Mbps/km^2]	per operator [Mbps/km^2]	
#1	20% heavy users	83	28	$8-9$
#2	50% heavy users	155	52	$8-9$
#3	100% heavy users	276	92	$8-9$
#4	Reference PC only scenario from 2010 with 10% heavy users	2	0.65	$1-2$



t	α(t)
0h	13%
1h	10%
2h	7%
3h	4%
4h	3%
5h	2%
6h	2%
7h	3%
8h	4%
9h	6%
10h	8%
11h	9%
12h	10%

t	α(t)
13h	10%
14h	11%
15h	12%
16h	12%
17h	12%
18h	13%
19h	14%
20h	15%
21h	16%
22h	16%
23h	15%
24h	13%

FIGURE 5. Illustration of data traffic average daily profile $\alpha(t)$ in Europe

Somewhat connected to the population density, it is natural that the dense urban areas have the most traffic demands. The ratio of the traffic demands in deployment areas other than dense urban is shown in FIGURE 6. For each area type, a typical range and a reference value are given according to current cell planning maps of Europe:

- the traffic in urban areas is between 20% and 40% of dense urban areas and we propose to use 33.3% as reference;
- the traffic in suburban areas is between 5% and 20% of dense urban areas and we propose to use 16.7% as reference;
- the traffic in rural areas is less than 5% of dense urban areas using and we propose to use 3.3% as reference.

As an example, FIGURE 6 also includes the daily traffic profiles of the different deployment areas of Europe. The shape of the profiles in a first approximation can be considered to be independent of the particular area, just the absolute values are downscaled according to the above reference values.

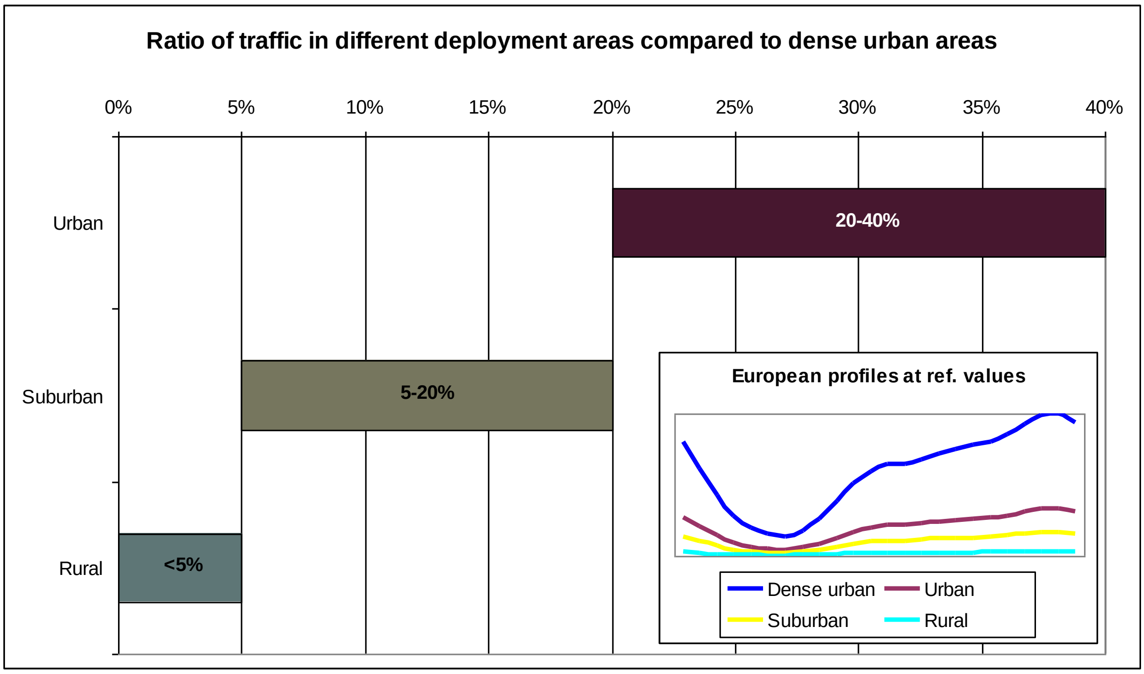


FIGURE 6. Daily traffic profile of different deployment areas

As a conclusion, the reference numbers for the data traffic peaks in different deployment areas can be found in TABLE 2.

TABLE 2. Data traffic peaks in deployment areas

Deployment area	#1: 20% heavy users	#2: 50% heavy users	#3: 100% heavy users
Dense urban	83 Mbps/km^2	155 Mbps/km^2	276 Mbps/km^2
Urban	28 Mbps/km^2	52 Mbps/km^2	92 Mbps/km^2
Suburban	14 Mbps/km^2	26 Mbps/km^2	46 Mbps/km^2
Rural	2.8 Mbps/km^2	5.2 Mbps/km^2	9.2 Mbps/km^2

We have to note that in particular cells, there can be significant differences compared to the averages, e.g., crowded areas can have 2 or even 5 times higher traffic above the average daily curves. Moreover, in hotspots, one can see 10-15 times higher traffic than the peaks of the averages at any time, i.e., in such areas the cells are utilized to the technology limits. We also have to note that there can be areas just to provide coverage and such areas are practically empty in the lowest traffic hours.

3.2.3. Voice/VoIP Traffic Model

Despite the fact that voice traffic is volume-wise negligible in broadband networks, it is prioritized over data traffic as universal service to be provided to everyone. The voice activity of people is different in different regions of the world [IE MARKET RESEARCH] as illustrated in FIGURE 7. As a reference voice traffic activity to be used in EARTH 180 minutes per month per subscriber (MoU) value is chosen, which roughly corresponds to typical European user behaviour and is not assumed to be drastically changed in the near future.

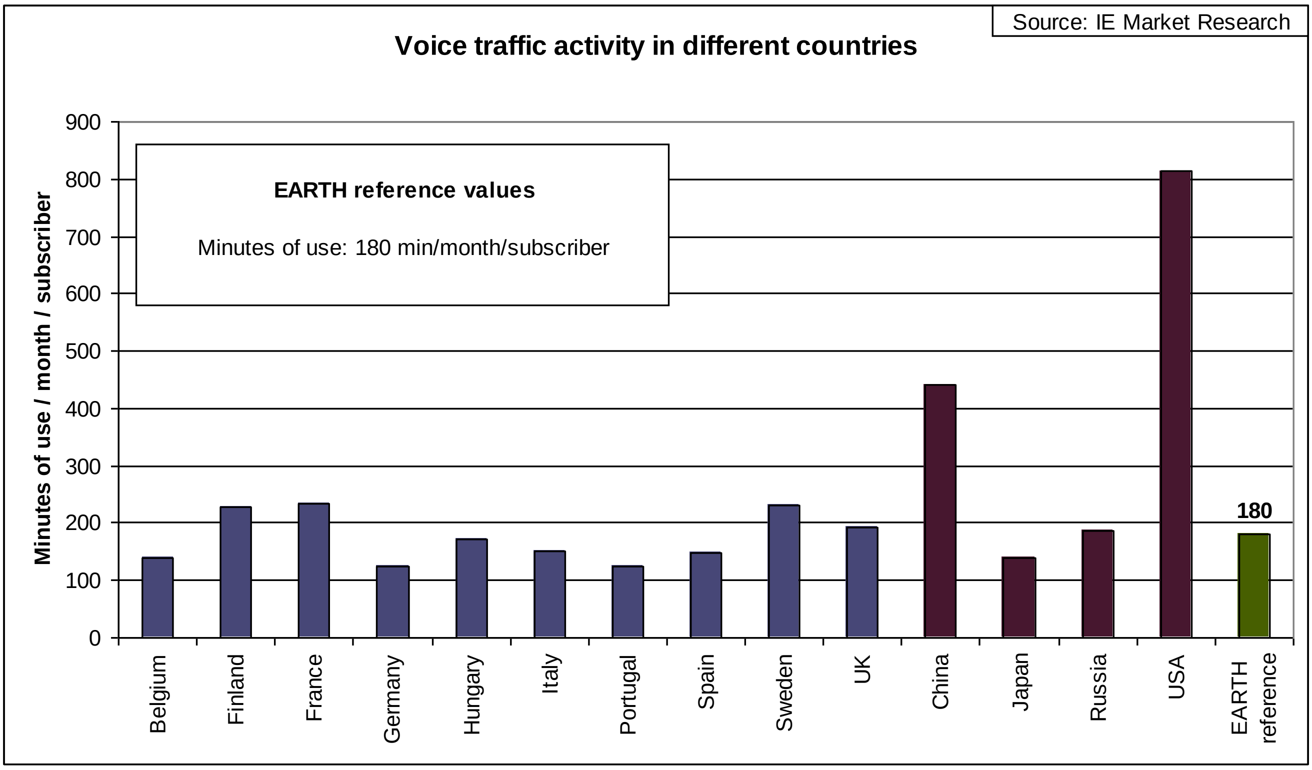


FIGURE 7. Voice traffic activity in different countries

The daily variation of the voice activities is connected to the culture and daily life of people, e.g., the voice activity is practically zero in the night. On the other hand, operator policies and pricing greatly influence the current shape and typical aim to distribute the daylight traffic as much evenly as possible, i.e., the “peak” is not a single hour but a high activity typically between 9am and 19pm. In spite of that aim, there are local maximums, e.g., in the early working hours and at the end of working hours or early evening. FIGURE 8 illustrates the daily variation of the voice traffic intensity.

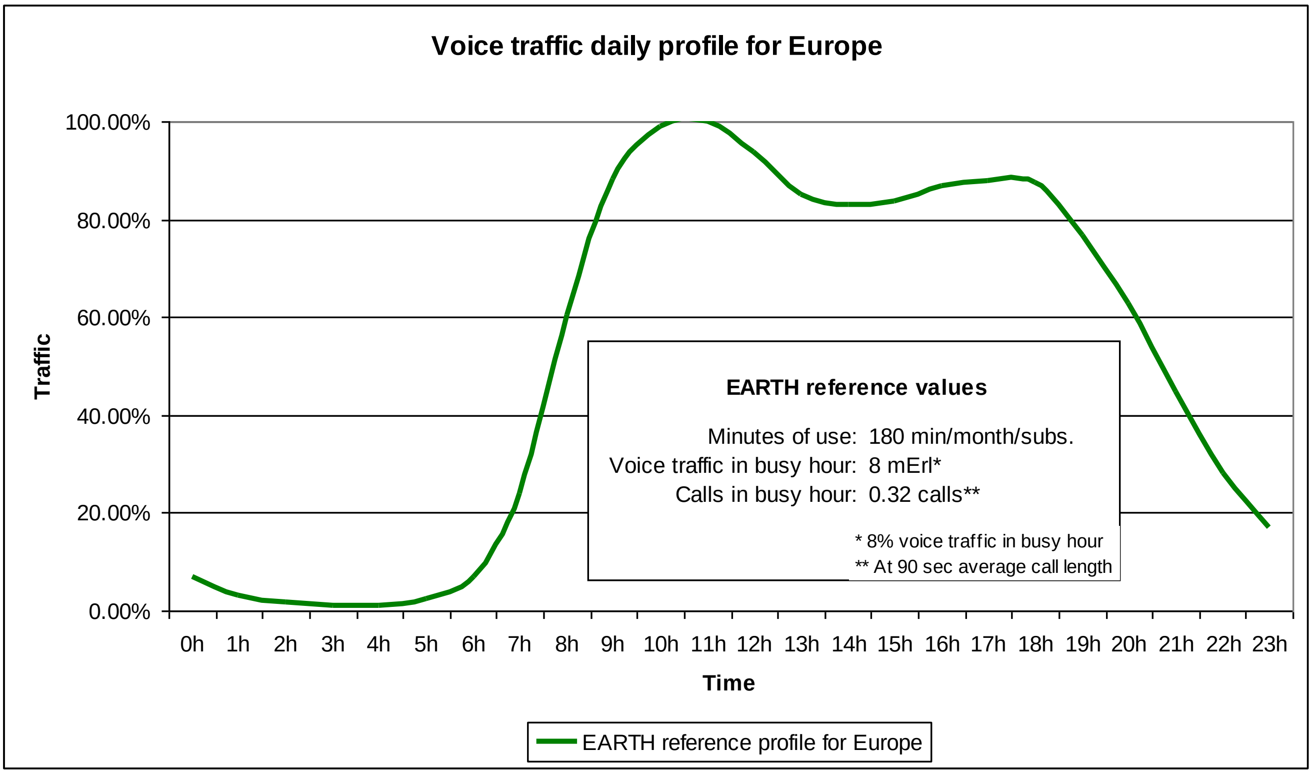


FIGURE 8. Illustration of voice traffic average daily profile in Europe

Based on the daily profile, one can calculate the busy/peak hour activity [mErl] and the number of busy hour calls. Roughly 8% of the voice calls are in the busy hour, which corresponds to 8mErl. If we assume that the average call length is 90 seconds, than one get that there are 0.32 calls per subscriber in the busy hour.

Note that the VoIP traffic is simply a technical realization of the voice traffic, e.g., in LTE, but the main user behaviour is assumed to be the same independently of the technical realization.

In sum, the reference values to be used in EARTH are as follows:

- the ratio of voice users is 100% of the whole population;
- 8% of the calls are in the busy/peak hour, i.e., 0.32 calls of 90 seconds corresponding to 8mErl activity;
- i.e., these all roughly corresponds to 150 calls in the busy/peak hour in a typical urban cell.

3.3. SHORT-TERM, SMALL-SCALE TRAFFIC MODELS

In order to model the fluctuation of the traffic in short-time scale, one needs to know how the particular packets of the traffic are generated by different types of applications. As a consequence, the same short-scale traffic models should be applied per subscriber in all deployment areas and for all types of cells. The differences among the different various deployment areas and types of cells simply come from the differences in the corresponding user density figures.

In order to keep the simplicity and usability of the EARTH model for the most of the network simulators, we applied the following abstractions and simplifications:

- in higher traffic situations, full buffer maximum load considerations and FTP models are proposed;

- in lower traffic situations, FTP models and VoIP traffic models are proposed.

More detailed and advanced traffic models are out of scope of the current document; however, they can be found in [EARTH-D2.2]. Traffic models for system performance evaluations are provided in TABLE 3 based on [TR36.814R9].

TABLE 3. Traffic Models

Traffic Models	Models apply to
Full buffer	DL and UL continuous traffic and non-varying interference
Non-full buffer FTP model	DL and UL bursty traffic
VoIP	DL and UL real-time services

3.3.1. FTP Traffic Model

TABLE 4 shows the parameters for the FTP traffic models based on [TR36.814R9]: Model #1 is the baseline model, while Model #2 can be chosen to speed-up the simulations and to model more bursty background traffic.

TABLE 4. FTP traffic model

Parameters	Statistical characteristics	
	Model #1	Model #2 (optional)
File size, S	2 MB, single file download	10/100/500 kB, single file download
User arrival rate, λ	Poisson distributed with arrival rate λ Possible values of λ: [0.12, 0.25, 0.37, 0.5, 0.625]	Poisson distributed with arrival rate λ Possible values of λ: [0.5, 1, 1.5, 2, 2.5]

FIGURE 9 illustrates the user arrival process of the FTP traffic model.

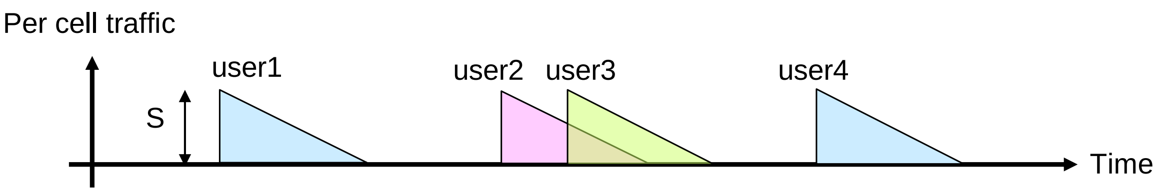


FIGURE 9. Traffic generation for FTP models

We have to note that the practical file download sizes visible in live networks can be considerably larger, e.g., 10MB for a high quality MP3 track and even 100MB in case of a shared video. Based on the LTE background and simulator knowledge of the project, however, the proposed file sizes allow us to investigate not only the LTE specific system parameters, but also to check the inherent properties of the TCP slow start and congestion avoidance which greatly effects real-life file downloads.

3.3.2. VoIP Traffic Model

The VoIP traffic model is based on the simple 2-state voice activity model illustrated by FIGURE 10.

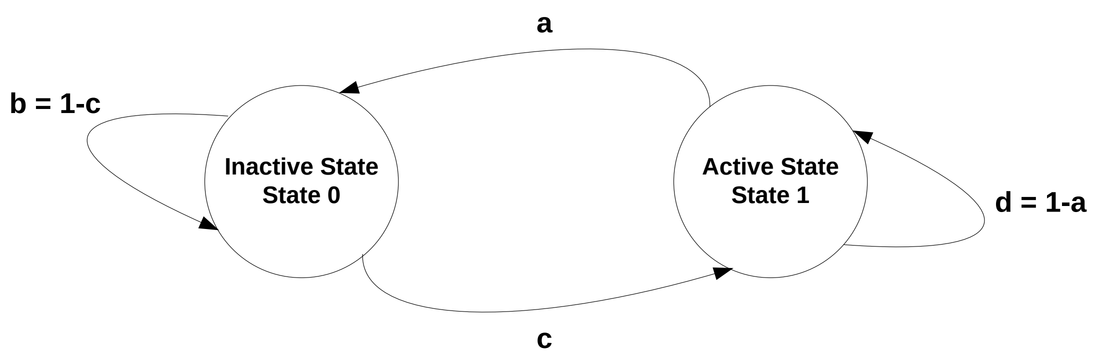


FIGURE 10. 2-state voice activity model

In the model, the probability of transition from state 1 (active speech state) to state 0 (inactive or silent state) is equal to “a”, while the probability of transition from state 0 to state 1 is “c”. The model is assumed updated at the speech encoder frame rate R = 1/T, where T stands for the encoder frame duration. TABLE 5 lists the relevant parameters of the VoIP traffic that should be considered in the simulations.

TABLE 5. Relevant parameters of VoIP traffic

Parameter	Characterization
Voice activity factor (VAF)	50% (c = 0.01, d = 0.99)
Silence Insertion Descriptor (SID) payload	Modelled 15 Bytes (5 Bytes + header) SID packet every 160 ms during silence
Protocol Overhead with compressed header	10 bit + padding (RTP-pre-header) 4 Byte (RTP/UDP/IP) 2 Byte (RLC/security) 16 bits (CRC)

Note that:

- the system bandwidth for VoIP simulations is reduced to 5 MHz for all cases and the baseline overhead assumed in the simulations shall be scaled accordingly;
- a VoIP user is not satisfied if the 98% radio interface tail latency of that user is greater than 50 ms;
- end-to-end delay lower than 200 ms is assumed for mobile-to-mobile communications;
- the system capacity is defined as the number of users in the cell when more than 95% of the users are satisfied.

4. POWER MODEL FOR LTE BASELINE SYSTEM

This chapter 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.

In order to perform an accurate estimation of the BS power consumption, we proceed as following:

1. By using a bottom-up approach, we define a BS high-level block diagram with the main radio HW components for each BS type;
2. Then, the power consumption in Watts is estimated individually for each sub-component at maximum load, which is the RF power needed to be complaint with the release 8 LTE standard;
3. Finally, the power consumption of a BS is evaluated as a function of signal load.

4.1. HIGH-LEVEL BASE STATION ANALYSIS

FIGURE 11 shows a simplified block diagram of a complete BS that can be generalized to all BS types, including macro, micro, pico and femto BSs. In general, it is made of multiple transceivers (TRXs) with multiple antennas.

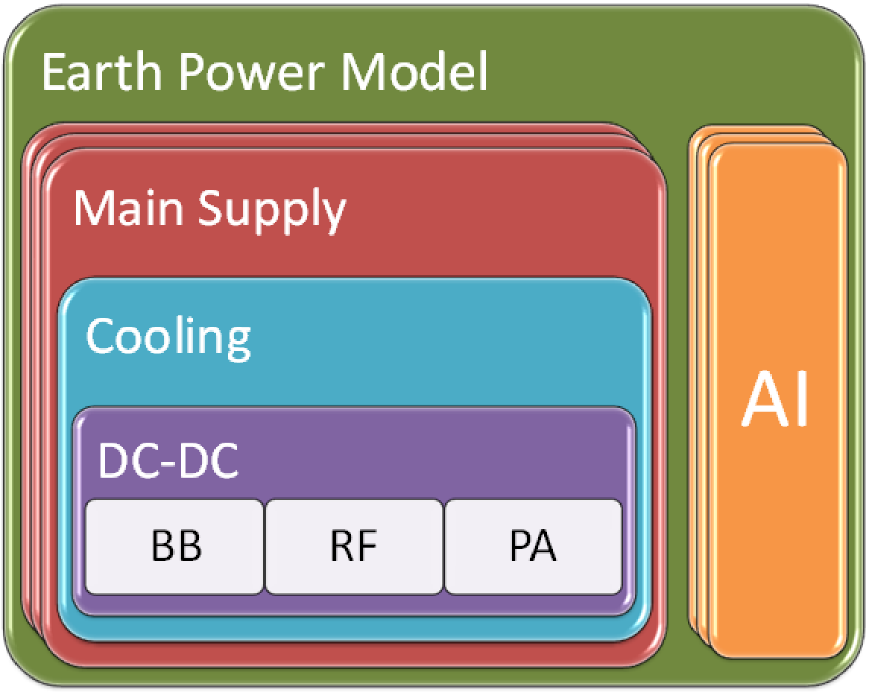


FIGURE 11. Simplified block diagram of a base station transceiver.

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 (Main Supply) for connection to the electrical power grid.

In the following the various TRX parts are analyzed.

4.1.1. Antenna Interface (AI)

The influence of the antenna type on power efficiency is modeled by a certain amount of losses, including the feeder, antenna band-pass filters, duplexers, and matching components. For macro BS a feeder loss of about σ_{feed} = 3 dB needs to be added, while the feeder loss for smaller BS types is typically negligible. The feeder loss of macro BSs may be mitigated by introducing a remote radio head (RRH), where the PA is mounted at the same physical location as the transmit antenna.

4.1.2. 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 [Cripps2006]. 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 η_{PA}, which translates to a high power consumption P_{PA}. Digital techniques such as clipping and digital pre-distortion [Xu2010, KiStKi+2005] in combination with Doherty PAs [Cripps2006] 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. 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.

4.1.3. Small-Signal RF Transceiver (RF TRX)

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 [DeGiGo+2011]. Parameters with highest impact on the RF-TRX energy consumption P_{RF}, are generally 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.

4.1.4. Baseband 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 [Borkar1999]. 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.

4.1.5. DC-DC, Cooling and Main Supply

Losses incurred by DC-DC power supply, main 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, and the removal of feeder losses σ_{feed} allows for a lower output power of the PA.

4.2. BS POWER CONSUMPTION AT MAXIMUM LOAD

This section defines a State-of-the-Art (SOTA) BS power consumption estimation assuming maximum load conditions. In order to provide a technology independent SOTA, we will define two SOTA values for **2010** and **2012**. The 2010 SOTA values correspond to a typical commercially available BS of the year 2010, which is the starting point of the EARTH project and is used as basis for most studies. However, such BSs were typically designed some years ago and hence based on SOTA components of that time. Since the EARTH project also will consider improvements on component level, there is a need to define additional SOTA values based on SOTA components of today in order not to let this work benefit from mere technology scaling. Hence, we introduce 2012 SOTA values, assuming a two years lead time from the design of a BS until commercial availability. Both results can however be combined assuming a technology scaling based on a literature study. TABLE 6 and TABLE 7 summarize and compare the power consumption of different BS types for 2010 and 2012 as reference years, respectively.

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, $P_{out} = P_{max}$, amounts to

$$P_{\mathrm{in}} = N_{\mathrm{TRX}} \cdot \frac{\dfrac{P_{\mathrm{out}}}{\eta_{\mathrm{PA}} \cdot (1-\sigma_{\mathrm{feed}})} + P_{\mathrm{RF}} + P_{\mathrm{BB}}}{(1-\sigma_{\mathrm{DC}})(1-\sigma_{\mathrm{MS}})(1-\sigma_{\mathrm{cool}})} \tag{4-2}$$

where the term $P_{\mathrm{PA}} = P_{\mathrm{out}} / \eta_{\mathrm{PA}}$ accounts for the power consumption of the PA. The *efficiency* is defined by $\eta = P_{out} / P_{in}$, whereas the *loss* factor is defined by $\sigma = 1 - \eta$. 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).

Note that the maximum RF output power per transmit antenna, P_{max}, 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.

In general, the BS energy efficiency degrades for smaller BS types, due to growing cost constraints for the more consumer type low power nodes, expressed in a lower power efficiency $\eta = P_{out} / P_{in}$, and a larger loss factor $\sigma = 1-\eta$. By introducing remote radio heads (RRHs), where feeder losses σ_{feed} and active cooling are avoided by mounting the PA close to the transmit antenna, the power savings for macro BS exceed 40%.

TABLE 6. LTE BS transceiver power consumption. **2010** State-of-the-Art estimation for different BS types.

			Macro	Remote Radio Head (RRH)	Micro	Pico	Femto/Home
PA	Max Transmit rms power	[dBm]	46.0	43.0	38.0	21.0	17.0
	Max Transmit rms power	[W]	39.8	20.0	6.3	0.13	0.1
	PAPR	[dB]	8.0	8.0	8.0	12.0	12.0
	Peak Output Power	[dBm]	54.0	51.0	46.0	33.0	29.0
	Pdc	**[W]**	**128.2**	**64.4**	**27.7**	**1.9**	**1.1**
	Power-Added Efficiency	[%]	31.1	31.1	22.8	6.7	4.4
TRX	Max Transmit rms power	[dBm]	-8.0	-11.0	-13.0	-13.0	-17.0
	TX Pdc	[W]	6.8	6.8	3.4	0.4	0.2
	RX Pdc	[W]	6.1	6.1	3.1	0.4	0.3
	Total Pdc	**[W]**	**13.0**	**13.0**	**6.5**	**1.0**	**0.6**
BB	Radio [inner rx/tx]	[W]	10.8	10.8	9.1	1.2	1.0
	LTE turbo [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 Pdc	**[W]**	**29.5**	**29.5**	**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
Main Supply	σ_{MS}	[%]	9.0	9.0	9.0	11.0	11.0
Total 1 Radio		**[W]**	**225.0**	**125.8**	**72.3**	**7.3**	**5.2**
# Sectors		#	3.0	3.0	1.0	1.0	1.0
#PAs/Antennas		#	2.0	2.0	2.0	2.0	2.0
# Carriers		#	1.0	1.0	1.0	1.0	1.0
Total N Radios		**[W]**	**1350.0**	**754.8**	**144.6**	**14.7**	**10.4**

TABLE 7. LTE BS transceiver power consumption. **2012** State-of-the-Art estimation for different BS types.

			Macro	Remote Radio Head (RRH)	Micro	Pico	Femto/Home
PA	Max Transmit rms power	[dBm]	46.0	43.0	38.0	21.0	17.0
	Max Transmit rms power	[W]	39.8	20.0	6.3	0.13	0.1
	PAPR	[dB]	8.0	8.0	8.0	12.0	12.0
	Peak Output Power	[dBm]	54.0	51.0	46.0	33.0	29.0
	Pdc	**[W]**	**102.6**	**51.5**	**22.1**	**1.6**	**1.0**
	Power-Added Efficiency	[%]	38.8	38.8	28.5	8.0	5.2
TRX	Max Transmit rms power	[dBm]	-8.0	-11.0	-13.0	-13.0	-17.0
	TX Pdc	[W]	5.7	5.7	2.9	0.4	0.2
	RX Pdc	[W]	5.1	5.1	2.6	0.4	0.2
	Total Pdc	**[W]**	**10.9**	**10.9**	**5.4**	**0.7**	**0.4**
BB	Radio [inner rx/tx]	[W]	5.4	5.4	4.6	0.6	0.5
	LTE turbo [outer rx/tx]	[W]	4.4	4.4	4.1	0.7	0.6
	Processors	[W]	5.0	5.0	5.0	0.2	0.1
	Total Pdc	**[W]**	**14.8**	**14.8**	**13.6**	**1.5**	**1.2**
DC-DC	σ_{DC}	[%]	6.0	6.0	6.4	8.0	8.0
Cooling	σ_{COOL}	[%]	9.0	0.0	0.0	0.0	0.0
Main Supply	σ_{MS}	[%]	7.0	7.0	7.2	10	10
Total 1 Radio		**[W]**	**160.8**	**88.0**	**47.0**	**4.5**	**3.1**
# Sectors		#	3.0	3.0	1.0	1.0	1.0
#PAs/Antennas		#	2.0	2.0	2.0	2.0	2.0
# Carriers		#	1.0	1.0	1.0	1.0	1.0
Total N Radios		**[W]**	**964.9**	**527.9**	**94.0**	**9.0**	**6.2**

FIGURE 12 shows the DC power consumption breakdown for different types of BSs at maximum load. It is interesting to note that in Macro BSs it is mainly the PA that dominates the total power consumption, owing to the high antenna interface losses. On the other hand, the breakdown is more balanced in micro BSs. Remarkably, in smaller BSs like pico and femto, it is the baseband part that dominates the overall power consumption.

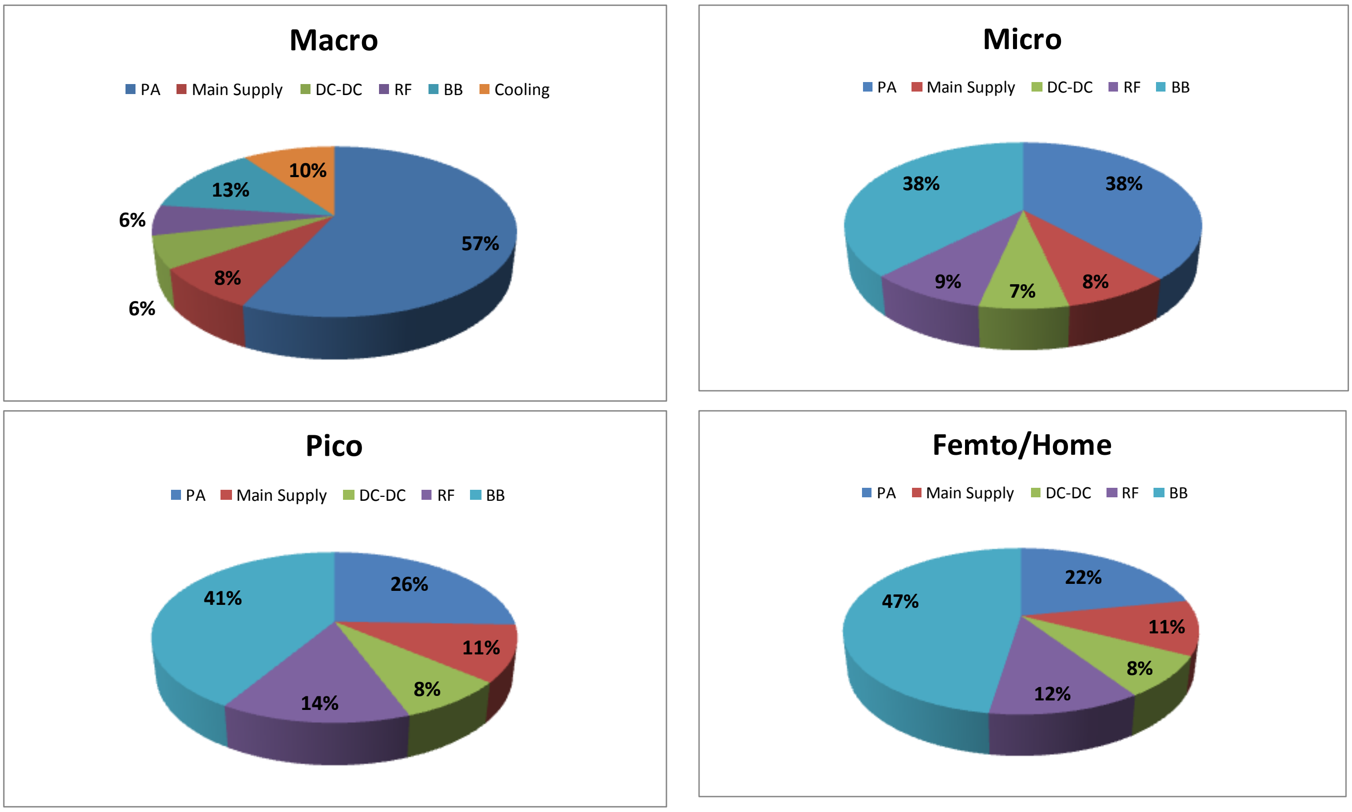


FIGURE 12. BS power consumption breakdown for different deployment scenarios.

4.3. 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.

FIGURE 13 shows BS power consumption curves for a LTE system with 10 MHz bandwidth and 2x2 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. In contrast, the share of BB power consumption increases in smaller BS types. 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.

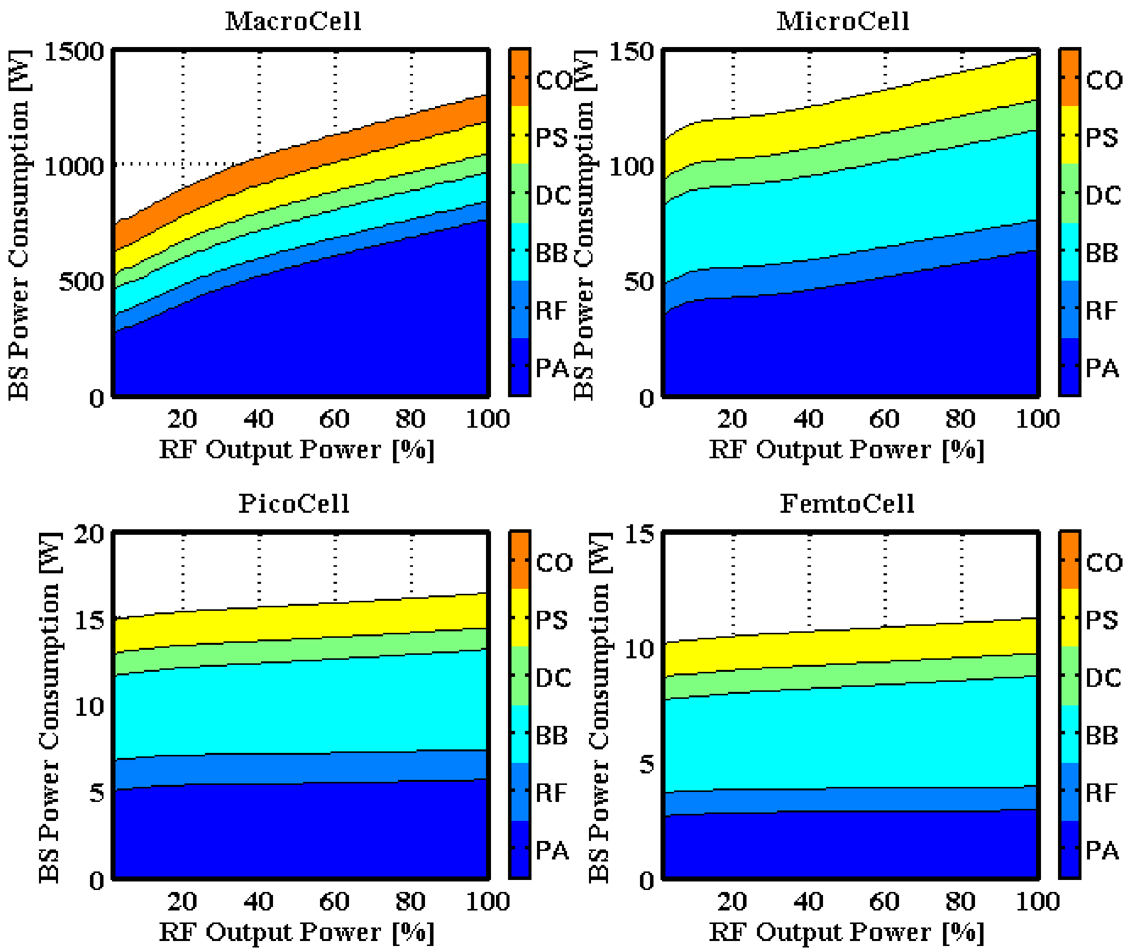


FIGURE 13. Power consumption dependency on relative linear output power in all BS types for a 10MHz bandwidth, 2x2 MIMO configurations and 3 sectors (only Macro) scenario based on the 2010 State-of-the-Art estimation. Legend: PA=Power Amplifier, RF=small signal RF transceiver, BB=Baseband processor, DC: DC-DC converters, CO: Cooling, PS: AC/DC Power Supply.

As can be seen in FIGURE 13, 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:

$$P_{in} = \begin{cases} N_{TRX} \cdot (P_0 + \Delta_p P_{out}), & 0 < P_{out} \le P_{max} \\ N_{TRX} \cdot P_{sleep}, & P_{out} = 0 \end{cases} \tag{4-3}$$

where P_{max} denotes the maximum RF output power at maximum load, P_0 is the linear model parameter to represent power consumption at the zero RF output power (it is actually estimated using the power consumption calculated at a reasonably low output power, assumed to be 1% of P_{max},) and Δ_p is the slope of the load dependent power consumption. The parameters for the different BS types based on the 2010 State-of-the-Art estimation are summarized in TABLE 8. In future BSs, 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. The sleep mode power consumption (P_{sleep}) is introduced in the same table to capture solutions for future base stations.

TABLE 8. Power model parameters for different BS types

BS type	N_{TRX}	P_{max} [W]	P_0 [W]	Δ_P	P_{sleep} [W]
Macro	6	20	130.0	4.7	75.0
RRH	6	20	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

5. PERFORMANCE METRICS FOR SYSTEM LEVEL EVALUATIONS

The work in EARTH to reduce the energy consumption of mobile broadband networks aims at improvements on component, node, and network levels. At all levels it is important that well-defined and relevant performance metrics are adopted in order to quantify the possible benefits of different technology solutions. This chapter describes the performance metrics that are adopted in order to assess the performance of the radio network, both in terms of user quality of service, served traffic, and energy consumption.

5.1. NETWORK PERFORMANCE METRICS

Traditionally, the design and analysis of radio networks has been performed assuming that spectrum is a scarce resource and an important objective has hence been to maximize the number of bits that can be delivered, or the number of users that can be supported, in a given time and within a certain bandwidth. The operation of the network can, however, not only be guided by the overall throughput but also by the quality of service (QoS) experienced by the users.

Depending on the service considered, dissimilar quality performance metrics are employed. For example, the user data rate may be an appropriate quality metric for a file download service whereas for VoIP, the user satisfaction may be determined by the fraction of packets that arrive within a certain delay bound. Most traffic classes have already been extensively studied in, e.g., 3GPP, ITU, and in academia where the descriptions of proper metrics to be applied exist in order to monitor the radio quality. Some examples are available in, e.g., [TR36.814R9] and [ITU2135].

An increased level of served traffic implies that the available radio resources (e.g., power and bandwidth) in a cell must be shared among a larger set of users, and also that the interference from neighbouring cells increases. Thus, it is typical that, independently of the quality performance metric used, the quality decreases with increasing network traffic load. A common problem formulation is to maximize the throughput in the network given some QoS constraint.

In a situation where not only the spectrum utilization and the user QoS, but also the network energy (or equivalently power) consumption levels, are of importance, the analysis must be extended such that the energy utilization is considered as well. It may generally be assumed that whereas the quality decreases with increasing traffic load, the energy consumption typically increases with it, as illustrated in the schematic picture in FIGURE 14. Consequently, when the traffic load increases it may not always be possible to combine a high degree of QoS with low energy consumption. A possible problem formulation may be to minimize the energy consumption given some constraints on the served traffic and the user quality of service.

For radio network studies, metrics that capture both the radio quality in the network as well as the energy consumption are included in the analysis. The two sub-sections below describe the radio quality performance metrics and the energy consumption metrics adopted in this report.

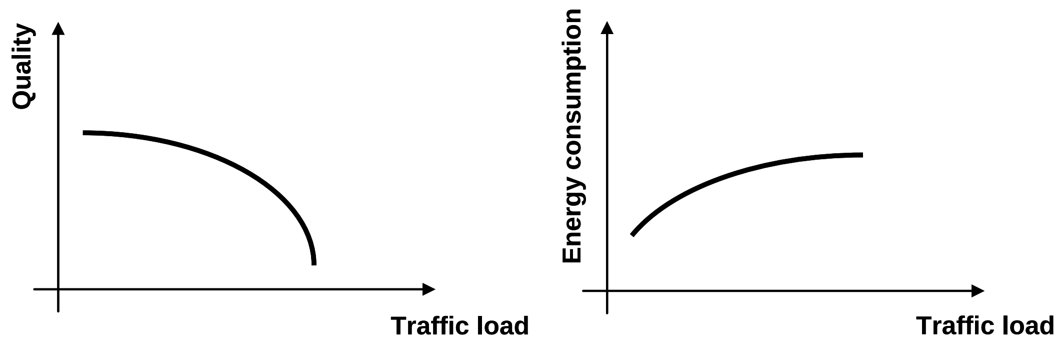


FIGURE 14. Quality of service and energy consumption versus traffic load.

5.1.1. Radio quality performance metrics

In this report the evaluations are performed assuming file download or voice (by mean of voice over IP). The employed radio quality performance metrics are presented in the sections 5.1.1.1 and 5.1.1.2 below.

5.1.1.1. File download radio quality performance metrics

The file download traffic model assumes that each user downloads a single packet of a given size. For the radio quality performance metrics, we follow the recommendations in 3GPP [TR36.814R9]-section A.2.1.3.2, which suggests that the following performance metrics should be employed for the file download traffic model[4]:

- Mean, 5th, 50th, and 95th percentile user throughput;
- Served cell throughput;
- Resource (block) utilization.

Here, the user throughput is defined as the file size (amount of data) divided by the time needed to transfer the data and the served cell throughput is defined as the total amount of transferred data divided by the observation time and by the number of cells. In this report, we choose to express the served traffic per area unit instead of per cell, and hence the served traffic is defined as the total amount of transferred data divided by the observation time and by the coverage area of the network.

5.1.1.2. Voice radio quality performance metrics

Voice is assumed to be implemented by means of a voice over IP solution and based on the recommendations in [TR36.814R9], section A.2.1.4, the system capacity is defined as the highest traffic load for which at least 95 % of the users are satisfied. A user is satisfied if at least 98 % of the packets arrive within a delay of 50 ms.

[4] 3GPP also recommends including the *harmonic mean normalized cell throughput* and the *normalized cell throughput* among the adopted performance metrics. Since these two performance metrics depend on the full buffer throughput, which is not evaluated here, they are not considered further in this report

5.1.2. Energy consumption metrics

To capture the energy consumption perspective in the analysis, we employ the two energy consumption indices (ECIs) given below:

- Power per area unit, measured in [W/m^2];
- Energy per bit, measured in [J/bit].

5.1.2.1. Power per area unit

The power per area unit metric is defined as the network average power usage (*P*) divided by the coverage area of the network (*A*) and is expressed in the unit [W/m^2].

$$ECI_{P/A} = \frac{P}{A} \left[W/m^2\right] \tag{5-4}$$

The metric focuses on the total network power (or, equivalently, the total energy consumption) and is closely related to the CO_2 emissions and the associated carbon footprint. Power per area unit is further a very relevant quantity at low traffic loads, as in this case the network is coverage limited rather than capacity limited. Moreover, since the coverage area A, for which the system is to be evaluated, is typically a predefined constant the metric avoids quotient of variables. This prevents misleading conclusions since when forming the quotient of variables it is impossible to understand whether an increase of the metric is due to the increase of the numerator, and/or the decrease of the denominator. [ETSI-TS102.706] also proposes this metric for cases in which the network area coverage is dominating the network dimensioning, even though in ETSI the quantity is expressed as an efficiency metric, i.e., as area coverage in relation to power, instead of the consumption metric adopted here.

5.1.2.2. Energy per bit

The energy per bit metric is defined as the network energy consumption (*E*) during the observation period (*T*) divided by the total number of bits (*B*) that were correctly delivered in the network during the same time period. Since the network energy consumption is simply the (average) power multiplied with the observation period, this metric could, equivalently, be described as the (average) network power (P) in relation to the (average) data rate (R) and expressed in [W/bps].

$$ECI_{E/B} = \frac{E}{B} = \frac{P}{R} \left[J/bit\right] or \left[W/bps\right] \tag{5-5}$$

This energy metric has been around for long and it is one of the most commonly used, especially for theoretical studies and single link evaluations, see, e.g., [Verdu2002]. Note that, in many scenarios it is used as an efficiency metric as [bit/J]. The energy per bit metric focuses on the amount of energy spent per delivered bit and is hence an indicator of network bit delivery energy efficiency, which may be important especially in scenarios where the traffic load is high.

Since both the numerator (the network energy consumption) and the denominator (the number of delivered bits) are typically variable, the metric is affected both by changes in the energy consumption and by changes in the number of delivered bits. Note further that this metric approaches infinity as the traffic load goes to zero (since the network energy consumption does not typically go to zero for low traffic loads).

6. EVALUATION OF REFERENCE SYSTEM

To demonstrate the handling of the energy efficiency evaluation framework from Chapter 2, this section provides a downlink evaluation of the *Reference System* as described in [EARTH-D2.2]. As a first step, Section 6.1 provides a small-scale, short-term evaluation of three scenarios. In this step, the power model derived in Chapter 4 is used in order to monitor the energy consumption of the network and the performance metrics from Chapter 5 are adopted. Secondly, based on the results derived in Section 6.1 and the data statistics presented in Chapter 3, the evaluation aggregation to global scale is provided in Section 6.2.

6.1. SMALL-SCALE, SHORT-TERM SYSTEM LEVEL EVALUATIONS

6.1.1. Models and Assumptions

The evaluation is performed following the description of the reference system and the reference scenarios from [EARTH-D2.2]. A brief summary of the most important models and assumptions are given in the two sub-sections below, however, for more details one should refer to [EARTH-D2.2].

6.1.1.1. Reference Scenarios

The reference system is evaluated under three distinctive scenarios, that is to say in an urban, a sub-urban, and a rural scenario, which are referred to as scenario 1, 2, and 3 in [EARTH-D2.2]. All three scenarios assume a homogenous, hexagonal deployment and uniform user distribution. TABLE 9 summarizes the main characteristics of the three environments. For scenario 3, two carrier frequency options are possible, namely 2.1 GHz and 0.8 GHz. Here, they are referred to as scenario 3a (2.1 GHz) and scenario 3b (0.8 GHz), respectively.

Note further that the antennas, both at the base station and in the user equipment, are cross-polarized and that the base station 2D antenna diagram [EARTH-D2.2] with a 14 dBi gain in the front direction as well as the FTP traffic model [EARTH-D2.2] using a packet size of 0.5 Mbyte are employed for the evaluations.

TABLE 9. Scenario parameters ([EARTH-D2.2]).

	Carrier Frequency (GHz)	Inter-site distance (m)	Bandwidth (MHz)	Fast fading channel model	Speed (km/h)
Scenario 1 (urban)	2.1	500	FDD: 10+10 TDD: 20	Urban macro (UMa)	3
Scenario 2 (suburban)	2.1	1732	FDD: 10+10 TDD: 20	Rural macro (RMa)	30
Scenario 3 (rural)	2.1 and 0.8	1732	FDD: 10+10 TDD: 20	Rural macro (RMa)	120

The environments differ mainly in terms of the inter-site distance of the deployment (cell size), carrier frequencies, and user mobility. Also the LOS probability and the small-scale fading characteristics differ. FIGURE 15 illustrates the path loss to serving cell and the wideband SINR distributions associated with the different environments. The path loss (L) is defined as the ratio, on average, between the transmitted and the received power, usually given in dB:

$$L = \frac{P_{tx}}{P_{rx}} = P_{tx}\;\; dB\;\; - P_{rx}\;\; dB\;\; , \tag{6-6}$$

where P_{tx} is the transmitted power and P_{rx} the received power, respectively. The path loss includes effects such as distance dependent attenuation, shadowing, and antenna gains whereas fast fading effects are not captured in this measure. The wideband SINR, also often referred to as the geometry, is defined as the ratio between the power received from the serving cell and the power received from all other cells and noise. The measure assumes full load, i.e., that all neighbour cells are transmitting. For a terminal connected to cell i the geometry (G) is defined as:

$$G = \frac{P_{rx,i}}{\sum_{\forall j \neq i} P_{rx,j} + N_0}, \tag{6-7}$$

where $P_{\text{rx,j}}$ is the power received from cell j and N_0 is the noise power.

Notice that since it is only the carrier frequency that differs between scenarios 3a and 3b, which results in a constant path loss difference, the associated path loss curves have a constant difference of around 8.4 dB. Moreover, in the interference limited environments studied here such a path loss difference has a very small influence on the wideband SINR, and indeed the wideband SINR statistics in scenario 3a and scenario 3b are almost identical. Moreover, scenario 2 and scenario 3a differ only in terms of user mobility, LOS probability and small-scale fading, and since neither the user mobility nor the small-scale fading influence the path loss or the wideband SINR, the characteristics of these two scenarios are very similar (although not identical).

Even though there are many additional factors that influence the radio performance, the path loss and the wideband SINR distributions provide an indication of what can be expected in the different environments. The path loss characteristics are more relevant at low traffic load, when there is no or very little interference in the network, whereas the wideband SINR is representative at high loads when the interference level is high.

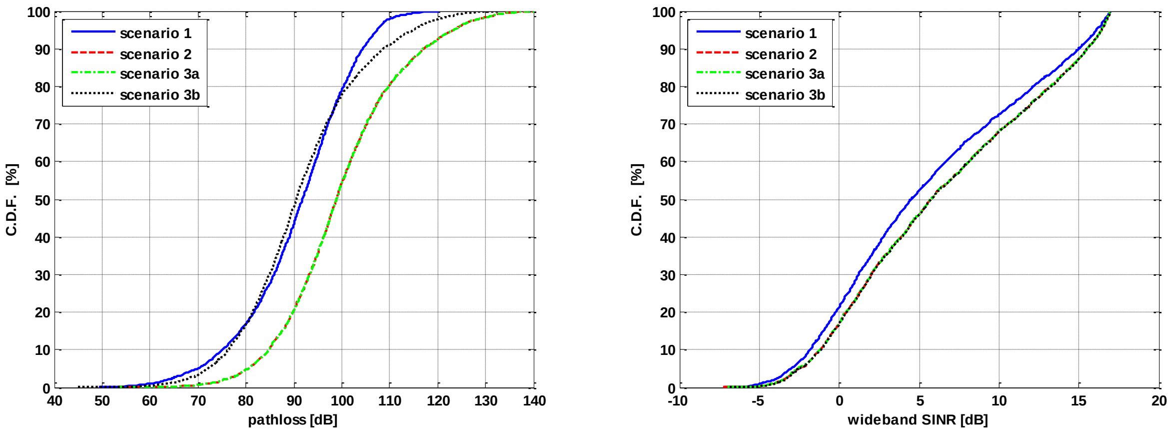


FIGURE 15. Distributions of path loss to serving cell (left) and wideband SINR (right) in the different scenarios.

6.1.1.2. Reference System

The reference system is a 10 MHz FDD LTE Rel-8 2x2 network using closed loop linear precoding with rank adaptation. The precoder used for transmission is selected from the LTE codebook for two antenna ports [TS36.211], in which there are four rank-1 and two rank-2 precoders, and the selection is based on estimated channel conditions. Downlink proportional fair scheduling is applied and used in combination with adaptive modulation and coding. Close to 30% of the resource elements are used for the transmission of control channels and reference signals. More specifically, the following overhead assumptions are adopted:

- Cell reference signals (CRS)
  In each resource block, 16 out of 168 resource elements are used for CRS for a 2 Tx antenna transmission scheme. This corresponds to an overhead of approximately 9.5%.
- Physical Downlink Control Channel (PDCCH)
  The three first OFDM symbols in each slot are used for transmission of the PDCCH, which corresponds to an overhead of around 21%. It is assumed that the PDCCH transmission occupies three symbols independent of the momentary traffic load, even in the case when the cell is empty.
- Physical Broadcast Channel (PBCH)
  The PBCH occupies 6 RBs over 4 OFDM symbols every 10 ms, i.e., 288 resource elements every 10 ms, which, for a 10 MHz bandwidth, corresponds to an overhead of approximately 0.3%.
- Primary Synchronization Signal (PSS)
  The PSS occupies 6 RBs over 1 OFDM symbol every 5 ms, i.e., 72 resource elements every 5 ms, which, for a 10 MHz bandwidth corresponds to an overhead of close to 0.2%.
- Secondary Synchronization Signal (SSS)
  Just like the PSS, the SSS occupies 6 RBs over 1 OFDM symbol every 5 ms, which corresponds to an overhead of close to 0.2%.

Note that since, e.g., the CRS and the PDCCH are partly overlapping the total overhead (just below 30 %) is slightly lower than the sum of all the individual overheads presented above. Furthermore, an important consequence of the reference signals and control channels is that even in the case when the traffic level in the network is low or non-existing, the network still transmits signals such that the energy consumption of the network is above the level associated with zero RF output power.

The power consumption model is based on the 2 Tx macro model presented in Chapter 4 and results are derived for the 2010 and 2012 year power models. Here, a linear approximation is used in which, for the 2010 year model, the site power consumption is 735 W at 0% RF output power and 1250 W at 100% RF output power. The corresponding figures for the 2012 year model are 538 W and 990 W, respectively. The model, illustrated in FIGURE 16, is applied on the OFDM symbol level.

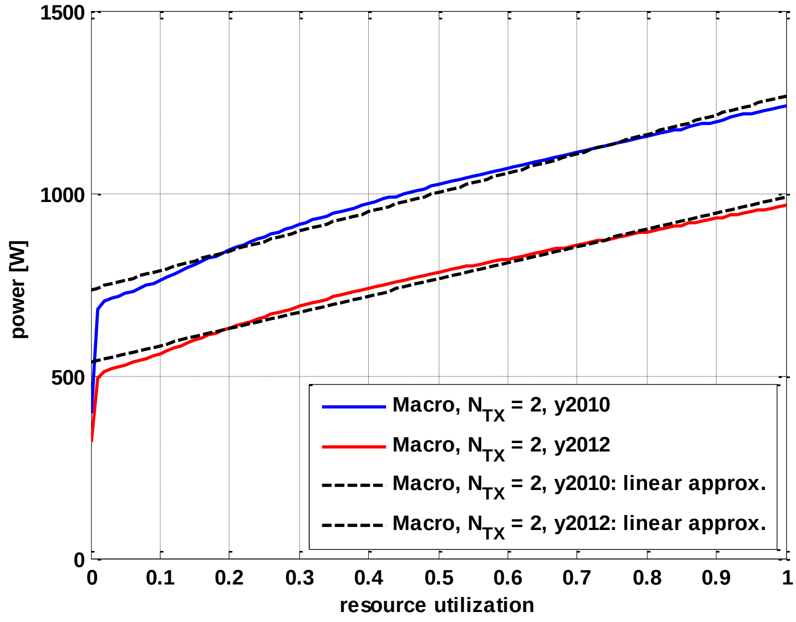


FIGURE 16. Site power model for a macro three sector site with 2 Tx antennas per sector. The figure illustrates the model for the macro 2 Tx case, as defined in Chapter 4, and the linear approximation used here. Power values for the 2010 and 2012 year power models are presented.

6.1.2. Numerical Results

This section provides results for the evaluation of the reference system in the scenarios 1, 2, 3a, and 3b. Results are generally presented as a function of the system throughput, i.e., the served traffic in the network. Moreover, results are only presented for stable operational points, i.e., for operational conditions for which the served traffic in the network, over time, equals the offered traffic.

FIGURE 17 illustrates the resource block utilization as a function of the system throughput in the different scenarios. The resource block utilization shows how large fraction of the resource blocks is scheduled for transmission, and is an indicator of the traffic load in the network. For the system throughputs studied here, the resource block utilization never exceeds 60 %. Note that there is a considerable difference between scenario 1 and the other cases regarding the amount of traffic that can be served per area unit. The maximum system throughput per sector, or site, is relatively similar in all cases. The inter-site distance in scenario 1, however, is 500 m compared to 1732 m in the other scenarios, with the result that the covered area per sector differs approximately 12 times and consequently, for the same throughput per sector the area throughput differs by about a factor of 12.

In FIGURE 18 different user data rate percentiles are plotted as a function of the system throughput. The plot indicates that at low system throughputs, the user data rates span from around 15 Mbps to above 60 Mbps. FIGURE 19 illustrates the mean user data rate as a function of the system throughput.

The power per area unit, expressed in [kW/km^2], is depicted in FIGURE 20 for the 2010 and 2012 year power models, respectively. This energy metric increases with the served traffic in the network. In scenario 1, using the 2010 year power model, 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. This can be compared to what can be expected for an empty network; in the (hypothetical) extreme case, when nothing at all is transmitted (i.e., no data and no reference signals and control channels) so that the RF output power is 0 W, the site power equals 735 W. With an inter-site distance of 500 m the site coverage area equals 0.2165 km^2, and the power per area unit then amounts to 3.4 kW/km^2. In the case when only reference signals and control channels are transmitted, but no user data, the energy consumption equals 885 W, which corresponds to a power per area unit of 4.1 kW/km^2. At full load, the site power reaches 1250 W, which for scenario 1 amounts to 5.8 kW/km^2. These reference figures are summarized in TABLE 10.

In scenarios 2 and 3, the network is deployed with an inter-site distance of 1732 m, which corresponds a site coverage area of 2.598 km^2. In this case, for the 2010 year power model, the 0 W RF output power case results in a power per area unit of 0.28 kW/km^2, whereas a network transmitting reference signal and control channels but no user data results in a power per area unit of 0.34 kW/km^2. In the full load case the power per area unit equals 0.48 kW/km^2.

TABLE 10. Power per area unit (P/A) in the different scenarios for three levels of traffic load. The figures refer to the energy consumption for the 2010 year power model.

	ISD (m)	Site coverage area (km^2)	P/A at 0 % RF load (no data, no RS or CCH transmitted) [kW/km^2]	P/A at 0 % data load (only RS and CCH transmitted) [kW/km^2]	P/A at 100 % RF load [kW/km^2]
Scenario 1	500	0.2165	3.4	4.1	5.8
Scenario 2, 3a, and 3b	1732	2.598	0.28	0.34	0.48

FIGURE 21, finally, contains the energy consumption per delivered bit. Also in this case, results are presented for the 2010 and 2012 year power models. Even though the total energy consumption increases with the traffic load, the energy consumption per bit decreases with traffic. That is, the number of delivered bits increases faster than the network energy consumption. The dominating reason for this is the fact that the power model is associated with a fixed cost at 0 W RF output power and when the traffic increases, this fixed cost is shared over a larger number of bits, which results into the energy per bit decrease. In scenario 1, for the traffic loads evaluated, the energy per bit is approximately in between 1.2 kJ/Mbit at low traffic loads and 0.05 kJ/Mbit at high traffic loads, which corresponds to around 2.67 kWh/GB and 0.1 kWh/GB, respectively. For the scenarios 2 and 3, the energy per delivered bit lies approximately within the same range as in scenario 1, however, here the system throughout figures are generally much lower. Comparing the scenarios at a fixed traffic load (supported by both deployments), say, e.g., at 5 $Mbps/km^2$ and using figures for the 2010 year power model, the energy per delivered bit is around 1 kJ/Mbit in scenario 1 whereas it is approximately 0.075 kJ/Mbit in the scenarios 2 and 3.

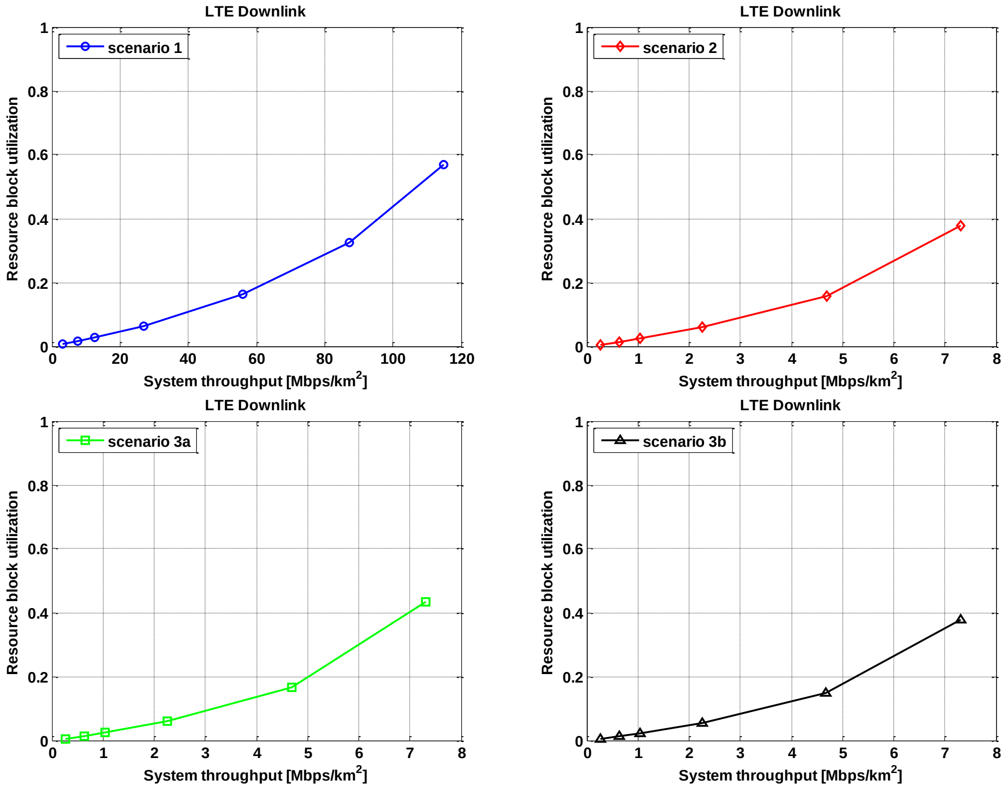


FIGURE 17. Network average resource block utilization as a function of the system throughput for scenario 1, 2, 3a, and 3b.

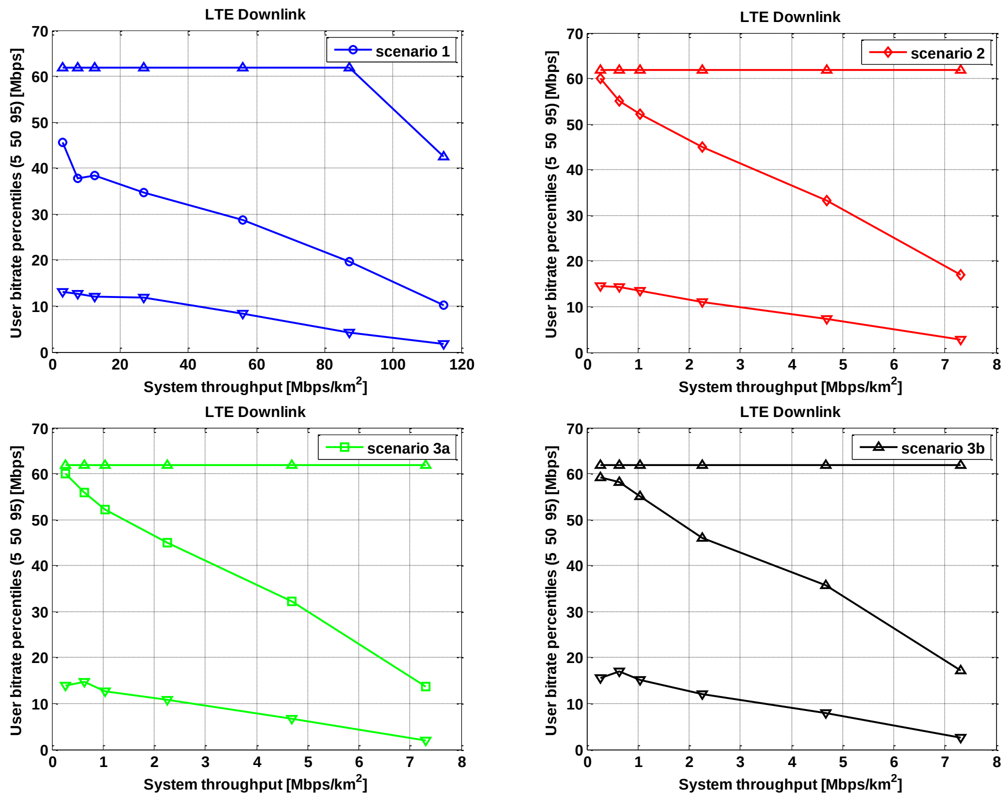


FIGURE 18. 5th, 50th, and 95th percentile user data rates versus system throughput in scenarios 1, 2, 3a, and 3b.

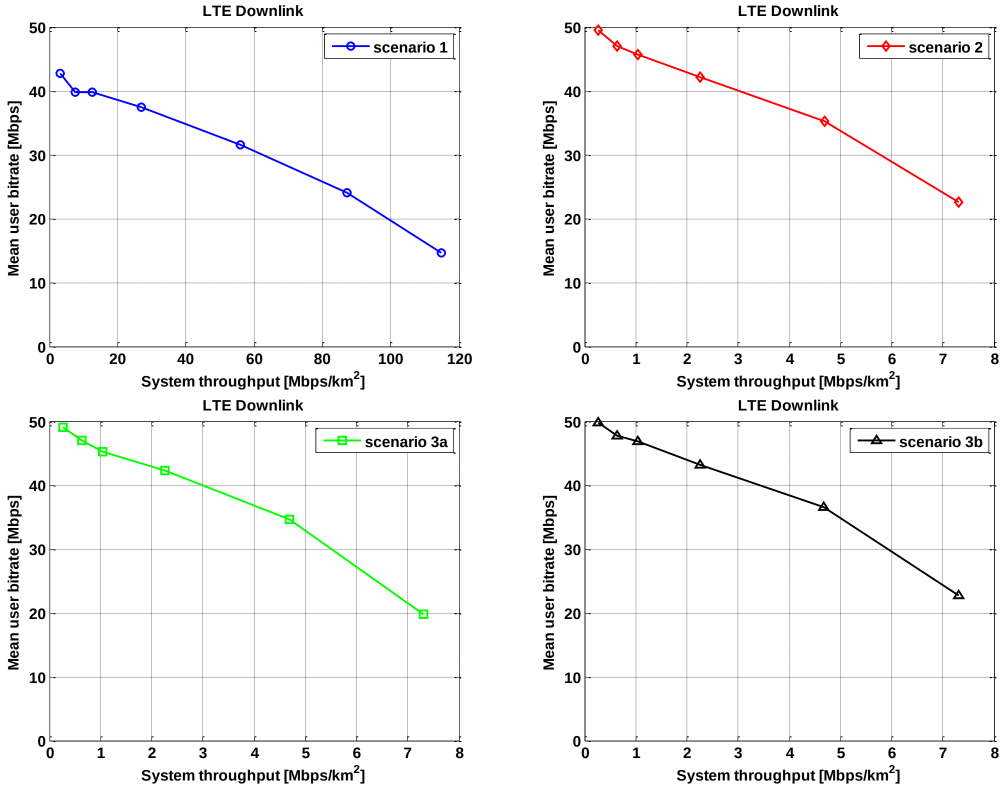


FIGURE 19. Mean user data rate versus system throughput in scenarios 1, 2, 3a, and 3b.

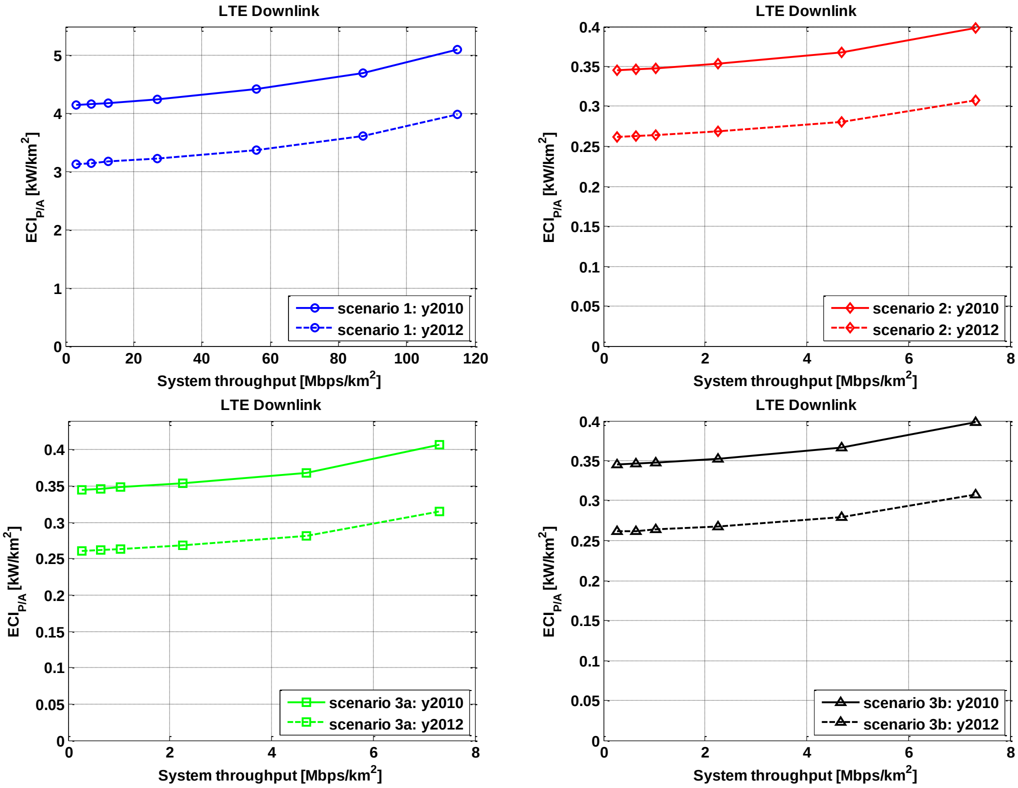


FIGURE 20. Power per area unit versus system throughput in scenarios 1, 2, 3a, and 3b.

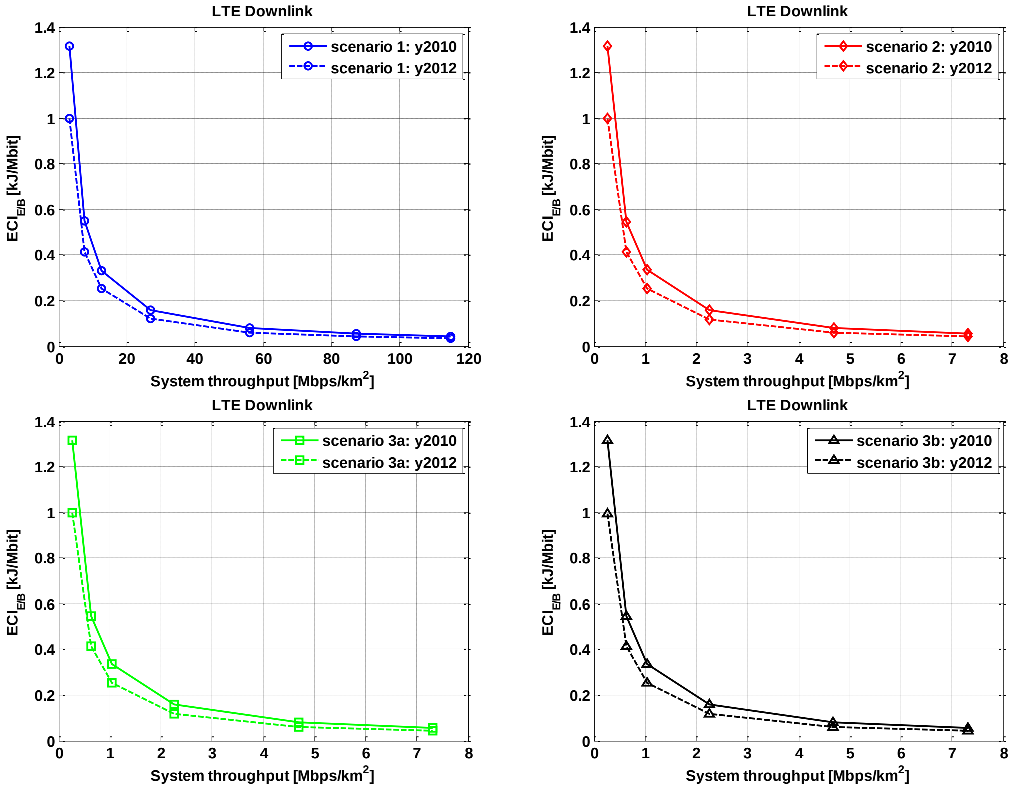


FIGURE 21. Energy per bit versus system throughput in scenarios 1, 2, 3a, and 3b.

Note that while the behaviour is similar in the dense urban, urban (scenario 1) and the suburban, rural environments (scenarios 2 & 3a), the absolute figures differ significantly. In terms of power per area unit, the deployment in the rural environment performs much better compared to the deployment used in the dense urban environment. In terms of throughput, the relation is the opposite.

6.2. AGGREGATION TO GLOBAL SCALE

In order to assess the expected performance over a large area, such as, e.g., a country, and over long time, like a day, the short-term, small-scale evaluations in Section 6.1 are combined with the long-term traffic models and the geographical distribution presented in Chapter 3. It is assumed that the performance of Scenario 1 is representative for the dense urban and urban environments, whereas Scenario 2 represents the performance of the suburban environment. Furthermore, Scenario 3a represents the performance of the rural environment. It is further assumed that no coverage is provided the sparsely populated and wilderness environments and hence, these environments are not included in the analysis below. Moreover, small-scale evaluations are performed for a single carrier, which is typically operated by a single operator. Here, it is assumed that the market share of the studied operator is 30% and that this operator also carries 30% of the total data traffic.

Applying the traffic demands for the envisaged shares of heavy users in scenario #1 to #3 (see Table 2), it turns out that the considered LTE network is unable to always serve the peak traffic demands anticipated for case #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 hot spot areas. Since any of these measures affects the power consumption of the considered network, case #3 is omitted in the subsequent analysis.

TABLE 11. Aggregation to global scale for the considered traffic scenarios

Share of heavy users	$ECI_{P/A}$	ECI_{EB}	Mean User Data Rate	5th perc. User Data Rate
#1: 20% heavy users	0.654 kW/km^2	0.615 kJ/Mbit	46 Mbps	14.4 Mbps
#2: 50% heavy users	0.656 kW/km^2	0.328 kJ/Mbit	44.4 Mbps	12.4 Mbps

TABLE 11 summarizes the aggregated results assuming different shares of heavy users, as defined in Section 3.2.2. These results are calculated by weighting the performance according to daily traffic patterns and geographical occurrence (representing an appropriate mixture of dense urban, urban, suburban and rural scenarios). Since more packets (and eventually bits) are transmitted during high traffic time period and in areas with high traffic densities, the performance in those cases influences the aggregated mean user data rate, 5th percentile user data rate and the aggregated energy per bit stronger than the performance observed during low traffic periods and in areas where the traffic density is low.

The outcome of the aggregation indicates that, with the models and assumptions used in this evaluation, the average power per area unit is around 0.65 kW/km^2 provided that the 2010 year power model is employed. This metric is very insensitive to the traffic load, which can be seen by analyzing the power over area metric for, e.g., the suburban environment. The power per area unit metric as a function of the system throughput is depicted in FIGURE 20 and the suburban environment is mapped to what is referred to as scenario 2. The power per area unit increases relatively slowly with system throughput, and even at the traffic loads close to the network capacity the fixed energy consumption makes up around 80% of the total energy consumption.

The energy per bit metric, on the other hand, is very sensitive to the traffic load. This is natural since as the power over area metric indicates, the overall energy consumption does not change much with the traffic load, and consequently the energy-per-bit metric is essentially proportional to 1/B, where B is the number of transmitted bits. The radio performance, here characterized by the average user data rate and the 5th percentile user data rate, varies moderately with the traffic density. The 2012 year power model reduces the energy consumption with 24 %, independent of the traffic load assumptions, but has no impact on the radio performance.

As discussed, the network operates at relatively low load levels, especially if low or medium traffic densities are assumed. Still, due to local temporal and geographical variations certain parts of the network must serve a large number of simultaneously active users during shorter time periods. A consequence of the relatively low average load level is, however, that a large fraction of the subframes are not utilized for data transmission. In the studied example, less than 10 % of the subframes are utilized for transmission of user data, also when the high traffic profile is assumed. For the medium and low traffic profiles, less than 2 % and 1 % of the subframes are utilized for data transmission.

7. BREAKDOWN OF POTENTIAL IMPROVEMENT AREAS

In this Chapter, we introduce the areas for potential improvement on energy efficiency, over the reference system discussed in Chapter 6. Section 7.1 first describes a range of promising approaches on component, node and system level with respect to hierarchical structure of the baseline system described in [EARTH-D2.2]. In section 7.2, some selected approaches of EARTH innovations will be assessed applying the energy efficiency evaluation framework of Chapter 2. As an example of synergy gains between improved components and resource management techniques we assess the energy consumption of different combinations of packet scheduler and power amplifiers with the traffic model of Chapter 3 and the power model of Chapter 4.

A more detailed analysis of energy savings in EARTH is provided in [EARTH-D3.1] and [EARTH-D4.1].

7.1. AREAS OF IMPROVEMENT

The EARTH project is following a holistic approach on the energy efficiency, leveraging improvements on component, node and system level. With the combined gains in an integrated system we aim to show that the target can be achieved to reduce the system energy consumption by at least 50%.

7.1.1. Improvement on Component Level

The various components, constituting the power model described in section 4.1, are categorized into 1) antennas, 2) RF transceivers, 3) baseband processor and 4) power amplifier, as parts of the BSs radio equipment[5]. The following subsections describe each component and potential gains by the EARTH project.

7.1.1.1. Antennas

The efficiency gain in specific types of omnidirectional, sectorized or directional antennas can be achieved by optimizing the antenna topology along with the feeding network. For printed antennas [PoSc1995] the use of new low loss materials like metal and dielectric materials [MaMcKe1981] will be investigated. Depending on specific configurations there is a significant technology potential to improve the antennas EE.

Innovative application of active antennas for spatial diversity and multiplexing techniques increases the spectral efficiency, coverage range and capacity per antenna site. These performance gains can be leveraged either for capacity improvements or for energy efficiency: MIMO and beamforming schemes will improve the obtained data rates for a given fixed transmit power, or equivalently reduce the transmit power required to achieve a given target data rate. Alternatively, the number of sites per covered area could be reduced resulting in increased overall EE of the network.

7.1.1.2. RF transceiver

Innovation for RF TRX architectures targets cost- and power -efficient operation, while offering high flexibility in terms of operation conditions, bandwidth variability and operation frequency. For our analysis we parameterise the TRXs and their building blocks in terms of architecture, technology, performance and power consumption. For every TRX chain we propose new architectural approaches that allow energy consumption scaling. These approaches cover both circuitry and transceiver system level techniques and algorithms, e.g. clipping and predistortion.

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[5] In this deliverable, we do not assess the potential improvement on cooling and AC-DC power supply components.

Specifically, a combination of flexible but energy efficient platform and algorithmic (software) techniques is proposed. The improvement is expected especially in low load situations.

7.1.1.3. Baseband Processing

Base station capacity and the number of supported subscribers have a direct impact on the processing power required by a single BS. For micro and pico base stations this significantly contributes to the electrical power consumption. To satisfy the requirements, more and more sophisticated signal processing algorithms are deployed. The challenge is to find a compromise between flexible and energy efficient BB architecture.

The BB processing is one of the most power consuming elements in the BS along with the PA, according to the analysis in section 4.2. To reduce the consumed power, we propose scalable BB signal processing algorithms which dynamically adjust energy consumption according to the communication environment and the number of active links. Further improvements can be achieved by BB processors supporting power management for variable load.

7.1.1.4. Power amplifier

In mobile communications, the PA of macro BSs is the component with the highest energy consumption (see section 4.2). At present, the PAs are operating on high DC power supply independently of the traffic load and thus, for a major part of the day, the power is wasted.

The reduction of power consumption can be tackled in two ways. The first approach defines *the operating point adjustment of power amplifiers* for minimizing the power consumption at arbitrary signal levels, so that the power efficiency is optimized for low, medium and high traffic loads. The second approach proposes *the deactivation of power amplifier stages* for saving power consumption in time slots without signal transmission.

In variable load situations, the full efficiency improvement is expected by joint application of both concepts.

7.1.2. Improvement on node level

Improvements on node level address RRM methods and solutions that use protocol features and radio interface improvements to reduce the energy consumption, e.g. with energy efficient (EE) schedulers. A sophisticated energy and traffic-aware scheduler can save energy of DL OFDMA transmissions while at the same time meeting the QoS requirements of the users in the system. Typically, these solutions leverage adaptive operation of PAs and other hardware.

In particular, we first discuss discontinuous transmission (DTX) and sleep modes of the radio BSs and dynamic bandwidth management according to daily traffic load profiles. We later focus on the concept of adaptability on system dynamics.

7.1.2.1. Discontinuous Transmission and Sleep Mode

During low traffic periods, the majority of BSs' capacity remains unused for many hours. Also, at moderate load, significant amount of resources are not used. Consequently, transmit and operation power consumption can be greatly reduced during low or moderate traffic period times, when no or few users are served, with respect to peak traffic hours, i.e. a BS can be put into a discontinuous transmission or sleep mode to reduce energy consumption.

Several levels of DTX are envisaged, ranging in terms of duration, from one or a few OFDM symbols to several hours. Hence we propose to relate the DTX level to the sub-frame (1 ms duration) and radio frame duration (10 ms duration) as follows:

- Micro DTX: less than one sub-frame.
- Short DTX: less than one radio frame (but at least equal to one sub-frame).
- Long DTX: one radio frame or longer. The long DTX duration shall, however, be sufficiently short, so as to enable UEs to perform initial cell search and mobility measurements.
- Sleep mode: Longer than long DTX. UEs are not able to find cells or component carriers that are operating in sleep mode.

Cell DTX is most efficient when the traffic load in a cell is low.

7.1.2.2. Dynamic Bandwidth Management

In contrast to DTX on the time axis, bandwidth management is operating on the frequency range of the available radio resource. High energy savings can be achieved in the PAs through dynamic bandwidth management according to daily variations of traffic load profiles. The appropriate bandwidth has to be determined based on traffic load monitoring.

The bandwidth adaptation approach offers further potential for energy savings on system level by significant reduction of inter-cell interference by applying a reuse scheme with a reuse factor higher than 1 in times of low traffic. This requires that the cells coordinate the bandwidth configuration with their neighbouring cells by means of signalling.

7.1.2.3. Adaptability on System Dynamics

The BS can adapt its data transmissions to the channel conditions and take the best decision in terms of resource allocation and energy efficiency. The following trade-off arises: more channel state information leads to a decrease in the transmission energy, but increases energy expenditure due to overhead. Important gains could be achieved during transmission and reception by careful adaptation to the system dynamics. The goal is to identify how much channel state information should the optimal algorithms utilize and from which channels they should acquire such information.

Algorithms for uplink control depend on periodicity and granularity of UE reporting of channel state information. The reporting periodicity has to be synchronized with channel fluctuation. Furthermore, reporting of the channel adaptation parameters can be itemized to the whole bandwidth (wideband) or a number of sub-bands.

In addition an enhancement of the energy efficiency can be achieved by reduction of packet retransmission. In multi-user OFDMA based communication systems this is addressed by a retransmission scheduler that re-computes the allocation of RBs for negatively acknowledged packets in an energy efficient manner.

Another possibility could be to provide more or less capacity according to the demand in the area and/or timeframe. On-demand functionality can reduce total base-station power consumption compared to the always-on state, without degradation on the network performance.

7.1.3. Improvement on system level

Improvements on the system level are achieved by establishing advanced BS deployment concepts and by introducing novel network management schemes.

The different deployment strategies taken into consideration are variable cell size and cell mixing, relays and repeaters, BS cooperation and multi-RAT deployment. Network Management can be powered by SON algorithms supporting reconfigurable network topology.

7.1.3.1. Variable cell size and cell mixing – Heterogeneous networks

An important gain in energy savings can be reached by varying cell sizes to reduce the transmission distance. Additional strategies used to complement the network are low power base stations, indoor deployments, repeater, relays, etc. First results show that heterogeneous overlay deployments with micro cells at the macro cell edge can boost system capacity by several times with only moderate increase of power per coverage area.

Another deployment strategy is the separation of the whole network into two parts: dense traffic zone and sparse traffic zone; the cell size can be adaptively adjusted based on the spatial traffic distribution. In the current network deployment this has been used from capacity planning point of view. We now study how the deployment can be optimised for energy efficiency. It has been shown that in scenarios with both dense and sparse traffic zones, a deployment with different cell sizes can save energy compared to a uniform deployment without reducing the QoS.

We expect further energy savings by solving the dimensioning/planning problem with a heterogeneous network consisting of the macro layer with an underlying capacity layer. The objective in that case will be to find the potential of optimizing the energy savings of the network consisting of macro base stations and a number of small cells used to complement coverage and capacity in indoor areas.

Moreover, one of the most influential design decisions that can be made to reduce the power requirement of the radio network is to specify the proper network BS configuration. Component development has to support this by providing optimised components individually for macro, pico and home BSs. Furthermore, in smaller BSs, more scalability is available in most sub-components due to the extra flexibility allowed by lower power transceivers and application specific processors.

7.1.3.2. Relays and repeaters

Relay nodes have significantly lower transmitted power compared to the macro BS and are expected to be more energy efficient. In order to achieve optimal energy efficiency in relay or multi-hop scenarios, hybrid selection might be the best choice. Different relaying techniques, e.g. amplify-and-forward and decode-and-forward, are considered and compared for their energy efficiency to use the best of them.

For mixed indoor and outdoor network deployments, macro cells complemented by additional relays for indoor coverage have been studied. In our simulations we discover that a scenario with 5 relays per outdoor macro cell provides sufficient coverage rate with lower energy consumption per area.

7.1.3.3. Cooperative base stations

Cooperation mechanisms enable increased energy efficiency of a base station by exploiting cooperative diversity, interference coordination between cells through coordinated scheduling, coordinated beamforming and joint processing.

The cooperation via joint processing is the most promising technique if a central unit or a network-centric processor is available. Besides, it is expected that joint processing achieves the highest gain among the presented CoMP schemes; however, it also requires the highest amount of signalling overhead.

To facilitate base station cooperation we evaluate different transport architectures as well as transport protocols. Use of ROADM-based rings (ROADM - Reconfigurable Add/Drop Multiplexers) and/or PONs (Passive Optical Networks) play an important role in the design of the backhaul network topology and can have an important impact on the overall RAN energy consumption.

7.1.3.4. Multi-RAT deployment

With GSM, UMTS, HSPA and LTE, multiple radio access technologies (RATs) are available and often deployed in the same area or even at the same site. Energy saving techniques in Multi-RAT deployment focus on optimizing the traffic distribution among RATs. Power consumption savings are expected in an optimal or “best” network deployment strategy, where low and high traffic load will be assigned to the most suitable and most energy efficient RAT.

Preliminary numerical results show that the increase of available bandwith on several RATs does increase energy efficiency,.

We see real potential in multi-RAT management by reducing the number of active base stations adaptively to the actual traffic demands of the network.

7.1.3.5. Network Management

A high saving potential has been identified in the dynamic management of the network capacity, adapted to the actual traffic demand, which varies on short term as well as over a day. Savings come from reduced power consumed by a base station, due to network reconfiguration in power savings states.

Network management strategies are greatly connected to network deployment strategies. For example, BS ON-OFF schemes, in heterogeneous deployments or in cooperative multi-RAT management, allow the network to efficiently adapt to the daily changes of total traffic.

For intelligent network management, self-organizing network (SON) algorithms which control and optimize the network, supported by centralised policies and knowledge databases are considered.

7.1.4. Integration of most promising tracks

It is likely that the most energy efficient solution will be a sophisticated combination of all techniques described above. Some combinations may even provide synergetic savings, while other individual solutions may be mutually exclusive. This is why the ambitious and unique target for the EARTH project is to look at all these aspects at the same time, and provide a global view which would be very difficult to achieve in other contexts. The ultimate objective will be to consolidate and align the most promising tracks, by taking a holistic approach, into an energy efficient integrated solution.

7.2. ASSESSMENT APPROACH FOR COMPONENT AND NODE LEVEL

In Section 7.1 a range of areas for potential improvement on energy efficiency has been presented. In this section, one promising approach from the described range is analysed.

Packet scheduling characteristics take a fundamental role in the overall system performance because the scheduler sets the principal PHY parameters for the transmission at each LTE subframe. In consequence, the radiated power depends on the subframe configuration decided by the scheduler. An energy efficient scheduling strategy can result in a more efficient transmission and in a better exploitation of the radio resources needed to satisfy the performance requirements. Thus, the energy efficiency of a packet scheduler can first be analyzed from the point of view of the radiated power and the guaranteed performance requirements (Section 7.2.1). For system level evaluation a more general analysis includes the full energy consumption of a base station (Section 7.2.2) to study the impact of energy efficient scheduling algorithms that leverage power amplifier innovations.

This example has been selected to show the synergy gains between hardware oriented work [EARTH-D4.1] and network management techniques [EARTH-D3.1]. The analysis has been conducted using a fine grained and extensible simulation methodology for component and node level using the Energy Efficiency Evaluation Framework, especially the long term traffic model of Chapter 3, and the power model of Chapter 4. Due to the node level scope of this approach the averaging over large scale areas is omitted here, because in different node types different solutions may be deployed. This final evaluation is left for further work and the integrated solution.

7.2.1. Analytical calculation of scheduled transmit power

In a simple model the radiated power P_{RF} is calculated at each subframe based on packet scheduler's decisions, i.e. the number of occupied physical resource blocks (PRBs). LTE specifications define RS EPRE (Reference Signal Energy Per Resource Element) as the main parameter indicating the power of the reference signal subcarrier, while all the other subcarriers (data channels, control channels, etc.) are defined by a power ratio with respect to this power. For example, the *PBCH_RA and PBCH_RB* parameters define the power ratio between the PBCH subcarrier and RS EPRE in OFDM symbols not containing RS.

RF power generated at each subframe can be simply calculated by considering the number of RE needed by the different channels (PBCH, SS, PDCCH, PDSCH, etc.), and in particular by knowing the number of PRB scheduled per subframe. We here assume a linear relationship of the transmit power on the number of scheduled PRBs $N_{PRB,\ allocated}$:

$$P_{RF} = m \cdot N_{PRB,\ allocated} + n \qquad (7\text{-}8)$$

where *n* is the fixed part of the radiated power, relative to PBCH, SSS, PSS, PCFICH, RS, etc. . The variable part of the radiated power depends on PDCCH and PDSCH and on the number of PRBs scheduled per subframe and the corresponding number of PRB allocated. The slope *m* of the curve depends on both RS power and power allocation options (cell specific, or user specific) [TR36.213R9].

FIGURE 22 shows a calculation with a simplified version of the linear model, in which the overhead is averaged in all subframes of the radio frame (actually not all subframes in the frame are equivalent in terms of overhead and transmitted power, e.g. PBCH is present only in the first subframe of the radio frame). According to this example, it can be noted that the slope of the transmitted power depends strongly on the value of RS EPRE, because the power of PDSCH resource elements is also defined with respect to that value. Moreover, for some RS EPRE values, the RF power at full load can exceed the limitation of maximum BS transmitted power, e.g. 46

dBm when a macro BS with 10MHz is considered, with a consequent maximum number of PRB being equal to 50. For that reason a first reference value of RS EPRE for this specific example is chosen to be 18 dBm.

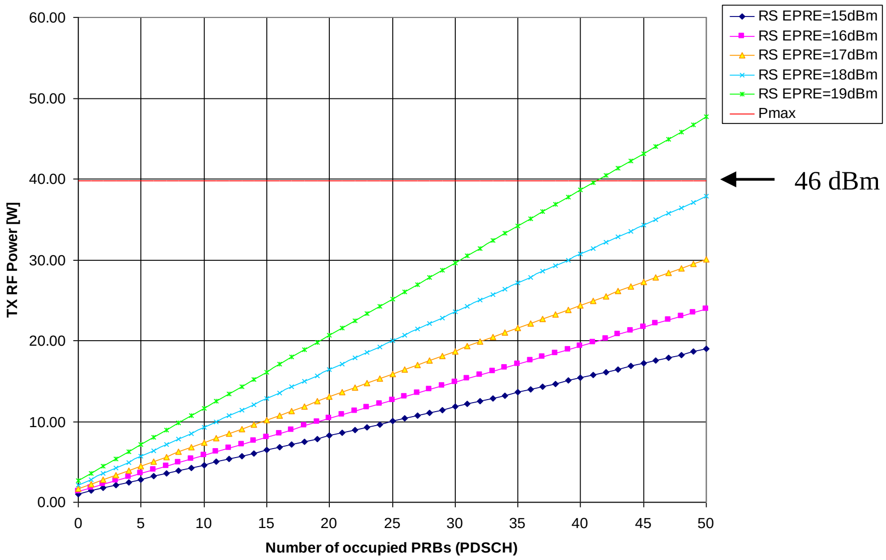

FIGURE 22. Example of dependency of RF power from RS EPRE [TR36.213R9].

FIGURE 22 shows the dependency of P_{RF} on the scheduled RBs and the dependency of the RF power on the RS EPRE. So, transmit power can be saved when the RS EPRE parameter is reduced, however, that would reduce the cell range. As long as the amplifier power model is close to linear, also the influence of the scheduling algorithms is very low, because the consumed power per PRB (i.e. the slope of the curves) is the same independently of the scheduled load. The different scheduler behaviour can only change the instantaneous power consumption, but the amount of energy for transmitting a data file stays the same. This has been verified in first system simulations using the power model of Chapter 4 and three different schedulers: Maximum Carrier Interference Ration per chunk (MCI) scheduler, Earliest Deadline First (EDF) scheduler and Proportional Fairness (PF) scheduler.

However, transmit power consumption can be lowered when the linear behaviour of the power amplifier assumed in (7-7) is changed, e.g. with a power amplifier that can be adapted to lower bandwidth (i.e. lower maximum number of PRBs) or that can be turned off during empty OFDM symbols (i.e. micro-DTX). Then the scheduler can leverage the different power amplifier states to schedule the traffic energy efficiently. This will be studied in more detail in the next section.

7.2.2. Energy efficiency evaluation of power amplifiers

In this section, we apply the evaluation framework described in Chapter 2 and adapt it to the problem at hand, along the lines of the assessment methodology discussed in Section 2.3.1.

The power consumed by the amplifier and other components of a BS is modeled as a function of load:

$$P_{cons} = f(load) \quad [W] \tag{7-9}$$

where P_{cons} is the consumed power of the respective investigated object. Different concepts of power amplifier for SOTA and EARTH solution are modelled by curves shown in FIGURE 24. The SOTA characteristic describes the power consumption of state-of-the-art Doherty power amplifiers. The adaptive PA characteristic describes power consumption of a Doherty amplifier with adjusted operating point (OPA PA) that adapts the saturation level of the amplifier according to the changes in the DC power supply (section 7.1.1.4). This allows the adaptation of the PA to the input signal characteristic, and hence to reduce its power consumption. The PA with stage deactivation (SD PA) is the state-of-the-art Doherty power amplifiers switching into a micro sleep at zero load during a fraction of a sub-frame (i.e. during one or several OFDM symbols that do not contain any signal). The DC power consumption then drops to only 5W. Finally, the adaptive and switchable PA (OPA & SD PA) curve describes power consumption of a Doherty amplifier with both adjusted operating point and a micro sleep possibility.

The power wastage of physical components with non-linear power consumption characteristic strongly depends on load characteristic and also on scheduling algorithms. Therefore, specific designs of schedulers and the LTE frame structure must be considered. We modelled three scheduler algorithms, i.e. as state-of-the-art Round-Robin scheduler that assigns UEs given resources, a bandwidth minimizing scheduler algorithm that fills the frames concerning a minimum of bandwidth, and an ON-OFF-scheduler that uses the full bandwidth to provide empty subframes to facilitate micro sleep.

Load profiles are used to explore areas of improvement in power consumption. The load profile for assessment of the BS and component design is based on European daily data traffic profile in dense urban and suburban region presented in Section 3.2.2, and shown in FIGURE 25. Based on a given load scenario, the standardised LTE frame structure and the selected scheduling algorithm, a normalised resource utilisation pattern for every OFDM symbol in a frame is calculated. In order to relate the traffic load of a BS to a normalized resource utilization pattern, dedicated small-scale, short-term system level simulations need to be carried out, as described in Section 2.3. The small-scale, short-term system level simulations determine the median SINR ratio and modulation scheme, the system and user throughputs of the specific deployments, as well as other figures of merit, as described for the EARTH reference scenarios in Section 6.1 (FIGURE 17).

The calculated resource utilisation pattern of a frame is then used to calculate the power consumption of individual components for the frame and finally to calculate the total energy consumed by all physical system components. FIGURE 26 shows two exemplary resource utilisation patterns at 50% load over 10 subframes for different schedulers. The pattern on the left represents the result of scheduler algorithm that uses a minimum bandwidth, while the pattern on the right represents the result of a scheduler algorithm that supports micro-sleeps. The spikes and high peaks are caused by control channels signalling and pilot symbols.

FIGURE 23 explains the modeling approach and how the relevant building blocks of the energy efficiency evaluation framework are applied. The figure highlights how the BS power consumption is determined, other integral parts of the EARTH energy efficiency evaluation framework, such as the SINR system simulations and computation of impact on user experience for realtime and best effort traffic and/or compromised coverage are omitted in FIGURE 23.

Using the power amplifier characteristics in FIGURE 24 we explore the combined impact of a particular scheduling scheme and of the power amplifier design on power consumption. The calculation is made iteratively for each time interval of the traffic load profile in FIGURE 25. While FIGURE 25 shows averaged traffic load over 15 min the calculation can also be performed for traffic patterns including faster fluctuation of load.

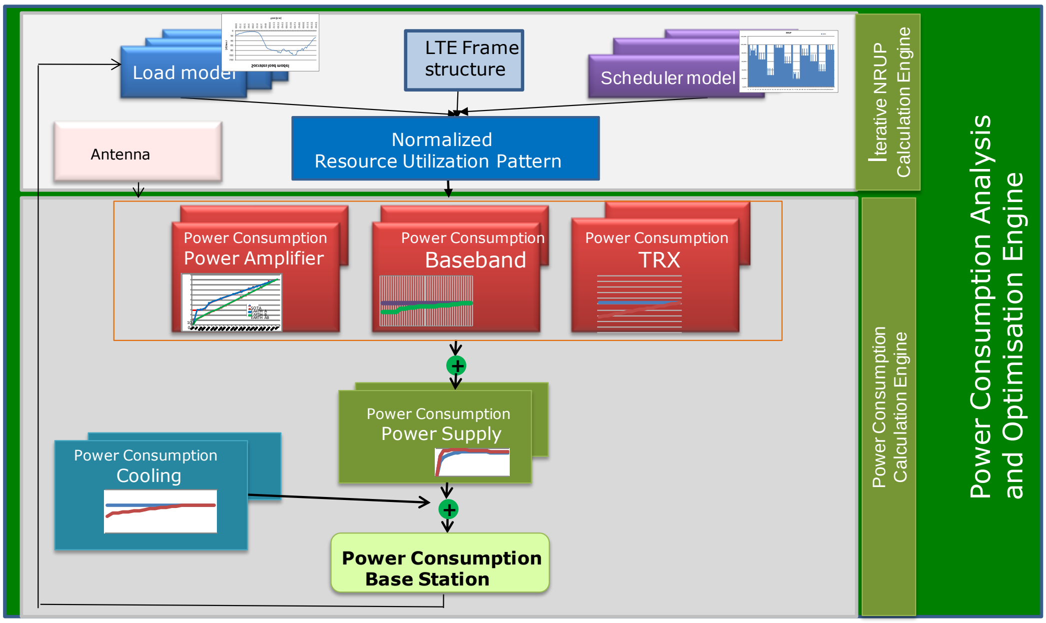

FIGURE 23. BS Power Consumption, Analysis and Optimization Tool

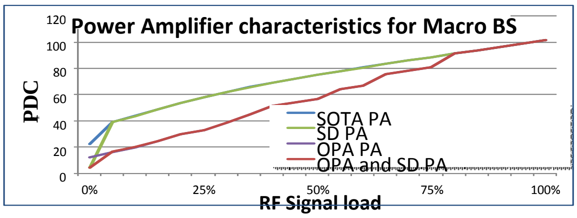

FIGURE 24. Characteristics of different power amplifier technologies

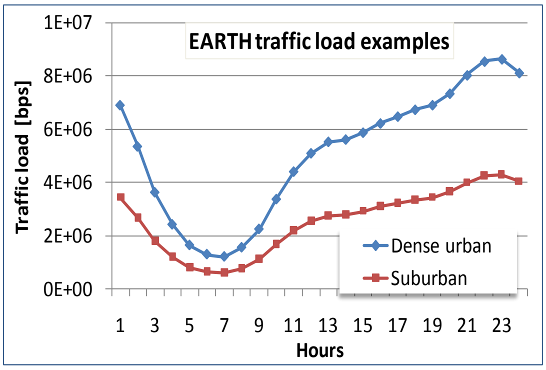

FIGURE 25. Traffic model over 24h

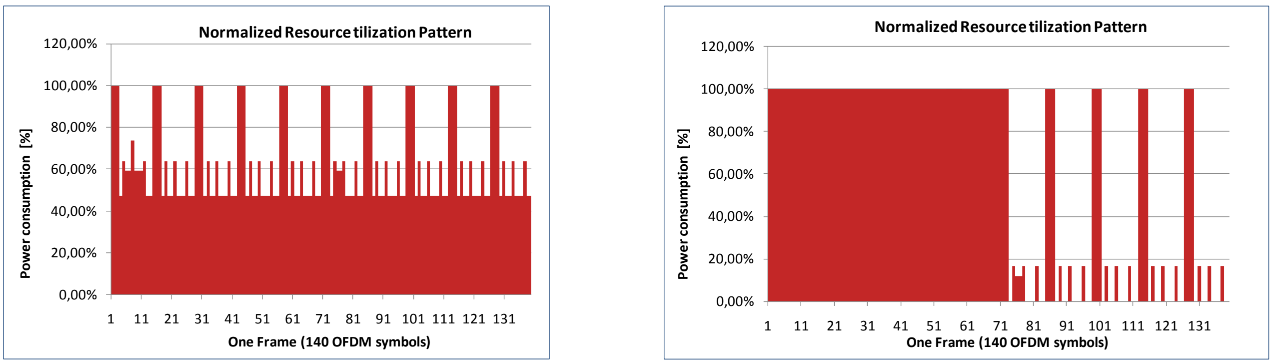

FIGURE 26. Examples of normalised resource utilization patterns for 50% load (simplified modelling assuming always maximum power for the control channel symbols). The scheduler on the left uses minimum bandwidth, the scheduler on the right supports as much micro-sleep as possible.

The system performance is not influenced by the high level scheduling scheme or by the PA power characteristic. In that way, we can directly assess the relative improvement potential that can be exploited by progress in the design and technology of power amplifiers. First we study 10MHz macro base station with 500m ISD in a dense urban region with 120Mbps/km^2 data traffic in busy hours (see TABLE 2). We compare the EARTH solutions to a SOTA base station with a RR scheduler. The resulting energy consumption for various schedulers and the different power amplifier models applied to EARTH traffic model are shown in FIGURE 27a. We can see that the best improvement potential can be achieved in the low load areas. On the other hand, the higher load areas tend to have nearly same power consumption for both compared power amplifier and scheduler architectures. The average energy savings over one day is of the order of 11% for stage deactivation PA (SD PA) with an ON-OFF-scheduler supporting micro-sleeps and 14% for an operation-point adaptive PA (PPA PA) with a bandwidth minimising scheduler. In principle, an ON-OFF scheduler can also be applied for a PA with the combined improvements. However, the additional savings are rather low, yielding in total 15.5%, because the ON-OFF-scheduler most of the time runs with full or zero resource utilisation.

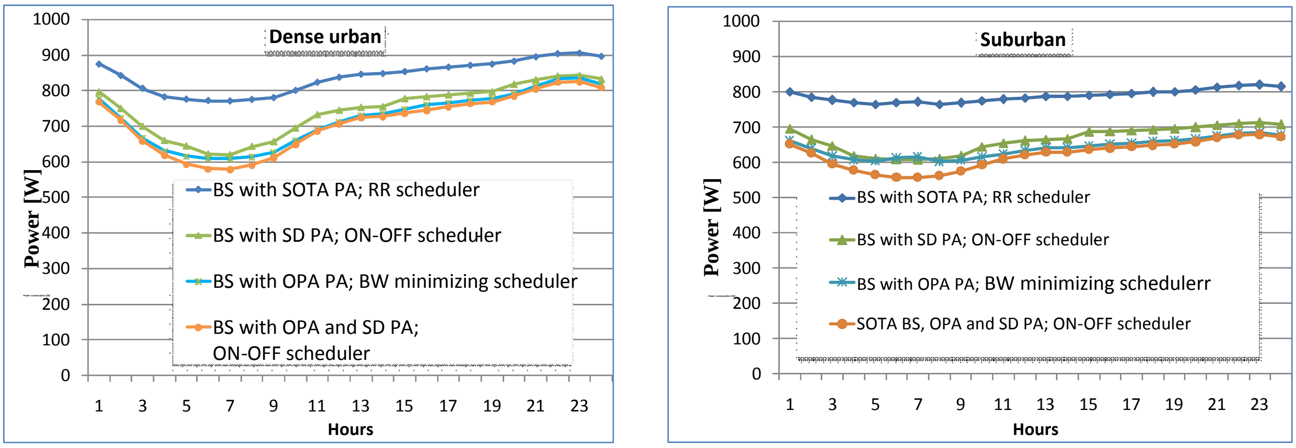

FIGURE 27. Variation in power consumption of different PA concepts and schedulers based on EARTH traffic model a) for dense urban and b) for suburban.

FIGURE 27b shows the results for a suburban scenario with 1750m ISD and mid profile traffic density of 5 Mbps/km^2 (see TABLE 2). The savings achieved for the suburban traffic model amounts 15.7 up to 21%. The lower the traffic load the higher is the saving potential, i.e. approx. 5% higher saving than for the dense urban scenario above. Obviously, even higher savings in the order of 30% are possible if we consider the low traffic profiles of TABLE 2. The real saving potential depends on the actual over-provisioning factor of the deployment.

For simplicity, in this calculation the control channels have been assumed to always use the maximum amount of resource elements foreseen by the standard. In reality at low load also less signalling information is transmitted in the control channels, e.g. in empty subframes also the control symbols are empty. With a refined modelling, some of the spikes in FIGURE 26 can be reduced or removed. First results indicate that the saving potential can increase from 20% to about 30%.

In conclusion of section 7.2, in this case the relative savings can be computed based on the system level performance modelling of the base line system and additional modelling of the changes in the power model. As an example we have presented a calculation for the effect of hardware adaptation in the power amplifier combined with a scheduling algorithm leveraging this and the EARTH traffic profile. Savings on the order of 13% were achieved on node level. The global EARTH energy efficiency evaluation framework in Section 2.2 suggests to average energy saving over the large scale mixture of all nodes in the network. This is left for the detailed work in deliverables following the selection of the most promising tracks.

8. FUNDAMENTAL CHALLENGES AND OUTLOOK OF FUTURE POTENTIAL

8.1. THE TWO CHALLENGES

Traditionally, radio access research both in the academy and the industry focuses on the challenge to achieve as high data rates as possible for a given maximum transmission power. Closer analyzing the challenges and the possibilities for the research area of network energy efficiency it is found that there is a second challenge, which is still not widely addressed or even accepted in the community. This second challenge addresses the power consumption of the system when it is not transmitting any data.

The first challenge is thoroughly addressed in research and specifications to allow for high peak data rates and capacity, for instance in LTE and HSPA. This very important work, which has been a main driver for the success of mobile telecommunication, as well as rapidly and steadily decreasing energy consumption per bit for the 3GPP technologies, will need to be continued although it is clear that it will be more and more difficult to maintain the rate of improvement with sinking energy consumption per bit. The reason is simply that the more straight forward solutions bringing considerable gains have already been implemented. Furthermore, not yet implemented solutions are typically more elaborate for a certain achieved improvement.

The second challenge, exploiting system operation whilst not transmitting, either by improving the energy efficiency during idle operation, or by finding efficient solutions to eliminate empty resource block transmissions, has so far been a neglected research area. Consequently, this is where the big unexplored potential lies. It is important to understand that this second challenge does not only address empty cells and no load scenarios. The potential of the non-transmitting scenario depends strongly on the considered time scale. Considering a traditional O&M time scales of 15 minutes there may not be many periods, if any, without any transmissions at all. However, LTE scheduling decisions are made per ms, i.e. per every LTE subframe; when addressing this time scale instead, the possibility for idle subframes becomes considerable, even in fairly loaded cells.

The EARTH-reference scenario simulations of a network covering the dense urban, the urban and the sub-urban areas of a country or region, and assuming the medium traffic profile as defined in Section 3.2, yield that more than 98% of the subframes do not contain any transmitted data (the corresponding figures for the low and high traffic profiles are more than 99% and 90%, respectively). Although the amount of empty subframes in today’s 3G and 4G network is somewhat reduced, e.g. by transmission of system information, the number of subframes not used for data transmission can be seen as a form of theoretical limit for how large the potential is for the second challenge. As in this 98% of time about 97% of energy is consumed by the system, mechanisms addressing individual subframes without data transmissions could deliver up to 97% of power savings. This is in addition to the power reduction achievable by features addressing subframes that are utilized for data transmissions.

The ultimate theoretical limit for energy consumption in a BS can be achieved if the BS consumes electricity only if there is something to transmit, defining the potential to reduce the consumed energy below 3% of state-of-the-art consumption by considering our current traffic and deployment models (see Section 3.2). These transmissions could be done with energy aware nodes able to provide top performance at maximum efficiency when needed, but also smart enough to dynamically null the power consumption if traffic conditions allow.

8.2. FUTURE POTENTIAL

In the following, we briefly present an overview of the fundamental potential of some selected tracks under investigation categorising them according to a hierarchical structure, i.e. air interface, components, deployments and node types.

8.2.1. Air Interface

Although 3GPP technologies have traditionally had a relatively low overhead compared to the amount of data sent, specifications still require a certain amount of fixed overhead in terms of system information, e.g. synchronization signals and cell specific reference signals (or common pilots). In addition, there is a certain load dependent overhead associated with each transmission, e.g. paging, random access information and physical control information. Once again, traditionally, the focus has been very much on reducing overhead at high load scenarios. Luckily this has, at the same time, meant that also the fixed overhead has been reduced to not hamper the peak performance of the system. From an energy efficiency perspective, we are reminded that, according to our estimates, subframes without scheduled data are in the order of 20 times more frequent than subframes with data. This makes it important to carefully consider the fixed non-transmission dependent overhead. The main purpose for that “overhead” is obviously fast accessibility; what is the trade-off between QoS and energy saving in this respect is yet to be determined. However, the EARTH project intends to address this aspect in the more long term related research.

The amount of energy needed for the actual transmission depends on 1) the amount of energy that needs to be received at the receiver side and 2) the losses in the air. The first depends on receiver performance, including noise factor, and also on the number of bits to transmit (here it seems natural to discuss in terms of the energy consumption metrics “Joule per bit”). On the other hand, the latter obviously depends on a large number of factors such as

- TX/RX distance;
- Propagation conditions;
- Directivity of TX antenna;
- Number of antennas at TX and RX side.

When it comes to the potential for energy efficient transmission based on beamforming with directional antennas, compared to omni-directional antennas, it is difficult to give any numerical values in advance. However, it is clear that the potential is considerable if the beam could be properly directed toward the receiver both azimuthally and in elevation domain. However, it should not be forgotten that the success of the 3GPP technologies are to a large extend based on their possibility to deliver large data rates in non-line of sight conditions and adapt to fast variations in the channel. This has made it necessary and suitable to adapt the technologies to multi-path fading, rather than forming one very narrow beam.

MIMO, in theory, has a huge potential of EE improvement in comparison with SISO; theory shows that the energy efficiency increases linearly with the number of receive antenna in the low spectral efficiency regime, and can be expressed as a function of the spectral efficiency itself in the high spectral efficiency regime. For instance, a 10x10 MIMO system can potentially be 10 to 100 times more energy efficient than a SISO system. In a practical setting, however, using a MIMO system with more than 2 transmit antennas at the BS is unlikely to provide any energy efficiency gain, or may even be less efficient than a SISO system, due to the inefficiency of some of the BS components. For instance, MIMO requires the incorporation of several transceiver chains, one for each antenna link, which may be particularly costly for low power applications.

Furthermore, CoMP uses macro-diversity to boost spectral efficiency of multi-cell systems but at the expense of extra energy expenditure. In theory, CoMP is equivalent to a distributed MIMO system and, thus, the conclusions drawn for MIMO in terms of EE hold as well to some extent for distributed MIMO. However, as for MIMO, in a practical case, CoMP seems to be more energy efficient than traditional systems mainly for cell-edge user scenarios.

8.2.2. Components

Until very recently, the BS hardware and the associated component development was the most important driver for reduced energy consumption per node. This important work cannot be overestimated and will need to be continued. In fact, some of the new features will need the support of continued component development work to reach its full potential.

There are two main drivers for increasing the energy efficiency of BS hardware components:

- Firstly, *advanced (nano) technologies*; this trend described by Moore's law has been setting the pace of improvements in the semiconductor industry for the last 45 years. Innovative materials, improved processes and smart design methodologies have a direct impact on the efficiency of every single component, making possible a slower but steady pace of improvements also at higher level and bigger nodes such as BSs.
- Secondly, *run time savings*; in order to take advantage of low and zero traffic periods, the BSs should be able to switch dynamically between different states, trading-off performance such as output power, signal to noise and distortion ratios, bandwidth etc. for reduced power consumption. These are system level solutions which require appropriate smart radio platforms. Software-Defined Radios may enable such features while providing the flexibility requirements needed to adapt radios to the ever changing standard requirements by simple software upgrades.

By including more and more radio components on a single chip, the benefit coming from these two drivers are actually amplified and faster efficiency improvements over time could be achieved. Increasing the level of integration is obviously easier for BSs with reduced output power as this allows relaxing requirements (such as cooling) otherwise critical in macro BSs.

8.2.3. Deployment and Node Types

It is often argued that small nodes are more efficient in terms of energy consumption than large macro nodes. In absolute terms, this is of course true but, keeping the radio performance metrics as well as the energy consumption metrics in mind, the picture becomes more complex. There are cases when a pico site can surely serve a certain user with a given data rate for a smaller number of kWh; typically, these scenarios are associated with a limited coverage area in which the traffic density is relatively high. However, this assumes that the user is within the pico-cell coverage area, being considerably smaller than the macro coverage area. On the other side, there are also cases where macro sites will perform better than pico sites in terms of energy consumption, often in scenarios where a large area with a rather low traffic density must be covered. In this case it is necessary to carefully consider what is most suitable for different scenarios, purposes, demands; while keeping the fixed as well as the load dependent energy contribution in mind. It has not been possible to find any unambiguous results regarding the optimal cell sizes with respect to energy consumption at this stage, but it is most likely that real systems will require a mixture of node types, e.g. macro and pico sites.

There are basically two straightforward approaches to address the fixed-energy cost here; via continuously improved component efficiency and by dynamically adaptable sleep modes of different types (also relying on hardware support). The latter becomes particularly relevant when considering smaller nodes whose primal function is not coverage but rather user performance and capacity. As discussed in Chapter 4, treating the power model, the desired component improvements look quite different for also different node types. For the large macro nodes, PA improvements stand in focus; for smaller nodes, RF going down to pico and femto nodes, the baseband processing needs to be addressed for improved energy efficient operation.

It should also be noted that, in order to reduce the overall power consumption of mobile networks globally, adding new nodes and technologies alone is not enough. What is needed in a long term is not only to improve future and new systems, but also to actually replace existing equipment. The Life Cycle Assessment (LCA) work within the EARTH project has come to the conclusion that, so far, very few base stations of any technology have actually been scraped in a global perspective. The operators assume an efficient second hand market where the common scenario is instead to sell outdated node equipment from mature markets to less mature markets and businesses.

Finally, it should be made clear that considering the different time perspectives for the respective solutions is crucial. Starting from what energy saving can be achieved on ms, or even μs scale, up to the possibility of savings when taking down cells or switching off whole BSs, something which will require actions on a time scale in the order of seconds or even minutes. As long as we are still far from the ultimate vision of loss free, 100% efficient nodes using electricity only when they transmit data, clever solutions on different time scales will be important. As a matter of fact, solutions on different time scales even constitute part of the road toward these future, ultimately energy-efficient radio-access networks.

8.3. CONCLUSION

In this deliverable, a suitable energy efficiency evaluation framework (E^{3}F) is defined to capture the overall system power consumption. We foresee the *EARTH E^{3}F* to become a widely accepted tool in the mobile-broadband industry and in the associated scientific community by encompassing methodologies, models and metrics which allow for a reasonable comparison between different strategies and networks. Ultimately, the EARTH E^{3}F shall enable the quantification of the potential energy savings in wireless systems.

The essential building blocks with the required level of detail are identified and analysed in this report in order to enable a holistic evaluation of the energy efficiency. In that direction, realistic long-term traffic models along with large-scale models for the deployment mix in Europe are provided, complementing the existing short-term and small-scale scenarios. Our aim is to capture the energy efficiency of an entire network, which typically consists of a combination of different small-scale deployments and experiences dynamic traffic variations.

Furthermore, an appropriate and sophisticated power consumption model describing each Base Station type (from LTE baseline system) is developed. The main focus is given to the radio equipment since it is the major contributor on the overall BS energy consumption. The scope of the power model is to constitute the interface between component and system level, allowing to quantify how energy savings on specific components enhance the energy efficiency at the node and network level. The power model is defined for both maximum and variable load conditions, providing a detailed analysis on how the BS sub-components power consumption dependends on the instantaneous traffic load.

In order to quantify the possible benefits of different technology solutions, well-defined and relevant performance metrics need to be adopted. The work in EARTH to reduce the energy consumption of mobile broadband networks aims at improvements on component, node, and network levels. In this document, appropriate metrics including sophisticated metrics to capture the energy consumption perspective in the analysis are defined. More specifically, the quality performance metrics, recommended by 3GPP, along with the *Power per area unit* and the *Energy per bit* energy consumption metrics are employed to provide the assessment of the overall performance and the *overall energy savings* at network level.

To demonstrate the handling of the energy efficiency evaluation framework we provide an example. We use the E^3F for a downlink evaluation of the LTE reference system as described in [EARTH-D2.2]. The proposed E^3F is used in order to evaluate the energy consumption of the network on a global scale. This example identifies the necessary steps leading to the overall system evaluation:

- the derived power model is used in order to monitor the energy consumption of the network sub-components;
- small-scale, short-term evaluations are conducted first;
- the selected performance metrics are adopted;
- the evaluation aggregation to global scale is provided based on
    - weighted summing of the small-scale, short-term evaluation results,
    - based on the large-scale deployment and long-term traffic models.

The reference system evaluations also deliver the reference results for comparison with the innovative EARTH tracks, and they provide guidance for the selection of the most promising tracks.

Moreover, the areas for potential improvement on energy efficiency over the reference system are introduced. The EARTH project aims to improve energy efficiency of a wireless system radio access at component, node and system level and the range of these promising approaches is described highlighting the important areas for improvement. To provide a meaningful example for evaluating and comparing the EARTH tracks with the reference system results, two selected approaches are studied, i.e. packet scheduler and power amplifier improvements.

Finally, we provide an overview of the fundamental potential of the areas the EARTH project explores for improvements of energy efficiency. Analysis of all tracks is currently ongoing and first results are presented in the EARTH deliverables [EARTH-D3.1] and [EARTH-D4.1]. Current results from ongoing investigations of selected tracks suggest that it is feasible to achieve, or even surpass, the original EARTH target to save 50% of energy for the integrated EARTH system.

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