Energy Aware Radio and neTwork tecHnologies

SEVENTH FRAMEWORK PROGRAMME

INFSO-ICT-247733 EARTH

Deliverable D2.4

Most suitable efficiency metrics and utility functions

Contractual Date of Delivery: December 31, 2011

Actual Date of Delivery: January 30, 2012

Editor(s): Jose Alonso-Rubio (EAB), Péter Fazekas (BME), Per Skillermark (EAB), Wieslawa Wajda (ALU)

Author(s): Muhammad Ali Imran (UNIS), Jose Alonso-Rubio (EAB), Gunther Auer (DOCOMO), Mauro Boldi (TI), Marco Braglia (TI), Péter Fazekas (BME), Dieter Ferling (ALU), Albrecht Fehske (TUD), Pål Frenger (EAB), Rohit Gupta (CEA), Efstathios Katranaras (UNIS), Shashika Manosha (UOULU), Pekka Pirinen (UOULU), Nandana Rajatheva (UOULU), Dario Sabella (TI), Per Skillermark (EAB), Liesbet Van der Perre (IMEC), Attila Vidács (BME), Wieslawa Wajda (ALU)

Participant(s): ALU, BME, CEA, DOCOMO, EAB, IMEC, TI, TUD, UNIS, UOULU

Work package: WP2

Estimated person months: 20

Security: Public

Version: 1.0

Keyword list: Mobile communications, energy consumption, performance metrics, utility function

Abstract: Evaluation of the energy consumption of dissimilar component, node, and network design options requires adequate performance metrics and such energy metrics are discussed in this report. Among the components a special focus is given to metrics suitable to assess the energy consumption of the transceiver system and the baseband, since it is these two units that dominate the energy consumption of a typical base station. In network level studies it is essential that both the quality of service as well as the energy consumption are properly measured. Finally, a utility based comparison framework is derived, which facilitates structured relative comparisons of different network solutions in which low energy consumption and high quality of service are conflicting requirements.

Authors

Partner	Name	Email and Phone
ALUD	Wieslawa Wajda	Wieslawa.Wajda@alcatel-lucent.com
	Dieter Ferling	Dieter.Ferling@alcatel-lucent.com
BME	Péter Fazekas	fazekasp@hit.bme.hu
	Attila Vidács	vidacs@tmit.bme.hu
CEA	Rohit Gupta	rohit.gupta@cea.fr
DOCOMO,	Gunther Auer	auer@docomolab-euro.com
EAB	Jose Alonso-Rubio	jose.alonso.rubio@ericsson.com
	Pål Frenger	pal.frenger@ericsson.com
	Per Skillermark	per.skillermark@ericsson.com
IMEC	Liesbet Van der Perre	liesbet.vanderperre@imec.be
TI	Mauro Boldi	mauro.boldi@telecomitalia.it
	Marco Braglia	marco.braglia@telecomitalia.it
	Dario Sabella	dario.sabella@telecomitalia.it
TUD	Albrecht Fehske	albrecht.fehske@ifn.et.tu-dresden.de
UNIS	Efstathios Katranaras	e.katranaras@surrey.ac.uk
	Muhammad Ali Imran	m.imran@surrey.ac.uk
UOULU	Shashika Manosha	manosha@ee.oulu.fi
	Pekka Pirinen	pekkap@ee.oulu.fi
	Nandana Rajatheva	rrajathe@ee.oulu.fi

Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

3GPP	3rd Generation Partnership Project
AC	Alternating Current
ATIS	Alliance for Telecommunications Industry Solutions
BSC	Base Station Controller
CDF	Cumulative Distribution Function
CF	Cooling Factor
CMOS	Complementary Metal Oxide Semiconductor
CPU	Central Processing Unit
DC	Direct Current
DciE	Data center Infrastructure Efficiency
DSP	Digital Signal Processing
DSPC	Digital Signal Processing Control
E^3F	Energy Efficiency Evaluation Framework
EARTH	Energy Aware Radio and neTwork technologies
ECI	Energy Consumption Index
EDGE	Enhanced Data rates for GSM Evolution
EE	Energy Efficiency
EEI	Energy Efficiency Index
ETSI	European Telecommunications Standards Institute
GOPS	Giga Operations Per Second
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HSDPA	High Speed Downlink Packet Access
HSS	Home Subscriber System
HTTP	Hypertext Transfer Protocol
IC	Integrated Circuits
ICT	Information and Communications Technology
IP	Internet Protocol
ITU	International Telecommunication Union
KPI	Key Performance Indicator
LTE	Long Term Evolution
M2M	Machine-to-machine
MPLS	Multi Protocol Label Switching
MSN	Multi-Service Node
MOS	Mean opinion Score
NE	Network Element
PA	Power Amplifier
PAE	Power Added Efficiency
PDH	Plesiochronous Digital Hierarchy
PE	Power Efficiency
PFF	Power Feeding Factor
PSF	Power Supply Factor
PUE	Power Usage Efficiency
RAN	Radio Access Network
RAT	Radio Access Technology

RBS	Radio Base Station
RF	Radio Frequency
RNC	Radio Network Controller
SDH	Synchronous Digital Hierarchy
SGSN	Serving GPRS Support Node
SGw	Serving Gateway
SLA	Service Level Agreement
SOTA	State Of The Art
TEEER	Telecommunication Equipment Energy Efficiency Rating
TRX	Transceiver (Transmitter and Receiver)
TX	Transmission (transmit)
UMTS	Universal Mobile Telecommunications System
UTRAN	UMTS terrestrial Radio Access Network
VoIP	Voice over IP
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
QCI	QoS Class Identifier
QoE	Quality of Experience
QoS	Quality of Service

1. INTRODUCTION

The overall goal of the EARTH project is to find solutions that reduce the radio access network energy consumption by at least 50 % [EARTH]. Solutions may take the form of improved components, such as, e.g., more efficient power amplifiers, and innovative network techniques that refine the network operation such that the energy consumption is reduced while still providing a high quality of service to the users. In addition, to verify that the proposed solutions provide gains also under close to real-life conditions, the EARTH project plans to test some selected techniques in lab or in a test plant.

In all cases proper performance metrics are needed to make sure that different solutions are evaluated and compared in an adequate and unbiased manner. That is, component level metrics are needed when investigating different hardware alternatives and node level metrics are used during the work in the lab or the test plant. Similarly, relevant network level metrics are essential in order to make a fair judgement of the considered network level techniques, and to eventually assess if the EARTH goal of 50 % energy reduction has been achieved.

In addition, it is likely that some new techniques provide improvements in a certain area at the cost of reduced performance in another, i.e., there exists a trade-off between different design objectives. A typical example may be that a technique that provides network energy savings is also associated with a reduced quality of service. It is then necessary to judge whether an improved performance in one area justifies a reduced performance in the other. A utility function provides a formalized means to evaluate the value of one design option relative to another and to assess which configuration that provides the highest overall performance.

This report discusses performance metrics and utility functions that are used throughout the work in the EARTH project. The metrics and utility functions aim to support the work in EARTH by means of providing a foundation for proper and fair analysis of different technical design options. The report is outlined as follows. Component level metrics are discussed in chapter 2, starting with a summary of the state of the art metrics available in the literature. Later in chapter 2, a set of new metrics, created based on the specific requirements of the EARTH project, are formulated. Node level metrics are handled in Chapter 3 with a special attention to the quite extensive material already existing from activities in study and standardization groups working with the energy efficiency of telecommunications equipment. Chapter 4 covers network level performance metrics and opens with a summary of classical commonly used radio network performance metrics. Next, chapter 4 introduces and discusses several energy consumption metrics that can be employed to monitor the energy usage in the network. Chapter 5 addresses the utility function and discusses how a utility function suitable to the specific needs of the EARTH project can be created and closes with two examples of how a utility function can be applied in practical study cases. Chapter 6, finally, concludes the report and summarizes the findings.

2. COMPONENT LEVEL ENERGY EFFICIENCY METRICS

An area for improvement on energy consumption in radio base stations can be seen in advanced design strategies of components. The most important investigated components, which significantly enhance the energy efficiency of a base station, are the transceiver system and the baseband component. The technological potential for energy efficiency improvement of the aforementioned components is investigated in [EARTH-D4.1] and [EARTH-D4.2]. Apart from transceiver system and baseband, technological improvements of power supply and cooling can also significantly reduce the overall energy consumption.

In this chapter we discuss the state of the art (SOTA) energy efficiency metrics and describe energy efficiency (EE) metrics for all of the components mentioned above in order to assist the evaluation of improvements. Metrics for the two most important units, namely the transceiver system and the baseband unit, are discussed in Section 2.1 and 2.2, respectively. Section 2.3 addresses the main power supply whereas section 2.4, finally, discusses the cooling unit.

2.1. TRANSCEIVER SYSTEM

The transceiver system, which is illustrated in FIGURE 1, represents the radio part of a base station providing the wireless interface to the mobile users. Its functionalities include signal conversions between digital and analogue domain, RF up- and down conversion and signal amplification providing the power level required for the radio link.

The main blocks of the transceiver system are:

- The Digital Signal Processing and Control (DSPC) unit, which adapts the base band (BB) signal to the analogue characteristics of the transceiver (TRX) and the power amplifier (PA) to meet the radio specification requirements. It ensures the signal quality, the compliance to the frequency band and the RF power. The reconfiguration of components in TRX and PA applied for power savings is controlled by the DSPC as well.
- The Transceiver comprises a radio frequency (RF) receiver for the uplink and a RF transmitter for the downlink. It provides signal conversions between digital and analogue domain, RF up- and down conversion and signal amplification.
- The power amplifier delivers the signal to be transmitted to an antenna with the power level adapted to the radio link.

The RF transceivers and the power amplifiers show a significant amount of power consumption in base stations dominating the power dissipation in the equipment for macro cells. Therefore the reduction of their power consumption is an opportunity for energy efficiency improvement. The components should be developed to be power-aware, i.e., able to scale power consumption in response to operating conditions. The power transmitted by the base station should be adapted to the load situation leading to lower power consumption at arbitrary load situation. The power performance of the RF transceiver and the PA is characterized by a set of metrics presented in following sections.

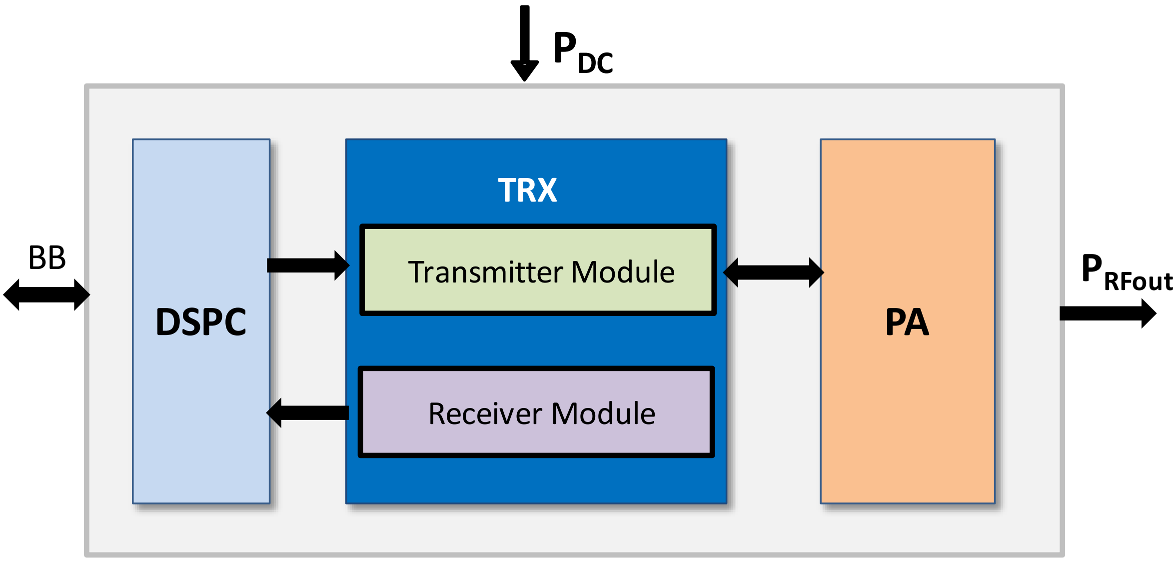

FIGURE 1. Transceiver System.

2.1.1. Power consumption in Transceiver System implementations

Different metrics used for defining the power performance of PAs are listed below. They show the basis for defining the most appropriate metric for energy efficiency assessment of hardware components in the EARTH project presented in section 0.

The power performance of PAs is described by its efficiency. References [ShWo2003], [LaCh2009], [Mcc2010], [LeTaVa2001] discuss total power efficiency, drain efficiency and power added efficiency metrics:

- **Total power efficiency**

  The total efficiency of the power amplifier is a significant metric with which the performance of power amplifier is assessed and compared with other amplifiers designed for the same application. In digital communication systems the RF input power (to the TRX system) is most typically zero.

$$PE_{total} = \frac{P_{RFout}}{P_{DC} + P_{RFin}} \qquad (2.1\text{-}1)$$

  where PE_{total} is the total power efficiency of the power amplifier, P_{RFout} is the RF output power, P_{DC} is the total power delivered from the supply and P_{RFin} is the RF input power.

- **Drain efficiency**

  The drain power efficiency is a ratio between the output RF power and the supply power. It indicates how well DC power is converted to RF power. The power efficiency (PE) can be given in percent.

$$PE_{drain} = \frac{P_{RFout}}{P_{DC}} \qquad (2.1\text{-}2)$$

  where PE_{drain} is the drain power efficiency of the power amplifier, P_{RFout} is the RF output power, and P_{DC} is the total power delivered from the supply.

- **Power added efficiency**

  Another power amplifier metric is the power added efficiency (PAE).

$$PAE = \frac{P_{RFout} - P_{RFin}}{P_{DC}} \tag{2.1-3}$$

Although, standardisation and specification developing organisations such as the Third Generation Partnership Project (3GPP), the International Telecommunication Union (ITU), the European Telecommunications Standards Institute (ETSI) and the Alliance for Telecommunications Industry Solutions (ATIS) have activities concerned with energy efficiency of wireless networks, no new energy efficiency metric for power amplifier are proposed to date.

Telecommunication operators have also been working on metrics. Verizon [VERIZON09] proposes a Telecommunication Equipment Energy Efficiency Rating (TEEER) metric for power amplifiers, which is a ratio of Total RF Power and Total Input Power multiplied by 10:

$$PA_{TEEER} = \frac{TotalP_{RFout}}{Total\ P_{DC}} * 10 \tag{2.1-4}$$

The $TotalPRF_{out}$ and $TotalP_{DC}$ consider the number of supported sectors, number of amplified carriers and the RF output power per carrier. In comparison, the calculation of PA Efficiency in EARTH is done only for one PA as shown in FIGURE 1. The number of sectors and any other parameters are taken into account at power calculation P_{RBS} on the site basis.

The TEEER value is a number that represents an energy efficiency rating on a scale of up to 10; the higher the TEEER value the better the energy efficiency of the measured device or system.

All of the metrics concern power amplifier operating at maximum power independently of the traffic load. However under real life conditions power amplifiers are operated at arbitrary load. Therefore metrics are required which describe the performance of PAs under varying load conditions.

2.1.2. EARTH energy efficiency metrics for transceiver systems

A unique metric is proposed for the entire transceiver system and its individual analogue components (DSPC, TRX, PA, power supply for PA) described in [EARTH-D4.1].

2.1.2.1. General power efficiency metrics

Starting from the different power efficiency definitions presented in section 0, the definition in equation (2.1-2) (drain efficiency) is considered as the most appropriate for describing the power performance of the transceiver system as it is independent from an input RF power. As the input signals for the transceiver systems are digital baseband signals (see FIGURE 1), the input RF power is zero, causing that all three equations (2.1-1), (2.1-2), and (2.1-3) lead to the same result.

The following equation is proposed as energy efficiency metric for transceiver systems:

$$PE = \frac{P_{RFout}}{P_{DC}} \quad (2.1\text{-}5)$$

where P_{RFout} represents the RF output power of the transceiver system, while P_{DC} denotes its total supply power. This PE definition is valid for every operation condition of the transceiver system.

2.1.2.2. Power efficiency metrics related to variable signal load

The efficiency of transceivers systems is strongly dependent on the level of the transmitted signal due to a respective dependency of PAs . The devices show a maximum efficiency when they are operating at maximum signal load (this corresponds to the highest allowed amplitude) and show lower efficiency when the signal is lower and has a certain back-off to the maximum. One main target of the project is to increase the energy efficiency for the operation with signal loads lower than the maximum. This demands adequate metrics to assess the performance. The following figures are defined to assess the power efficiency of PAs and transceiver systems dependent on the back-off to the maximum signal load. The signal load is defined as the instantaneous level of the transmitted signal related to the maximum RF output power defined for transmission.

The PE for maximum load (PEmL) represents the PE if no back-off is considered. It corresponds to the SOTA usage of PE definitions, as operation conditions at lower loads have not been considered up to now for performance assessment of power amplifiers.

$$PEmL = PE_{max\_signal\_load} \quad (2.1\text{-}6)$$

The PE for constant load (PEcL) defines the PE by considering arbitrary back-off values. For every arbitrary back-off value one single PEcL value is to be allocated by considering a constant signal level during the evaluation. This metric defines the performance of PAs for several load conditions with constant normalized load *c* in percent of the maximum load.

$$PEcL = PE_{constant\_load}(c) \quad (2.1\text{-}7)$$

To characterize a device performance a typical load profile should be used to calculate average power efficiency for variable load (PEvL), represented in the equation (2.1-8). The PEvL defines one single efficiency value for a given load scenario. The load profile is based on the traffic load defined for the reference scenarios in [EARTH-D2.3]. Based on the reference traffic load, test signals of variable load on the basis of a restricted number of load levels is defined and described in [EARTH-D5.2]

The variable output power $P_{RFout}(t)$ defines the variable load together with the variable supplied DC power $P_{DC}(t)$. In comparison to *PEcL* the definition of *PEvL* takes non-ideal transition times into account.

$$PEvL = \frac{\int_0^T P_{RFout}(t)dt}{\int_0^T P_{DC}(t)dt} \quad (2.1\text{-}8)$$

The presented metrics allows for capturing the energy efficiency performance of solutions proposed in the project by considering variable traffic conditions defined as reference scenarios in [EARTH-D2.3].

2.2. BASEBAND/DSP PROCESSORS

Most base-station baseband processors are integrated in advanced CMOS technologies. During the past three decades, the density and the speed of CMOS integrated circuits have increased roughly exponentially, following a trend described by Moore's Law [Claa1999]. While it is generally accepted that this exponential improvement trend will end, it is unclear exactly how dense and fast integrated circuits will get by the time this point is reached. Such trend somehow affects the efficiency of digital implementations and must be first analyzed in order to define some metrics. Therefore, this paragraph will first describe some general consideration of digital CMOS power dissipation and then will define some typical component-level metrics for baseband processors.

2.2.1. Power consumption in baseband/DSP digital implementations

The density and computing power of integrated circuits are limited primarily by power dissipation concerns. In modern digital CMOS circuit, the average power consumption, P_{avg}, is determined by two main parts, the dynamic and the leakage power consumption:

$$P_{avg} = P_{dyn} + P_{leak} = \alpha_{0\to 1} \cdot C_L \cdot V_{dd}^2 \cdot f_{clk} + I_{SC} \cdot V_{dd} \qquad (2.2\text{-}9)$$

where P_{dyn} is the dynamic power consumption and P_{leak} is the leakage power consumption, V_{dd} is the supply voltage level, f the frequency of operation, α is the switching activity of the capacitive node C_L on clock cycle f_{clk} *and* I_{sc} is the current leaking when transistors are on during switching.

The switching power P_{dyn}, also called dynamic or capacitive power, is the most significant part of the digital circuit overall power consumption. An integrated circuit chip contains many capacitive loads *C(y)*, formed both intentionally (as is the case with gate to channel capacitance) and unintentionally (between any conductors that are near each other but not electrically connected). Changing the state of the circuit causes a change in the voltage across these parasitic capacitances, which involves a change in the amount of stored energy. As the capacitive loads are charged and discharged through resistive devices, an amount of energy comparable to that stored in the capacitor is dissipated as heat. The energy required for this transition is $C_L \cdot V^2_{dd}$. Power-consuming transitions occur at a frequency $\alpha_{0\to 1}(y) \cdot f_{clk}$ proportional to the clock frequency f_{clk}, where $\alpha_{0\to 1}(y)$ is the probability of signal y to make a transition. The total switching power of a circuit is therefore

$$P_{dyn} = \frac{1}{2} \cdot f_{clk} \cdot V_{dd}^2 \cdot \sum_{signal\, y} \alpha(y) \cdot C(y) \qquad (2.2\text{-}10)$$

Some circuits require a minimum clock rate in order to function properly, wasting dynamic power even when it has nothing to do. Other circuits use "fully static logic" that have no minimum clock rate, but can "stop the clock" and hold their state indefinitely. When the clock is stopped, such circuits use no "dynamic power", but they still have a small static power consumption caused by "leakage current".

On the other hand, in advanced CMOS technologies, sub-threshold leakage current is becoming more and more important. This leakage current results in power consumption even when no switching is taking place and with modern chips this is frequently more than 50% of power used by the IC. This loss can be reduced by raising the threshold voltage and lowering the supply voltage. Both of these changes slow the circuit down significantly, and so some modern low-power circuits use either dual supply voltages to provide speed on critical parts of the circuit, and lower power on non-critical paths or extra transistors to shut down parts of computation units when not needed.

2.2.2. Power Efficiency Metrics in Baseband Processors

In computing, performance per watt is a measure of the energy efficiency of a processor/DSP architecture. Literally, it measures the rate of computation that can be delivered by a computer for every watt of power consumed. The performance and power consumption metrics used depend on the definition; reasonable measure of performance is GOPS (Giga Operations per Second), which is a measure of a computer's performance of a generic add or multiply computation.

The highest power efficiency per computation is achieved with techniques that allow voltage scaling and down-sizing of data-path logic [Brod2002], [Brod2007]. The metric for power efficiency is a ratio of number of *K* giga operations per second and power *P* consumed when providing the corresponding operations.

$$P_{eff1} = \frac{K}{P} \left[\frac{GOPS}{W} \right] \qquad (2.2\text{-}11)$$

Since energy corresponds to power multiplied by execution time, equivalently, energy efficiency measured in number of operations per Joule can be defined. Let M denote the number of operations performed during the time period T, and E the energy consumed during the same period:

$$E_{eff} = \frac{K}{P} = \frac{(M/T)}{(E/T)} = \frac{M}{E} \left[\frac{GOP}{J} \right] \qquad (2.2\text{-}12)$$

An alternative metric takes the clock frequency into account instead of the GOPS.

$$P_{eff2} = \frac{f_{clk}}{P_{avg}} \left[\frac{Hz}{W} \right] \qquad (2.2\text{-}13)$$

2.2.3. EARTH Energy Efficiency Metrics in baseband

The above described efficiency metrics are based on specific operations and data types and thus are rather designed to compare competing hardware architectures. In principle, energy consumption for baseband processing can be computed using the complexity of the baseband algorithms, given in GOPS/W. But focusing the baseband energy consumption metric on GOPS relates only to the CPU itself and makes other factors unconsidered.

Instead of using the operations which have to be carried out for processing we normalize to the number of information bits. By this, all implementation is taken into account since the metric is oblivious to how the task has been executed. Furthermore considering that the common task for the components is to provide data transmission service the required effort can be expressed as energy consumed by the component to provide this service as shown below:

$$E_{eff} = \frac{\int_0^T I(t)dt}{\int_0^T P(t)dt}\left[\frac{bit}{J}\right] \qquad (2.2\text{-}14)$$

where E_{eff} is the energy efficiency, I the transmitted bits in the given time and P power consumed by the baseband in a given time.

2.3. MAIN POWER SUPPLY

Howbeit the EARTH project has no direct impact on design and development of power supply we need to specify assessment criteria also for this part of the system. It is because calculation of overall system performance depends also on power supply efficiency.

The efficiency of a power supply EE_{PS} is described as ratio of output power P_{out} to input power P_{in}:

$$EE_{PS} = \frac{P_{out}}{P_{in}} \qquad (2.3\text{-}15)$$

The efficiency of a power supply varies depending on the load and input voltage applied. Concerning this matter power efficiency over variable load (*PEvL*), similar to equation (2.1-8), is defined

$$PEvL = \frac{\int_0^T P_{out}(t)dt}{\int_0^T P_{in}(t)dt} \qquad (2.3\text{-}16)$$

The above efficiency metrics show the technology advancement of a power supply in assayed base station.

2.4. COOLING

The internal and external cooling of a base station is not a part of EARTH development. Nevertheless, new generation of cooling systems will support base station in dynamic work environment and will have the potential to satisfy both full and partial load conditions. The Cooling Index is determined as the ratio of power demand for the cooling module to base station power consumed in a dedicated load.

$$CI = \frac{P_{CL}}{P_{BSL}} \tag{2.4-17}$$

where *CI* is the cooling index by defined load, P_{cl} is the power consumed by cooling at defined load, and P_{BSL} is the power of the base station consumed at defined load.

In this regard the computation of power consumption and further computation of power efficiency of a base station will reflect different cooling for different system load situations, see equation (2.3-16). In case of passive cooling, e.g. by fanless convection, the cooling index is zero.

3. NODE LEVEL ENERGY EFFICIENCY METRICS

The EARTH project aims to enhance the RAN energy efficiency by means of deriving solutions that lower the energy consumption on individual components, such as a power amplifier, and methods that can be applied on a network level to reduce the energy consumption of the network as a whole, e.g., clever base station inter-working principles. Furthermore, a base station (node) power consumption model [EARTH-D2.3] is derived in order to assess how the improvements on component level transfers to node level and, eventually, to network level. The improvements of selected concepts are also to be validated in a test plant or using lab prototypes. Typically, such validations cannot be performed in full-scale networks but must be limited to setups comprising a few or even a single node. Energy efficiency metrics on node level are hence a necessity and metrics for such purposes have previously been studied by organizations that have an interest in measuring the energy efficiency of telecommunication equipment, like ATIS and ETSI.

This chapter is devoted to conclude findings related to the definition, interpretation and measurement of energy efficiency metrics characterizing single network nodes. Besides some basic clarifications in Section 3.1, this chapter contains in Section 3.2 and 3.3, respectively, the definitions and evaluations provided by the two standardization bodies ATIS and ETSI.

3.1. NODE LEVEL CONCEPT

The EARTH project deals with the energy efficiency improvement of the Radio Access Network (RAN) part of cellular systems. This scope excludes considering core network elements (e.g. SGSN or SGw), or database entities (e.g. HSS) in EE investigations, as well as other networking elements necessary for implementing core network routing and switching (e.g. MPLS routers, MSNs, etc.). The RNC element of 3G UTRAN (although part of the radio access network) is also not considered as “node” in EARTH examinations. As the main system examined by the project is LTE and there is no central entity in LTE RAN, this question is not raised for LTE.

The main target of the project is the radio interface and the EE of radio base stations, therefore a node should generally mean a base station. Backhauling concepts are integral part of EARTH research within certain topics, hence the energy consumption of individual backhaul links between two base stations may be considered. Generally, in EARTH research a node means a radio base station (with or without backhaul link), or a radio base station site (may include several base stations and/or backhauls). In this latter case the notion node correspond to the ATIS facility level concept, as described in section 3.2. It might be possible that the characterization of a single backhaul link (without taking into account the base station it connects to) is necessary. In this case a node should be considered to be the backhaul equipment (with its individual energy consumption).

Typically there are other networking equipment in a physical RAN (creating the transport network for base station traffic), like PDH/SDH multiplexers or Ethernet switches, depending on the underlying technology chosen by the operator. Although these equipments may considerably contribute to the total energy consumption of the RAN, they are not in the focus of EARTH investigations, hence not considered in the definition of a “node”.

According to these considerations, a node level metric should definitely characterize the energy efficiency of a radio base station (or a site) and occasionally could include (depending on the actual research topic looked at within a particular task of the project) or be applicable for individual backhaul links. A straightforward approach may be to base the node level metric on the same physical quantities as are included in the network level metrics, which are discussed in Chapter 4. This fact intuitively can be seen by considering the smallest radio access network possible (a single base station), when the node is equal to the network. In this case the node level metric characterizes the network itself, thus it should not be different.

In general, the total energy consumed by the base station (or total site, possibly including backhaul links) should be taken into account. In case energy over transmitted information (throughput) measure is applied, the total throughput of the base station site is to be measured. Note that this approach enables the evaluation of the case of co-located base stations as well as multi-RAT base stations. It should be noted that although the network under consideration consists of several nodes, the network level metric (energy over information) is *not* the sum of corresponding individual metrics of each node (although the network energy and network throughput individually are the sums of node energy consumptions and node throughputs in most cases). If an individual backhaul link in isolation is examined, the metric is applicable as the energy consumption of the backhaul link equipment over the transmitted backhaul link information.

The power over covered area is also a relevant metric for characterizing a node. In this case the total consumed power of the node (either base station, or site, with or without backhaul) is divided by the covered area. Again, this type of metric does not sum up, that is the network level metric is not composed as sum of node level metrics. This type of metric is not applicable for individual backhaul links, as the coverage area of a backhaul link is not defined.

The following subsections summarize the relevant information and results of ATIS and ETSI, in relation to the EARTH concept of node level energy efficiency metrics. Both ATIS and ETSI concentrate on node level – i.e. base station – energy efficiency, when considering wireless network EE within the ICT domain. ATIS concept of facility level view is in line with the broader sense of considering a node within EARTH, namely a complete base station site. Also the ETSI RBS site model considers the auxiliary equipment necessary for running a base station.

One key observation is that these standards bodies seriously consider power efficiency type measures (ratio of usefully spent and total input powers), along with other metrics that are in consideration within EARTH project as well. These power efficiency measures are applicable for characterizing the loss of energy due to several factors (not necessarily in close relation to EARTH investigations, e.g. loss due to DC-DC voltage conversion, or inefficient coating of the base station container). However, having these factors characterized by the efficiency ratio, their impact on the node level EE should be taken into account by means of multiplication with this efficiency factor. With a similar approach, ETSI defines cooling factor and power input factors accounting for extra energy usage in a site.

ETSI also defines the average power consumption for different base station considerations. This is very relevant to test plant measurement activities in EARTH WP5, where EE enhancements will be verified by measurements on an operating testbed system. Moreover, as one considered node level measure is power over average capacity, the power in the nominator should accordingly be an average power; using ETSI definition is one possibility here.

3.2. ATIS ENERGY EFFICIENCY WORK

Document [ATIS2009] provides the results of an initial study into the topic of environmental sustainability for ICT. This document was developed by the ATIS Exploratory Group on Green (EGG) ad-hoc group.

For comparing efficiencies and analyzing scenarios, it is generally recommended that metrics related to power are to be used. Once a power consumption-based measure is known, estimates of the CO_2 emissions equivalent are possible using carbon-equivalence calculation tools.

ATIS terms and definitions

- **Energy Efficiency –** Any measure of the ratio of useful energy output to energy input.
- **Metric –** A general term used to describe a measurable value available from a particular system or service. A metric must be based on high level parameters applied to its measurement.
- **Measurement Methodology –** A system of principals, practices and procedures applied to metrics. Energy efficiency can be measured at the discrete equipment or device level to a more broadly measured system or network level. When referencing energy efficiency it becomes important to understand the context in which measurements are being made and efficiencies are being reported.

Energy Metrics

Energy metrics can be divided into two broad categories:

- **Equipment Level Metrics** – ICT equipment level metrics include the ATIS TEEER which is a ratio of work performed divided by power dissipated or energy consumed over time. This standard provides ICT equipment manufacturers and service providers with a methodology to calculate the TEEER of an individual piece of ICT equipment or network configuration. There are separate TEEERs for separate ICT equipment categories – just as there are with common kitchen appliances. Just as the ENERGY STAR rating of a refrigerator to a dishwasher cannot be compared, similarly, the TEEER of a router to a fiber optic terminal are not comparable. Comparison of the TEEER of one router to the TEEER of a similarly equipped competitive router will be possible. This tool drives continuous improvement in the energy efficiency of virtually all types of ICT equipment.
- **Facility Level Metrics** – Facility level metrics can help organizations better understand and improve the energy efficiency of their existing facilities. In addition, these metrics provide a dependable way to measure their results against comparable organizations. Facility level metrics include Green Grid Power Usage Effectiveness and / or data center Infrastructure Efficiency (PUE / DciE). While not perfect, these metrics do allow for meaningful comparisons of facilities within similar geographical areas / meteorological patterns and data measurement methodologies.

Base Station Wireless Access Network EE rating Reference Model

A high-level wireless access network node energy efficiency rating model is given, which can be used for estimating product energy consumption.

FIGURE 2 depicts specific steps for estimating energy consumption. The first step is to develop a traffic model that represents the average daily traffic behavior towards a given network. In addition, the performance parameter of the product must be gathered and ready to be used in mathematical equations to compute the energy efficiency rating of the product.

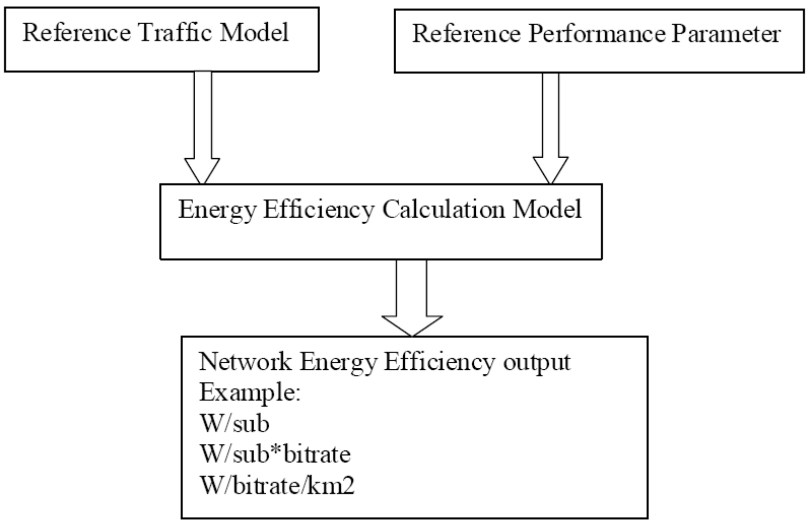

FIGURE 2. Wireless Access Networks Energy Efficiency Calculation Model ([ATIS2009]).

Performance parameters of an existing product in operation can be estimated based on data from the field.

The Reference Traffic Model shall contain:

- Number of active users in the network
- Type of services the users are using
- Average number of attempts per user per service

The Reference Performance Parameter shall contain:

- Coverage performances and traffic handling capability of the system
- Site reference parameters (power supply, cooling solution, shelter solution, etc.)
- Product parameters (number of sectors, frequency band, capacity, bandwidth, etc.)

Energy Efficiency Calculation Model shall contain:

- Calculation assumption and formulas
- Measured input values

Power Usage Effectiveness (PUE)

Document [ATIS2009] also addresses the energy efficiency of data center infrastructures. However, the metrics defined are general enough to be applied to node level EE modeling as well. This approach could be used in EARTH if the ICT Equipment below is considered to be the base station, while the Total Facility Power is the power required for running the complete base station site, including e.g. air conditioning.

The **Power Usage Effectiveness** (PUE) is determined by dividing the amount of power entering a data center by the power used to run the computer infrastructure within it:

$$PUE = \frac{\text{Total Facility Power or Energy}}{\text{ICT Equipment Power or Energy}} \tag{3.2-18}$$

Total Facility Power is defined as the power measured at the utility meter – the power dedicated to support the telecommunications network elements. This includes the Network Element (NE) equipment load and everything that supports the NE equipment load, including building electrical and mechanical systems, standby AC plant, DC power plant, lights, etc.

ICT Equipment is a generic term that includes both IT equipment and telecommunications NE equipment.

IT Equipment Power includes the load associated with all of the IT equipment, such as compute, storage, and network equipment, along with supplemental equipment.

For example, if a PUE is determined to be 3.0, this indicates that the data center demand is three times greater than the energy necessary to power the IT equipment.

PUE is inversely related to energy efficiency – the higher the PUE, the poorer the facility energy efficiency.

3.3. ETSI ENERGY EFFICIENCY WORK AND RELATION TO EARTH

In this section the ETSI work on energy efficiency of wireless access network equipment [EARTH-TS102.706] is described and the relations of this to corresponding EARTH activities is briefly outlined.

Document [ETSI-TS102.706] covers the GSM/EDGE, WCDMA and WiMAX radio access technologies and defines a method to analyse the energy efficiency of wireless access network equipment. In particular only the RBS site energy consumption is taken into account, being the main part of the total energy consumption, while functionality located in RNC or BSC nodes are not included in the document.

3.3.1. RBS Power Consumption

The energy efficiency model for wireless access networks suggested by ETSI considers at first the measurements of the RBS equipment power consumption for concentrated and distributed RBS, where

- reference configuration
- frequency band
- load levels

are specified. The reference parameters for the GSM/EDGE, WCDMA/HSDPA and WiMax technologies are provided in the Annexes D-E in [ETSI-TS102.706]. The average power consumption of RBS equipment, $P_{equipment}$ in [W], is defined for concentrated and distributed RBS considering three different load levels (busy hour load, medium term load, low load) as follows:

Concentrated RBS

$$P_{equipment} = \frac{P_{BH} \cdot t_{BH} + P_{med} \cdot t_{med} + P_{low} \cdot t_{low}}{t_{BH} + t_{med} + t_{low}} \qquad (3.3\text{-}19)$$

where P_{BH}, P_{med} and P_{low} are respectively the power consumption [W] with busy hour load, medium term load and low load while t_{BH}, t_{med} and t_{low} [hour] are the time duration of the different load levels.

Distributed RBS

$$P_{equipment} = P_C + P_{RRH}, \qquad (3.3\text{-}20)$$

where P_C and P_{RRH} are the power consumption of central and remote parts of the RBS and are defined as follows similarly to the above mentioned concentrated RBS equation:

$$P_C = \frac{P_{BH,C} \cdot t_{BH} + P_{med,C} \cdot t_{med} + P_{low,C} \cdot t_{low}}{t_{BH} + t_{med} + t_{low}} \qquad (3.3\text{-}21)$$

$$P_{RRH} = \frac{P_{BH,RRH} \cdot t_{BH} + P_{med,RRH} \cdot t_{med} + P_{low,RRH} \cdot t_{low}}{t_{BH} + t_{med} + t_{low}} \quad (3.3\text{-}22)$$

The voice and/or data traffic per hour are reported in the Annexes D-E in [ETSI-TS102.706] for each technology considered.

3.3.2. Site Power Consumption

In order to consider the overall consumed power, a site average power consumption, P_{site} in [W], is defined, in which besides RBS equipment, other different support system and/or auxiliary cabinets power consumption terms are included. A scheme of site reference model of outdoor RBS is shown in FIGURE 3.

For the comparison of different RBS types, scaling factors have been introduced that take into account the power supply including losses, and a particular cooling solution for the site level power consumption.

With respect to the current power model introduced in EARTH project [EARTH-D2.3], the site efficiency parameter adds further information since the focus is on the overall consumption of the site, due to all the possible sources that are not included in the single node consumption. The cooling factor and the power supply factor here refer to the aspects related to the whole site and excluding the base station and are not to be confused with the corresponding factors referring to the bases station and defined in [EARTH-D2.3].

Concentrated RBS: The site average power consumptions, measured in [W], for concentrated RBS amounts to

$$P_{site} = PSF \cdot CF \cdot P_{equipment} \quad (3.3\text{-}23)$$

where PSF [unit less] is the power supply factor and CF [unit less] is the cooling factor. The possible values suggested by ETSI group are reported below:

PSF, Power Supply Factor

- Equipment with AC power interface → PSF=1.0
- Equipment with DC power interface → PSF=1.1

CF, Cooling Factor

- Indoor RBS equipment with fresh air fan based cooling solution → CF=1.05
- Indoor RBS equipment with air condition controlled to 25 °C → CF=1.5
- Outdoor RBS equipment→ CF=1

PFF, Power Feeding Factor,

- to compensate for power supply losses for remote units → PFF=1.05

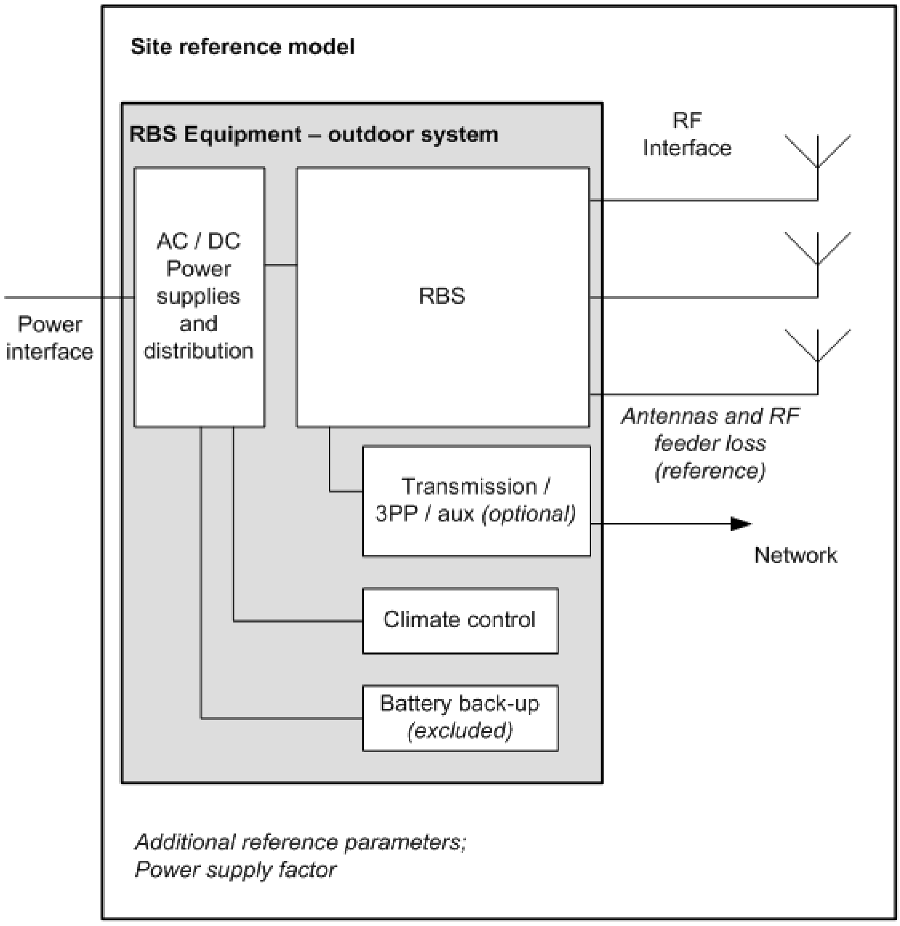

FIGURE 3. Outdoor RBS site model showing RBS equipment and support system infrastructure ([ETSI-TS102.706]).

Distributed RBS: The site average power consumptions, in [W], for distributed RBS amounts to

$$P_{site} = PSF_C \cdot CF_C \cdot P_C + PSF_{RRH} \cdot CF_{RRH} \cdot PFF \cdot P_{RRH} \qquad (3.3\text{-}24)$$

where P_{SFC}, PSF_{RRH} are the power supply factors and CF_C and CF_{RRH} are the cooling factors related to the central and remote parts of the RBS respectively. PFF is the power feeding factor [unit less] for the remote units introduced to compensate for power supply losses. For remote radio heads PFF=1.05.

Following [ETSI-TS102.706], the calculated equipment power and the power per site must be reported in a table (Annex A of [ETSI-TS102.706]) together with the TX output power. The ratio between TX output power and power site consumption gives the energy efficiency of the RBS.

3.3.3. Relation to EARTH Energy Consumption Index

The Energy Consumption Index (ECI) of the site or node can be generally written as:

$$ECI = \frac{P_{site}}{KPI} \quad (3.3\text{-}25)$$

where P_{site} is the total input power of the node and *KPI* can be the coverage or the throughput, respectively, described by the performance metrics $ECI_{P/A}$, measured in [W/m^2], and $ECI_{E/B}$, measured in [J/bit], as proposed in Chapter 4, discussing network level energy consumption metrics.

The ECI can be also written as a contribution of two terms in order to highlight the input power of the radio base station P_{RBS} alone as reported in the following equations:

$$ECI = \frac{P_{site}}{KPI} = \frac{P_{site}}{P_{RBS}} \cdot \frac{P_{RBS}}{KPI} = \frac{1}{\eta_A} \cdot \frac{P_{RBS}}{KPI} \quad (3.3\text{-}26)$$

where $1/\eta_A$ is a factor defined in [ETSI-TS102.706] as:

$$\lambda_A = \frac{1}{\eta_A} = PSF \cdot CF \cdot PFF \quad (3.3\text{-}27)$$

3.3.4. Metric interpretation

Furthermore, as it is schematically shown in FIGURE 4, the Energy Consumption Index (ECI) can be further detailed splitting the network consumption to highlight the radio frequency power P_{RF} as reported in the following equation:

$$ECI = \frac{1}{\eta_A} \cdot \frac{P_{RBS}}{KPI} = \frac{1}{\eta_A} \cdot \frac{P_{RBS}}{P_{RF}} \cdot \frac{P_{RF}}{KPI} \quad (3.3\text{-}28)$$

With the ECI divided in three terms, it is possible to highlight the radio frequency power contribution according with the [ETSI-TS102.706] standard in which the P_{RF} measure must be reported in the table of the performed measurement.

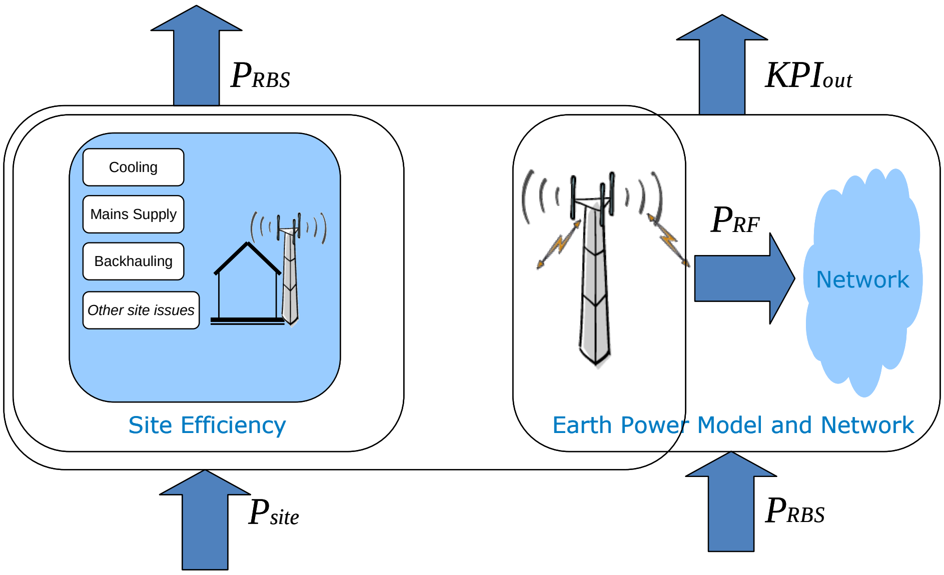

FIGURE 4. Graphical representation of the Energy Consumption Index with Site Efficiency Factor

The explication of the Energy Consumption Index (ECI) with P_{RF} gives information also on the scheduling efficiency and on the efficiency of the network where the RBS operates. Assigned a scheduler policy different power models could be captured by P_{RBS}/P_{RF} factor and P_{RF}/KPI could be useful not only to capture scheduling efficiency in the RBS but also as a measure of the efficiency of the surrounding network where the RBS operates, e.g. in terms of deployment or cooperative schemes. In particular, if we consider the two partial efficiency ratios:

$$\lambda_{RBS} = \frac{1}{\eta_{RBS}} = \frac{P_{RBS}}{P_{RF}} \tag{3.3-29}$$

and

$$\lambda_{RF} = \frac{1}{\eta_{RF}} = \frac{P_{RF}}{KPI} \tag{3.3-30}$$

the following considerations can be made:

- at full load the relative gain in terms of η_{RBS} is mathematically equal that in terms of η_{RF} (see [EARTH-D3.1] appendix 8.7); this means that at full load the energy efficiency of the system is limited by the spectral efficiency (depending on the packet scheduler), and relative gains do not depend on the particular linear power model considered

$$\frac{\Delta\eta_{RBS}}{\eta_{RBS}} = \frac{\Delta\eta_{RF}}{\eta_{RF}} \tag{3.3-31}$$

- results showed also that a tradeoff between EE and fairness should be carefully considered
- at lower load levels the influence of the power model is important because it has huge effects on the η_{RBS} ratio and also on the energy efficiency of the system. System level simulation has been performed by fixing a certain required cell throughput and by monitoring QoS and radio parameters (as defined in [EARTH-D2.2] and [EARTH-D2.3]);

- in these conditions, at low load the served cell throughput is equal to the target one, and it is reasonable to say that different schedulers will differ in terms of used RF power in order to provide that throughput (η_{RF} ratio). On the other hand the term P_{RBS}/P_{RF} is for sure influenced by the power model of the RBS.

As a consequence results indicate that it may be helpful to keep trace of all the three proposed terms in future evaluations (devoted to the ECI assessment), in order to monitor the contributions to the energy efficiency of all the parts of the systems (e.g. gains are essentially given by spectral efficiency, EE properties of the hardware, deployment and site effects, etc.).

3.3.5. Ongoing ETSI work

For the sake of completeness, the ongoing ETSI EE activity on network level extension of the energy efficiency measurements has to be briefly reported. As well as the static measurement set-up, which is sketched in FIGURE 5, ETSI EE has introduced a new test set-up, described in FIGURE 6, about dynamic measurements in [ETSI-TS102.706].

In the dynamic set up it has to be noted that the RBS is connected to the “core network” and is loaded by a number of UEs to emulate a real traffic scenario. The aim of this set up is to evaluate RBS behavior in terms of energy efficiency when it runs in a nearly “real” condition. Currently the dynamic set up foresees 4 UEs per sector of the RBS with a given and pre-defined traffic profile and a throughput threshold is set for each UE in order to ensure a sufficient quality of service for all the users, and avoid measurements with RRM procedures unfair for some UEs in the coverage area.

A Work Item to evaluate the feasibility of this dynamic set up together with the possible extension of the specification with the inclusion of more specifications (e.g., fading, temperature range, GSM for data, and multiple carriers for HSPA) has been opened, aiming to prepare a Technical Report by the first half of 2012.

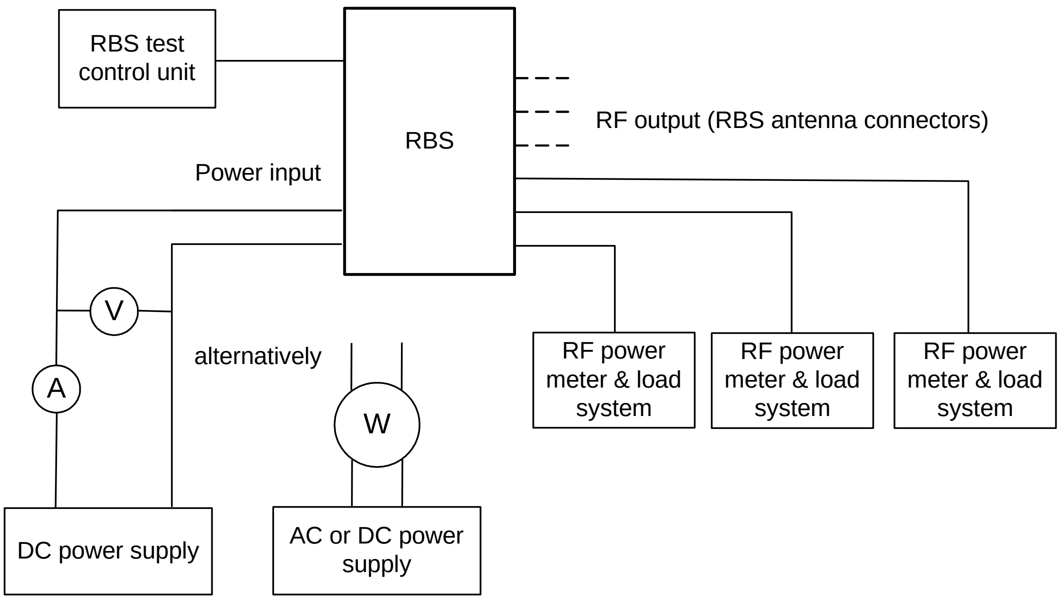

FIGURE 5. Test set-up for static measurement ([ETSI-TS102.706]).

Furthermore, [ETSI-TS102.706] presents two network level energy efficiency indicators for GSM for rural and urban areas. The network level performance indicator for the rural area is defined as:

$$PI_{rural} = \frac{A_{coverge}}{P_{site}} \qquad (3.3\text{-}32)$$

where the $A_{coverage}$ is the RBS coverage area in [km^2], calculated with the Okumura-Hata model, while the indicator for the urban area is defined as:

$$PI_{urban} = \frac{N_{busy\_hour}}{P_{site}} \qquad (3.3\text{-}33)$$

where N_{busy_hour} is the number of subscribers based on the average busy hour traffic demand by subscribers and average RBS busy hour traffic defined in the specification. According to above discussion, these metrics are applicable to serve as node level metrics to characterize a single base station.

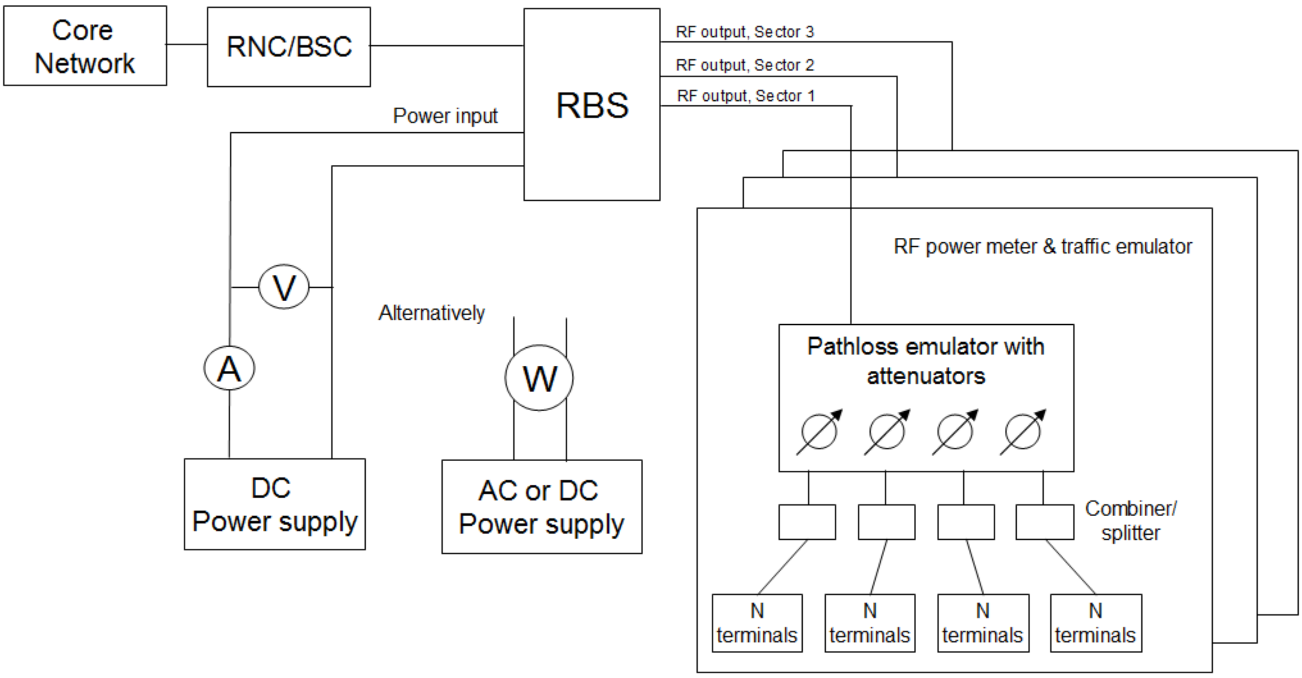

FIGURE 6. Test set up for dynamic measurement with mobile terminals.

4. NETWORK LEVEL ENERGY EFFICIENCY METRICS

This chapter addresses performance metrics on network level with special attention to metrics that can be used to quantify the energy consumption of a network. In relation to this we note that ETSI has recently started up a network level power efficiency activity [ETSI-DTR/EE-EEPS004] that targets, e.g., energy measurements on real network as well as models and simulation for radio network simulation. Section 4.1 explains the underlying models and assumptions and defines the quantities that are used throughout the chapter. In Section 4.2, an overview of the current ways of working is provided, in which the focus is on the spectrum efficiency of the network and the quality of service delivered to the subscribers. Section 4.3 introduces the energy consumption perspective and discusses the advantages and disadvantages of the different metrics that can be used to measure the radio network energy consumption. Section 4.4 discusses long term global averages of energy efficiency metrics and their predicted evolution over time. Section 4.5, finally, provides a ways of working recommendation for the EARTH project.

4.1. BACKGROUND, MODELS, AND ASSUMPTIONS

A simplified description of a cellular network is a system comprising multiple sites and cells, which are distributed geographically in order to provide wireless access connectivity over a certain area. FIGURE 7 provides a schematic illustration of a seven site system with three sectors per site, in which a few users are present. The coverage area of the network is denoted by *A*.

Observing the network over some time period *T*, one can measure the traffic flowing through the network and the network power usage. Denoting by $r_i(t)$ the rate by which bits are correctly delivered in cell *i*, the total information (number of bits) delivered in a network comprising *N* cells is calculated as:

$$I = \sum_{i=1}^{N} \int_{0}^{T} r_i(t)dt \quad [bit] \qquad (4.1\text{-}34)$$

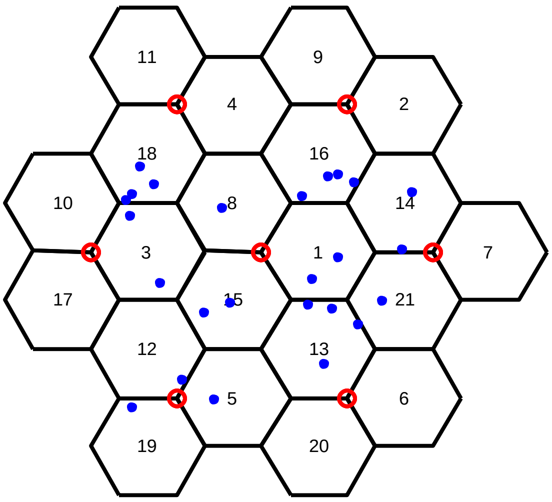

FIGURE 7. Schematic picture of a cellular system with a few users.

Typically, the energy consumption of the radio base stations dominates the energy consumption of the radio access network. Hence, for simplicity, we here approximate the total network power usage by the sum power used in the different cells. Let $p_i(t)$ denote the power usage in cell i, the total energy consumption in the network is calculated as:

$$E = \sum_{i=1}^{N} \int_{0}^{T} p_i(t)dt \quad [J] \tag{4.1-35}$$

The average rate R and the average power P in the network is then simply I/T and E/T, respectively. It may often be helpful to normalize the rate R and the power P by either the number of cells or the network area. To make the normalized measures independent of the deployment, we here choose to work with rate and power per area unit. The average rate per area unit R_A and the average power per area unit P_A are then calculated as:

$$R_A = \frac{R}{A} = \frac{I}{A \cdot T} = \frac{1}{A \cdot T} \sum_{i=1}^{N} \int_{0}^{T} r_i(t)dt \quad [bit/m^2] \tag{4.1-36}$$

and

$$P_A = \frac{P}{A} = \frac{E}{A \cdot T} = \frac{1}{A \cdot T} \sum_{i=1}^{N} \int_{0}^{T} p_i(t)dt \quad [W/m^2] \tag{4.1-37}$$

respectively.

4.2. CLASSICAL RADIO NETWORK PERFORMANCE METRICS

Spectrum has traditionally been considered as a scarce resource for cellular networks and an important objective in the design of cellular systems has hence been to maximize the number of bits that can be delivered over a certain time and in a given bandwidth. The operation of the network can, however, not only be guided by the overall throughput but it is also required to keep control of the perceived user quality. To quantify and measure the user perceived quality may sometimes be difficult and what metric to use typically depends on the service or application.

Even though the choice of quality metric depends on the service or application, some general observations regarding the evaluations are still possible. When studying a system in a given scenario (characterized by the type of environment, user behaviour and traffic type, etc.) at different traffic loads, the analysis typically shows that the quality decreases with the traffic load. The traffic load is often expressed as the number of users served by the system (typically in the unit users/cell or users per area unit) or the amount of traffic that the system handles (often measured in bps/cell or bps per area unit). The quality metric depends on the service, however, some common examples are the fraction of satisfied users (e.g., for VoIP) and the cell-edge user data rate, measured in [Mbps], for data services. Further details on quality metrics for different services are provided in the sections 4.2.1- 4.2.4 below.

One schematic example is provided in FIGURE 8, which shows the quality as a function of traffic load for two different system configurations A and B. In this example configuration B may be considered as superior to configuration A, since it delivers higher quality for all studied traffic loads. To make sure that users are satisfied we can define a minimum quality level (Q*) that the system should support. The corresponding traffic load, which is the highest traffic load for which the quality requirement is fulfilled, is often denoted as the system capacity. In the example in FIGURE 8, configuration A and configuration B achieve the capacities C_A and C_B, respectively. A typical radio network problem formulation is to maximize the capacity of the system, given the quality constraint. Another approach may be to define not only a quality requirement Q* but also a capacity requirement C*, and any system configuration that supports these two requirements may be considered as sufficiently good and the selection may then be performed based on other aspects, such as, e.g., cost or complexity.

In the EARTH reference scenarios, the full buffer traffic model and the FTP model are selected as default traffic models for the maximum load and the variable load cases [EARTH-D2.2]. An HTTP model and a VoIP model are available as well. These traffic classes are well-known and extensively studied in, e.g., 3GPP, from which also proper quality metrics are available. Short descriptions of quality metrics for the different traffic types are provided in the sub-sections below. It is proposed that EARTH follows the 3GPP ways-of-working and adopts the quality metrics as described in 4.2.1- 4.2.4 below.

4.2.1. Quality performance metrics for the full buffer traffic model

In [TR36.814R9], section A.2.1.4, 3GPP proposes that the following performance metrics are adopted for the full buffer traffic model:

- Mean user throughput
- Throughput CDF
- Median and 5th percentile (worst) user throughput

In addition, the served traffic (throughput), measured in [Mbps/km^2] or [Mbps/cell], should be provided for EARTH studies.

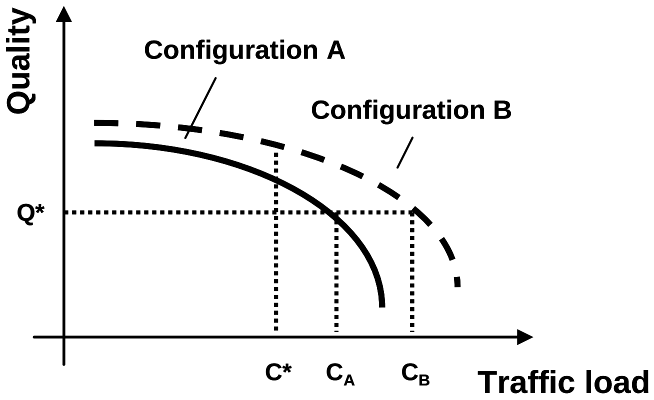

FIGURE 8. Quality versus traffic load.

4.2.2. Quality performance metrics for the FTP traffic model

For the FTP traffic model, in which a single file is transferred, the following performance metrics are proposed in [TR36.814R9], section A.2.1.3.2:

- Mean, 5^{th}, 50^{th}, 95^{th} percentile user throughput
- Served (cell) throughput
- Harmonic mean normalized cell throughput
- Normalized cell throughput
- Resource utilization

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 the number of cells. For EARTH purposes it is recommended 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 the area size.

Moreover, considering that the harmonic mean normalized cell throughput metric and the normalized cell throughput metric depend on the full buffer throughput in the corresponding case, these metrics are optional within EARTH.

4.2.3. Quality performance metrics for the VoIP traffic model

For VoIP traffic, 3GPP proposes in section A.2.1.4 of [TR36.814R9] that the number of satisfied users is studied as a function of the traffic load in uplink as well as in downlink. The system capacity is defined as highest traffic load for which still at least 95 % of the users are satisfied, and a user is satisfied if at least 98 % of the packets arrive within a delay of 50 ms.

4.2.4. Quality performance metrics for the HTTP traffic model

For bursty, non-full buffer traffic models, such as the HTTP traffic model [EARTH-D2.2], 3GPP proposes in [TR36.814R9] section A.2.1.4, that the following performance metrics are employed:

- User perceived throughput (during active time), defined as the size of a burst divided by the time between the arrival of the first packet of a burst and the reception of the last packet of the burst
    - Average perceived throughput of a user defined as the average from all perceived throughput for all bursts intended for this user.
    - Tail perceived throughput defined as the worst 5 % perceived throughput among all bursts intended for a user
- User perceived throughput CDF (average and/or tail user perceived throughput).
- Percentage of users with 1 % or more dropped packets.
- Median and 5% worst user perceived throughput (average and/or tail user perceived throughput).
- Overall average user throughput defined as average over all users perceived throughput.

4.3. INTRODUCING THE ENERGY CONSUMPTION PERSPECTIVE

When including the energy consumption perspective in the analysis, it is natural to consider also the energy as a scarce resource that should be carefully utilized. Accordingly, we now have to extend the above analysis to cover also the aspect of the network energy consumption (or, energy efficiency). The spectrum efficiency and the quality aspects are still important, so the analysis must cover multiple perspectives and it will sometimes be needed to trade one desired property for another, e.g., quality versus energy consumption.

FIGURE 9 provides a schematic picture of how such an analysis may look like. The left plot depicts the quality as a function of the traffic load, as discussed in section 4.2. In the right plot the network power usage is plotted as a function of the traffic load. We here assume that the power increases with traffic load. In this example, configuration B provides higher quality than configuration A but is also associated with a higher power. What solution is preferable now depends on the individual preferences – is higher quality more important than lower power consumption? If there exists a specific requirement in terms of quality (Q*) and capacity (C*), one possible way to formulate the problem is to minimize the power usage given the constraints on quality and capacity.

The metric selection is based on the fact that a well-chosen energy consumption metric should capture the relation between the value that the network has created (the work that has been performed) and the resources that has been used to create this value. For a radio network, the value can be expressed as the amount of data that the network transfers, the area over which the network provides coverage, or the number of subscribers that the network serves. Moreover, the resource usage is, in this case, the energy consumption.

The energy metric can either be presented as an energy consumption index (ECI), λ, or as an energy efficiency index (EEI), ε. A consumption index is defined as the quotient between the consumed resources (here energy) and the performed work (here number of bits transferred, the area covered, or the number of subscribers served) whereas an efficiency index is defined the other way around, i.e., as the quotient between the performed work and the consumed resources. In other words, $\lambda = 1/\varepsilon$. The consumption index and the efficiency index are equivalent in the way that they both contain exactly the same information.

During the course of the work, three network energy metrics were selected for further consideration. Below, these metrics are expressed as consumption indices; however, they could equally well be expressed as efficiency indices.

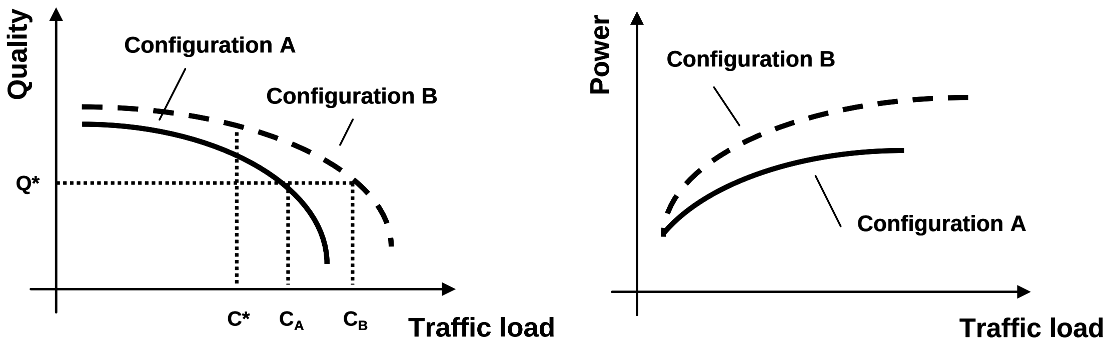

FIGURE 9. Quality versus traffic load and power versus traffic load.

- Energy per Information Bit

One metric of interest is to relate the network energy consumption (*E*) to the number of bits transferred (*I*). This ratio is equivalent to the ratio between the average power used (*P*) in the network and the average data transfer rate (*R*). The metric can be expressed either in the unit [J/bit] or [W/bps].

$$\lambda_I = \frac{E}{I} = \frac{P}{R} \; in \; [J/bit] \; or \; [W/bps] \tag{4.3-38}$$

- Power per Area Unit

Another possibility is to relate the average power used (*P*) to the size of the covered area (*A*). This metric is expressed in the unit [W/m^2].

$$\lambda_A = \frac{P}{A} \; in \; [W/m^2] \tag{4.3-39}$$

- Power per Subscriber

Yet another relevant metric is the quotient between the average power usage (*P*) and the number of subscribers (N_S) in the network.

$$\lambda_S = \frac{P}{N_S} \; in \; [W/sub] \tag{4.3-40}$$

4.3.1. Energy consumption index versus energy efficiency index

A metric of energy usage can be expressed either as a consumption index or as an efficiency index. For automobiles both the “miles per gallon” or MPG metric and the “liters per 100 km” are commonly used. In essence these two indexes both contain the same information. The American MPG metric is an efficiency index, i.e., a car that consumes less fuel will have a higher metric compared to another car that consumes more. The European “liters per 100 km”, on the other hand, is consumption metric. A car that consumes less fuel will have a smaller metric. In theory this difference is not important since the same information (fuel and distance) is included in both metrics and hence it is straightforward to convert any efficiency metric to the equivalent consumption metric and vice versa. However there are subtle differences to consider.

The main benefit with an efficiency index, where the useful work is in the nominator and the energy used to achieve it is in the denominator (work/energy), is that a bigger metric is better and many people find that satisfying. The drawback is that with an efficiency index it is difficult to interpret the effect an efficiency increase has on the energy saving. As an example, 20% better MPG does not mean 20%, but 16.7% less fuel (20% is 1.2 times bigger distance, therefore 100% / 1.2 = 83.3% of the original fuel consumption, or 16.7% less fuel for the same distance). It is even more difficult to interpret the efficiency metric correctly if we need to compare two different upgrade options. This is visualised in FIGURE 10, drawing the efficiency metric (left) and the consumption metric (right) over the consumed energy (for a fixed provided work).

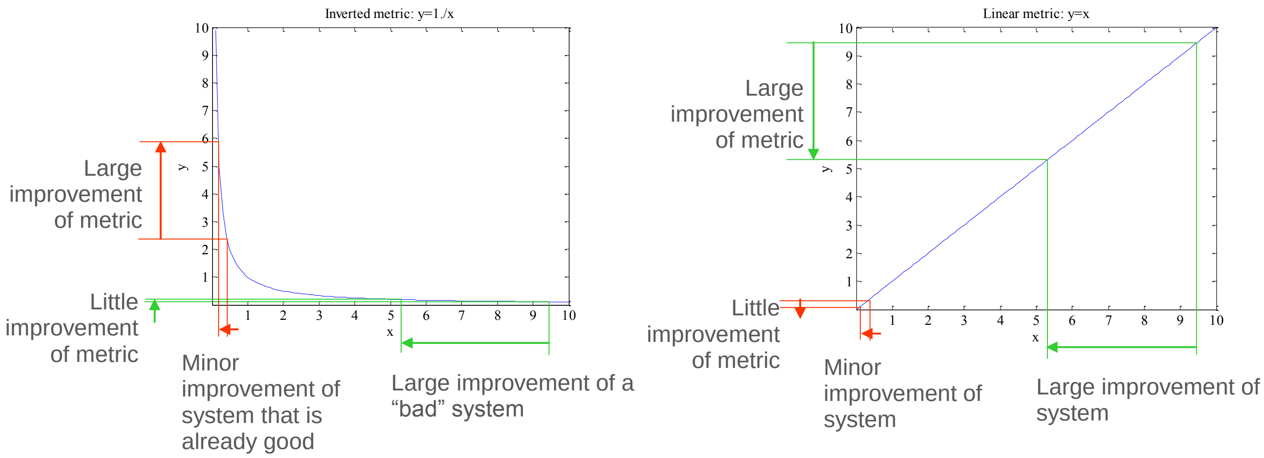

FIGURE 10. A linear consumption metric (right) is easier to interpret than an inverted efficiency metric (left).

This example shows that a small reduction in energy consumption in an already efficient system can result in a much higher increase of the efficiency metric compared to a large reduction in energy consumption in an inefficient system. In contrast, the consumption metric will in both cases show the same improvement. This may lead to an underestimation of the improvements that actually provide the highest energy savings. Therefore, a consumption metric, where the energy use (or the power use) is in the numerator is preferred since this is intuitive and it guides people to take correct decisions.

4.3.2. Energy per Information Bit

One of the most commonly used energy metrics, especially for theoretical analytical studies and single link evaluations, is the relation between the energy consumed (E) and the number of information bits (I). For example, the transmitted energy per information bit (E_b), in [J/bit], is a well-established metric and has been around for long, see, e.g., [Verdu2002]. The relation between the number of information bits and the energy is also used to define the Bits-per-Joule channel capacity [KwBi1986], [RoMe2007].

The former metric relates the energy consumption to the basic utility information, measured in bits. As both the energy consumption and the information may be variable – for example, the energy consumption is affected by the technology solution and the information is affected by the network load that, e.g., changes during a day – the metric is composed by two variable quantities. This implies, obviously, that the metric may change if the energy and/or the information changes, which is associated with both pros and cons. Study for example a scenario in which the traffic (information) increases faster than the energy consumption, e.g., let us say that a 25 % traffic increase causes the energy consumption to go up with 10 %. In this case the metric decreases, indicating an improved performance, which is correct in the sense that per information bit less energy is required, i.e., the system delivers more output for each unit of input. On the other hand, if this is the only energy metric studied, it may not be obvious that even though the consumption metric decreases the total energy consumption has increased. Furthermore, assuming that the network consumes some power (P>0) even during time periods when there is no traffic to serve, yet another important observation is that when the traffic load approaches zero this metric approaches infinity.

The energy per bit metric can easily be applied in simulations studies, in which both the energy consumption and the number of transferred bits are well-defined outputs. The metric may also be applied in measurements on real networks provided that both the energy consumption and the number of transferred bits in the network can be monitored.

4.3.3. Power per Area Unit

As described by equation (4.3-38), the power per area unit metric relates the average power (P) to the network coverage area (A). The area *A* may include different deployments, e.g. cells with variable size, or heterogeneous networks with overlapping cells.

This metric appears to be particularly relevant for EARTH due to the following properties:

- The power consumption per unit area is closely related to CO_2 emissions and the associated carbon footprint, which is the primary objective of EARTH.
- Power consumption per area coverage is the most relevant at low loads, as in this case the network is coverage limited and not capacity limited. Since the most significant energy savings are expected at low loads, this metric appears to be a natural choice for EARTH.
- The coverage area *A*, for which the system is to be evaluated and which might contain multiple base station sites, is typically predefined as a constant. Hence, this metric does not include *quotients of variables*, which avoids misleading conclusions as the inclusions of variables at the denominator tend to distort the metric. Moreover, with the quotient of two (or more) variables valuable information conveyed by the metric may be lost; it is impossible to understand, whether an increase of the metric is due to the increase of the nominator, and/or the decrease of the denominator.
- The power consumption per area allows comparison networks of different cell sizes and different degrees of heterogeneity, i.e., mixes of site types.

The metric is well-suited for radio network simulations studies, in which both the average power usage and the coverage area are well-known quantities. The metric may be more difficult to apply to real network measurements, since the precise coverage area of the network may not always be well-known and it may also change over time following network deployment changes.

4.3.4. Power per Subscriber

The power per subscriber metric relates the average network power usage to the number of (satisfied) subscribers present in the network. The metric is appealing for several reasons. First, the number of subscribers is a well-known concrete quantity that is intuitive and easy to relate to. Second, if the number of satisfied users is considered, i.e., the set of users for which the QoS requirements are fulfilled, this metrics indirectly considers also the QoS in the network while this must be studied separately when using the power per area unit or the energy per bit metric as of above. Third, compared to the energy per bit metric, the power per subscriber metric is well suited to study the development of network energy consumption over long time periods during which the data volumes change (increase) significantly, see further discussion in Section 4.4.

More in detail, the power per subscriber metric is subject to the definition of "satisfied users", which corresponds to the set of users for which QoS requirements are fulfilled by the system[1]. As a consequence, from a practical perspective, gains in terms of the power per subscriber metric should be measured by comparing two systems with the same traffic mix and the same number of satisfied users: in this case the gain gives also an indication of the savings in terms of power consumption.

An important advantage of the present metric is further to indirectly consider also fairness (or, more in general, QoS) constraints, while gains calculated in terms of energy per bit metric do not directly take a possible loss in fairness into account, and thus do not directly guarantee anyQoS fulfilment in the system. Instead, for the energy per bit metric such considerations must be handled separately.

[1] Consider, e.g., possible traffic types corresponding to standardized QCI as introduced in [TS23.203R8], where each standardized QCI corresponds to a set of QoS related parameters (packet delay budget, packet error loss rate, etc.) to be guaranteed by the system.

Finally, a metric based on the ratio between power and throughput can be suitable to perform comparisons between systems (or network solutions) relative to the same deployment phase, but in general is unsuited if the goal is to consider different years and perform evolutionary comparisons, especially due to the increasing traffic demand foreseen for next years. In fact, a simple assessment based on energy per bit metric could give an incomplete (even if correct) indication to the operator, e.g. not totally aligned with OPEX and network operation costs: as an example, a network with a constant J/bit performance year by year could be judged in a first stage as a good network, even if after a deeper analysis it can be noted that in an evolutionary perspective the traffic demand per user in the network and related QoE requirements grow year by year, and in general this growth isn't compensated by a proportional increase of revenues. On the other side, a metric based on W/user ratio gives a more reliable indication of increasing *unitary costs per user* (with respect to a J/bit based metric), thus providing more suitable messages for the operator. For that reason the W/user metric can be considered more future-proof and better suitable for evolutionary comparisons from the point of view of the operator (see further discussion in Section 4.4).

A possible disadvantage of the metric is that, when used in simulation studies, it is not always perfectly clear what a subscriber refers to in this context. In simulation studies the focus is typically on the active subscribers, i.e., the set of subscribers that transmit or receive data during a studied time period. This active set of users is, however, often quite small in comparison to the entire population of users out of which only a small fraction is active at a time. For example, when using a FTP traffic model [EARTH-D2.3], the number of simultaneously active users is most often quite small (less than 5 users per cell). The model, however, assuming an arrival intensity that is invariant to the traffic load, implies an infinite user population [RoSi1989].

As both the power consumption and the number of subscribers are well-known to a network operator, the metric is well suited for measurements and assessments in real network, in particular considering that it offers stability over long time periods.

4.3.5. Other Energy Consumption Metrics

During the course of the work also other network energy metrics than the three above were considered. One metric that is associated with several good attributes is the energy per bit and area unit metric. The metric was however rejected due to undesired scaling properties. The details are provided in Section 4.3.5.1 below.

4.3.5.1. Energy per Bit and Area Unit

As both the number of transferred bits (I) and the area coverage (A) are indicators of the value created by the network - all other things equal, the more net transferred bits the better and, similarly, all other things equal the larger the coverage area the better – it is appealing to construct a metric where both these quantities are reflected. One option is then to study the energy consumption in relation to the number of transferred bits and the area coverage. This is equivalent to analyzing the average power usage in relation to the average rate and the area coverage. The metric can be expressed either in [J/bit/m^2] or [W/bps/m^2].

One problem associated with this metric is, however, that it does not scale as desired with the network size. Study, for example, a network that covers the area A and that during the observation time T transfers I bits and consumes energy E. The energy consumption index associated with this network is then:

$$\lambda_{IA} = \frac{E}{I \cdot A} \qquad (4.3\text{-}41)$$

If we now study a network of the double size, comprising two identical copies of the original network, we expect the metric to be unaffected by the changed size. The new, larger network, however, covers an area of *2·A*, transfers *2·I* bits and has an energy consumption of *2·E*. The metric then reads:

$$\lambda_{IA}^{'} = \frac{(2 \cdot E)}{(2 \cdot I) \cdot (2 \cdot A)} = \frac{1}{2} \cdot \frac{E}{I \cdot A} \tag{4.3-42}$$

i.e., it is just half of the metric associated with the original network. Due to this undesired way of scaling with the network size this metric is not considered as appropriate for the work in the EARTH project.

4.4. LONG TERM GLOBAL AVERAGES OF EE METRICS

The EARTH consortium aims at developing methods and technologies that allow cutting the energy consumption of radio access networks in half [EARTH] while at the same time supporting future growth in mobile data rates and services. A thorough understanding of energy efficiency of currently deployed radio access networks (RANs) is fundamental as a reference value for simulations as well as for estimating the potential impact of the EARTH project in terms of these metrics.

Energy per bit is a suitable metric to assess network efficiency under well-defined service requirements per user, as common in simulations or measurement campaigns. If those conditions cannot be specified, are hard to assess, or change during the observation, the Power per area metric provides an alternative, since typically in those investigations the considered area stays constant.

For investigations on real networks, the covered area is hard to assess and will undergo changes as the network develops. For observations over longer time periods also the user service requirements are hard to fix, hence it is convenient to use Power per subscriber as efficiency metric.

In the following we will provide a comparison of the Energy per bit and the Power per subscriber consumption indices of currently deployed global RANs and their potential development during the period 2007-2020. The analysis reveals a strong change in the Energy per bit consumption index until 2020 due to increasing mobile data traffic. As the total area covered globally by mobile communications is hard to assess we exclude detailed analysis of Power per area unit here.

The analysis uses roll-out models for cellular base stations, covering all equipments newly deployed and taken out of service each year. We further present predictions of the number of mobile subscriptions globally between 2007 and 2020. Global mobile data traffic is estimated for the same period based on estimations from [Cisco2010] and own projections.

The figures between 2007 and 2014 are based on statistical data and projections from analysts Gartner and ABI Research [Gartner2007], [ABI2008]. Estimates presented for the period 2015 to 2020 are based on modelling and extrapolation of current trends and data, conducted within the EARTH project [EARTH-D2.1]. For the convenience of the reader, statistical data for 2007 and projections for the years 2014 and 2020 are summarized in TABLE 1. Detailed modelling assumptions are presented in [EARTH-D2.1].

In equation (4.3-40) the power per subscriber metric is defined as :

$$\lambda_S = \frac{P}{N_S}$$

where N_S denotes the average number of subscribers that can be served in the network and P denotes the average required power. Note that, as already stated in section 0, the Power per subscriber metric depends on the definition of user satisfaction and the traffic model relevant for the investigation at hand. In this regard, it allows specifically incorporating constraints on delays of delivered bits as well as the burstyness of errors that render a communication service in outage, even though the average required rate is provided.

In our definition we consider a “subscription” as belonging to a regular mobile phone, smartphone, or a data card for tablets or laptops. M2M subscriptions are excluded.

The following discussion considers three scenarios of technological development and roll-out of networks until 2020 corresponding to different levels of improvements in hardware and use of site equipment. For each scenario, we present the network energy consumption indices in [J/bit] and [W/sub], respectively. The scenarios (relative to FIGURE 12 and FIGURE 13) are defined as follows.

The first scenario (blue line in the figures) assumes no reduction in energy consumption through technological advancements after 2010, which can be considered as a worst case scenario. This scenario corresponds to the case where all improvements on component level contribute towards increasing spectral efficiency rather than reducing energy consumption as can be observed for mobile phones.

The second scenario (red line in the figures) assumes a continuing reduction of energy consumption of newly installed equipment by 8% per year. This trend of continuing improvements has been observed for over the last decade of intensive 3G development. Under the assumption that current research efforts in industry and academia continue, we expect this trend to also continue until 2020.

The third scenario (green line in the figures) assumes an additional 50% reduction of overall RAN energy consumption in 2020 relative to the continuous improvements in Scenario 2. Scenario 3 reflects a favourable case, where technological improvements are rapidly deployed.

TABLE 1. Wireless communication networks: Global statistical data and projections [EARTH-D2.1].

	2007	2014	2020
Global wireless subscriptions (millions)	2950	5600	7600
Global mobile data traffic (million TB)	0.3	43	755
Worldwide BS sites (millions)	3.3	7.5	9.75
Global RAN power, Scenario 2 (GW)	5.6	9.7	11.3
Average Energy per bit [J/bit], Scenario 2	28000	836	59
Average Power per subscriber [W/sub], Scenario 2	1.9	1.67	1.48

4.4.1. Global RAN EE between 2007 and 2020

The global figures between 2007 and 2020 suggest a tremendous increase in mobile data traffic by more than a factor of 1600 and at the same time a comparably moderate increase in base station sites by a factor of about 3.3 as depicted in FIGURE 11. As a consequence, the global average of the Energy per bit metric will be governed by the strong change in denominator over time and significantly decrease as depicted in FIGURE 12. We estimate the total RAN power in 2020 to be about twice that of 2007 while the Energy per bit quantity is expected to be more than 100-fold less (compare values in TABLE 1). This development is facilitated by higher density and higher average load conditions of future networks on the one hand and much higher capacity of future 4G+ heterogeneous networks, stronger demand for wireless services and suitable business models – all of which factors outside of the scope of the EARTH project. Against this background, the optimistic target of 50% reduction of energy consumption only has marginal effect on the energy efficient metric.

In contrast to the Energy per bit index, the Power per subscriber index is not expected to exhibit exponential change over time as depicted in FIGURE 13. Considering a global penetration of over 60%, certainly no exponential increase in the number of subscriptions can be expected until 2020 and the dramatic increase in traffic is due to much larger traffic per user rather than many more users.

Considering that the purpose of a communication network is ultimately serving people's communication demands, we conclude that Energy per bit alone does not appear suitable to compare efficiencies of wireless networks. Future communication demands may only be satisfied with exponentially increasing traffic, which in turn renders mere traffic volume ineffective in comparison of user satisfaction over longer periods. If future demands are met, any realistic reduction in RAN energy consumption over a time scale of several years may consequently not be adequately reflected in the Energy per bit metric. Here, the Power per subscriber metric appears to be more meaningful since it abstracts from the actual traffic volume of future wireless services. Quantitatively, our analysis suggests that the Power per subscriber might be reduced globally from 1.7 W/sub in 2010 to 0.74 W/sub in 2020 if technology improvements proposed by initiatives such as EARTH are adopted in a timely manner.

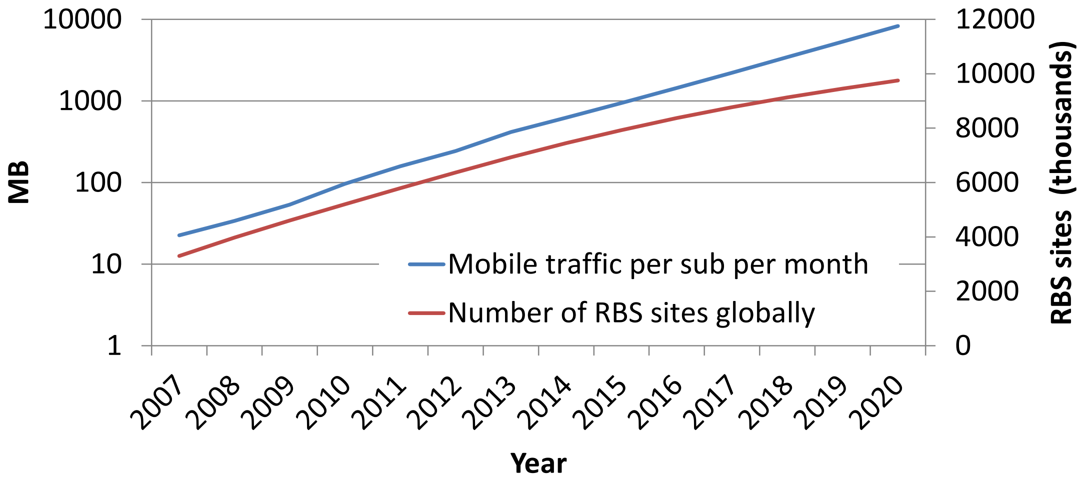

FIGURE 11. Monthly mobile traffic volume per subscriber and number of RBS sites. Global averages.

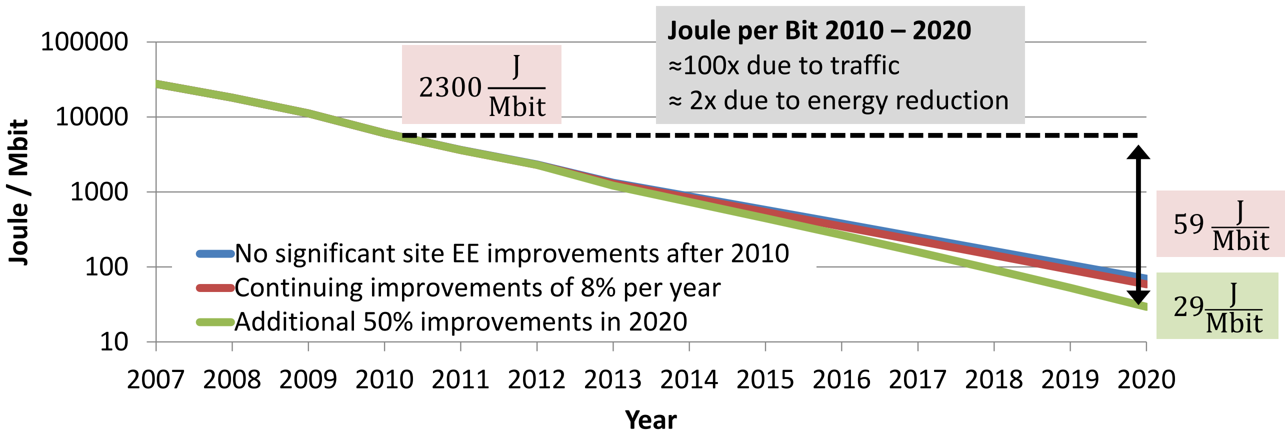

FIGURE 12. Estimation of global averages of Joule per bit efficiency 2007-2020

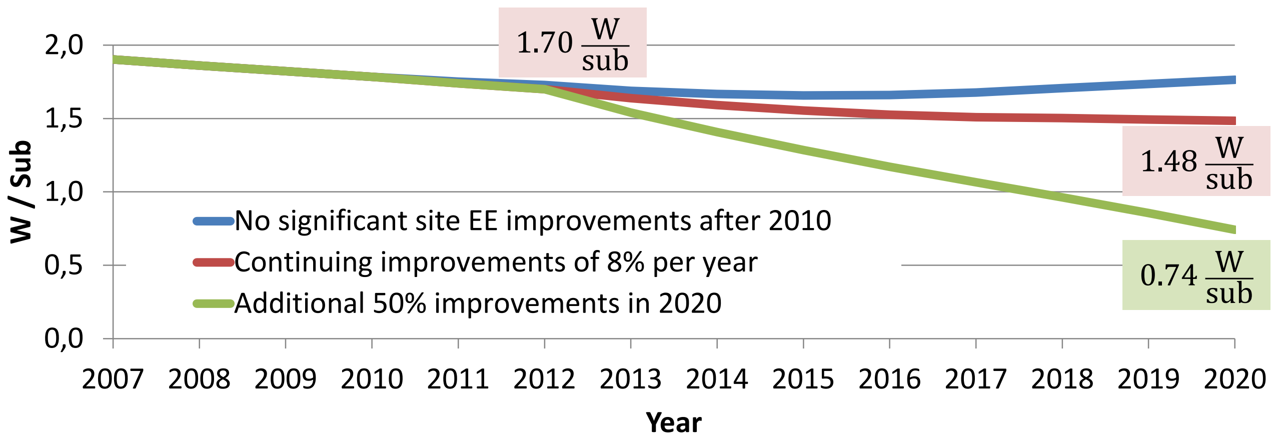

FIGURE 13. Estimation of global averages of Watt per subscriber efficiency 2007-2020

4.5. RECOMMENDATION

For radio network (system level) simulation studies within EARTH, it is recommended to include metrics that capture both the quality of service in the network as well as the energy consumption, typically as a function of the traffic load. Which quality performance metric to use depends on type of traffic that is studied, and we here choose to follow the recommendations in 3GPP. Section 4.2 outlines quality metric recommendations for a few traffic classes, such as full buffer, FTP and VoIP traffic.

For the selection of energy metric the power per area unit metric, in [W/m^2], is the primary choice in network simulation studies, but both the energy per bit metric, in [J/bit], and the power per subscriber metric, in [W/sub], make up useful complementary metrics. The different metrics provide dissimilar perspectives on the energy consumption, all useful for the EARTH project. Whereas the power per area unit metric focuses on the total energy consumption, the energy per bit metric provides a figure on the bit delivery energy efficiency. The power per subscriber metric is easily observed in real networks, and offers stability over long time periods, which makes it a suitable candidate for energy consumption measurement in real networks.

5. EARTH UTILITY FUNCTION

The EARTH project aims to reduce the energy consumption of wireless networks while still preserving a high level of QoS. Sometimes, however, energy saving come at a cost of reduced Qos and in such a case it is helpful to use a structured means of assessing if, considering the overall performance of the network, the energy saving is worthwhile. A utility function may be used for this purpose. This chapter discusses how a utility function may be used in the context of the EARTH project in order to evaluate the (relative) goodness of dissimilar design options.

Section 5.1 gives general motivation of the utility function and in Section 5.2 the utility function is defined as a relative measure. Section 5.3 illustrates in more detail how a utility function, for which the utility increases when the energy consumption decreases and the user quality increases, can be constructed whereas Section 5.4 and Section 5.5, discusses large scale averaging and possible extensions of the utility function, respectively. The chapter is closed in Section 5.6, which illustrates by means of two examples, possible applications of the utility function.

5.1. THE PURPOSE OF THE UTILITY FUNCTION

The traditional way to asses the performance of a radio network in a system simulator is to look at user performance versus system performance graphs for a specific scenario. As we add more and more users in our simulators the system performance increases, i.e. we transmit more bits per area unit. At the same time the performance per user starts to decrease once the system load becomes sufficiently high. In order to asses the energy performance we need to also consider the energy metric ([W/m^2], [J/bit], or [W/sub]) as function of the system load.

The EARTH Energy efficiency evaluation framework (E^{3}F) [EARTH-D2.3] defines the different scenarios and how the system load varies over time. This provides user throughput distributions and energy metric distributions for each scenario. Now if we consider a certain algorithm that is intended to save energy and which also affects the performance of the users' then we might want to answer a simple question like: is this algorithm good or bad in this scenario? In FIGURE 14 we show an example of what kind of data we might have to examine if we would have followed the E^{3}F and performed two different simulations; one with the energy saving algorithm activated (the green bars) and one representing a reference case where the energy saving algorithm is not activated (the red bars). Clearly we see that in this example the energy saving algorithm has an effect on the energy consumption, but there is also some degradation of the user bitrates. Now we need some kind of function that could help to provide the answer on which system is the best one. Is it the system with a certain energy saving feature implemented, or another one without? The function that we need is the utility function.

5.2. THE UTILITY AS A RELATIVE MEASURE

A utility function that can only be used to provide answers if something is better or worse relative to some reference case might be consider as limiting. Would it not be better if we could express the utility in absolute terms? Both the energy metric and the user performance metric are expressed in absolute terms, so why not the utility?

First of all, what we consider to be good or bad changes over time. What is really good today might be considered to be poor soon in the future. This is exemplified in FIGURE 15 where the red circles to the left and right both have the same size. Even an absolute metric is constantly subject to relative comparisons, and it is the comparison that matters most when we need to take a decision.

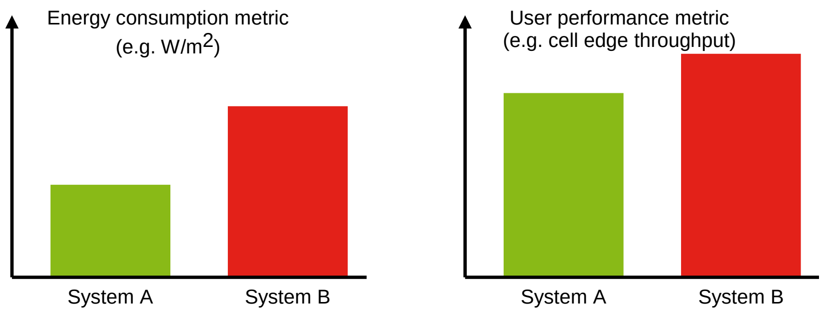

FIGURE 14. A utility function is needed to decide which system is the best? The one with a certain energy saving feature (green bars) or the one without (red bars).

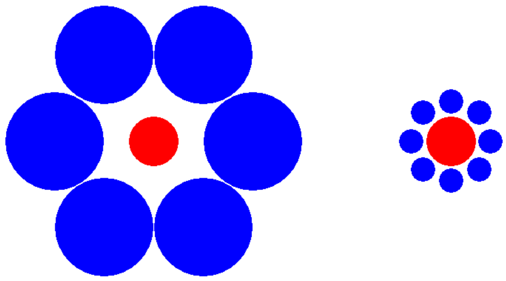

FIGURE 15. The red circles have the same size. Are they large or small?

Relative measures are also much easier to work with. We can not just add an energy metric and a user performance metric together and expect something that has a relevant interpretation as a result since the units are totally incompatible. Choosing appropriate scaling factors is also difficult since the scale of the numerical values might be several magnitude orders different.

A relative utility puts the focus on the *comparison purpose* of the utility. Utility is also used in other fields such as economics where it is defined (according to Wikipedia) as follows:

> *"In economics, utility is a measure of relative satisfaction. Given this measure, one may speak meaningfully of increasing or decreasing utility, and thereby explain economic behaviour in terms of attempts to increase one's utility."*

It is worth noting that since we are using a relative definition of the utility, it cannot be used to assess whether the overall goal of the project (50% energy reduction) is fulfilled or not. It is just a tool that may be used during the selection process, i.e., when we select between different technology solutions.

5.3. INCREASING UTILITY BY IMPROVING ENERGY AND USER PERFORMANCE

With a relative utility definition we need to have a reference case to compare with. The default reference case is the EARTH reference system, but in other comparisons it might be more natural to define the reference system as a system that does not have the specific feature that we are studying. We will define the energy metric of the reference case as E_{ref} and the quality metric of the reference case as Q_{ref} respectively. If we assume that our system under evaluation has the energy metric E and the quality metric Q then we may define the additional utility due to energy as

$$\Delta U_E = -100\,(E - E_{ref}) / E_{ref} \qquad (5.3\text{-}43)$$

In similar manner we define the additional utility due to quality as

$$\Delta U_Q = 100\,(Q - Q_{ref}) / Q_{ref} \qquad (5.3\text{-}44)$$

Thus the energy and quality difference in percent is used as a measure of how much the utility increases. Note that the utility increases in case the energy of our system under evaluation is less than the reference system energy while the utility increases when the quality is higher than the reference system, see FIGURE 16.

The overall utility can now be defined by introducing weighting functions on how much we value an energy improvement and a quality improvement. By defining the utility of the reference system to equal 100 and by introducing weighting factors α_E and α_Q for which $\alpha_E + \alpha_Q = 1$ we obtain an expression of utility as

$$U = 100 + (\alpha_E\, \Delta U_E) + (\alpha_Q\, \Delta U_Q) \qquad (5.3\text{-}45)$$

In FIGURE 17 we show two examples of this function. To the left energy and quality utility increases are equally valued ($\alpha_E = \alpha_Q = 0.5$) and to the right additional utility due to quality is valued nine times more than additional utility due to energy ($\alpha_E = 0.1$ and $\alpha_Q = 0.9$). This type of curves is sometimes called iso-performance curves (or performance invariant contours). Every combination of E and Q along an iso-performance curve provides the same utility.

The parameterization of the utility function, i.e. the selection of the weighting factors α_E and α_Q, is subjective and only based on the user's preferences. It will never be possible to define a single set of parameter values that suits everyone’s needs. Different users will need to use different weighting factors. However for the purpose of enabling comparisons is of course good to have a default set of weighting factors. We propose to use the $\alpha_E = 0.1$ and $\alpha_Q = 0.9$ as the default parameters. By valuing quality ten times higher than energy we are basically saying that we are willing to sacrifice 1% of user quality for every 10% of energy reduction.

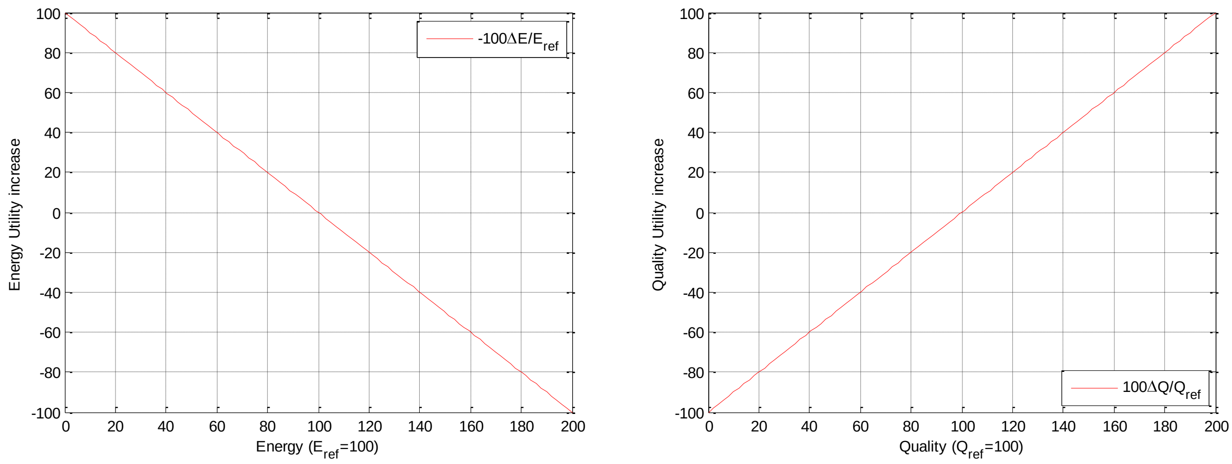

FIGURE 16. Additional utility due to energy (left) and quality (right).

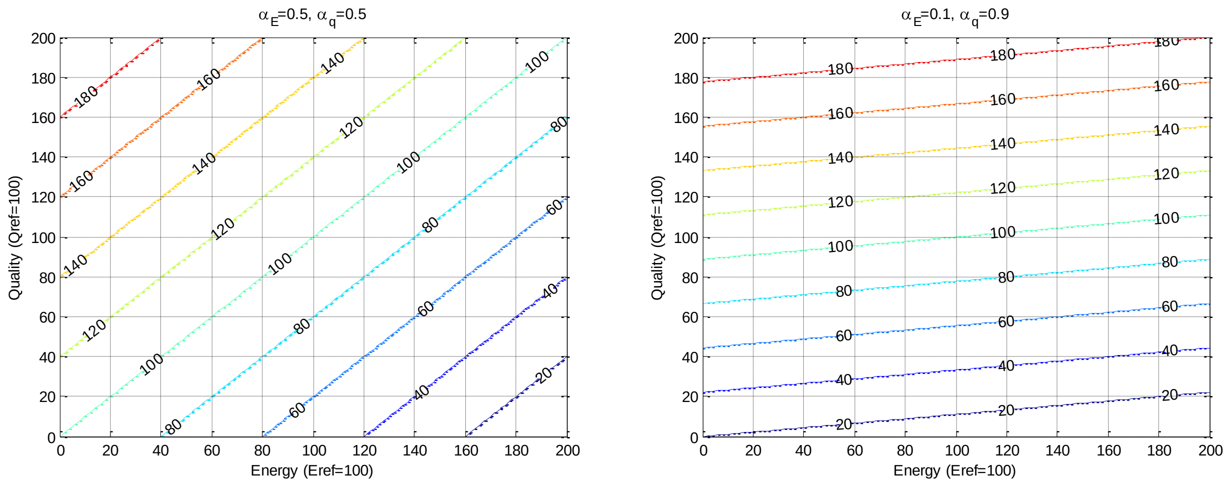

FIGURE 17. Examples of utility curves. Left: $\alpha_E = \alpha_Q = 0.5$; right: $\alpha_E = 0.1$ and $\alpha_Q = 0.9$.

5.4. LARGE SCALE AVERAGING OF THE UTILITY

The utility function can be applied before or after various kinds of averaging. The simplest way is to first perform all the long term and the large scale averaging according to the E^3F before applying the utility function. However, there might be reasons to perform different weighting in different scenarios. In dense urban areas the cost of running the sites is small compared to the revenues the operator get from the users. Saving energy in the dense-urban sites, covering around 1% of the total area, might not be the main focus of an operator. Rather, it might be more interesting to save energy in rural areas, representing 36% of the area. This can easily be done if we define different energy and quality weighting function for each area, as in equation (5.4-46). The overall utility can then be calculated as

$$U = 100 + [\Delta U^{DU} + 2\Delta U^{U} + 4\Delta U^{SU} + 36\Delta U^{R} + 57\Delta U^{S}] / 100 \qquad (5.4\text{-}46)$$

Where the additional utility for scenario *Z* is calculated as

$$\Delta U^{Z} = (\alpha_E^{Z}\, \Delta U_E^{Z}) + (\alpha_Q^{Z}\, \Delta U_Q^{Z}) \qquad (5.4\text{-}47)$$

and *Z* = {DU, U, SU, R, S} for the {Dense Urban, Urban, Sub-urban, Rural, Sparsely populated} scenarios respectively. Note that in case sparsely populated areas are not covered then the utility expression instead becomes

$$U = 100 + [\Delta U^{DU} + 2\Delta U^{U} + 4\Delta U^{SU} + 36\Delta U^{R}\,] / 43 \qquad (5.4\text{-}48)$$

TABLE 2. Example of different weighting functions for different scenarios

	Dense Urban	*Urban*	*Sub-urban*	*Rural*	*Sparsely Populated*
α_E	0.1	0.1	0.3	0.3	0.5
α_Q	0.9	0.9	0.7	0.7	0.5

5.5. EXTENDING THE UTILITY FUNCTION

5.5.1. More than one quality measure

Most often the most critical user performance metric is the cell edge user throughput, here defined as the 5th percentile user bit-rate. However, we might want to refine the utility function to include not only cell edge performance but also other performance metrics, e.g. median or mean user throughput. This type of extension of the utility function is straightforward if we e.g. denote the first quality metric $Q1$ and the second $Q2$. Then we can calculate the utility as

$$\Delta U = \alpha_{\mathrm{E}}\Delta U_{\mathrm{E}} + \alpha_{Q1}\Delta U_{Q1} + \alpha_{Q2}\Delta U_{Q2}\ ;\ \text{with } \alpha_{E} + \alpha_{Q1} + \alpha_{Q2} = 1 \qquad (5.5\text{-}49)$$

5.5.2. Incorporating performance requirements

Performance requirements can easily be included in the utility function. Typically we might accept some user performance degradation as long as a certain minimum quality is maintained. But the quality provided by a solution falls below a certain minimum quality $Q_{\min}$ then we can no longer accept that solution, no matter how large the energy saving gains might be. To include this we simply define the additional quality utility as

$$\Delta U_{Q} = 100\ (Q - Q_{\mathrm{ref}})/Q_{\mathrm{ref}} \text{ if } Q \geq Q_{\min}\ ;\ -\infty \text{ otherwise} \qquad (5.5\text{-}50)$$

5.5.3. Including network cost in the utility calculations

If we are able to reliably calculate any other type of metric for the system than that can also be included in a utility function. One example is the network cost. Assuming that we can calculate the network cost (C) for a system with a certain feature as well as the network cost for a system without that feature (C_{ref}). The additional utility due to network cost can then be defined as

$$\Delta U_{C} = -\ 100(C - C_{\mathrm{ref}})\ /\ C_{\mathrm{ref}} \qquad (5.5\text{-}51)$$

With a cost weighting factor (α_C) in addition to the energy (α_E) and quality (α_Q) weighting factors defined above we can proceed to calculate the overall utility as

$$U = 100 + (\alpha_{E}\ \Delta U_{E}) + (\alpha_{Q}\ \Delta U_{Q}) + (\alpha_{C}\ \Delta U_{C}) \qquad (5.5\text{-}52)$$

where $\alpha_E + \alpha_Q + \alpha_C = 1$.

5.6. APPLICATION OF UTILITIES

5.6.1. Perceived user performance

Extending the work in section 5.5, we describe here ways to compute measure of quality, *Q*. More specifically, we show how user perceived quality can be computed as a function of network based measurements and user perception. Finally, the measure of Quality, *Q* can be applied in equation (5.3-45) to compute the overall Utility measure, *U*. The perceived user quality in general is subjective and dependent on the specifics of the application. For example, one scenario of network level service level agreement (SLA) can have high perceived user quality for one application, whereas it could be insufficient for another type of application. In general, it is a challenge to map the user perceived quality to the network level performance metrics and there is no one size fits all solution. This problem is exacerbated by the fact that current and next generation wireless networks are evolving rapidly leading to the development of large number of applications, which have significantly different QoS requirements. However, it is important to develop a framework in which the user perceived QoS parameters can be mapped to network level QoS so as to measure the performance of different innovations in the system in terms of energy efficiency improvements. Such a mapping also allows us to tune the different network operation parameters to save energy, while at the same time maintaining the user perceived QoS within acceptable levels. An example of QoS from network performance point of view for different applications is given in TABLE 3 [Shin2008].

We can define user perceived QoS as QoS_{Metric}, which in general is a multi-dimensional function of the individual network performance metrics given by:

$$QoS_{Metric} = f(QoS_1, QoS_2, \ldots, QoS_N) \qquad (5.6\text{-}53)$$

where QoS_i can be based on different network based performance metrics such as {throughput, delay, Jitter, packet error rate, etc}. The main idea here is to map the different performance characteristics offered by the network to a multi-dimensional function that results in the user perceived QoS_{Metric}. It is quite obvious that QoS_{Metric} is dependent on the application context in which it is measured.

TABLE 3. Example of network performance requirements from different applications

Application	*Bandwidth*	*Latency*	*Jitter*
Multiplayer interactive	50 kbps	<25 msec	N/A
VOIP video conference	32-64 kbps	<160 msec	<50 msec
Streaming	5 kbps ~2Mbps	N/A	<100 msec
Web Messenger	10 kbps ~2Mbps	N/A	N/A
Media Download	< 2 Mbps	N/A	N/A

We now define certain properties of QoS_{Metric} and the associated multi-dimensional mapping function *f(.)*, which are useful to gain more insight into the development of such mapping functions.

1. In general, we limit the range QoS_{Metric} to facilitate easier design of the mapping function *f(.)*. The user perceived satisfaction increases with the QoS_{Metric}.

$$QoS_{Min} \leq QoS_{Metric} \leq QoS_{Max} \quad (5.6\text{-}54)$$

2. QoS_{Metric} is a non-decreasing function with respect to its individual parameters $\{QoS_i\}$. This implies that any increase in the network performance metrics cannot result in degraded performance of user perceived QoS_{Metric}. We show this behavior in FIGURE 18, where the $\mathrm{QoS}_{\mathrm{Metric}}$ in general increases with offered rate and then it gets saturated as any further offered rate has no significant increase in the perceived user QoS_{Metric}, but results in increased utilization of system resources, hence increased energy consumption. This behavior in general is typical for most application scenarios.

3. QoS_{Metric} is a parameter that is based on the subjective quality tests conducted based on the application. For example, it can be mean opinion score [MOS] for voice and video, or based on Quality of Experience (QoE) [BaDa+2010] or some other metric which is specific for different applications such as, e.g., peer-to-peer traffic or gaming.

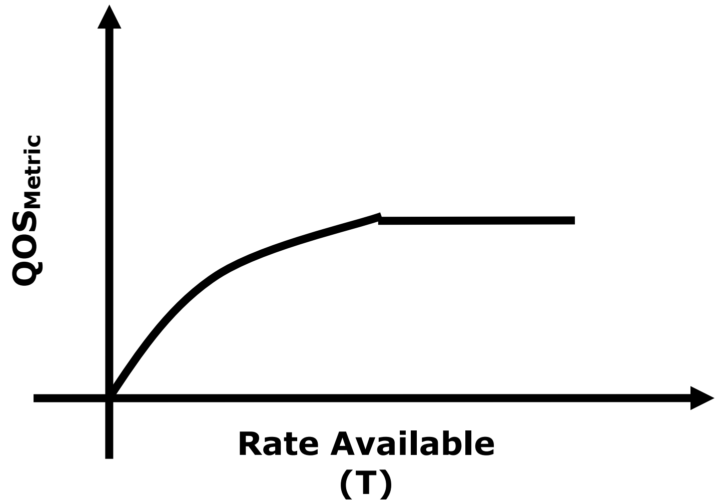

FIGURE 18. Example property of QoS_{Metric} function

The above two are the basic properties of QoS mapping function, $f(.)$. However, we envision more such mathematical properties based on the specific application context. We now describe some example mapping functions, which can be used to compute QoS_{Metric}.

Example Mapping functions:

Unit Step based mapping function: This is the simplest case of mapping function, in which user perceived QoS is either satisfied or not. For example, as long as the network can meet the minimum requirements set forth by user application, the user perceived QoS_{Metric} is QoS_{Max}. Such a function can be written as,

$$QoS_{Metric} = QoS_{Max} \cdot S(QoS_1 - QoS_{1,Min}) \cdot S(QoS2 - QoS_{2,Min}) \cdot \ldots \cdot S(QoS_N - QoS_{N,Min}) \qquad (5.6\text{-}55)$$

S(.) is a unit step function such that

$$\begin{aligned} S(x) &= 1, \text{ for } x >= 0 \\ S(x) &= 0, \text{ for } x < 0 \end{aligned} \qquad (5.6\text{-}56)$$

QoS_{Metric} in this case is either 0 or QoS_{Max}.

The main drawback of such an approach is that it does not allow us to tune different network performance to adapt the user QoS to save energy in the system.

1. ***Parametric based mapping function:*** In this type of mapping function, we estimate the parametric version of mapping function. The various parameters of the mapping function can be derived empirically using the subjective QoS measures like Mean Opinion Score [MOS]. The mapping function is given by,

$$QoS_{Metric} = \prod_i clip_i \left(\frac{QoS_{measured}(i)}{QoS_{application}(i)} \right)^{a_i} \qquad (5.6\text{-}57)$$

$$clip_i(x) = \begin{bmatrix} 0 & \text{for} & x < \min_i \\ x & \text{for} & \min_i < x < \max_i \\ \max_i & \text{for} & \max_i < x \end{bmatrix} \qquad (5.6\text{-}58)$$

The clipping function $clip_i(x)$ is given in FIGURE 19. We can use the parameter ai to incorporate different weighting metrics for individual network QoS parameters.

Finally, the mapping function can be used to generically compute the QoSMetric performance for different network performance scenarios to incorporate QoSMetric in the utility framework described in earlier section.

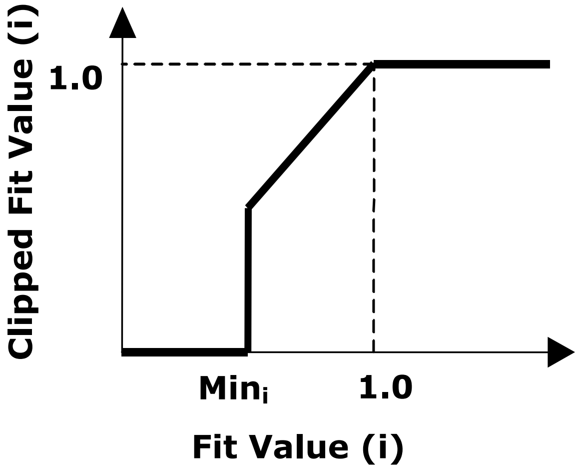

FIGURE 19. Example clipping function

5.6.2. Optimisation based energy efficiency improvements of wireless networks

The objective function of an optimization problem appears either as utility function or a cost function. A cost function is generally used for resource usage and the utility function is for measuring the satisfaction of resource usage. For example, we can introduce sum power minimization problem as a ‘cost minimization problem’ and sum rate maximization as a ‘utility maximization problem’. In communication networks, both these functions are being explored since last few decades and ample of significant results can be found in, e.g., [CHLT2008]. The nature of these functions plays a significant role when it comes to solve the problem with mathematical optimization theory. The metrics (SINR, delay, distortion), which determine the behaviors of those functions are dependent on transmit power, time, beamforming vectors and base station assignment indexes etc. In [FoMi1993], the objective is to minimize the total power consumption of the base station-mobile user pairs subject to rate constraints in a multi-cell, single channel setting and is solved to global optimality by a power control algorithm. Power control with active link protection is studied in [BCP2000], with a robust version of SIR constraint, which can be introduced as an application of power minimization in wireless networks. A more general problem formulation; where each user is not pre-assigned to a base station is identified as NP hard [AADM2009] with the base station assignment indexes (integers) involved. Another branch of, utility maximization is ‘opportunistic utility maximization’ in which the power allocation strategy is executed by exploiting the channel variations [CHLT2008]. In the user scheduling phase, this opportunistic power allocation strategy is followed by the proportional fair scheduling algorithm [KMT1998], [TsVi2005] to maximize the network throughput being fair to all the users. By analyzing the nature of the function, [BoVa2004] helps one to find a solution method to solve different types of utility functions either with closed form solutions or by numerically with a novel algorithm. A more general framework is presented in [PaCh2007] to find distributed solutions to the above mentioned utility/cost functions.

We have developed a cost function which considers the energy consumption over the information of the entire network which can be used in the hierarchical cellular networks. The proposed function is capable of evaluating the efficiency of the entire network as well as different tiers separately. In addition to that, the function considered should be within the framework of convex optimization techniques. The proposed function is bundled with a set of constraints which together act as a unified framework focusing on the QoS of the end user as well as possible power savings at the base station. Considering all these facts, we introduce the following function. Considering all these facts, we use equation (4.3-38) to form the energy consumption per bit as below:

$$\lambda_I = \frac{E}{I} \quad [J/bit]$$

where *E* is the sum energy consumption of the entire network, measured in [J], and *I* is the sum of transmitted bits to each user in the network, measured in [bit].

Most of the utility functions found in the literature mainly concentrate on the energy consumption of individual entities. However, here we consider the entire network. Therefore, the objective function drives towards the direction of reducing the energy consumption per bit of all the users while maintaining the QoS of them. In order to characterize the hierarchical cellular networks, the proposed framework can be easily decoupled into sub frameworks which are identical to individual cells. Afterwards, we obtain a set of sub frameworks which can be individually optimized at each tier level as well as specific cell level. This helps to avoid centralized solution methods. The decoupled unified framework into sub frameworks is given below.

Minimize

$$\frac{\sum_{u_{i,S_k} \in S_k} p_{u_{i,S_k}} t_{u_{i,S_k}}}{\sum_{u_{i,S_k} \in S_k} t_{u_{i,S_k}} W \log(1 + SINR_{u_{i,s_k}})} \tag{5.6-59}$$

Subject to

$$R_{u_{i,S_k}} \geq R_{th,u_{i,S_k}} \forall u_{i,S_k} \in S_k$$
$$I_{u_{i,S_k},u_{i,S_j}} \leq I_{th,u_{i,S_j}} \forall u_{i,S_i} \in S_i, \forall S_j \in M, k \neq j$$
$$E_{S_k,allocated} \leq E_{S_k,available}$$
$$\sum_{u_{i,S_k} \in S_k} t_{u_{i,S_k}} = T$$

where

$$SINR_{u_{i,s_k}} = \frac{p_{u_{i,S_k}} \left| h_{BS_k,u_{i,S_k}} \right|^2}{\sigma^2_{u_{i,S_k}} + \sum_{S_j \in M, S_j \neq S_i} p_{u_{i,S_j}} \left| h_{BS_j,u_{i,S_k}} \right|^2} \tag{5.6-60}$$

$$R_{u_{i,S_k}} = t_{u_{i,S_k}} W \log(1 + SINR_{u_{i,S_k}}) \tag{5.6-61}$$

$$I_{u_{i,S_k},u_{i,S_j}} = p_{u_{i,S_k}} \left| h_{BS_k,u_{i,S_j}} \right|^2 \tag{5.6-62}$$

$$E_{S_k,allocated} = \sum_{u_{i,S_k} \in S_k} p_{u_{i,S_k}} t_{u_{i,S_k}} \tag{5.6-63}$$

The set of cells in the network is defined as $M = \{M_1, M_2, ..., M_n\}$. The set of users in each cell is defined as $S = \{S_1, S_2, ..., S_n\}$, where the cell M_i serves the user set S_i. The user set in the cell M_i is given by $S_i = \{u_{1,S_i}, u_{2,S_i}, ..., u_{n,S_i}\}$. We assume that, each base station schedules only a single user within a time slot. The variable $p_{u_{i,S_k}}$ is the allocated power to the user i in the cell S_k and the variable $t_{u_{i,S_k}}$ is the fraction of time allocated, $SINR_{u_{i,S_k}}$ is the signal to interference plus noise ratio of that user. The channel bandwidth is given by W. $SINR_{u_{i,S_k}}$ is as defined in (5.6-56) where we denote the channel gain from the signaling base station (BS_k in the cell S_k) to the user i as $h_{BS_k, u_{i,S_k}}$. The interfering channel gain to the user i in the cell S_k from the BS_j (in the cell S_j) is denoted by $h_{BS_j, u_{i,S_k}}$. Additive white Gaussian noise power spectral density for the user i in the cell S_k is denoted by $\sigma^2_{u_{i,S_k}}$. According to this formulation, there will be only one user interfering from each cell to the scheduled users in other cells at that particular time slot. The number of bits that has been transmitted to the user i in the cell S_k is given by $R_{u_{i,S_k}}$ which is given by (5.6-57) and $R_{th,u_{i,S_k}}$ is the threshold that should be achieved by that user. The interference generated per time slot by the BS_k (for scheduling user i) in the cell S_k, to the user u_{i,S_j} is given by $I_{u_{i,S_k}, u_{i,S_j}}$, as formulated in (5.6-58) and it should be lower than the agreed interference threshold ($I_{th,u_{i,S_j}}$) for that user. We define the amount of energy allocated to the set of all the scheduled users in cell S_k during the scheduling cycle (T) by $E_{S_k, allocated}$ (5.6-59) and the available energy at the BS_k in the cell S_k during that period is given by $E_{S_k, available}$.

The sub framework is an optimization problem with variables (allocated) power and (allocated) time and has the objective of reducing the energy consumption per bit in each base station by maintaining the QoS of the end users. In reality, the behaviour of objective function is quasi –convex or even non-convex. However, with the analysis found in [BoVa2004], we can convert it into a modified problem in the convex domain. As an example, we can use epi-graph form to convert a quasi-convex problem into a series of convex problems and solve those with existing methodologies. As a very generic example, the problem becomes non-convex if we use transmit beam forming. Here, we can use decomposition techniques to simplify the main problem and solve the resultant problems. Therefore, this unified framework may be a helpful tool in theoretical analysis and can be used to predict the energy efficiency of a wireless network.

We have identified that the EARTH power model [EARTH-D2.3] is applicable to this framework to investigate the energy consumption of the entire network. The framework can be further extended to MIMO networks easily. Hence, we can obtain the energy efficient rate regions using information theoretic fundamentals. Applications like energy efficient scheduling and hand-offs are some practical situations where we can expect this utility function to play a important role in improving the energy consumption of the entire network.

6. SUMMARY AND CONCLUSIONS

The EARTH project develops and evaluates solutions that are used to reduce the energy consumption of radio access networks. This report discusses energy metrics and utility functions that aim supporting an adequate and unbiased evaluation of different technology solutions and covers component, node and network level metrics.

The overall power consumption of a base station depends on power consumed by its components and is dominated by the transceiver system, including the power amplifier, and the baseband. Based on the SOTA metrics defined for a constant (often full) load, a performance metric reflecting the power consumed by the components during variable load situations, typical to a base station, is derived both for the transceiver system and the baseband unit. The metric allows for evaluations using test signals of variable load like described in [EARTH-D5.2]. The metrics are further able to capture the technology potential of the in EARTH proposed component solutions and will help to analyse the state-of-the-art implementations from the energy efficiency perspective.

On node level, study and standardization groups such as ATIS and ETSI have already derived recommendations for metrics suitable to use when measuring the energy consumption of telecommunications equipment, like a base station. The EARTH project has not identified any need of complementary metrics on node level, but follows the ongoing work and progress in the relevant bodies.

When evaluating the energy consumption of a radio network, the energy consumption metric must be used as a complement to performance metrics that quantifies the quality of service delivered by the network. Which quality of service metric to use depends on the service, however, for common services there exist well-established quality of service metrics from, e.g., 3GPP or ITU. For radio network simulation studies, the power per area unit, in [W/m^2], is the preferred energy consumption metric and recommended by the EARTH project. The energy per bit metric, in [J/bit], and the power per subscriber metric, in [W/sub], may both serve as useful complementary metrics. During measurement campaigns or assessments on real, full-scale radio networks the power per subscriber metric followed by the energy per bit metric appear as most practically applicable.

A utility is a measure of relative satisfaction and a utility function is a helpful tool to rate the overall value of one design option relative to another. In EARTH, the typical application of a utility function is to map a two- or multi-dimensional performance metric, including the network energy consumption and the user perceived quality of service, into a one-dimensional quantity that represents the overall value of the design option and can be used in comparative studies. In the proposed framework, the additional utility due to reduced energy consumption and increased quality is calculated relative to a well-known reference case. The overall utility is formed by a weighted sum of the relative energy and quality utilities, respectively, using weighting factors that are determined based on how reduced energy consumption is valued relative to increased quality.

7. REFERENCES

[AADM2009] Abrardo, Alessio, Detti and Moretti, "Radio resource allocation problems for OFDMA cellular systems", Computers & Operations Research, pp. 1572-1581, 2009

[ABI2008] ABI Research, "Mobile Networks Go Green", Q3 2008

[ATIS2009] ATIS, "ATIS Report on Environmental Sustainability", March 2009

[BaDa+2010] Batteram, H., Damm, G., Mukhopadhyay, A., Philippart, L., Odysseos, R. and Urrutia-Valdés, C. "Delivering quality of experience in multimedia networks", Bell Labs Technical Journal, 15: 175–193. doi: 10.1002/bltj.20431, 2010

[BCP2000] N. Bambos, C. Chen, and G. Pottie, "Channel access algorithms with active link protection for wireless communication networks with power control", IEEE/ACM Transactions on Networking, 8(5):583–597, October 2000

[BoVa2004] S. Boyd and L. Vandenberghe, "Convex Optimization", Cambridge University Press, Cambridge, UK, 2004

[Brod2002] R. Brodersen, "Technology, architecture, and applications," presented at the IEEE Int. Solid-State Circuits Conf. Dig. Tech. Papers, Special Topic Evening Session: Low Voltage Design for Portable Systems, Feb. 2002.

[CHLT2008] M. Chiang, P. Hande, T. Lan, and C. W. Tan, "Power Control in Cellular Networks", NOW: Foundations and Trends in Networking, 2008

[Cisco2010] Cisco, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2009-2014", 2010

[Claa1999] T. A. C. M. Claasen, "High speed: Not the only way to exploit the intrinsic computational power of silicon," in IEEE Int. Solid-State Circuits Conf. Dig. Tech. Papers, Feb. 1999, pp. 22–25.

[EARTH] EARTH home page: https://www.ict-earth.eu/default.html (accessed November 28, 2011)

[EARTH-D2.1] EARTH project deliverable, D2.1, v2.00 "The Ecological and Economic Impact of Mobile Communications"

[EARTH-D2.2] EARTH project deliverable, D2.2, v1.0.0 "Definition and Parameterization of Reference Systems and Scenarios"

[EARTH-D2.3] EARTH project deliverable, D2.3, v1.0 "Energy Efficeincy Analysis of the Refererence System, Areas of Improvement and Target Breakdown"

[EARTH-D3.1] EARTH project deliverable D3.1, v1.0 "Most promising Tracks of Green Radio Technologies"

[EARTH-D4.1] EARTH project deliverable D4.1, v1.0 "Most promising Tracks of Green Radio

Technologies"

[EARTH-D4.2] EARTH project deliverable D4.2, v1.0 "Green Radio Technologies"

[EARTH-D5.2] EARTH project deliverable D5.1, v1.0 "Test scenarios and Validation Capabilities"

[ETSI-TS102.706] ETSI TS 102 706 v1.1.1 (2009-08) "Environmental Engineering (EE); Energy Efficiency of Wireless Access Network Equipment"

[ETSI-DTR/EE-EEPS004] ETSI Work Item DTR/EE-EEPS004 "Environmental Engineering (EE); Network level power efficiency",

http://webapp.etsi.org/WorkProgram/Report_WorkItem.asp?WKI_ID=38228 (accessed December 15, 2011)

[FMBF2010] A. Fehske, J. Malmodin, G. Biczok, and G. Fettweis, "The Global Carbon Footprint of Mobile Communications – The Ecological and Economic Perspective", IEEE Communications Magazine, June 2011

[FoMi1993] Foschini and Miljanic "A simple distributed autonomous power control algorithm and its convergence", IEEE Transactions on Vehicular Technology, pp. 641-646, 1993

[Gartner2007] Gartner, "Green IT: The new industry shockwave", Gartner Symposium, ITxpo 2007

[KMT1998] Kelly, Maullo and Tan, "Rate control in communication networks: shadow prices, proportional fairness and stability", Journal of the Operational Research Society, pp.237-252, 1998

[KwBi1986] H. M. Kwon and T. G. Birdsall "Cannel Capacity in Bits Per Joule" IEEE Journal of Oceanic Engineering, Vol. OE-11, No. 1, January 1986, pp. 97-99

[LaCh2009] J. Laskar, S. Chakraborty et al, "Advanced Integrated Communication Microsystems", Wiley, 2009

[LeTaVa2001] D. M. W. Leenaerts, J. van der Tang, C. S. Vaucher, "Circuit design for RF transceivers", Kluwer Academic Publishers, 2001

[Mcc2010] Earl McCune, "Practical Digital Wireless Signals", Cambridge University Press, 2010

[MOS] Wikipedia: http://en.wikipedia.org/wiki/Mean_opinion_score (accessed November 28, 2011)

[PaCh2007] D. P. Palomar and M. Chiang, "Alternative distributed algorithms for network utility maximization: Framework and applications," IEEE Trans. Autom. Control, vol. 52, no. 12, pp. 2254–2265, Dec. 2007

[RoMe2007] V. Rodoplu and T. H. Meng "Bits-per-Joule Capacity of Energy-limited Wireless Networks", IEEE Transactions on Wireless Communications, Vo. 6, No. 3, March 2007, pp. 857-865

[RoSi1989] R. Rom and M. Sidi "Multiple Access Protocols", Springer-Verlag, 1989

[Shin2008]	Sun-Young Shin; Jin-Chul Kim; Sang-Yong Ha; Yeong-Ro Lee; , "A Study on the QoS Metric for measuring BcN Wireless Service Quality," Advanced Communication Technology, 2008. ICACT 2008. 10th International Conference on , vol.1, no., pp.774-776, 17-20 Feb. 2008
[ShWo2003]	A. Shirvani and B. A. Wooley "Design and control of RF power amplifier", Kluwer Academic Publishers, 2003, ISBN 1-4020-7562-6
[TR36.814R9]	3GPP TR 36.814 V9.0.0 (2010-03), "Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA physical layer aspects (Release 9)"
[TsVi2005]	D. Tse and P. Viswanath, "Fundamentals of Wireless Communications", Cambridge University Press, 2005
[TS23.203R8]	3GPP TS 23.203 V8.10.0 (2010-06), 3rd Generation Partnership Project; "Technical Specification Group Services and System Aspects; Policy and charging control architecture; (Release 8)"
[Verdu2002]	S. Verdú "Spectral Efficiency in the Wideband Regime", IEEE Transactions on Information Theory, Vol. 48, No. 6, June 2002, pp. 1319-1343
[VERIZON09]	Verizon, "Verizon NEBSTM Compliance: Energy Efficiency Requirements for Telecommunications Equipment, Verizon Technical Purchasing Requirements", VZ.TPR.9205, Issue 4, August 2009