Teemu Alviola

Energy efficiency in wireless networks

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University of Jyväskylä

Department of Mathematical Information Technology

Author: Teemu Alviola

Contact information: teemual@gmail.com

Supervisor: Tapani Ristaniemi

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Abstract: This Master's thesis is a literature review that discusses energy efficiency and power savings in different wireless networks. The overall focus in this paper is set dominantly in 3G and LTE-networks. The thesis begins by recognising different types of reasons in the mobile industry to practice energy savings, and the reasons why energy efficiency is being so widely researched these days. Breakdown of energy consumption in wireless networks, as well as various different ways to improve energy efficiency in these networks follow in the latter part of the paper. The thesis also includes a brief Octave-simulation concerning the energy efficiency of a collaborative mobile cloud. The thesis concludes with a summary of the current state of the various energy savings technologies in use.

Keywords: Energy, Efficiency, Energy-efficiency, Wireless, Networks, 3G, 4G, 5G, LTE, Wi-Fi, WDC, WMN, Green, TANGO, Beamforming, Mobile

Suomenkielinen tiivistelmä: Tämä pro gradu -työ on sekundääritutkimuksena tehty kirjallisuuskatsaus energiatehokkuuden tarkastelusta langattomissa verkoissa. Työssä tarkastellaan erilaisia mobiiliverkkojen energiansäästömahdollisuuksia. Pääpaino työssä on suunnattu erityisesti 3G ja LTE -verkkoihin, kuitenkin eksoottisempiakaan verkkoja unohtamatta. Työ alkaa erilaisten mobiiliverkkojen energiansäästösyiden ja tutkimusmotivaattoreiden tunnistamisella ja jatkuu langattomien verkkojen energian kulutuksen jaotuksella, sekä erilaisten energiansäästömahdollisuuksien vertailuilla. Työn empiirisessä osassa nostetaan lisäksi esille lyhyt Octave-simulaatio kollaboroivan mobiilipilven noodien energiansäästöstä. Työ päättyy yhteenvedolla erilaisista jo käytössä olevista energiansäästötavoista.

Avainsanat: Energia, Tehokkuus, Energiatehokkuus, Langaton, Verkko, 3G, 4G, 5G, LTE, Wi-Fi, WDC, WMN, Green, TANGO, Beamforming, Mobiili

Preface

I would like to thank my thesis supervisor, Dr. Tapani Ristaniemi for his advice and guidance. Acknowledgments also extend to Mr. Zheng Chang for meaningful discussions concerning the mobile cluster research simulation.

Jyväskylä, September 13, 2013

Teemu Alviola[1], BEng.

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Glossary

3G	3rd Generation of mobile telecommunications technology
4G	4th Generation of mobile phone communication standards
AP	Access Point
ATM	Asynchronous Transfer Mode
BER	Bit Error Rate
BS	Base Station
BSC	Base Station Controller
BTS	Base Transceiver Station
CDMA	Code Division Multiple Access
CDMA2000	A group of 3G mobile technology standards
DSP	Digital Signal Processor
DVB	Digital Video Broadcasting
DVS	Dynamic Voltage Scaling
E1	E-carrier (level 1), a digital transmission system used throughout Europe and most of the rest of the world.
FCC	Federal Communications Commission
GigE	Gigabit Ethernet
GPRS	General Packet Radio Service
GSM	Global System for Mobile communications, commonly known as *the 2nd Generation digital cellular network (2G)*
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ITU	International Telecommunication Union
Li-Fi	Light Fidelity
LOS	Line-Of-Sight
LTE	Long-Term Evolution, alternative nomenclature 4G LTE
MAC	Media Access Control
MIMO	Multiple-Input, Multiple-Output
MSC	Mobile Switching Centre

MT	Mobile Terminal, (*e.g. the cell phone*)
MTX	Mobile Telephone eXchange
Node B	Node B is the UMTS equivalent to the BTS used in GSM.
OFDM	Orthogonal Frequency Division Multiplexing
PA	Power Amplifier
PAN	Personal Area Network
QoS	Quality Of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RBS	Radio Base Station
RF	Radio Frequency
RRM	Radio Resource Management
RSSI	Received Signal Strength Indication
SGSN	Serving GPRS Support Node
SNR	Signal-to-Noise Ratio
T1	T-carrier (level 1), digital transmission system used primarily in the USA. Incompatible with E1.
TD-SCDMA	Time Division Synchronous Code Division Multiple Access
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
Transceiver	An unit that contains both the transmitter and the receiver.
UMTS	Universal Mobile Telecommunications System
UTRA	UMTS Terrestrial Radio Access
W-CDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Alternative commercial nomenclature: *"Wi-Fi"* – a set of IEEE 802.11 standards defining a Wireless Local Area Network
WMAN	Wireless Metropolitan Area network
WPAN	Wireless Personal Area Network
WRAN	Wireless Regional Area Network

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1 Introduction

This master's thesis is a literature review of the currently used energy efficiency methods in wireless networks, with a focus set dominantly in the 3G and LTE -networks and their derivatives. The thesis is loosely based on and motivated by an unpublished report on wireless efficiency I wrote as a research project at the University of Jyväskylä during the spring of 2012. I then chose to continue investigating this topic and to expand the report into a form of a master's thesis, because I found the subject rather interesting and because I felt the topic needed further update and research.

This thesis consists of 6 sections. Section 1 serves as an introduction to the various energy efficiency -related issues in mobile computing and mobile communications. It also discusses the reasons why energy efficiency is becoming more and more important these days, not only for the wireless service providers, but also for the end-users themselves. Section 2 discusses some of the background issues concerning energy efficiency, as well as some of the different motivators and reasons to research energy efficiency. Section 3 discusses different possible implementations of practicing energy savings found in literature, as well as the efficiencies of the presented methods. Section 4 reflects the energy efficiency for some of the upcoming wireless technologies. Section 5 presents a scheme called *distributed mobile cloud*, as well as some more analytical evaluations of the energy efficiency possibilities arising from deploying the introduced method. Summary of findings, as well as conclusions is presented in section 6.

1.1 Some background on energy efficiency

There are a number of reasons why different mobile network operators and mobile network device manufacturers are together globally researching different ways to optimise their network performance from the energy efficiency and capacity standpoint. The ever-increasing number of peripheral equipment running online has, and will continue to lead to increased demands for energy supplies. The pressure to optimise the energy efficiency is not entirely on the operator's shoulders, but also on the device manufacturers, who all have to be able to design and manufacture more compelling solutions for the operators to implement and for the consumers to purchase.

A lot of money in the mobile networks is being wasted, particularly in the network's RBSs, in the form of energy consumption – partly because the RBSs are not being used in the most optimal and efficient way, and partly because more efficient and elegant solutions have been developed to handle some of the RBS's features better than the current RBS's themselves. Operating costs are also being jacked up because of the increase of the carbon footprint of the wireless networks. This increase is due to the fact that the mobile networks are growing more and more each day, together with the data volumes transferred by each customer. Network growth is mainly due to the fact that the traffic of the network rises as the user base expands each day. Users's faster data plans, USB-data dongles for laptops, smartphones, tablet computers, and the fact that the MT prices are going gradually down are the main reasons that further contribute to the congestion of the networks (Sutton and Cameron 2011).

Ratio of mobile voice traffic versus mobile data traffic gradually shifts more and more towards mobile data. Furthermore, the content that the users consume online is not just traditional email and static webpages anymore, but it's rapidly moving more towards the modern dynamic Web 2.0/Web 3.0 and online social video services, which account for a very big role in the used bandwidth. Growing CO_2 emissions also mean that the price of the energy will eventually go up, not only due to the CO_2 emission limitations (or more specifically, CO_2 emission credits trading), (Grubb 2003), but also simply because more greener and thus more expensive-to-use power plants are needed to meet the future clean power needs of the wireless networks and their users.

The Japanese telecommunication operator *NTT DoCoMo* has released data, that the ratio of the power consumption between the MT and the mobile network is nearly 1:150 – more specifically, meaning that the MT consumes a mere 0.83 Wh/day (incl. battery chargers and terminals), whereas the network uses 120 Wh/day (Etoh, Ohya, and Nakayama 2008). In TDMA networks, the RF uplink constitutes 60% of the total energy usage of the MT's radio (Kim, Yang, and Venkatachalam 2011). Within the energy usage of a mobile device, the manufacturing of the device itself costs the most when it comes to the CO_2 emissions – well over two-thirds (Auer et al. 2010).

Figure 1 on page 3 illustrates the global ICT footprint in gigatonnes of CO_2e[1] in the year 2002, 2007, as well as a CAGR[2] estimate for 2020 (Group 2008). ICT in this context represents the PCs, telecommunications networks and -devices, printers and data centres. The year 2007 figure represents roughly a mere 2% of the estimated human global annual total emissions. Embodied carbon refers to the amount of carbon in CO_2, that was once used for resource extraction, transportation, manufacturing and fabrication of the devices or products themselves.

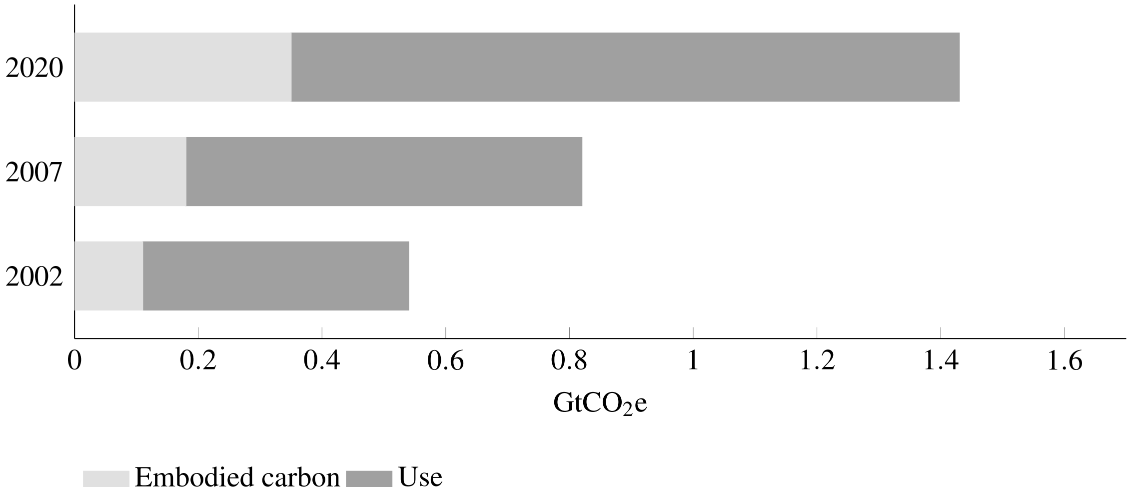

Figure 1. Illustration of the global ICT footprint (in $GtCO_2e$).

Figures 2 and 3 on page 4 represent the global telecoms footprint (in megatonnes of CO_2e)[3] in 2002 and 2020 for devices and infrastructure (Group 2008). The relative amount of mobile traffic, as well as fixed broadband traffic increases quite noticeably, whereas for the fixed narrowband, the traffic is going to shrink.

The European Union (within the framework program FP7) started and funded a project in 2010 along with 15 partners from the industry, academia and business called *Energy Aware Radio and neTwork tecHnologies* (EARTH). The purpose of EARTH was to search for effective solutions and results for the improvement of wireless energy efficiency in communication networks, especially LTE and LTE-A in particular (but it will also consider 3G

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[1] Equivalent carbon dioxide.

[2] Compound Annual Growth Rate.

[3] One unit of carbon is equivalent to 3.664 units of CO_2.

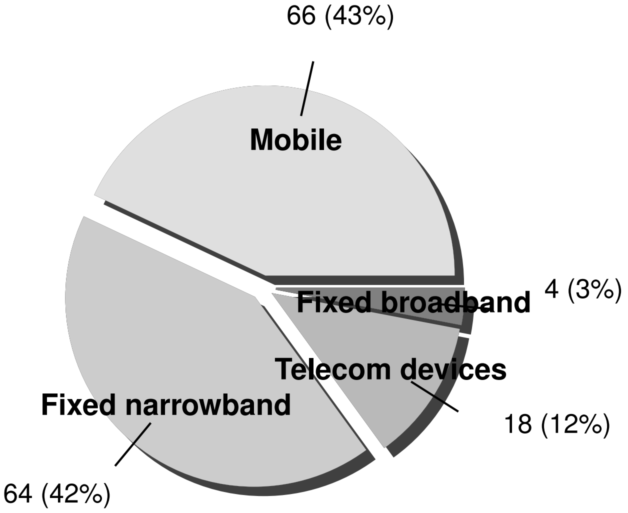

Figure 2. Illustration of the global telecoms footprint (in $MtCO_2e$) in 2002 (100% = 152 $MtCO_2e$).

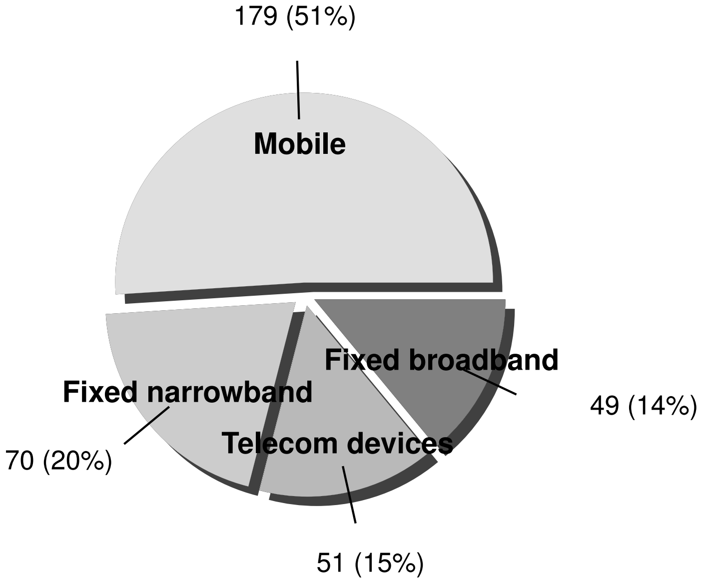

Figure 3. Illustration of the global telecoms footprint (in $MtCO_2e$) in 2020 (100% = 349 $MtCO_2e$).

(UMTS/HSPA) technology for immediate impact), and the ICT in general. The target was set especially for low load situations (Gruber et al. 2009). A goal was set for EARTH to cut the energy consumption of wireless broadband networks by 50%.

International Data Corporation (IDC) expects smart connected device shipments to grow by 14% annually through 2016, led by tablets and smartphones. The worldwide total unit shipments for smart connected devices is expected to reach nearly 1.2 billion in 2012, and grow to 1.4 billion in 2013, and that the combined worldwide smart connected devices market will surpass 2 billion units in 2016 (USA 2012).

There are several other research projects that cover the open issue of energy efficiency in wireless systems, as well as in their components too:

- OPERA-Net

  OPERA-Net (*Optimising Power Efficiency in mobile RAdio Networks*) (Celtic-Plus 2013), which investigated the different ways to improve the energy efficiency of broadband cellular networks by focusing on the optimised cooling and energy recovery from the BSs, and the optimisation of the components used in communication systems.

- PANAMA

  PANAMA (*Power Amplifiers aNd Antennas for Mobile Applications*) -programme (CATRENE-Programme 2013) focuses on different ways to save energy by more efficient design of the PAs, due to the fact that the PAs are the BS's major energy consumers, that typically still run at a fairly low efficiency.

- Cool Silicon

  Cool Silicon (Silicon 2013) -project focuses on making recommendations for high performance communication systems with low energy consumption, by focusing on three main areas: micro/nano technology, broadband wireless access, and wireless sensor networks. The project focuses also on the optimisation of the individual aspects of the communication systems like the architecture of the system, communication algorithms and protocols, as well as physical components.

The technologies implemented to enhance the energy efficiency of one end of the communication system (either in the transmitter or receiver) may adversely affect the energy efficiency of the other end. For example, increasing the frequency reuse in a multiuser system, and adopting efficient multiuser scheduling techniques may lower the transmit energy requirement for the same spectral efficiency, but on the other hand the receiver needs more computation (and thus more computational energy) for performing the multiuser detection (Gruber et al. 2009).

A lot of energy is also being wasted into the cooling of the RBS's, as the RBS's normally operate at full power even when they are not being used at all, or when the usage is quite minimal (*e.g. during the night or in the rural area*). Reducing the time the RBS's operate at full power also reduces the need to cool them down. It is not only the networks themselves that will have to be reassessed to help improve the energy efficiency, but also the electronics manufacturers' solutions and the signal processing techniques have got to improve. The only way to meet the ever heightening power needs of the users's mobile computing, is when the electronics manufacturers, signal processing improvements and RBS redesigns work together – none of these alone will suffice. Fundamental architectural redesigns are essential.

The energy optimisation, and thus lessened power requirements also paves way to the possible scenario, where parts of the network are being powered by the limited, renewable energy sources (*e.g. solar panels or windmills*). This also makes the usage of picocells more reasonable and realistic. More on picocells at section 3.4.3 on page 38. Increasing the energy efficiency is the only way to maintain sustainable growth of the mobile industry.

1.2 Energy usage in wireless systems

About 70-80% of a typical mobile network's power consumption accounts either for the BS, or the radio sites (EARTH-Project 2010), (Huawei Technologies Co. 2013). According to a paper by (T. Chen et al. 2011), the energy consumption of a typical mobile phone operator's RBS site composes mainly of the power usage of the RBS itself, MTX, and the core network. Data centre and retail energy consumptions, which are both in a more of a supportive role in the big picture, play quite an insignificant role.

From the energy consumption standpoint, the BS itself comprises of the RBS, power supply (DC-DC and AC-DC), RF-transceiver, climate control, battery back-up, as well as an optional transmission link in the baseband unit in the bigger BSs to connect to the operator's network for platform control and medium access control. The RBS itself consists of the PA and multiple transceiver units. At full load the BS's radio units dominate the site's power consumption, which is completely reasonable (and to be expected), but at *near zero* load they still remain significant. To be more exact, the power consumption at 1% traffic load is in the order of 50% of the maximum (Ferling et al. 2010).

Power losses exist also in the power and signal transmission lines, as well as in the feeder lines, which also contribute to the overall power consumption. For smaller BSs, these feeder losses become less significant due to the smaller transmitted power levels. The climate control unit that keeps the main heat dissipator, the PA, cool plays a large role in the overall energy consumption as well.

This is also the reason why the usage of the PA must be placed under a tight scrutiny in order to keep the need of its cooling equipment at a minimum as well. The semiconductor- and the silicon technology also play a large role in the BS's overall power usage. The higher the power efficiency gets, the more leakage also occurs. The International Technology Roadmap for Semiconductors believes that doubling the power efficiency multiplies the leakages by threefold, thus also vitiating the possible power reduction away (Auer et al. 2011), (Borkar 1999).

Losses occur also at the antenna interface due to the impedance matching losses, bandpass filters and duplexers. For low power nodes, picocells, etc, the PA constitutes of fewer than 30% of the total power usage, whereas for larger macrocells, the PA accounts up to 55-60% of the BS's total power usage. Implementing a scenario where the PA is mounted at the same physical location as the macrocell BS site's transmit antenna, technique also known as *remote radio head*, enables the feeder losses and active cooling to be reduced greatly.

Impedance mismatches are reflections from the transceiver's amplifier into the antenna, and back again into the transceiver's amplifier. The phenomenon is more commonly known[4] as *standing wave ratio* (SWR). SWR is essentially the ratio of the partial standing wave amplitude at the maximum, compared to the amplitude at the minimum. These reflections depend on the impedance (mis)matching between the amplifier (and feeder), and the antenna, which in turn depends on the power level, frequency and the antenna environment. SWR ratio is always the same as the ratio of the impedances of the feeder and the antenna elements. Active tuning of the matching network can aid with these reflections. SWR is defined mathematically in (1.1) with the help of (1.2) (Dana George Reed 2002):

$$SWR = \frac{1+|\rho|}{1-|\rho|} \tag{1.1}$$

From which the complex reflection coefficient (ρ) can be determined with:

$$\rho = \frac{(Z_a - Z_0')}{(Z_a + Z_0)} = \frac{(R_a \pm jX_a) - (R_0 \mp jX_0)}{(R_a \pm jX_a) + (R_0 \pm jX_0)} \tag{1.2}$$

where:

Z_a is the characteristic load impedance
Z_0 is the characteristic impedance of the transmission line
Z_0' is the complex conjugate of Z_0
R_a is the load resistance
R_0 is the line's characteristic resistance
X_a is the load reactance
X_0 is the line reactance

Usually the characteristic impedance Z_0 is for most transmission lines practically entirely resistive, in which case the above formula (1.2) can be modified to be $Z_0 = R_0$, and $X_0 \cong 0$, and expressed as in formula (1.3):

$$|\rho| = \sqrt{\frac{(R_a - R_0)^2 + X_a^2}{(R_a + R_0)^2 + X_a^2}} \tag{1.3}$$

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[4] Just ask any ham radio operator.

To obtain and calculate the ρ more commonly (and *easily*) using a RF-wattmeter is expressed in (1.4). An even easier trick however would be to just use an SWR-meter or an antenna or vector network analyser.

$$\rho = \sqrt{\frac{Reflected\ wave\ power}{Forward\ wave\ power}} \tag{1.4}$$

Mobile networks normally require a large number (in the order of thousands) of BSs to provide nationwide coverage. Each BS can require – depending on its configuration, load of the cell, and age of the equipment, up to 2.7 kW of power (Rinaldi and Veca 2007). The energy consumption for a nationwide coverage can thus be in the order of several MW. Mobile networks are therefore systems where the effects of energy efficiency can be considerable.

A lot of energy has also obviously once been used to manufacture the wireless equipment themselves, but for entities such as the BS site, this manufacturing cost is negligible, due to the comparably long life span of the system itself, during which the system uses a fair bit more energy than once went into the manufacturing of the equipment itself. For BS sites, the equipment's operating power is in a much more important role than for the end-user terminals, due to the fact that the end-user devices (MTs) typically don't last as long and have to be replaced much more frequently anyway. In addition, the end-user devices use much less power to operate than the BSs do.

The non-working time (*i.e. the time during the holidays and nighttime*) is in fact more than 50% of the year. The needlessly spent energy of the existing wireless networks is thus astounding. Typical Internet service providers experience long time network utilisation average of about 20% – which is to say that a lot of resources are being wasted just in order to provide a constant preparedness for the potential high load situation. A 0,5% call dropping probability requires 30% of system's capacity to be constantly reserved (Kim and Veciana 2010), (Oliveira, Kim, and Suda 1998). This misuse grows into an even more severe problem for the future wireless networks, where the size of the cells is going to get even smaller and smaller (*e.g. micro- or pico-cellular*), to be able to serve even more high-data-rate users and to increase the frequency reuse factor – which will in effect further increase the dynamics of the traffic in a cell.

This brings up an important notion of how to get the network's transmitters to adapt to the traffic fluctuation, and to completely switch off the BSs if the load in the network drops below a specific threshold – furthermore, how to guarantee satisfactory service to the users in the case the transmitter's power is indeed reduced, or the BS is turned off completely? The distribution of the radio resources over heterogeneous[5] cellular networks should be optimised in a global way, hence the colloquial term (*Globally Resource-optimised and Energy-Efficient Networks (GREEN)*). More on GREEN at section 3.2 on page 21.

In essence, there are two types of wireless traffic load fluctuations in a cellular network that can be distinguished. First one is the large-scale fluctuation, in which the traffic load varies notably from one time period to another throughout the day – this can be thought to represent the workforce commuting from one region of the city to another. The second type is the small-scale fluctuation, in which the wireless traffic load varies only slightly around some average value – this can be thought to represent the random city life with people going about their business throughout the day and the MT sporadically experiencing impaired service quality.

1.2.1 3G overview in brief

Different views exist throughout the wireless industry as to what exactly does the term *3G* contain. First generation (1G) cellular services were implemented by using analogue RATs only. As the analogue networks were upgraded to digital ones in the late 90's, it was rather straightforward to call it the second generation (2G) network. The naming transition from 2G to 3G wasn't however so obvious. Throughout the years, the ageing 2G networks were upgraded extensively to incorporate better capabilities into them with higher performance, thus narrowing the gap to what later on became known as *3G* or *UMTS*. The naming issue hasn't really changed all that much with the introduction of 4G, which in a sense is nothing more but an evolution of the 3G technologies – however, it can be safe to say that 3G can be thought to be the third generation of mobile service capabilities.

In order to distinguish 3G from 2G, the ITU[6] defined substantially higher performance lev-

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[5] Superposed small and large cells in a wireless network.

[6] A United Nations specialised agency responsible for information and communication technology matters.

els for 3G compared to those obtained from 2G mobile networks (ITU 2013). Comparing to its predecessor, 3G supports higher capacity, enhanced network functionalities, as well as the capability to multimedia applications (IMT2000-Project 2002). There are also applications for 3G in wireless voice telephony, mobile Internet access, mobile video calls and mobile TV. Various radio interfaces for UMTS are available (*e.g. W-CDMA, TD-SCDMA and CDMA2000*).

No clear definitions of the available minimum or average data rates in a 3G network, or for the 3G equipment have been defined by the ITU. Performance specifications were once limited to an open ended comment (covering indeed for a wide variety of data rate possibilities), stating that: "It is expected that IMT-2000 will provide higher transmission rates: a minimum speed of 2 Mbit/s for stationary or walking users, and 348 kbit/s in a moving vehicle" (ITU 2011). The vagueness itself leaves plenty of headroom for the operators to more freely choose the advertised data rates and thus sell the products easier with the "3G"-label attached to them.

1.2.2 LTE overview in brief

LTE, whose RAT is called *Evolved UMTS Terrestrial Radio Access Network* (E-UTRAN), was set aggressive performance requirements relying on physical layer technologies, such as, OFDM, MIMO and Smart Antennas to achieve these targets in a variety of coverage scenarios. The main objectives of LTE were set to minimise the system and user equipment complexities, allow flexible spectrum deployment in either existing or new frequency spectrum and to enable co-existence with other 3GPP[7] RATs (Motorola 2008) at least for the next 10 years and beyond – hence the term "Long-Term Evolution of the 3GPP radio-access technology" (3GPP 2013b, 3GPP TR 25.913 V9.0.0 (2009-12)). Smart antennas are discussed in more detail along with beamforming antennas at section 3.5.

Core qualities of LTE (3GPP 2013b):

- Objectives

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[7] The 3rd Generation Partnership Project, which with its member organisations, produces reports and standards.

The objective of Evolved UTRA and UTRAN is to develop a framework for the evolution of the 3GPP RAT towards a high-data-rate, low-latency and packet-optimised RAT.

- Data rates

  E-UTRA should support significantly enhanced instantaneous peak data rates over legacy technologies, which should in turn scale according to the size of the allocated spectrum.

- Latency

  LTE should significantly reduce the system latencies.

- User throughput

  Several fold difference in user throughput (per MHz) over previous technologies.

- Spectrum efficiency

  Significantly improved spectrum efficiency and increased cell edge bit rate using already existing site locations.

- Mobility

  Mobility should be optimised for low mobile speeds between 0 $\sim$ 15 km/h, while speeds up to 500 km/h should be nevertheless supported.

- Coverage

  E-UTRA should be sufficiently flexible to support a variety of coverage scenarios using the existing UTRAN sites with the same carrier frequency.

- Further Enhanced MBMS

  E-UTRA systems should support enhanced *multicast broadcast multimedia services* (MBMS) -modes, compared to UTRA (3G) operation.

- Spectrum

  Support for diverse and different sized spectrum allocations, as well as requirements to co-exist with other networks and operators on adjacent channels, or to exist standalone.

- Co-existence and interworking with 3GPP RAT.

2 Energy Efficiency background and motivators

Power consumption has a direct impact on energy consumption. Power reductions, as well as energy efficiency are critical factors when operating using green energy sources (such as solar or wind power), which are power and not energy constrained. The MT's active mode power consumption is not the only property critical from energy efficiency standpoint – throughput (*e.g. Joules/Mbit*) also plays an important role. Consider the situation where the device has a high active mode power consumption – it might still be comparably energy efficient to use the device if it had a very fast data connection, and thus a low time period of highly consuming active mode (Shor 2008).

Mobile data is growing at such a high rate that the conventional macrocell networks cannot meet the demand set by the ever growing number of clients, either economically, or functionally. It is impossible to set up macrocells absolutely everywhere, where the capacity is needed due to the regulatory, spatial, or financial constraints. The only reasonable solution to serving a high number of MTs with a relatively low cost is to break the large macrocells down into much smaller areas, and to assess the cooperation possibilities of the macrocell BSs with much smaller and lower powered cells in it – such as placing a pico- or femtocell BS into an office, or for example a metrocell (or a few) into a large football arena. The cells smaller than macrocells have a colloquial term *small cells*. More on different cells at section 3.4.1 on page 31.

Deploying a network with only small cells would imply using a large number of BSs. However, a large number of BSs also increases the handoff rates of the MTs among the adjacent cells, and may also therefore degrade the gross energy efficiency of the whole network. A joint deployment of BSs with differing cell sizes is suitable, and above all necessary in order to upkeep the balance of different cell sizes for the highest energy efficiency network layout. Moreover, the overusing of the small cells increases the number of BS operating at low loads, which may cause the overall energy efficiency to degrade. This is also why for each deployment scenario (*e.g. urban vs. rural*), heterogeneous deployment with an optimal balance of macro-, micro-, pico-, and femto -cells must be found for the highest energy efficiency network layout.

The deployment of cellular networks is usually optimised for omnipresent radio access for the MTs. This however requires that a significant portion of BSs is primarily only providing coverage, and therefore not operating at full load – even at peak traffic hours. During off-peak hours, almost all BSs operate obviously at low load, or they might not even serve any MTs at all (Correia et al. 2010).

Regrettably, the energy efficiency of BSs is exceptionally poor in these circumstances. The inefficiencies can be further broken down into (Correia et al. 2010):

- Component level

  The efficiency of the PA substantially degrades at a lower power output level.

- Link level

  System information, synchronisation, and reference signals (or pilots) are to be transmitted continuously. This requires that BSs are incessantly on.

- Network level

  The wireless network deployment paradigm with large macrocells in it needs small cells to supplement and fulfil the peak capacity demand. This is however rather static topology and doesn't therefore adapt very well to low load situations.

In order to meet these inefficiencies, a holistic strategy for network operation must be developed.

Easily one of the most popular metrics for measuring the energy efficiency of a communications link is the consumed energy for the number of information bits, or *Joules/bit*. In wireless networks, this formula gives the total energy consumed by the whole network per the aggregate network capacity. Whereas this energy efficiency -metric relates to processed information and its cost at full load, at lower loads the formula W/m^2 fits better for the demand to minimise the power consumption to cover a certain area.

3 Implementations for attaining higher energy efficiency

This section discusses several different possible implementations for achieving energy savings in wireless communications, as well as the following paramount topics regarding the wireless energy efficiency improvements:

- Green-communication

  Globally Resource-optimised and Energy-Efficient Networks – Green is a marketing term for the improvement of energy efficiency and energy independence of telecommunications without any notable impact on the QoS. Green is discussed in more detail at section 3.2 on page 21.

- Traffic-Aware Network planning and Green Operation (TANGO)

  TANGO aims at the optimisation of the radio resources as well as the energy efficiency within, without impeding the coverage using the Green -framework. TANGO is discussed in more detail at section 3.3 on page 27.

- Different wireless network cell types

  Evaluations of the different wireless network cell types, as well as the following small cell technologies beginning from section 3.4 on page 29:

  - Small cells, at section 3.4.1 on page 31.
  - Femtocells, at section 3.4.2 on page 36.
  - Picocells, at section 3.4.3 on page 38.
  - Microcells, at section 3.4.4 on page 40.
  - Metrocells, at section 3.4.5 on page 40.
  - Macrocells, at section 3.4.6 on page 41.

- Beamforming

  The electronic steering of the antenna array with the purpose of creating higher directionality and thus sensibility to a specific sector while minimising the directionality to