Technical University Berlin

Telecommunication Networks Group

An Overview of Energy-Efficiency Techniques for Mobile Communication Systems

Holger Karl (ed.)

karl@ee.tu-berlin.de

Berlin, September 2003

TKN Technical Report TKN-03-XXX

TKN Technical Reports Series

Editor: Prof. Dr.-Ing. Adam Wolisz

An Overview of Energy-Efficiency Techniques for Mobile Communication Systems

Report of the Working Group 7 "Low-power broadband wireless communication" of the Arbeitsgruppe Mobikom, DLR/BMBF

Holger Karl, editor[1]

Abstract

This document provides a concise overview of energy consumption of wireless mobile communication devices and systems on a number of abstraction layers: the hardware, the communication protocol layer, and the system architecture as a whole are considered. In addition, an overview of current research approaches to improve energy efficiency is presented.

This paper resulted from the cooperation of many individuals of several institutions. In particular, Lars Berlemann, Aachen University, Jean-Pierre Ebert, TU Berlin, Josef Fenk, Infineon, Georg Fischer, Lucent, Eckhard Grass, IHP, Patrick Herhold, TU Dresden, Ralf Kakerow, Nokia, Martin Kubisch, TU Berlin, and Joachim Sachs, Ericsson, deserve special mention (in alphabetic order).

---

[1] Corresponding author. Contact address: Dr. Holger Karl, Fachgebiet Telekommunikationsnetze, Einsteinufer 25, 10587 Berlin, Tel. +49 30 314 23826, karl@ee.tu-berlin.de.

1 Introduction

The goal of this report is to provide an overview of power consumption and energy efficiency issues in mobile communication systems. It starts from the hardware level and characterizes the main sources of power consumption in current mobile devices and base stations. Based on these considerations, system concepts are discussed with respect to energy efficiency. Protocol mechanisms for energy-efficient communication complete the report.

2 Characterizing the power consumption of devices for mobile communication

2.1 Performance parameters of a typical WLAN Application (Hiperlan/2; IEEE802.11a)

Contributor to this section: Eckhard Grass, IHP Frankfurt (Oder), e-mail: grass@ihp-ffo.de

Based on the IEEE 802.11a standard a complete single-chip modem including Analog Frontend, Baseband processor, and MAC-Processor was designed and implemented. Based on simulation and synthesis results the following observations for the processing power (and power dissipation) of 5GHz WLAN chips have been made:

In *transmit direction* the overall processing power will only slightly be increased if the bit rate increases from 6 to 54 Mbit/s. This is due to the increased number of bits per subcarrier.

In *receive direction* the Viterbi decoder consumes most of the calculation power. This results in a significant increase in power dissipation of the Baseband Processor when compared to the transmit mode.

To start of with an example of current technology, the following table gives an approximate overview of the chip area of an IEEE802.11a capable WLAN modem.

Estimated parameters of the single chip solution for 0.25 um SiGe BiCMOS technology:

Digital BB:	Viterbi	6 mm^2
	FFT/IFFT	4 mm^2
	Synchronization	8 mm^2
	MISC	6 mm^2
MAC:	μ-Controller	20 mm^2
Analog:	DAC & ADC	10 mm^2
	Transceiver	12 mm^2
Total:		**≈65 mm^2**

The following table gives an overview of the approximate power dissipation of an IEEE802.11a capable modem.

Estimated parameters of the single chip solution for 0.25 um CMOS technology:

Digital BB:	600 mW	+200 mW (RX-Viterbi Decoder)
MAC:	500 mW	
Analog:	300 mW	+200 mW (TX-Power Amp)
Total:	**1600 mW**	**(both for RX and TX!)**

Power dissipation in Receive and Transmit mode is approximately the same. However, in Transmit mode the power amplifier adds about 200 mW whereas in Receive mode the Viterbi Decoder contributes about 200 mW. Since Power amplifier and Viterbi Decoder are operating mutually exclusive either in transmit or receive mode, the power dissipation in this technology will be approximately the same for both modes of operation.

2.2 Power supply of mobile devices

The primary reason to worry about power consumption of mobile wireless communication devices is the limited energy supply available via current battery / rechargeable battery (secondary battery) technology. With the prospect of mobile devices being equipped with additional peripheral devices like cameras, efficient power supply is still an important issue.

Current secondary batteries are typically based on Lithium-Ion (Li-Ion) or Lithium-Polymer (Li-Po) technology, sometimes, Ni-Cd or Ni-Mh cells are also still in use. The relative advantages and disadvantages of these technologies (in particular, capacity, recharging duration, memory effect, weight, robustness, and costs) are well known. A key metric is the energy density, expressed as Watt hours per kilogram or as Watt hours per liter. For Li-Ion technology, is around 120-140 Wh/kg as of 2002. However, the rate of increase is rather modest: about 10% to 15% increase per year can be expected with current technologies [69].

Alternative technologies like Zinc-Oxygen primary batteries or fuel cells are under development, but it is not clear when they will be ready for market. Fuel cells in particular promise a considerably higher energy densities than available today, combined with the possibility to quickly recharge. A good, popular overview of fuel cell technology can be found in [76].

In addition, energy scavenging techniques are under discussion: using solar cells or mechanical devices to use ambient energy to boost battery life by continuous recharging. The quantitative impact on device lifetime, however, appears to be rather small. Nevertheless, these technologies could have a very large importance for sensor networks where the data rate and duty cycle requirements are much more modest than in the system and application scenarios discussed here.

A further possibility is to design communication systems and protocols so as to exploit available battery idiosyncrasies in the best possible fashion: For example, many technologies show pronounced self-recharging effects when not used for a certain time. An evident possibility is to design communication protocols to work in a burst fashion, using high data rates at a time and shutting down completely for some time, optimizing usage of effectively available battery capacity. Exploiting such ideas has consequences for system design, e.g., splitting the battery pack in two independent devices to enable shutting down one of them at a time. Some investigations in these directions have started (cp. e.g., [41]), but much research remains to be done here.

2.3 Power consumption of other device components

Depending on the specific device type, different kinds of periphery components have to be considered. From the perspective of power consumption, the following components could be relevant:

- Processor

  Adapting the main CPU's power consumption to the processing needs of communication protocols is enabled by modern CPU's capabilities to work at various settings of clock rate and supply voltage. How to handle this adaptation is an active research area.

- Display devices

  Depending on the device's form factor, displays can constitute a considerable amount of power consumption. For typical 2''-3''-class displays, power consumptions of only 1 mW for still images and up to 20 mW for dynamic display/video applications is currently estimated [69]; on top of that, power for display illumination can be very high. Actually, in typical laptops, a backlight display is the most power-hungry component at all! Reflective and transflective TFT displays are expected to ameliorate this situation, as will possible organic polymer displays.

- Hard drives

  While storage devices like hard disks can also constitute a large source of power consumption, they are not the main focus of this document.

- Cameras

  While cameras would definitely require a lot of power, their usage is highly application-specific and outside the scope of this document.

2.4 Power budget of basestations

Georg Fischer, Lucent, email: georgfischer@lucent.com

The previous discussion was centred around the power consumption of mobile devices. But also the power consumption of a basestation is relevant to the overall power efficiency of a mobile communication system. The power consumption of basestations is relevant under several perspectives:

- Power consumption is a significant cost factor for the operation
- High power consumption results in additional construction costs (e.g., for fans) and space requirements; reducing power consumption allows less battery backup, smaller and cheaper basestations

- Reduced power consumption could mean an increased mean time between failures (MTBF)
- Low power consumption allows basestations owners to strive for ISO 14001 certification

Figure 1 and Figure 2 give an overview of the distribution of losses of power within a typical basestation [71].

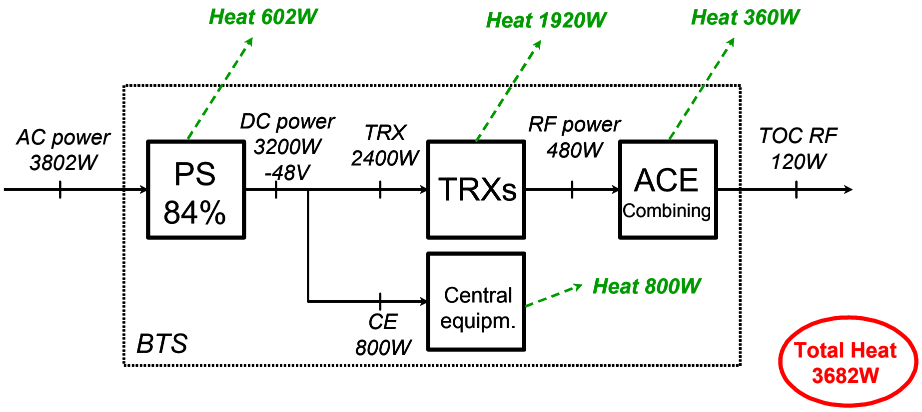


Figure 1: Overview of basestation power budget [71]

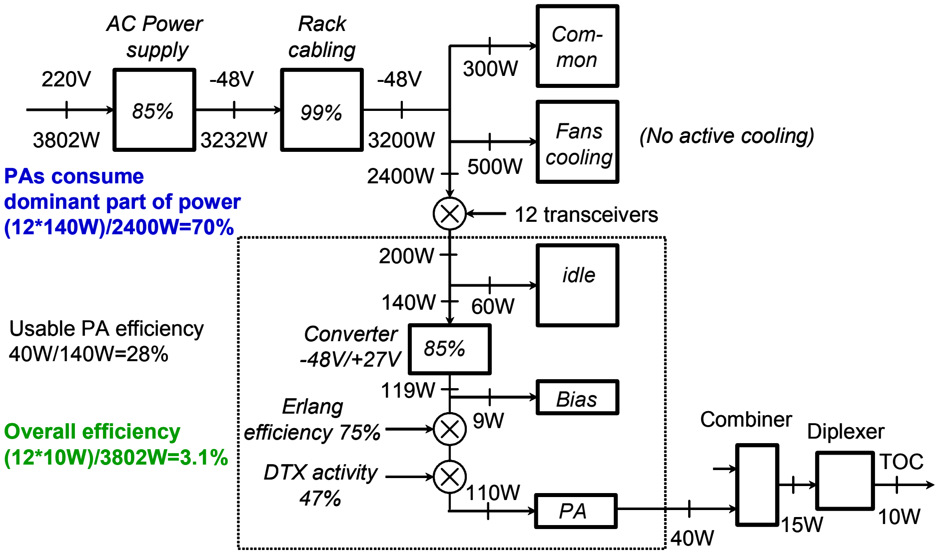


Figure 2: Detailed power budget of a base station [71]

These figures show that base station power consumption is mostly dominated by the TRXs. More precisely, the generation of the RF, especially, the power amplifier, is a crucial part of the overall power budget. As this equipment is only necessary when the base station is operational, one promising approach is to shut down TRX units when they are not needed. This can be done on shorter or longer time scales, where the longer time scales are easier to manage but can only reflect long-term trends (e.g., reduced traffic density during the night); shorter time scales are potentially more powerful and flexible but require a more detailed analysis of the communication protocol in use as well as on the particular amplifier / TRX hardware in use. As examples for typical problems with simple approaches consider the low efficiency of the power amplifier for low output power or the need to take into account reboot times for TRX is case they are completely switched off – similar to the mobile terminal case.

2.5 Designing circuits with low power consumption

Ralf Kakerow, Nokia, email: ralf.kakerow@nokia.com

Design methodologies for low power consumption circuitry play an important role in enabling energy efficient devices. This applies especially to battery operated systems that are typical for mobile communication. The topic of low power circuit design techniques has e.g. been examined in public projects like MEDEA-A453 LPDDT ("Low Power Digital Design Techniques") and MENVOS ("Methoden zum Entwurf verlustleistungsoptimierter Schaltungen und Systeme", supported by BMBF). Key issue in power optimised design is the availability of an appropriate design flow that covers power estimation as well as design techniques in all phases of a design. Especially in early stages of designing mobile communication systems it is important that the power consumption can be easily estimated and simulated. MENVOS developed a top-down power driven design flow that covers all abstraction levels of a design, from functional description on system level down to the layout. Moreover power conscious design concepts are introduced and discussed within this project. The developed optimisations are geared towards system on chip implementations and specifically towards the radio subsystem as a whole, including digital baseband and front-end. An overview of the MENVOS results can be found in [69].

The power driven design flow is concerned with the functional correctness of a system and also considers circuit and layout optimisation methods. The latter ones are not only limited to power optimised standard- and sub-cells that are optimised in a bottom-up manner, they also consider top-down methods like dual-voltage place and route and the according tool environment.

More specifically power driven design is concerned with the following aspects:

- Taking into account static power consumption caused by leakage and saturation currents, depending on temperature, circuit geometry, and voltage, which will become more and more important with reduced gate sizes and lower threshold voltages in deep sub-micron processes
- The effect of short-circuit currents during switching events is dependent on the switching frequency. A proper design is required to minimize this effect
- Charging of parasitic capacitors and wiring dominates the dynamic power consumption and depends linearly on frequency and quadratic on voltage
- It is difficult to derive general rules for analog circuitry. Often proper device models, e.g. for operation in the sub-threshold region, are not available

An important result is that mistakes – with respect to power consumption – done in early stages of a hardware design cannot be corrected later on. Wrong decisions on architecture level can not be compensated by a good circuit design. Nevertheless a low power system requires optimisations and power visibility on all abstraction levels. As a ballpark number, such a power-conscious design flow can result in power consumption improvements of more than 50 % over standard designs.

2.6 MEMS for power-efficient, flexible radios

Georg Fischer, Lucent, email: georgfischer@lucent.com

One specific technology that is rather promising for the implementation of both power-efficient and flexible radios are so-called *Micro Electro-Mechanical Systems (MEMS)*: systems that are based on mechanical actuation to change components of an electronic system, but on a micro-scale. Examples for such MEMS are switches or capacitors, on a scale of typically 50 – 100 µm. Figure 3 and Figure 4 show some examples for such MEMS devices.

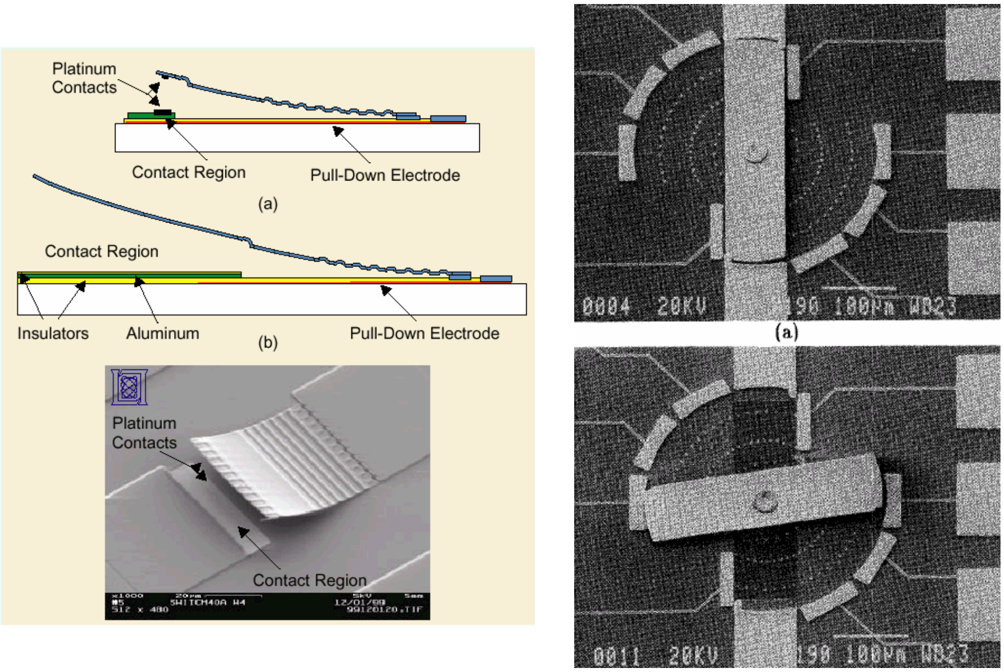
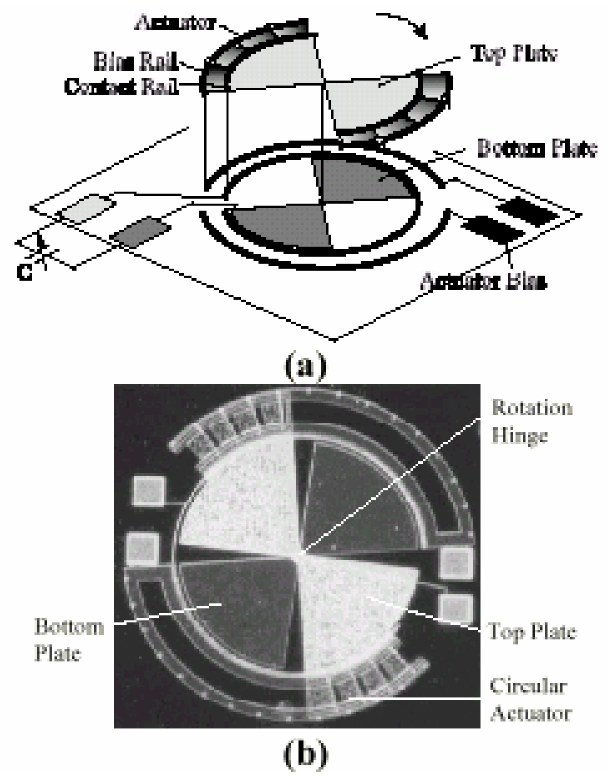


Figure 3: Examples for MEMS switches, MIT Lincoln Laboratory



(a)

(b)

Figure 4: MEMS Varactor, HRL Labs

The need for flexibility on top of power efficiency can be briefly motivated by the diversification of both mobile communication standards and radio bands in use world-wide, which has lead to a large variety of products serving all markets. Radio designs that can flexibly adapt to various frequency bands would be very useful. The classical approach to build such “frequency-agile” radio is to shift all signal processing into the digital domain, resulting in high costs and high power consumption for the signal processing part of a terminal. A possible alternative is to put some of the flexibility into the analog part back again. This is what MEMS allow to do at the required degree of accuracy – it is also goal of the BMBF-funded project Reconfigurable Mobile Systems (RMS).

While with a digital software-defined radio (SDR), the frontend needs to be rather wideband to allow all the information to be passed onto the digital signal processing, in an analog SDR, the frontend is narrowband but configurable using RF-MEMS based signal conditioning technology, allowing a simpler, slower, less power-hungry digital part.

Additional advantages of MEMS devices are the wide tuning range and some superior electrical properties. E.g., a MEMS switch has a much better separation between control and signal path and has no signal degradation due to Bias-T circuits. Moreover, operating such a switch only requires power during switching as such, but not while the switch is in a given operation – a highly useful property for energy-efficient operation; a digital device would draw power permanently during operation. This is combined with near ideal switch performance: low loss when closed, high isolation when open. Similarly, MEMS-based reconfigurable capacitors, inductances, or filters have also advantageous properties. In addition, analog-based SDR radios can probably be produced at much lower cost than digital ones.

In summary, while RF-MEMS devices are currently not yet ready for prime time and much research still has to be done on how to best use this technology in real systems, the potential for power-efficient operation is considerable.

Further info on RF-MEMS for software reconfigurable basestations can be found in [73], [74], [75].

3 Technology Trends and their Effect on Power Dissipation of Mobile Communication Systems

Contributor to this section: Eckhard Grass, IHP Frankfurt (Oder), e-mail: grass@ihp-ffo.de

3.1 Development of Feature Size and Complexity

Figure 5 shows the growth of complexity, i.e. number of transistors, which is partly due to reduced feature size and partly comes from the increase in chip area.

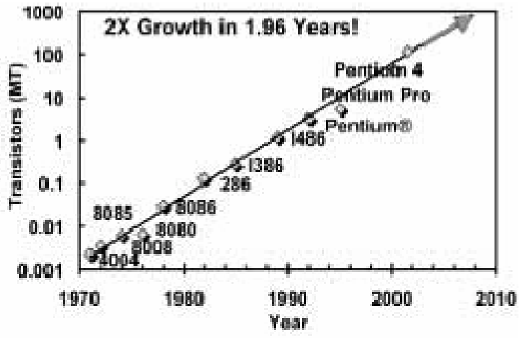


Figure 5 Increase in complexity (transistor count) of digital circuits (from [45])

The reduction in feature size until year 2011 is shown on the X-axis of the diagram in Figure 9. As can be seen, the feature size halves approximately every 6 years. This results in a halving of the circuit area every three years. The remaining increase of the transistor count shown in Figure 5 comes from an increase in chip area.

The clock frequency doubles approximately every 2 years as shown in Figure 6.

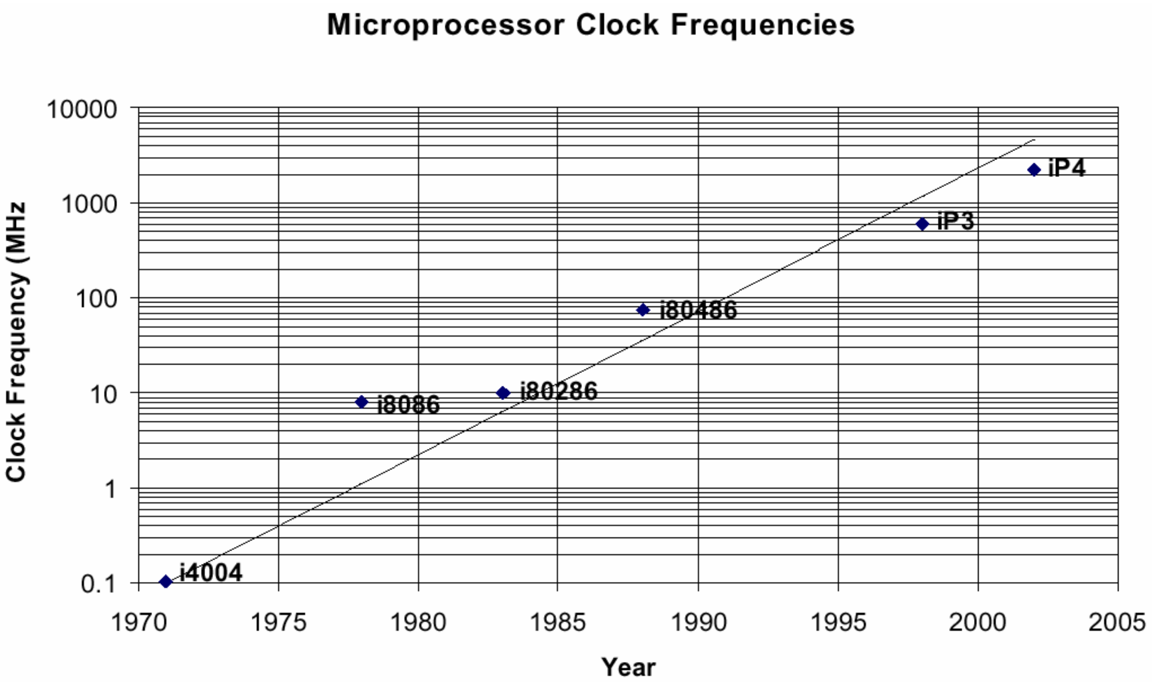


Figure 6 Increase in clock frequency for microprocessors (from [44])

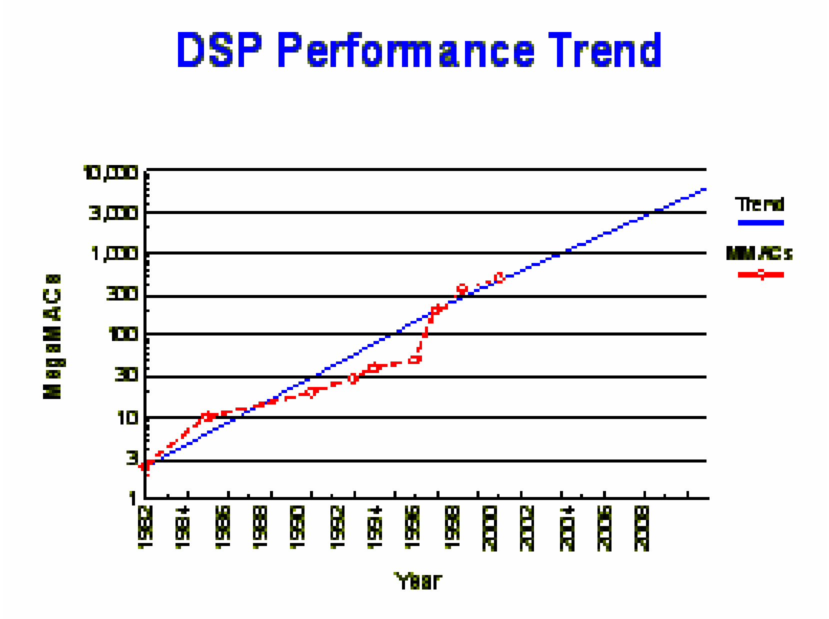


Figure 7 Increase in DSP performance (from [46])

The increase in transistor count and increase in clock frequency leads to a performance improvement of a factor of 2 every 2.4 years as shown in Figure 7. Here the number of Multiply Accumulate operations (MAC) that can be executed by a DSP is plotted against time.

3.2 Power Dissipation trends for Digital Circuits (DSP)

The reduction of power dissipation for digital circuits is based on two mechanisms. Firstly the shrinking feature size results in smaller gate areas of transistors. This causes the gate capacitance and interconnect capacitances to get smaller. Secondly the shrinking feature size is accompanied by reduced supply voltage. This reduced supply voltage has a significant effect on Power dissipation. The following equation gives the relationship between Total power dissipation (P_t), switched capacitance (C_{sw}), supply voltage V_{DD}, and clock frequency (f). Depending on the architecture an activity factor can be introduced which related the switched capacitance to the total capacitance. For typical designs a = 0.5 can be assumed (1).

$$C_{sw} = C_{totoal} * a \qquad (1)$$

$$P_d = C_{sw} * V_{DD}^2 * f \qquad (2)$$

$$P_t = P_d + P_l + P_s \qquad (3)$$

The total power dissipation (P_t) is the sum of the dynamic power dissipation (P_d) the leakage power (P_l) and the short circuit power (P_S) (3). The dynamic power dissipation is the most significant contributor as can be seen in Figure 10. However, for future technology generations the leakage power will have to be taken into account too. Since P_l ~ Chip area (A), this will lead to the demand to design smaller circuits in future.

As can be seen, a reduction in V_{DD} leads to a quadratic reduction in P_d. The short circuit power P_s can normally be neglected or is absorbed in P_d.

Figure 8 shows an exponential decrease of power dissipation versus technology i.e. the power dissipation halves approximately every 1.5 years.

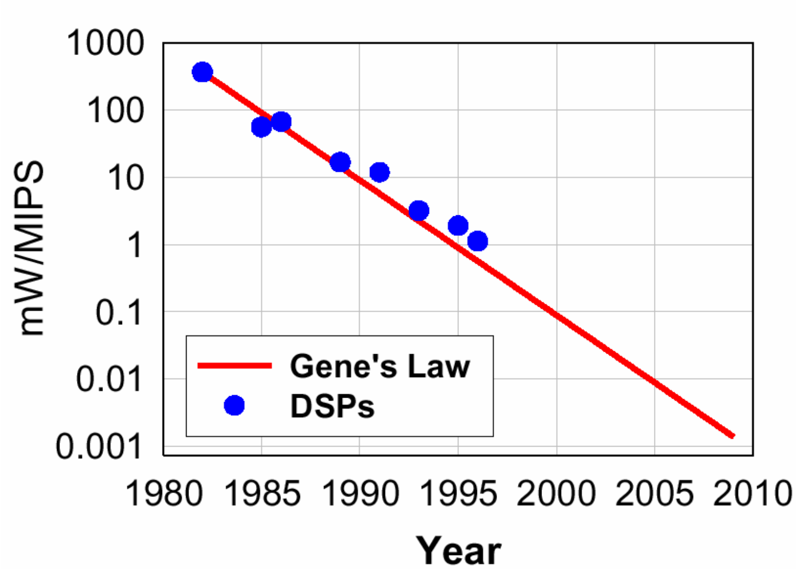


Figure 8 Power reduction trend for DSP implementations (from [47])

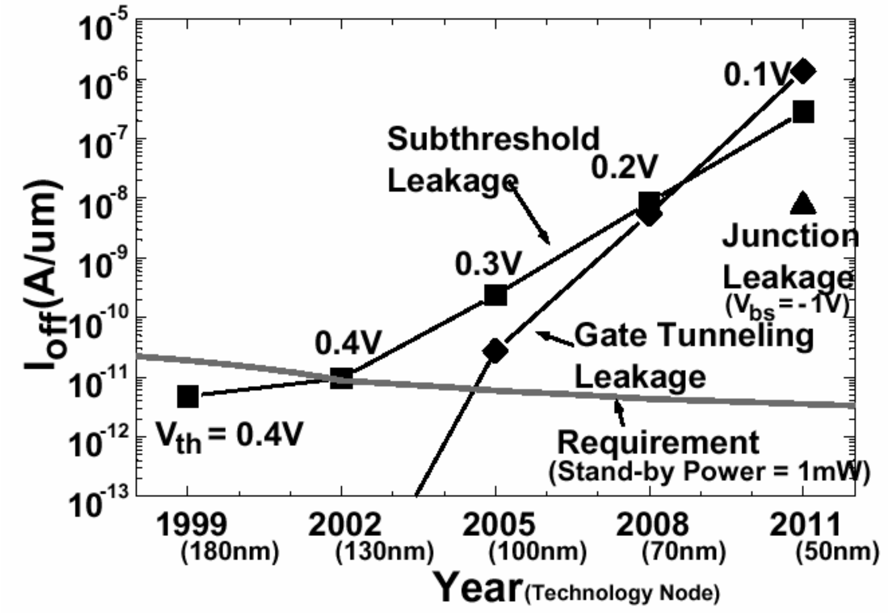


Figure 9 Estimation of leakage current for various technology nodes (from [48])

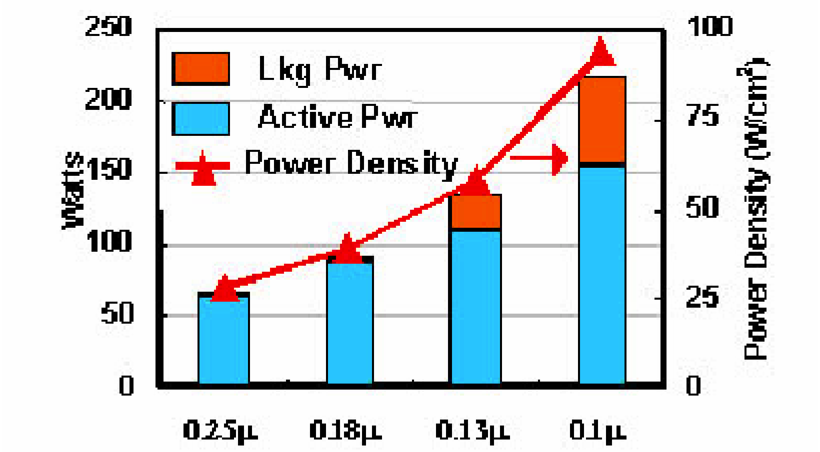


Figure 10 Power density trends for dynamic (active) power and leakage power (from [45])

3.3 Power Dissipation Trends for Analog Circuits

For analog circuits it is much more difficult to estimate the power dissipation trends. To a certain degree similar effects will exist as for digital circuits. However, some analog components do not scale very well. This is in particular true for inductors and resistors. Also active components can usually not be scaled at a similarly aggressive rate as digital circuits.

For some circuits the reduction in supply voltage cannot be utilized. In particular the performance of power amplifiers will not significantly change with the process technology enhancements. For mobile phone and WLAN applications a high dynamic range (and voltage swing) of signals is required. This is difficulty to achieve with supply Voltages of $V_{DD} < 2$ V. For the tables in Section 3.4 it is assumed that the power amplifier consumes 200 mW for 100 mW transmit power, i.e. the efficiency is 50%.

The most significant improvements can be achieved for such analog circuits which are operating at the limit of the parameters achievable with the current technology. Since we do make use of a SiGe BiCMOS technology, for the 5 GHz modem described in Section 1, the required performance can be achieved without hitting the limitations of this process technology.

As a rough estimate the power dissipation of analog circuits halves every 2 to 3 years. Similarly the circuit area is reduced at a less aggressive rate and can be estimated to half approximately every 4 to 6 years.

3.4 Conclusions

Above some estimates on the performance and power dissipation for future communication systems are given. Based on current trends the main parameters are extrapolated. This extrapolation is valid for approximately the next 10 years. After this period, physical limitations of the process technology will have a significant impact. It remains to be seen if Moore’s Law will still be applicable after this period.

For our communication system briefly described in Section 2.1, the impact on chip area and power dissipation in 3 and 6 years is shown in Table 1 and Table 2 respectively.

Table 1 Chip area estimation of 5 GHz WLAN modem for technology nodes from 2002 to 2008 (in mm^2)

Year	2002	2005	2008
Area digital	44	22	11
Area analog	22	15	11
Area all	65	38	22

Table 2 Estimation of power dissipation for 5 GHz WLAN modem for technology nodes from 2002 to 2008 (in mW)

Year	2002	2005	2008
Power dissipation digital (RX)	1300	325	80
Power dissipation digital (TX)	1100	275	70
Power dissipation analog (RX)	300	150	75
Power dissipation analog (TX) (100 mW TX-power)	500	350	275
Power dissipation all (RX)	1600	475	160
Power dissipation all (TX) (100 mW TX power)	1600	625	350

4 System concepts

From the system point of view wireless nodes and particularly the communication part can be designed to work power-conserving by optimizing the data flow and protocol processing order and parallelism. This is shown by Lettieri in [17].

4.1 Cellular Networks

Patrick Herhold, Technische Universität Dresden, herhold@ifn.et.tu-dresden.de

While the protocols section primarily discusses issues of power and range control for *ad-hoc networks and WLANs*, this section addresses measures that determine transmission powers in cellular communications systems and outlines possibilities for their optimization.

4.1.1 Influence of Radio Network Planning and Optimization

The maximum transmit power of a node determines the maximum achievable transmission range for a given propagation model; likewise, the distance that needs to be overcome has a direct impact on the required transmission power. Transmit powers in both second and third generation systems therefore heavily depend on the propagation loss between transmitter and receiver: the transmitter's power must be set such that this propagation loss is overcome to guarantee a minimum received power (receiver sensitivity).

The effective propagation loss is determined by *radio network planning and optimisation* that determines important parameters, such as

- The **position of base station sites**: placing sites close to the traffic that is to be served is crucial; however, given recent public interest in the field of electromagnetic radiation made network operators face strong challenges in acquiring sites that, from a technical point of view, would be ideal. In fact, "nonideal" base station locations that emerge as a compromise between network operators on one side and concerned parties on the other side will in many cases lead to increased transmit powers.
- **Antenna types and tilts**: different antenna types have different gains, thereby influencing the transmit powers. Large BS antennas have stronger gains, but they are less attractive from an optical point of view. While small omnidirectional microcell antennas have gains as small as 2 dBi, large sectorized macrocell antennas have gains of up to 18 dBi. In addition, the *tilt* of sectorized antennas can strongly affect the effective antenna gain: transmit powers can be saved by directing the main lobe towards the served traffic area. Moreover, such a tilt has the advantage of reducing intercell interference in 3G WCDMA systems, which in turn directly leads to transmit power savings due to the fast power control mechanisms.
- **Sectorization vs. omnidirectional cells**: From the viewpoint of reducing transmit powers, sectorized configurations are in most cases favourable. For example, enhancing an omni-directional cell site to three-sectorization typically allows for replacing an 11 dBi gain antenna by an 18 dBi gain antenna, thus yielding a 6 dB potential for power savings simply by changing the network configuration [49].
- **Handover parameters**: Besides placing sites at "appropriate" locations, it is important to guarantee that the mobiles communicate at all times to the optimum cell. This is controlled by handover parameters such as hysteresis (2G, 3G) and reporting range (3G).
- **Power control types**: Third generation networks have sophisticated power control features, as the system performance crucially depends on adjusting each individual transmit power. Second generation systems often do not have means for power control, or their usage depends on operators' decisions and vendor capabilities.

While this list could be extended, it is more important to highlight the common potentials of these examples: such means of optimisation at network layer have the power to reduce transmitted powers by several dBs, often achieving savings on the order of 10 dB. Compared to physical layer improvements, these potentials are enormous.

4.1.2 Second Generation Networks

Second generation networks (GSM) were designed as noise-limited systems. However, since tight reuse patterns became necessary as the number of users tremendously increased, these systems may today be regarded as practically interference limited. Examples of power-aware techniques include MS and BS power control for GSM; MS power control with a slow adaptation rate is used in existing systems to adjust the transmission power to the required level.

4.1.3 Third Generation Networks

In contrast to second generation systems, *transmit power efficiency* has a much stronger importance in 3G CDMA systems as the strength of interference ultimately determines capacity; hence, in order to optimize capacity, efficient means for controlling transmit powers have been implemented.

Power Factors

In an ideally power controlled CDMA system, the transmit powers for a fixed number of nodes are primarily determined by four measures: *pathloss, noise level*, the required receive signal quality in terms of a *target SINR*, and the *processing gains* (spreading factors) [50].

As discussed in one of the previous paragraphs, lowering the pathloss is a common measure for power reduction. For conventional systems cellular systems, this can be achieved by acquiring new base station sites, which is an extremely expensive way of reducing transmit powers as the costs associated with setting up a new site are tremendous. Relaying systems, in which the pathloss is reduced as longer distances are broken up into shorter links, will be discussed later.

Reducing the *noise level* and the *target SINR* essentially requires the development of more sensitive receiver architectures and algorithms; see the physical layer part of this report. Adjusting processing gains, i.e. assigning data rates, is done by the load- and admission control, and will be discussed in the next subsection.

Load- and Admission Control

It is widely known that transmit powers in CDMA increase *nonlinearly* with the load of the network. This network load, which is defined as the amount of interference caused by users' signals normalized to the total interference, rises as either the number of nodes or their data rate increase. Described by a number between zero and one, the measured network load factor is used as an input for load- and admission control in 3G systems. Typical values for macro-cellular loads are 0.6-0.7, while the loads in microcells may well exceed this number [52].

The operators' decision on the limitation of the load factors directly has an impact on the transmit powers; see Figure 11. For example, allowing the network load to increase from

0.6 to 0.9 causes an increase of the power level of 6 dB. In other words, the 30% improvement in capacity comes at the cost of a power rise by a factor of four - an example that stresses the strong influence of radio network optimization parameters on system transmit powers. With respect to power considerations it would be beneficial to operate the network at loads smaller than 0.6, for which transmit power are primarily *pathloss-determined* instead of *load-determined* [53].

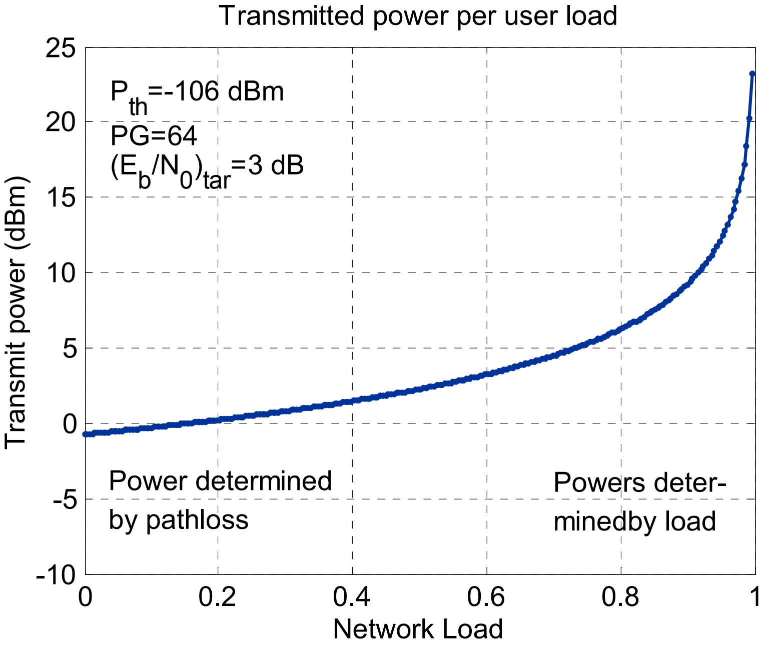


Figure 11: Uplink transmit power of a 3G terminal as a function of the network load ("load curve"). For low system loads, transmission power is determined by pathloss and thermal noise, while for high loads the mutual interferences become dominant and cause the transmit power to be primarily load-determined. (Parameters: thermal noise power -106 dBm, processing gain 64, target SINR 3 dB, perfect power control, uplink.)

Pilot- and Common Channel Power

Another power-critical setting for 3G systems is the choice of the power allocated to a sector's pilot- and common channels. Typically, the total transmit power of a WCDMA macro-cellular sector is limited to approximately 43 dBm, and a certain fraction of this maximum power is allocated to the pilot and other non-power controlled channels. As the majority of these channels is constantly transmitting in the DL, their power level ultimately determines the power consumption of the Node B. Moreover, as these common channels inherently act as an interference source for in-cell mobiles and neighbour-cell terminals, the transmit powers of these common channels affect the DL power level of the whole system.

Note that the existence of the pilot- and common channels is the primary reason for the fact that DL powers are significantly stronger than UL powers. The *dominant and fixed reference power level provided by pilot- and common channels* also explains the lower dynamic range required for the DL DCH powers. Typical values of a total pilot- and common channel power allocation are 10% of the total maximum sector output power; each reduction of this fraction reduces the total transmit power of a BS more than proportionally. From the viewpoint of power efficiency, the emission of the pilots at the lowest possible power should be targeted, just providing sufficient E_c/N_0 for the intended coverage area.

Power Control Types in WCDMA

Different means of power control affect the transmission powers in 3G systems: open loop (initial power adjustment), inner loop (a fast feedback loop with feedback increasing or decreasing the power to match the requested SINR) and outer loop (setting the target SINR). Parameters that can be optimized are the power control itself as well as its step size.

4.1.4 Enhanced Power Reduction Techniques for WCDMA Systems

In addition to the "off-the-shelf" power optimization techniques presented in the previous section, a number of more enhanced techniques has been developed, which are the focus of this section. These include space-time processing, advanced resource management, and interference cancellation techniques.

Space-Time Processing and Beamforming

A large number of proposals and suggested algorithms exist for implementing techniques that exploit either diversity or apply some form of fixed, switched, or adaptive beamforming; some of them are to be integrated in current 3G standards [54]. Moreover, various methods have been studied recently with the focus of their potential for power reduction; see the *miniWatt* study [51]. Depending on the system assumptions and modelled algorithm, power savings of MIMO systems at the order of 4 dB for the UL and 7 dB for the DL have been presented. Similarly, beamforming may yield potential savings of almost 3 dB in the DL.

Advanced Resource Management

Advanced resource management has likewise been studied in the miniWatt framework [51]. Power savings at the order of 2.5 dB have been reported for the DL.

Interference Cancellation

Interference cancellation may be implemented in various forms, ranging from true multi user detection (MUD) to serial or parallel interference cancellation techniques (SIC, PIC). Currently, no reliable source of information is available that references the achievable power reduction for 3G systems.

Chip Equalization

An additional simple and low-complexity technique for interference reduction is provided by *chip equalization* in WCDMA systems [68]. This technique is especially suited for the downlink, in which all intra-cell signals pass through the same channel from the BS to the user terminals. Power reduction has been shown to be on the order of 1 to 4 dB [51].

4.2 Local area networks

Holger Karl, Technische Universität Berlin, karl@ee.tu-berlin.de

On a high level of abstraction, the power consumption and energy-efficiency considerations are the same for local area networks (LAN) as for cellular networks. For both network types, the fundamental trade-offs between distance, transmission power, data rate, and time required for communication, and the resulting energy required to successfully transmit a bit from sender to receiver are similar. Wide-area cellular and local area networks differ, however, in some important details:

- Local area networks are installed in an unorganized, grassroots, ad hoc fashion – think of apartment or office buildings.
- In the currently most popular schemes for LANs, IEEE 802.11, access control is distributed among all participants of the network; terminals decide for themselves when and how to transmit. The coordinated access schemes of IEE 802.11 are not widely used in practice.

  This markedly distinguishes IEEE 802.11 from other LAN standards like HIPERLAN/2. Consequently, energy has to be invested by all terminals to distributedly organise medium access, but on the other hand, overhead for signalling information regarding medium access can be saved.
- This ties in with the typically symmetric construction of LANs, where all entities, including the access points, use essentially the same hardware. Hence, architectural concepts that put energy-intensive operations on the (tethered) base station and attempt to be energy-economic on the mobile terminals is at best possible at higher protocol layers where such differentiations can be done in software; hardware-differentiations would unlikely to be economically viable.
- Typically, LANs are used only over much shorter distances: body area networks (BAN) or intended for merely 1-2 meters, personal area networks (PAN) for about up to 10 m, LANs up to 50-200 meters typically.
- On the other hand, the required data rates are considerably higher for LANs than for cellular networks: gross rates between 11 to 54 MBit/s are currently expected by users.
- Concepts like load or transmission control are typically not applied in LANs, but in principle this would be possible.
- Some of the enhanced techniques like beamforming are also applicable to local area networks, but cost issues have so far prevent that, especially since the access point itself also has to be very cheap.
- Most of the energy efficiency work for LANs has been carried out on a protocol level rather than on a system architecture level. These approaches are discussed in more detail in Section 5.

4.3 Relaying Strategies

Patrick Herhold, Technische Universität Dresden, herhold@ifn.et.tu-dresden.de

Although some general aspects of relaying systems have been reported in the protocols section, this part of the report details some power aspects of relaying for *cellular systems*. A large number of proposals exist for incorporating relaying techniques into today's cellular standards, and some publications address the potential power savings that result from the lower total pathloss that relaying systems exhibit in comparison to conventional, direct systems.

Pathloss Savings

The achievable pathloss savings depend on various parameters, such as the pathloss model, cell sizes, shadowing conditions etc. Naturally, strong differences in the achievable pathloss reduction result for different assumptions. For example, the pathloss reduction range from 21 dB for a cellular multi-hop system [55] to 3-7 dB for a two-hop system [53]. Depending on the system approach taken, these *pathloss savings* provide a potential for reducing transmit powers.

System Examples and Power Savings

System approaches exist for a wide variety of existing cellular radio networks; the following paragraphs briefly address conventional repeaters, ideas for F/TDMA systems, WLAN standards, and 3G WCDMA proposals.

Repeaters. The classical version of a relaying system is the conventional repeater; in cellular systems, repeaters *provide coverage* for areas that would otherwise be shaded or that would necessitate the use of extremely strong transmit powers. These devices, which simultaneously receive and transmit at the same carrier frequency and perform an amplification at RF, are specified and operable for both GSM and UMTS [56]. Repeaters enhance the system noise by amplifying in the analog domain. Moreover, a strong separation of receive- and transmit antenna paths is required in order to prevent from oscillations caused by feedback. These major drawbacks have limited their application to selected scenarios.

Enhanced concepts include repeaters that are switched on only when a terminal is within its service area. The output signals of the repeaters are directly fed to the antenna port of the BS. For these assumptions, power reductions and capacity gains have been reported recently [57].

F/TDMA systems. Different approaches exist for relaying in F/TDMA based networks. For example, one may consider *reusing a time slot* from neighbouring cells for the relay operation in a cell [58], [59]. *Power control* is required in order to turn the pathloss savings into transmit power reductions. For selected scenarios, the resulting interference reduction then allows for a capacity improvement as higher order modulation schemes are being used for the relaying links [58]. Other methods for relaying in TDMA based networks include the concept of *subdividing timeslots* for communications with mobile terminals attached to a relay station. This is for example envisaged in [60], in which a concept for introducing forwarding stations in HiperLAN/2 is proposed. For this subdivision approach, which is similarly also applied in other publications, the transmit power savings come at the cost of a reduced capacity as the additional time resources that need to be allocated are taken from the common pool that is otherwise available for the whole cell. A similar concept in principle, but with a focus on capacity and energy-efficiency and a simplified signalling concept, is presented in [77]. In this approach, capacity can actually be increased by relaying since the shorter distances enable faster modulations to be used, but here also trade-offs exist between energy efficiency and capacity.

Hybrid system approach. In [61], the authors describe the usage of an additional *relaying interface* to be used for enhancing a cellular system. The idea is to redirect traffic from congested cells to less loaded areas of the network, thus achieving lower blocking probabilities. The system is analysed from an Erlang-B traffic point of view, and no information is provided on the power reduction potential of this technique.

Relaying in CDMA Systems

Numerous proposals have been made for introducing relaying components into CDMA systems. Most frequently, a *time-division* approach is taken in which a relay station or router receives data in one time instant and retransmits this data in the next time slot. This *store-and-forward* operation is specially suited for packet data application.

For example, the *SOPRANO* project ([62], [63]) considers FDD CDMA packet radio networks with a cellular component. However, the transmit power savings reported have been obtained for idealized assumptions (e.g., the power control ensures a constant received power instead of a constant received signal quality, only the UL is considered, receivers are equipped with perfect multi-user detection capability). Routing is based on the available pathloss information between the nodes.

ODMA. Although named “Opportunity Driven Multiple Access”, ODMA [64] is not a true multiple access technique. The name rather reflects the initial idea of a 3G system enhancement in which a terminal may dynamically select the FDD or TDD mode for accessing services. Later, the term ODMA was primarily used to refer to the relaying technique that was part of the ODMA proposal. For the TDD mode, relaying was envisaged as a means of enhancing coverage [65]; moreover, transmit *power savings* were shown [66]. The ODMA content, however, was removed from the specifications, and currently no effort is being made towards implementing a relaying technique in 3G systems.

CDMA FDD Relaying. Another possibility for relaying in CDMA FDD network results from the use of mobile terminals as relay stations that use *two different carriers* for the relay operation [53], [67]. By doing so, a time continuous operation is enabled. *For realistic system assumptions*, the transmit powers savings are on the order of 1 dB to 10 dB, depending on the traffic load and other parameters. The dominant drawback is the increased mutual interference that appears in the relaying case; these effects and possible solutions are discussed in more detail in [53].

4.4 Coordinated Multi-Access Systems

Main contributor: Joachim Sachs, Ericsson, Joachim.Sachs@ericsson.com; Josef Fenk, Infineon, josef.fenk@infineon.com;

Cellular radio access networks based on different radio access technologies are increasingly deployed in the public. Such networks are, for example, cellular and wireless local area networks, which provide specialized support for different communication needs. In future it will be possible to communicate via a multitude of radio access schemes and as a consequence an increasing number of mobile devices and terminals will incorporate modems for different wireless networking standards. These different access technologies differ in their system characteristics therefore different deployment strategies will be applied. For example, cellular systems will be dimensioned for wide-area coverage while WLAN type systems will be deployed in hot-spot areas. Consequently, the availability of different access systems will depend strongly on the position of a mobile terminal, as indicated in the coverage map in Figure 12. Furthermore, radio access systems differ in their capabilities with respect to data rates, support for mobility and QoS, but also in their cost for operation and deployment. An evident approach is to combine these system concepts for mutual support, which is a field also investigated in the BMBF-funded IPonAir project.

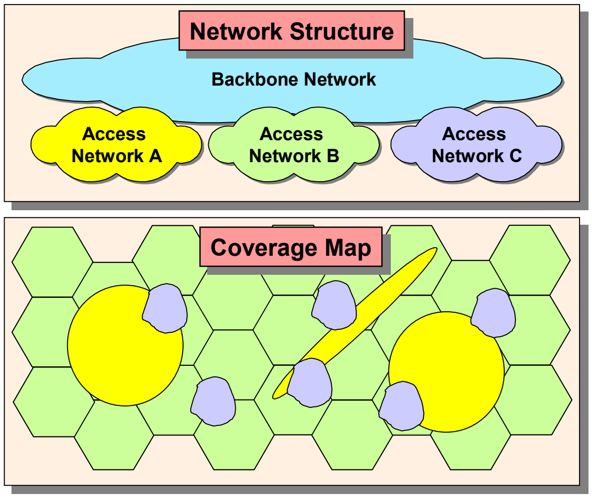


Figure 12: Deployment of multi-access systems for wireless communications

Coordinated assignment of users to different access technologies can be motivated by different objectives. One goal can be to improve the system capacity. This can be achieved by always allocating a user to the access technology with the lowest load. This method increases the pool of resources which can be allocated which leads to an increased trunking gain and thus to an improvement in capacity. This has been demonstrated for under simplified system assumptions in [81]. Alternative approaches have been presented in [80] where the allocation of a user to an access technology is based on the type of service. In 3GPP a study item has been created to investigate the improvements of coordinating WCDMA and GSM/EDGE [83]. One basic requirement to achieve the resource pooling of different access technologies is to introduce some common radio resource management function, which coordinates the assignment and consumption of radio resources between those different systems (see Figure 13). For such a coordinated multi-radio access management many open issues still need to be resolved. This includes, for example, handover mechanism between different technologies, an integrated security solution, etc. But the energy efficiency aspects of such an integration have so far not been really considered. Evidently one optimisation criteria is to use the most energy-efficient communication system at a given moment, if multiple of them are available at the same time in the same place. The goal to increase capacity by coordinated multi-access management may go hand in hand with improved energy efficiency. A load dependent resource allocation strategy reduces interference, which enhances capacity and is also beneficial for energy consumption, as explained in a previous chapter. At the time being, no work is known to the authors to specifically exploit the differing properties in energy consumption of various access technologies for further improve energy efficiency.

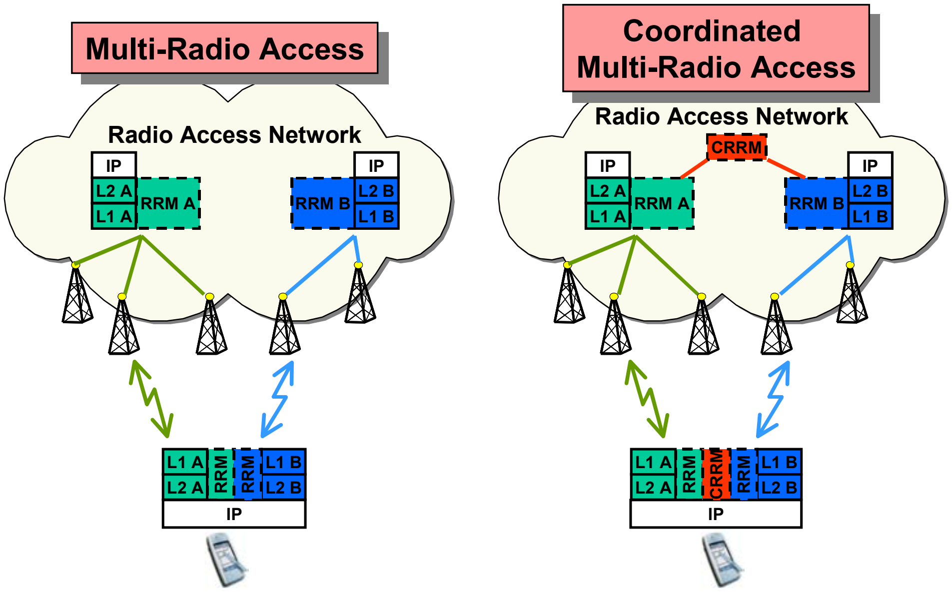


Figure 13 Coordinated multi-radio access

In this context a crucial question is how to determine which alternative access options exist! For example, a multi-access/multi-system mobile terminal that permanently scans different frequency bands to check for the mere availability of an alternative system (say, when using a cellular network also scanning the 2.4 or 5.6 GHz range) would require far too much energy even to detect possible alternatives than it would possible gain by obtaining a more energy-efficient communication afterwards. Hence, mechanisms are required that can provide information about possible alternative access opportunities. Possible approaches to this problem are the provision of “availability maps” that contain information about where which access system is available. The information in this map can be correlated by the mobile terminal with position information obtained from e.g. GPS or with implicit information such as the base station/cell identifier. If the availability map is known in a mobile terminal it can determine – depending on its location – when to turn on transceivers to scan certain frequency bands for certain radio technologies. Alternatively, this could be an access discovery service provided by an entity in the network. The information about the availability of an access system and possibly more specific access parameters could then be distributed via some kind of common coordination channel, which is to some extent discussed in [84]. This could be a channel with low data rate but it should be ideally accessible at any location. Such a channel could be realised e.g. via a wide-area cellular network or even by a GPS-like system. However, the type of coordination of access availability has to be jointly considered with the type of deployment of multi-access networks. It is conceptually easy to do if all systems belong to the same operator (say, a 3G operator that also runs WLAN hot spots). When, however, the alternative systems belong to competing operators, there is no incentive for any one operator to provide information about a better, competing system access. Therefore, it depends on the type of network deployment if the access availability service will be a service provided by an access network operator, or if it will be an location-based services independently provided by some service provider via the Internet. It is still an open question what potential savings can be achieved by coordination of system availability and what additional overhead is introduced.

4.5 Optimizing the Energy-Efficiency of Coexisting Wireless LANs

Lars Berlemann, ComNets, Aachen University, ber@comnets.rwth-aachen.de

As *Wireless Local Area Networks* (WLANs) operate in unlicensed frequency bands at 2.4 and 5 GHz, they often have to deal with interference from other WLANs, especially in hot spot scenarios. As they have to share a common radio channel, these coexisting WLANS are also referred to as overlapping WLANs. The known coexistence problem arises if overlapping WLANs attempt to support *Quality of Service* (QoS) under the assumption that the overall utilization of the resource is at its limit [89]. Such coexistence problems are not addressed in the standardization of WLANs.

Solving the coexistence problem of overlapping, QoS supporting, WLANs means reducing their energy consumption, as the utilization of the shared resource is optimized. The destructive interference of the coexisting WLANs implies a significant reduction of the overall system throughput. Hence, an aimed interaction of these WLANs, which results in a sharing of the common resource, will increase the energy-efficiency.

The coexistence problem of QoS supporting WLANs arises due to the absence of a central coordinating instance which controls the allocation of the shared resource. The overlapping WLANs have no exclusive access and consequently compete to utilize the radio resource. The classic approach to support QoS in the face of the coexistence problem is dynamic channel allocation, which requires a lot of resources and is thus not spectrum efficient. We propose a new approach based on channel reservation through cooperation. This approach, derived from *Game Theory*, is introduced in the following.

Single Stage Games of Radio Resource Sharing

The coexisting WLANs can be modeled as competing players that support QoS in the presence of other players. Their competition again is modeled with a stage-based game structure [90]. The players' QoS requirements, given by the supported applications of the player, define an individual *utility* function. This utility function is used to map QoS requirements into *behaviors*, and achieved QoS into levels of satisfaction (i.e. outcome, payoff). The achieved QoS can differ from the required QoS, because the players' resource allocations influence each other. This mutual influence together within an analytic model of this radio sharing game is analyzed in detail in [91]. The mutual influences and the corresponding utility degradation lead to the *payoff* of a player. In the following the game structure is referred to as *Single Stage Game*. A detailed analysis indicates that the players may benefit (i.e. players may achieve a higher payoff) from a dynamic interaction, by adapting behaviors to the environment and the behaviors of other players. This analysis of the Single Stage Game considers in particular the micro economic concepts of *Nash Equilibrium* and *Pareto Efficiency* [92].

Multi Stage Games of Radio Resource Sharing

To improve the game outcomes of all players, the Single Stage Game is extended in modeling existing games by means of repeated stages. This is referred to as *Multi Stage Game*. During the course of a Multi Stage Game, players adapt behaviors, i.e. modify their protocol parameters, by taking into account the history of past achieved utilities (the payoffs per stage). We show in [93] that players attempting to maximize their payoff are able to improve their payoffs through dynamic strategies. Strategies define what behavior a player selects under consideration of a potential interaction. Further on, a discounting-based decision process for determining what behavior to select is introduced. Simulation results indicate that setting the player's discounting factors based on the QoS requirements leads to predictable outcomes in many competition scenarios.

Strategies of different complexities can be defined in the context of Multi Stage Games: Static strategies, trigger strategies and adaptive strategies. The existence of Nash Equlibria within Multi Stage Games is evaluated with the help of a discounting factor, which reflects the players' importance of future payoffs. Thereby the *Subgame Perfection*, another concept derived from micro economics, is considered to enable a determination of reachable steady game outcomes as the solution of the coexistence game [94]. These strategies show promising results for solving the coexistence problem.

The introduced concepts enhance the Single Stage Game through the aspect of dynamic interaction and are a step towards the successful support of QoS in a scenario of competing WLANs. A deaper analysis of the learning mechanisms within strategies might lead to a further improvement of the coordination between the players.

5 Protocol contributions to energy efficiency

Main contributors: Jean-Pierre Ebert, Martin Kubisch, Holger Karl, Technical University Berlin, ebert|kubisch|karl@ee.tu-berlin.de

While the underlying hardware determines the core power consumption properties of a wireless communication device, these properties can be more or less efficiently used by communication protocols that determine the operations of a communication device. This section gives an overview which parameters and mechanisms of communication protocols can have a large impact on the overall power consumption and energy efficiency of wireless communication; it also highlights some approaches to improve communication protocols with regard to these metrics.

This section is based on the hardware and system architecture discussion in the previous section and proceeds upwards through the traditional protocol layers, starting with controlling properties of the RF hardware like the transmission power and proceeding to routing- and transport-layer mechanisms.

5.1 Transmission Power Control

Choosing optimal power to communicate with a given partner

As the hardware section has discussed, amplification to large transmission power values is power-intensive. Often, maximal transmission power is not necessary. In fact, traditional GSM handsets are optimized to operate at large power values which are only needed in rarely encountered bad channel conditions. A very simple means of conserving power would be to optimize the amplifier to operate at the most commonly encountered transmission power and sacrificing efficiency for the maximum output.

Depending on the RF hardware, dynamically choosing transmission power can also safe energy, but this is not necessarily the case. In traditional cellular environments, transmission power is adapted to account for signal degradation and interference (e.g., in CDMA systems), however, energy efficiency is usually not regarded as the primary optimization goal.

In ad-hoc networks, the situation is usually somewhat different: Ad-hoc networking is often identified with multi-hop communication, and therefore, there is not necessarily a clear idea of who controls the power assignments. If centralized knowledge is available, the necessary power setting is determined [24], simultaneously controlling the network topology. Other approaches attempt to only use local information, either exploiting them heuristically [9],[24] or by integrating some additional data such as location [25],[15] or direction to neighboring nodes [33] to find optimal transmission power values by using distributed algorithms.

Of high interest from a reliable and scalable point of view are the distributed algorithms of Rodoplu and Meng [25], which tries to find the most energy-efficient neighbors (used as relay) in surrounding of a node, and Wattenhofer [33], which also tries to find the most energy-efficient neighbors but uses the angle of receiving a signal to estimate direction.

These algorithms are faced with a number of open problems: How is the time-varying characteristics of the radio channel taken into account by these algorithms? What about mobility? How does additional information like location correlate with the radio channel? What is the performance penalty when estimations are not correct?

Adapting transmission power to packet size

Another way to minimize energy consumption is to adapt the transmission power according to the packet size or vice versa which is described in [6]. Small packets are less vulnerable and need therefore less RF power to be transmitted to the intended destination and vice versa.

Adapting transmission power to channel state

Depending on information about the channel state, transmission power can also be adapted on short time scales; examples for this approach include [12] and [14]. This approach is discussed in more detail in Section 5.3.

5.2 Medium Access Control

Apart from deciding *which* transmission power to use, deciding *when* to invest it is crucial: When a transmission is lost due to collisions, bad channel conditions, etc., this investment was futile. The medium access control (MAC) layer decides about the point in time when a transmission starts.

ON/OFF switching of network interface and processor

Another possibility to save energy is to shut down nodes or network interfaces within a wireless network. The decision when to shut down can depend on the network as a cooperative system or local information, where each node optimizes the energy consumption for itself. The main problem is uncertainty when the network interface has to be turned on again in combination with the fact that powering up an interface incurs overhead in both time and energy.

Power-saving protocols as applied in common IEEE 802.11 WLAN cards [7] turn off the network interface according to a local decision based on the traffic need. If a node has to transmit or receive data, it stays awake; otherwise it can go asleep to save energy for a while. A node has to check periodically whether packets have to be sent or received, which requires a centralized or more complex distributed synchronization algorithm. In a centrally scheduled communication system, e.g., HiperLAN/2, some of these decisions are simplified. However, because of the additional overhead in both time and energy to turn a transmitter on again, the scheduling periods (e.g., two milliseconds for HiperLAN/2) can be too short to justify aggressive turning off.

Power saving by intermittently turning of transmission and reception has been investigated for WCDMA in [85][86]. In the so-called gated transmission mode, only a subset of the time slots is used for data transmission and reception. It is also discussed how power control performance may be influenced due to the reduction in power control frequency. The performance evaluation of gated transmission in [85] indicates that, depending on the number of slots assigned for gated transmission, a reduction in uplink interference of up to be 2.5 dB might be achievable. It is not quantified to what amount power consumption and battery life time can be conserved.

Turning off network interfaces can also be applied to multi-hop networks. For instance, the ASCENT protocol [5] is a distributed protocol where each node assesses its connectivity and adapts its participation in the multi-hop network according to the measured operating region with the objective to minimize the network energy consumption.

Similar concepts can be applied to the processor or other components of a mobile device. The processor in particular is a promising component, which in addition can enable a gradual adaptation of energy consumption and delivered performance by techniques like dynamic voltage scaling [42]. Such gradual consideration is considered to be more effective than completely turning off a processor; however, some amount of foreknowledge about processing requirements is necessary – but this can be available for many types of interactive applications. As many processor cores for embedded devices support this concept (e.g., Intel StrongArm), dynamic voltage scaling is promising for practical application.

Avoiding collision

Collisions may have several reasons. One reason might be the protocol itself which was designed explicitly to deal with collisions. Another reason is the network topology which may lead to hidden terminals. Collisions in turn cause retransmission and waste of energy. Hidden terminals can be avoided using some derivate of the PAMAS protocol [27], which is a busy tone channel protocol, and more complex but single-channel-based protocols like the one published in [32]. MAC protocols which are explicitly designed to work energy-efficiently avoid or minimize the likelihood of collisions. An example is the EC-MAC protocol [29]. Also, centralized MAC protocols like HiperLAN/2 belong to this category as do other TDMA-based systems. The downside for these protocols is the additional overhead of synchronization, with requires some energy as well. The tradeoff between these two aspects is crucial in evaluating the energy efficiency.

Miscellaneous

Complementing the above mentioned option of energy-efficient scheduling, e.g. [23], the problem of unnecessary TX/RX and RX/TX turnarounds should be considered. The latter can be achieved by buffering data and sending it out in consecutive transmission slots [29]; this technique might not be applicable in interactive applications.

5.3 Logical Link Control

While the MAC layer decides *when* to attempt to send a packet, the link layer control (LLC) determines the precise form of the packet, e.g., its size, and what to do about errors. Most of the link layer's procedures have a direct impact on the energy efficiency of a communication system.

Packet size adaptation

On the link layer, the packet size may be adapted according to the channel characteristics as it is proposed by Modiano [18]. Modiano developed an ARQ protocol that automatically adapts the packet size to changing channel conditions (bit error rates) with the objective to improve the performance. As a side effect, the energy consumption is decreased with a better performance. The challenge for this protocol is how to obtain a sufficiently good estimate of the channel condition and the predictive power of such estimations.

FEC/ARQ schemes

Lettieri and Srivastava [16] proposed a combined FEC/ARQ scheme. The tradeoff between number of retransmissions and longer packets with FEC is evaluated and an algorithm is proposed which adapts it to be energy-efficient.

Packet Pacing

An energy-efficient adaptive ARQ protocol is presented in [35]. The protocol slows down the transmission rate (pace of packet transmission) if the channel is impaired and vise versa. Additionally, Zorzi proposed a kind of channel probing where the channel is tested with short low power packets at a certain pace as long as the channel is impaired and data transmission is resumed at high power if the channel is assumed to be good again. This is exemplary of a basic approach: do not waste energy in a bad channel as attempting to overcome the bad channel is prohibitively expensive.

Rate adaptation

Another option is to adapt the transmission rate to optimize throughput and energy efficiency as well for varying channel conditions [12],[14],[87],[88]. If the channel quality decreases, a more robust modulation scheme is used which usually results in lower transmission rates.

Rate adaptation may also be used to avoid energy-hungry radio processing. For instance, in HIPERLAN 1 [8] packet headers are sent at 1Mbit/s while the payload information is sent at a rate of 23Mbit/s; IEEE 802.11 follows a similar paradigm. A higher data rate requires the use of a receiver which consumes considerably more energy than operation without. Therefore, a node can decide on the basis of the control information within the packet header sent at 1Mbit/s whether the payload should actually be received. As this is a widespread concept, the hardware model of Section 2.4 has to take it into account.

Asymmetric protocols

Another approach towards energy-efficiency and lifetime extension of mobile nodes are asymmetric protocols. An example is the AIRMAIL protocol [1]. Protocol processing and scheduling in conjunction with a combination of FEC and ARQ scheme is mainly located at a central facility (base station) having extended power sources or access to a fixed power supply. This concept is familiar from most cellular systems and, in a sense, is extended to multi-hop communication systems where responsibilities are shared over time, e.g., depending on the currently available resources. Often, responsibilities are assigned to so-called "clusterheads" which take on certain tasks in the context of routing; Section 5.4 gives more details.

Exploiting channel predictions

Ana Aguiar, TU Berlin, aaguiar@ft.ee.tu-berlin.de, Horst Miesmer, Siemens AG, horst.miesmer@siemens.com

If the future channel state can be predicted with some minimal accuracy even for a rather short period of time, this knowledge can evidently be exploited to improve the protocol's energy efficiency by postponing transmissions, modifying transmission power, selecting appropriate modulation schemes, etc. The main questions to answer here are:

- Does the prediction process result in any power consumption on its own? E.g., does prediction involve active probing?
- What is the accuracy of the prediction process, what is the consequence of incorrect predictions on the energy efficiency?

Current research has shown that this approach is indeed very beneficial, but that it largely depends on the precise interactions between

- Type/level of channel prediction (analog or digital models?)
- Precision of the channel prediction (with how many dBs accuracy can the channel be predicted how often, depending on how far into the future the prediction is expected to happen?)
- Related to that: what is the hardware complexity of the prediction algorithm (software implementations are unlikely to be practical) and the related power consumption?
- What is the load mix?
- Where does the prediction take place? (basestations or mobile terminal) and consequently: Where is prediction information exploited? (uplink, downlink, both? How is channel access managed?).

This is currently a field of active research and only few definite results are known in this field. While the potential benefits are clear (and related work is in fact already a part of the intended 3GET project), the costs that have to be paid to harvest these benefits are not well understood. More specific research on this topic would be highly desirable.

5.4 Routing

In traditional cellular system, the routing problem reduces to the handover problem: which access point should be selected to serve a mobile device. As a handover decision is usually based on the channel quality between mobile device and access points, energy efficiency is at least implicitly considered in this process.

In cellular systems the precision of location of a mobile terminal, which is tracked by the network, is adapted to the traffic activity [82]. This allows a terminal with low traffic activity to determine its position less frequently and perform less numbers of location update procedures. In this case the location of a terminal is known within a routing area which covers several radio cells. On the other hand, when a data connection or a voice call is established to an idle terminal and the location is only coarsely known the terminal needs to be paged in a larger area by a broadcast message. Consequently, reduced signaling overhead stemming from location update procedures needs be traded against the increased overhead introduced by paging. Thus, a suitable selection of routing area sizes allows to minimize the overhead and energy required for mobility management signalling.

From a system perspective, it could be conceivable that a handover decision that is optimal for a particular mobile device could be suboptimal when considering all mobiles together; this suboptimality could, e.g., be due to a modification of the interference situation in neighboring cells. This effect is, however, likely to be rather small and there are also no investigations of this problem known to us.

The routing problem becomes much more difficult when multi-hop radio communication is considered. In such a multi-hop system, it is no longer clear which sequence of nodes should be traversed to reach a given destination; several optimization metrics can be introduced to steer this choice. A number of routing protocols have been developed for the specific need of such multi-hop networks (pro-active protocols like DSDV [22], which periodically sends route updates to know all routes to destination in the network, reactive protocols like DSR [13] and PARO [10], which start searching for the destination only when there is a packet to transmit, and hybrid schemes like AODV [21], FSR [20] and TORA [19]), but energy-efficiency was not the prime target for these protocols.

More recently, energy efficiency has come more into focus, particularly motivated by the vision of wireless sensor networks. A frequently used concept is to assign routing and forwarding responsibilities to a node acting on behalf of a group of nodes (a “cluster”); routing and forwarding then only takes place among these “clusterheads”. The choice of clusterheads can be based on the availability of resources (battery capacity) and is in many approaches rotated among several nodes. Examples for such clustered protocols are ZRP [28] and LEACH [11]. Additionally, some routing protocols take into account the physical location of nodes (e.g., GAF [34]). Good overview papers are [78] and [79].

The challenge for all these multi-hop routing protocols is to evaluate the trade-off between energy savings by clever routing and the overhead required to obtain the routing information, particularly in the face of uncertainties induced by mobility, time-variable channels, etc.

5.5 Transport

Variants of TCP protocols were studied with respect to energy efficiency in [31],[36] though no single TCP version can be referred to as appropriate in wireless or heterogeneous environments.

So far, transport protocols were designed to work optimally for reliable links. They get confused in the sense of energy efficiency (unnecessary retransmission, long awake times of the NIC) if one or more intermediated links are error prone (e.g. wireless links). To alleviate the problem, several approaches can be used:

- Splitting Connection: On the wireless sub-link a specialized protocol is used (e.g. I-TCP [2], M-TCP [4] and ReSOA [26]).
- Supporting link protocols: A specialized link protocol for the wireless part is used which actively influences the control and data message exchange of TCP by means of a daemon at the edge of the wireless part (SNOOP protocol [3]). Similarly, the interaction of the MAC power saving protocol with TCP can be improved: Here the awake time of a mobile / the beacon window size is adapted to the pace/rate of packet transmission.
- TCP-Probing: In [30] TCP-Probing is proposed where data transmission is suspended when a data segment is lost rather than immediately invoking congestion control. Instead a probe cycle is invoked, which test the link characteristics. Transmission is resumed with the available bandwidth if the error conditions are random and transient. If the error conditions are persistent, normal congestion control is invoked.
- Adaptation of the beacon window according to TCP throughput characteristics: Having the IEEE 802.11 power saving protocol in mind the beacon window size is adapted according to the measured TCP throughput.

6 Summary: Today, three years, the future

The power and energy efficiency of a communication system depends largely on these three components:

- Hardware structures
- System architectures
- Communication protocols

This report has given an overview of these three aspects and collected the current state of the art and innovative developments. To sum up the salient parts of the report, three time horizons are given: today, the likely accepted state of the art in three years, and the long-term trend perspective.

6.1 Today

Energy efficiency of hardware components depends to a large degree on technology. Depending on the used design flow, already today savings up to 20% are possible when using a “power-conscious design flow”, for some extreme cases, up to 50% have been reported when a group of experts optimizes a design explicitly for energy efficiency and power consumption.

Today’s communication architectures are only to a small degree determined by energy efficiency considerations. Cellular systems exhibit a large parameter space (e.g., 3G systems, which are to a large degree determined by network planning aspects like the positioning of basestations) – while there is a lot of leeway for energy efficient and low power solutions, this is not yet a focus of practical work today and the complex interdependencies between parameters (e.g., fast power control in UMTS) are not well understood, neither in theory nor by practitioners. Local wireless networks also have the potential to improve upon their current power and energy efficiency, perhaps using even very simple protocol solutions; however, not all interdependencies are completely understood here, either. Cross-layer mechanisms, e.g., taking semantic aspects into account when making protocol decisions whether or not or how to transmit e.g. an MPEG4 video frame, are a current area of intensive work and are in principle applicable to both system structures. Newer types of system architectures like wireless ad hoc networks or wireless sensor networks, where energy efficiency is a much more pressing issue, are still more a research topic than used in practical deployment.

For the communication protocols used in these systems, a plethora of optimizations at isolated levels exist, but integrated solutions are still missing.

6.2 Three years

The ongoing miniaturization process will certainly lower the power consumption of hardware. Regarding different types of devices, the progress will however be progressing at quite different speeds: Battery development, e.g., will likely remain slow in the foreseeable future. Also, principle changes in RF architecture, like e.g. a working wakeup radio concept, are speculated about but can not be reliably forecasted – even though their impact on system architecture and protocol design would be tremendous.

The overall system architecture is unlikely to change over a three year time horizon, as we are still undergoing the change to third generation systems in the cellular context and wireless ad hoc networks are slowly emerging. Experience in operational networks will clearly lead to a better practical understanding of parameter trade-offs and of questions how to distribute complexity between terminals and basestations. This will improve energy efficiency, in particular since this goes often hand-in-hand with an increase in capacity.

The progress in communication protocol energy efficiency is difficult to estimate and will largely depend on the underlying hardware and system architecture context. Individual progress like e.g. interference cancellation can be expected to be commonly accepted standard in three years.

6.3 Long-term trends

Concerning hardware, the question when the "CMOS curve" will end and with it the energy optimization is still an open debate; moreover, the total power budget of smaller chip structures is still not entirely clear (problems with leakage current, e.g.). Principally different hardware concepts like, e.g., MEMS have the potential for profound changes in hardware structure and the ensuing power budgets.

Regarding the system architecture, the introduction of advanced physical layers can be expected: MIMO systems, software-defined radio or the opportunistic use of (perhaps only intermittently) available spectrum. While these systems will certainly improve the performance of communication systems, their energy efficiency remains to be seen, as e.g. techniques like MIMO or software-defined radio are likely to be combined with a large power consumption due to their algorithmic complexity. On the conceptual level, the mutual support between systems of different technologies, between different users, and perhaps even between different providers should be common state of the art in the foreseeable future.

Evidently, new system architectures will require new communication protocols to realize these systems. They will to a large degree determine the energy efficiency of the complete system, end-to-end. Details yet remain to be seen.

7 Conclusions

Low-power and energy efficiency is an important characteristic requirement of current and future communication systems. It is important both from a mobile terminal perspective, when especially the lifetime on a single battery charge is an important figure of merit, as well as for a base station, where electricity costs and thermal problems are major reasons to look for low power solutions. Moreover, low-power communication can potentially contribute to ameliorate public concerns about health issues related to mobile communication.

This paper has given an overview of the main sources of power consumption in mobile terminals and in base stations. Improving energy efficiency in these systems can be achieved both by architectural improvement of the entire system as well as by individual improvements on a hardware, terminal design, and protocol mechanisms.

While there are many individual solutions already in place, there is still room for improvement in a lot of different specific areas as well as a need for integrated solutions.

Some of the more important issues are:

- Hardware solutions with low power consumption, specifically for the power amplifier, low power consumption in "idle" mode when not actually receiving, eventually resulting in wakeup radio solutions. Hardware that can quickly and with low overhead be switched between different operational modes. Hardware that can adapt its efficiency to the particular needs of transmission power (alternatively, system concepts that leverage heterogeneous devices).
- Protocol suites that take an integrated look at power consumption /energy-efficient operation, where cross-layer interactions assist in improving these characteristics. An improved understanding how interactions between different layers or even an unfortunate combination of individually optimal protocol layers can affect energy efficiency.
    - A specific example of such interaction is channel prediction: how expensive – in energy terms – is it to perform this prediction, what are the returns on this investment? What are the architectural concepts to support this approach?
- An architectural concept for multi-access, multi-radio, multi-operator mobile communication systems that takes energy efficiency and low power consumption into account.

8 Literature

[1] E. Ayanoglu, S. Paul, T. F. LaPorta, K. K. Sabnani, and R. D. Gitlin. Airmail: A link-layer protocol for wireless networks. *ACM/Baltzer Wireless Networks*, 1(2):161-174, 1995.

[2] A. Bakre and B. R. Badrinath. I-TCP: Indirect TCP for mobile Host. In *Proc. of 15th Int. Conf. on Distributed Computing Systems*, pages 136-143, 1995.

[3] H. Balakrishnan, S. Seshan, and R. Katz. Improving reliable tranport and handoff performance in cellular wireless networks. *ACM/Baltzer Wireless Networks*, 1(4), 1995.

[4] K. Brown and S. Singh. M-tcp: Tcp for mobile cellular networks. *Computer Communication Review*, 27(5):19-43, 1997.

[5] A. Cerpa and D. Estrin. Ascent: Adaptive self-configuring sensor networks topologies. In *Proc. INFOCOM*, New York, NY, June 2002. http://lecs.cs.ucla.edu/Publications/papers/ASCENT-Infocom-2002.ps.

[6] J.-P. Ebert and A. Wolisz. Combined tuning of rf power and medium access control for WLANs. *Mobile Networks & Applications*, 6(5):417-426, September 2001.

[7] The Editors. Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY): Higher Speed Physical Layer (PHY) Extension in the 2.4 GHz band. IEEE Standard 802.11b, Institut of Electrical and Electronics Engineers, Inc., September 1999.

[8] The Editors. Etsi hipeerlan/1 standard. Standard, European Telecommunications Standard Institute, April 2001.

[9] T. A. ElBatt, S. V. Krishnamurthy, D. Connors, and S. Dao. Power management for throughput enhancement in wireless ad-hoc networks. In *ICC 2000*, New Orleans, LA, June 2000. IEEE.

[10] J. Gomez, A. T. Campbell, M. Naghshineh, and C. Bisdikian. Conserving transmission power in wireless ad hoc networks. In *9th International Conference on Network Protocols*, Riverside, California, November 2001. IEEE.

[11] W. R. Heinzelman, A. C., and H. Balakrishnan. Energy-efficient communication protocol for wireless microsensor networks. In *Hawaii International Confercence on System Sciences*, Maui, Hawaii, January 2000. IEEE.

[12] G. Holland, N. Vaidya, and P. Bahl. A rate-adaptive mac protocol for multi-hop wireless networks. In *Conference on Mobile Computing and Networking (MOBICOM)*, pages 236-250. ACM/IEEE, July 2001.

[13] D. B Johnson and D. A Maltz. Dynamic source routing in ad hoc wireless networks. In Imielinski and Korth, editors, *Mobile Computing*, volume 353. Kluwer Academic Publishers, 1996.

[14] A. Kamerman and L. Monteban. Wavelan-ii: A high performance wireless lan for the unlicensed band. *Bell Labs Technical Journal*, pages 118-133, Summer 1997.

[15] B. Krishnamachari, R. Bejar and S. B. Wicker. Distributed constraint satisfaction and the bounds on resource allocation in wireless networks. In *Sixth Intl. Symp. on Communications Theory and Applications*, Ambleside, UK, July 2001. ISCTA.

[16] P. Lettieri and M. B. Srivastava. A QoS-aware Energy-Efficient Wireless Node Architecture. In *Proc. of the Sixth IEEE International Workshop on Mobil Multimedia Communications (MoMuC'99)*, pages 252-261, San Diego, CA, USA, November 1999.

[17] P. A. Lettieri. *Architectural Strategies for Energy Efficient Wireless Multimedia Systems*. Dissertation, University of California, Los Angelas, USA, 2000.

[18] E. Modiano. An adaptive algorithm for optimizing the packet size in wireless arq protocols. *Wireless Networks*, 5:279-286, 1999.

[19] V. D. Park and M. S. Corson. A highly adaptive distributed routing algorithm for mobile wireless networks. In *INFOCOM 1997*, pages 1405-1413, Kobe,Japan, April 1997. IEEE.

[20] G. Pei, M. Gerla, and T.-W. Chen. Fisheye state routing in mobile ad hoc networks. In Ten-Hwang Lai, editor, *ICDCS Workshop on Wireless Networks and Mobile Computing*, pages D71-D78, Taipei, Taiwan, ROC, April 2000.

[21] C. E. Perkins. Ad-hoc on-demand distance vector routing. In *MILCOM '97 panel on Ad Hoc Networks*, November 1997.

[22] C. Perkins and P. Bhagwat. Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers. In *ACM SIGCOMM'94 Conference on Communications Architectures, Protocols and Applications*, pages 234-244, 1994.

[23] C. E. Price, K. M. Sivalingam, J. C. Chen, and P. Agrawal. Power-aware scheduling algorithms for wireless networks. In *Proc. of Intl. Conference on Intelligence Computing and VLSI*, Kalyani, India, 2001.

[24] R. Ramanathan and R. Rosales-Hain. Topology control of multihop wireless networks using transmit power adjustement. In *Proc. IEEE Infocom*, Tel-Aviv, Israel, March 2000.

[25] V. Rodoplu and T. H.-Y. Meng. Minimum energy mobile wireless networks. *IEEE Journal on Selected Areas in Communications*, 17(8):1333-1344, August 1999.

[26] M. Schlaeger, B. Rathke, S. Bodenstein, and A. Wolisz. Advocating a remote socket architecture for internet access using wireless LANs. *Mobile Networks & Applications (Special Issue on Wireless Internet and Intranet Access)*, 6(1):23-42, January 2001.

[27] S. Singh and C. S. Raghavendra. Pamas - poweraware multi-access protocol with signalling for ad hoc networks. *Computer Communication Review, Volume 28*, July 1998.

[28] P. Sinha and S. Krishnamurthy. Scalable unidirectional routing using zrp (zone routing protocol) extensions for ad-hoc networks. Technical report, HRL Laboratories, Malibu, CA, August 1999.

[29] K. M. Sivalingam, J.-C. Chen, P. Agrawal, and M. Srivastave. Design and analysis of low-power access protocols for wireless and mobile atm networks. *ACM/Baltzer Wireless Network Networks*, 6(1):73-87, 2000.

[30] V. Tsaoussidis and H. Badr. TCP-Probing: Towards an Error Control Schema with Energy and Throughput Gain. In *Proc. of Int. Conference of Network Protocols*, Osaka, Japan, 2000.

[31] V. Tsaoussidis, H. Badr, X. Ge, and K. Pentikousis. Energy Throughput Tradeoffs in TCP Error Control Strategies. In *Proc. of 5th Symposium on Computers and Communication*, France, 2000.

[32] Y.-C. Tseng, C.-S. Hsu, and T.-Y. Hsieh. Power-saving protocols for ieee 802.11-based multi-hop ad hoc networks. In *The 21st Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2002)*, New York, June 2002.

[33] R. Wattenhofer, L. Li, P. Bahl, and Y.-M. Wang. Distributed topology control for power efficient operation in multihop wireless ad hoc networks. In *vol. 3*, Anchorage, April 2001. IEEE.

[34] Y. Xu, J. Heidemann, and D. Estrin. Geography-informed energy conservation for ad hoc routing. In *Seventh Annual ACM/IEEE International Conference on Mobile Computing and Networking*. ACM, July 2001.

[35] M. Zorzi and R. R. Rao. Energy constrained error control for wireless channels. *IEEE Personal Communication Magazine*, 4:27-33, December 1997.

[36] M. Zorzi and R. R. Rao. Energy efficiency of TCP in a local wireless environment. *ACM Mobile Networks and Applications*, 6(3):265-278, June 2001.

[37] J.-P. Ebert and A. Wolisz, "Combined Tuning of RF Power and Medium Access Control for WLANs", *Mobile Networks & Applications*, vol. 6, no. 5, pp. 417-426, September 2001.

[38] “JouleTrack: A web-based software energy profiling tool”, http://dry-martinie.mit.edu/JouleTrack/, May 2002.

[39] J.-P. Ebert, B. Burns, and A. Wolisz, "A Trace-based Approach for determining the Energy Consumption of a WLAN Network Interface", In *Proc. of European Wireless 2002*, pp. 230-236, Florence, Italy, February 2002.

[40] J.-P. Ebert and A. Wolisz, "Power Saving in Wireless LANs: Analyzing the RF Transmission Power and MAC Retransmission Trade-Off", In *Proc. of European Wireless '99 and ITG Fachtagung Mobile Kommunikation*, pp. 187-192, München, Germany, October 1999.

[41] B. Matzen, "Design and test of a simulation model for pulsed battery discharge in communication devices", Studienarbeit, Technische Universität Berlin, Telecommunication Networks Group, Berlin, April 2002.

[42] J. Pouwelse, K. Langendoen, and H. Sips. Dynamic voltage scaling on a low-power microprocessor. In *Proc. 7th Ann. Intl. Conf. on Mobile Computing and Networking*, pages 251-259, Rome, Italy, July 2001. ACM.

[43] International Technology Roadmap for Semiconductors (ITRS Roadmap) 2001; http://public.itrs.net/Files/2001ITRS/Home.htm

[44] Luke Seed, "Trends in VLSI", University of Sheffield, http://www.shef.ac.uk/eee/teach/resources/eee310/ohps/OHP_VLSI_Trends.pdf, Feb. 2002.

[45] Stefan Rusu, INTEL, "Trends and Challenges in VLSI Technology scaling to 100 nm", http://www.esscirc.org/esscirc2001/proceedings/data/404.pdf, Sept. 2001.

[46] C. Robert Hewes, Texas Instruments, "Device Technology Enablers of Digital Communications", http://www.txtec.org/conference2000/Presentations/ti/sld019.htm

[47] Wai Lee, Texas Instruments, "Low Power DSP for Wireless Communications", http://engr.smu.edu/orgs/ssc/slides/19991020.pdf, Oct. 1999.

[48] T. Sakurai, University Tokyo, "Recent topics in realizing low-power high-speed VLSI", http://lowpower.iis.u-tokyo.ac.jp/pdf/2001/2001ts05s.pdf, Oct. 2001.

[49] KATHREIN. 790-2200 MHz Base Station Antennas for Mobile Communications. Catalog, KATHREIN-Werke KG, Rosenheim, Germany, 2001. Issue 01/01.

[50] Jaana Laiho, Achim Wacker, and Thomáš Novosad, editors. Radio Network Planning and Optimisation for UMTS. John Wiley & Sons, 2002.

[51] miniWatt Study, Final Report, to be published in December 2002

[52] Patrick Herhold, Wolfgang Rave, and Gerhard Fettweis. Joint Deployment of Macro- and Microcells in UTRAN FDD Networks. In Proc. European Wireless Conf. 2002, pages 719-725, Florence, Italy, February 2002.

[53] Patrick Herhold, Wolfgang Rave, and Gerhard Fettweis. Relaying in CDMA Networks: Pathloss Reduction and Transmit Power Savings, September 2002. 57th Vehic. Technol. Conf., Korea, April 2003.

[54] 3GPP. TR 25.869 V1.0.0 (2002-2), Tx Diversity Solutions for Multiple Antennas. Technical report, 3GPP, 2002.

[55] T.J. Harrold and A.R. Nix. Intelligent Relaying for Future Personal Communication System. In IEE Colloquium on Capacity and Range Enhancement Techniques for the Third Generation Mobile Communications and Beyond, February 2000.

[56] ETSI. TS 125 106 V4.1.0 (2001-09), UTRA Repeater: Radio Transmission and Reception. Technical specification, ETSI, 2001.

[57] Wan Choi, Bong Youl Cho, and Tae Won Ban. Automatic on-off switching repeater for DS/CMDA reverse link capacity improvement. IEEE Communications Letters, 5(4):138-141, April 2001.

[58] Holger Karl, Seble Mengesha. Analysing Capacity Improvements in Wireless Networks by Relaying, In *Proc. Of IEEE Intl. Conf. on Wireless LANs and Home Networks, pp. 339-348,* Singapore, December 2001.

[59] V. Sreng, H. Yanikomeroglu, and D. Falconer. Coverage Enhancement through Peer-to-Peer Relaying in Cellular Radio Networks. Unpublished, 2002.

[60] Norbert Esseling, Erik Weiss, Andreas Krämling, and Wolfgang Zirwas. A Multi Hop Concept for HiperLAN/2: Capacity and Interference. In Proc. European Wireless Conf. 2002, pages 1-7, Florence, Italy, February 2002.

[61] Hongyi Wu, Chunming Qiao, Swades De, and Ozan Tonguz. Integrated Cellular and Ad Hoc Relaying Systems: iCAR. IEEE J. Select. Areas Commun., 19(10):2105-2215, October 2001.

[62] Ali N. Zadeh and Bijan Jabbari. Throughput of a Multihop Packet CDMA Network with Power Control. In Proc. 51st IEEE Vehic. Techn. Conf., volume 1, pages 31-35, Tokyo, May 2000.

[63] Ali Nabi Zadeh and Bijan Jabbari. Performance Analysis of Multihop Packet CDMA Cellular Networks. In Proc. IEEE Globecom 2001, volume 5, pages 2875-2879, San Antonio, Texas, November 2001.

[64] 3GPP. 3G TR 25.924 version 1.0.0, Opportunity Driven Multiple Access. Technical report, 3GPP, 1999.

[65] T. Rouse, S. McLaughlin, and H. Haas. Coverage-Capacity of Opportunity Driven Multiple Access (ODMA) in UTRA TDD. In 3G 2001 Mobile Communications Technologies, IEE Conf. Publication 477, pages 252-256, March 2001.

[66] T. Rouse, I. Band, and S. McLaughlin. Capacity and Power Investigation of Opportunity Driven Multiple Access (ODMA) Networks in TDD-CDMA Based Systems. In IEEE Int. Conf. Commun. (ICC) 2002, volume 5, pages 3202-3206, 2002.

[67] M. Bronzel, W. Rave, P. Herhold, and G. Fettweis. Interference Reduction in Single-Hop Relay Networks. In Proc. 11th Virginia Tech/MPRG Symposium on Wireless Personal Communications, pages 49-60, June 2001.

[68] O. Praetor, C.Unger, A. Zoch, and G. Fettweis. Performance of Adaptive Chip Equalization for the WCDMA Downlink in Fast Changing Environments. In Proc. IEEE ISSSTA 2002, vol. 1, pages 273-277, Prague, Czech Republic, September 2002.

[69] UMTS Forum, "Key Components for 3G Devices", *Report No. 15 UMTS Forum*, 2002. http://www.umts-forum.org.

[70] R. Kakerow. Low Power Design Methodologies for Mobile Communication. In *Proc. ICCD*, Freiburg, 2002.

[71] G. Fischer. RF-Architecture of Mobile Communication Basestations, Lecture at University of Erlangen, Dept. of RF, SS 2002.

[72] G. Fischer. RF-MEMS and SiC/GaN as enabling Technologies for frequency agile Software Radios, Talk at Institute for Communication Technology, Prof. Jondral, UNI Karlsruhe, 26th November 2002, Karlsruhe.

[73] G. Fischer, RF-MEMS for Base Stations, IEEE/ÖVE International Workshop on W-CDMA RF issues and Future Trends, an Ultrasonics Symposium Post Conference Workshop, Salzburg, 14th October 2002

[74] G. Fischer, RF Architecture of Frequency Agile Base Stations, IEEE/ÖVE International Workshop on W-CDMA RF issues and Future Trends, an Ultrasonics Symposium Post Conference Workshop, Salzburg, 14th October 2002

[75] G. Fischer, W. Eckl, G. Kaminski, RF-MEMS and SiC/GaN as enabling technologies for a reconfigurable Multiband/Multistandard radio, Bell Labs Technical Journal, Vol. 7, No. 3, 2002

[76] N.N., Brennstoffzelle statt Akku, c't, pp. 94ff, Vol. 10, 2003.

[77] M. Kubisch, S. Mengesha, D. Hollos, H. Karl, and A. Wolisz, "Applying ad-hoc relaying to improve capacity, energy efficiency, and immission in infrastructure-based WLANs", In Klaus Irmscher, editor, Proc. of Kommunikation in Verteilten Systemen (KiVS 2003), Leipzig, Germany, February 2003.

[78] R. Rajaraman, „Topology control and routing in ad hoc networks: A survey", in ACM SIGACCT News, 33(2):60-73, 2002.

[79] P. Bergamo, D. Maniezzo, A. Travasoni, A. Giovanardi, G. Mazzini, and M. Zorzi, "Distributed Power Control for Energy Efficient Routing in Ad Hoc Networks", in Wireless Networks, 10(1), 2004.

[80] Anders Furuskär, "Allocation of Multiple Services in Multi-Access Wireless Systems", Fourth IEEE Conference on Mobile and Wireless Communication Networks (MWCN), Sep. 9-11, 2002, Stockholm, Sweden.

[81] A. Tölli, P. Hakalin and H. Holma, "Performance of Common Radio Resource Management (CRRM)", in proceedings of IEEE International Conference on Communications (ICC), 2002.

[82] 3GPP. TS 23.060 version 5.2.0, General Packet Radio Service, Service Description, Stage 2, Technical specification, 2002.

[83] 3GPP. TR 25.881 version 5.0.0, Improvement of RRM across RNS and RNS/BSS, Technical report, 2002.

[84] DRiVE, Specification for Radio Network-, API-, and CCC Interfaces, project deliverable D14, March 2002. Available at http://www.ist-drive.org/.

[85] 3GPP. TR 25.840 Version 2.3.0, Terminal power saving features, Technical report, 2001.

[86] 3GPP. TR 25.938 Version 2.0.0, Terminal Power Saving Features (Iur/Iub aspects), 2001.

[87] A. Furuskär, J. Näslund, H. Olofsson, EDGE - Enhanced data rates for GSM and TDMA/136 evolution, Ericsson Review No.1, 1999.

[88] S. Parkvall, E. Dahlman, P. Frenger, P. Beming, M. Persson, "The Evolution of WCDMA Towards Higher Speed Downlink Packet Data Access", in Proceedings VTC Spring 2001

[89] Mangold, S. "Analysis of IEEE 802.11e and Application of Game Models for Support of Quality-of-Service in Coexisting Wireless Networks", PhD Thesis, Aachen University ComNets, 2003.

[90] Mangold, S. and Berlemann, L. and Hiertz, G. "QoS Support as Utility for Coexisting Wireless LANs," in Proc. of *International Workshop in IP Based Cellular Networks*, Paris France, 23-26 April 2002.

[91] Mangold, S. and Berlemann, L. and Walke, B. "Radio Resource Sharing Model for Coexisting IEEE 802.11e Wireless LANs," in Proc. of *International Conference on Communication Technology*, Beijing China, 9-11 April 2003.

[92] Mangold, S. and Berlemann, L. and Walke, B. "Equilibrium Analysis of Coexisting IEEE 802.11e Wireless LANs," in Proc. of *International Symposium on Personal, Indoor and Mobile Radio Communications*, Beijing China, 7-11 September 2003.

[93] Berlemann, L. and Mangold, S. and Walke, B. "Strategies, Behaviors, and Discounting in Radio Resource Sharing Games", in Proc. of *10th WWRF Meeting*, New York USA, 27-28 October 2003.

[94] Berlemann, L. and Mangold, S. and Walke, B. "Strategies in Multi Stage Games of Coexisting IEEE 802.11e Wireless LANs", submitted to *European Wireless Conference*, Barcelona Spain, 24-27 February 2004.