Challenges and Enabling Technologies for Energy Aware Mobile Radio Networks

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ABSTRACT

Mobile communications are increasingly contributing to global energy consumption. In this article, a holistic approach for energy efficient mobile radio networks is presented. The matter of having appropriate metrics and evaluation methods that allow assessing the energy efficiency of the entire system is discussed. The mutual supplementary saving concepts comprise component, link and network levels. At the component level the power amplifier complemented by a transceiver and a digital platform supporting advanced power management are key to efficient radio implementations. Discontinuous transmission by base stations, where hardware components are switched off, facilitate energy efficient operation at the link level. At the network level, the potential for reducing energy consumption is in the layout of networks and their management, that take into account slowly changing daily load patterns, as well as highly dynamic traffic fluctuations. Moreover, research has to analyze new disruptive architectural approaches, including multi-hop transmission, ad-hoc meshed networks, terminal-to-terminal communications, and cooperative multipoint architectures.

INTRODUCTION

Today, the worldwide mobile communication infrastructure offers ubiquitous mobile connectivity and unprecedented service levels. More than 4 billion subscribers around the world depend on their mobile phones for their private and professional lives; however, this has come at the cost of increasing energy consumption. Thus far, the mobile communications industry has focused on highly energy efficient terminals, so to make mobile phones reliable and attractive for consumers, a factor that has strongly contributed to the global success of mobile radio. The emerging trend towards energy-efficient network operation shifts the focus towards the energy consumption of the wireless access network infrastructure, which has triggered activities in standardization and regulatory bodies, such as 3GPP, ITU, ETSI, and ATIS.

There are several reasons for the growing awareness of energy-efficient wireless networks in the telecommunication community. Increasing energy prices imply that electricity bills have become a significant cost factor for mobile operators. In addition, mobile telephony and mobile broadband are entering new emerging markets, with an increasing share of base stations that are not connected to the electricity grid. Such off-grid sites are typically diesel powered, where fuel is costly and distribution often unreliable for distant sites that are difficult to access. For operators with many off-grid sites, energy provision may contribute up to 50 percent of their total operational cost. There is also an increasing awareness in the society about manmade climate effects, and the need to slow down global warming. Moreover, political initiatives are beginning to put requirements on manufacturer and operators to lower CO_2 emissions of communication networks. The European Commission research project EARTH [1], consolidates the energy efficiency activities from major vendors, operators and academia in Europe. The project concentrates on energy efficiency in radio access networks, covering a wide span of activities from near future component research and development to long term research for theoretical limits of different concepts; the goal is to find solutions and concepts that can reduce the energy consumption of mobile broadband systems by 50 percent.

Unlike mobile phones, where the manufacturing of the devices is the main contributor to CO_2 emissions, on the network side the big saving potential lies in the operation [2]. The main

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reason for this difference is the limited lifetime of mobile phones, the effort for distribution of the devices, and the small recycling fraction of mobile phones compared to radio network equipment.

This article elaborates on all levels of the communication system, covering network level aspects, including deployment, architecture and network management; link level perspective; and the component level, including hardware implementation targeted for improved energy efficiency in radio access network operation. Furthermore, a framework for the evaluation of these concepts in a holistic way is presented, revealing the mutual dependencies, and trade-offs are discussed together with suitable metrics.

Framework for Energy Efficiency Evaluation

The deployment of cellular networks is typically optimized for ubiquitous radio access of mobile users. This implies that a significant portion of base stations are primarily providing coverage, therefore not operating at full load, even at peak traffic hours. During off-peak hours, virtually all base stations operate at low load, or might not even serve any user at all. Unfortunately, the energy efficiency of base stations is particularly poor in this condition, which can be attributed to:

- Component level: The efficiency of the power amplifier (PA) substantially degrades at lower output power.
- Link level: System information, synchronization, and reference signals (pilots) need to be transmitted continuously, so that base stations are required to be always on.
- Network level: The cellular network deployment paradigm with large macro-cells requires additional (micro- or pico-) cells to fulfill peak capacity demand, but this rather static topology does not adapt to low load situations.

This underlines the fact that energy efficient network operation requires a holistic approach including all system aspects. The standardization of an energy efficiency evaluation framework has already started in a number of bodies; for instance, ETSI and 3GPP have initiated work on the specification of energy efficiency metrics for mobile cellular networks. However, today's proposals exhibit three major shortcomings:

- System performance is optimized for capacity and evaluated at full load, which implies that the system is poorly configured at low loads;
- The output power at the antennas is taken as performance measure; clearly, in order to evaluate the energy consumption, one should considered the total input power instead;
- Performance metrics that measure the energy efficiency.

In what follows, the necessary modifications to existing performance evaluation frameworks are discussed, such that the actual power consumption of the entire network can be quantified.

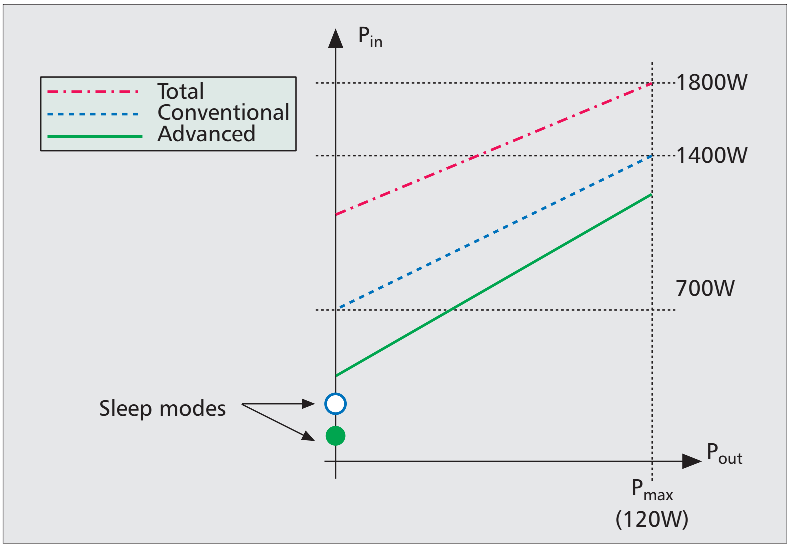

Figure 1. *Linear model approximating the relationship between input and output powers of a 3-sector macro base station.*

A Power Consumption Model

To date, studies on energy efficiency for wireless networks typically regard the output power as performance measure. Often, such energy performance metrics only capture a small fraction of the overall power budget of wireless networks, and therefore may lead to incomplete and potentially misleading conclusions. In order to evaluate the energy efficiency of a wireless network, the power to operate the entire access network is to be taken into account, comprising RF signal generation, digital and analogue signal processing, backhaul data link, AC/DC power conversion, and cooling.

The prohibitive complexity of the problem makes a certain level of idealization unavoidable. Already a fairly simple, yet powerful, linear power model allows one to assess the energy efficiency of the entire network; Fig. 1 shows such a model, which maps the consumed input power P_{in} to achieve a certain output power at the antenna P_{out}, with power consumption values based on [3, 4]. This model determines how the power efficiency, denoted by P_{out}/P_{in}, degrades with decreasing output power P_{out}; in particular, at zero output power a base station still consumes a non-negligible fraction of the maximum input power. The DC power consumption of a typical 3-sector site at *zero* load is still 50 percent of the peak power [3]. The *conventional* model without power supply and active cooling/air conditioning can be 400 W lower than the *total power consumption* of a site.

Moreover, the introduction of base station sleep modes, where the required input power at zero load can be significantly reduced, are an enabler for discontinuous transmission (DTX) modes, and therefore need to be considered in the linear power model as well.

The proposed model allows one to understand the system power consumption at network level, as a function of base station load, cell size, and system parameters. This allows one to optimize the radio resource management (RRM) for energy efficient operation, given a certain PA.

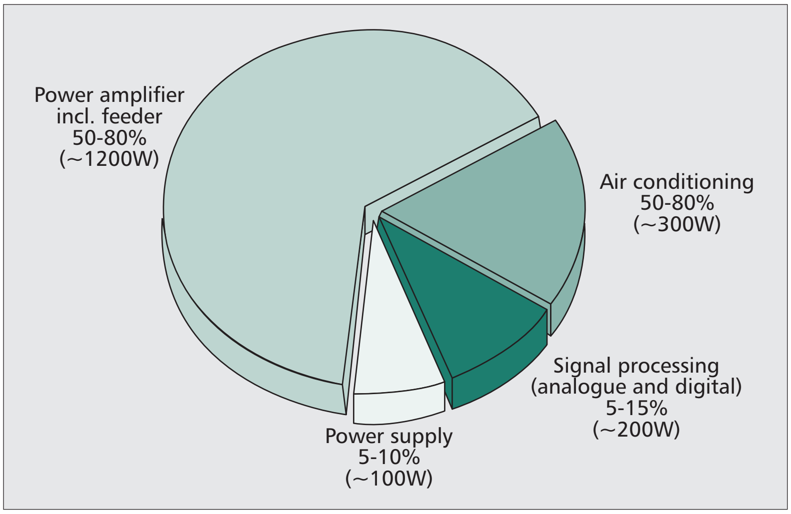

Figure 2. *Typical power consumption distribution in radio access technology (absolute values relate to the base station of Fig. 1) [5].*

On the other hand, the potential energy savings of advanced PAs and other system components that, e.g., improve the power efficiency at low load, may also be assessed.

Energy Efficiency Metrics

One of the most commonly used metric for measuring the energy efficiency of a communication link is the consumed energy over the number of information bits in [Joule/bit]. For cellular networks, this metric relates the total energy consumed by the entire network to the aggregate network capacity. As the measure [Joule/bit] relates the cost (in terms of energy) to the generated utility (information bits), this metric is appropriate to assess the energy efficiency at full loads. On the other hand, when the network is operated well below its capacity, the main objective is to minimize the power consumption to cover a certain area, in which case [W/m^2] is deemed the most relevant energy efficiency metric.

There is a multitude of further figures of merit for optimising the different aspects and components of the wireless system, e.g., quality of service parameters, such as error rate, delay (jitter), as well as a fair distribution of the individual user throughputs throughout the network. Energy efficiency metrics complement the aforementioned figures of merit, rather than replacing them; otherwise, optimisation may just improve towards one direction, at the expense of other important aspects.

Component Level Potential

In order to improve the total energy efficiency of cellular networks, special attention needs to be paid to the different base station components, as they are the main contributors to the total energy consumption. To this end, one needs to analyze the power consumption of different radio components for relevant traffic scenarios. As an example, Fig. 2 shows a typical power consumption of macro-cellular radio access equipment.

Figure 2 reveals that a significant portion of the energy is consumed in the power amplification process, since sufficient power is needed to reach distant terminals with high path losses. Unfortunately, power amplification has a rather poor efficiency, reaching up to 50 percent for maximum load, but degrading to much lower values in medium and low load situations. This is a major reason why the power consumption in cellular networks is, to a large extent, independent of the traffic load (Fig. 1).

For this reason, in addition to the application of advanced power amplifiers, new power management concepts are to be devised that adapt to varying traffic load. Introducing scalability into hardware components, and supporting them by dynamic power management, enables the adaptation of energy consumption to actual performance requirements. Further power savings are facilitated by the deactivation of components in time periods of no operation.

Improving the Power Amplifier Efficiency

Modulation schemes used in WCDMA/HSPA and LTE are characterized by strongly varying signal envelopes, with peak-to-average power ratios (PAPR, also known as crest factor) exceeding 10 dB. On the other hand, to attain the quality of transmitted radio signals requested by the standards, a high linearity of the amplifiers is required, hence, PAs must operate well below saturation, leading to poor power efficiency.

To increase the power efficiency, signal conditioning algorithms, like crest factor reduction (CFR) for decreasing the PAPR and digital predistortion (DPD) for increasing the PA linearity, must be applied to enable the PA operation closer to saturation. Furthermore, PAs based on special architectures must be used to achieve high efficiency values. For example, Doherty PAs, which contain one main amplifier always active and an auxiliary one active only when signal peaks occurs, show maximum efficiency at power levels of 6 to 10 dB below the saturation point, matching with the PAPR values of interest. By using CFR and DPD with Doherty PAs, up to 50 percent efficiency can be achieved for full load; at low loads, the power efficiency decreases significantly to only around 5 percent, at 10 percent load.

Base Station Power Management

In order to achieve energy efficiency, the consumed power in the base station front end should scale, as far as possible, to the amount of served traffic.

To this end, load adaptive CFR combined with adaptive power supply of the PA shows a promising solution in the analogue chain. This has to include energy efficiency optimization of the power supplies for variable input power.

Energy efficient power management requires reconfigurable circuits as key elements. A low power front-end that supports different levels of transmit power with adjustable performance (quantified as signal to distortion ratio, mainly depending on the back-off) has been proposed in [6]. In this solution, both driver and power amplifier are digitally controlled and flexible in terms of output power, linearity, and DC power consumption. Measurements indicate that instantaneous transmitter energy can be scaled by 30 percent. Considering also adaptive scheduling, the average energy efficiency is even improved by up to 40 percent, compared to non-scalable systems.

It is highly desirable to extend this kind of techniques to high power transceivers commonly used in base stations serving macro-cells. Techniques like dynamic voltage and frequency scaling can adapt the voltage and clock frequency of the platform depending on the work load, which allows for scaling the power consumed in the digital chain with traffic.

DEACTIVATION OF COMPONENTS

Component deactivation is required to exploit energy saving potential of downlink DTX and base station sleep mode techniques managed from link or network levels.

Base station components must allow switching off inactive digital and analogue circuits. In this case, inactive digital circuits should be power gated in order to reduce the leakage power on the platform. The analogue chain should be totally or partly switched off during the inactive time periods, providing significant power savings of the transceiver, especially by the power amplifier.

The benefit of DTX techniques is highly dependent on how fast deactivation and reactivation can be supported by the functional unit. The shortest DTX, within a 1 ms subframe, requires timescales in the order of tenths of microseconds, to suppress the power consumption during time periods of no transmission. This functional unit consists of PA, power supply, and signal conditioning.

LINK LEVEL POTENTIAL

In the last decade, quite a number of improvements of radio interfaces [7] have been achieved, boosting user data rates to the order of 100 Mb/s. State-of-the-art radio link designs focus on achieving high peak data rates, optimal spectral efficiency, appropriate coverage, and low latencies. In addition, it now becomes necessary to rethink the way radio interfaces are designed from an energy efficiency perspective.

Transceivers employing multiple transmit and receive antennas boost spectral efficiency, in terms of b/s/Hz, which potentially allows to transmit more bits for a given transmit power. In practice, however, these improvements hardly reduce the power consumption of the network. The reasons for this are manifold, three examples being discussed below.

REFERENCE SYMBOL AND CONTROL SIGNAL OVERHEAD

Systems equipped with multiple transmit and receive antennas are an integral part of beyond 3G mobile communication systems, e.g., LTE. Combined with adaptive transmission techniques that exploit channel knowledge at the transmitter, improvements in spectral efficiency are obtained. On the other hand, accurate knowledge of the actual radio channel conditions is required, both at the transmitter and the receiver, which is achieved by transmitting auxiliary information in the form of reference symbols (pilots) known to the receiver; in particular, the amount of reference symbols grows strongly with the number of transmit antennas. At full load the energy consumed to transmit this overhead is overcompensated by the enhanced spectral efficiency; in fact, in theory, up to 50 percent of reference signal overhead is acceptable to still see capacity gains by adding transmit and receive antennas at fixed total power [8]. However, the amount of the auxiliary information remains the same in low load situations, where the radio interface carries only a fraction of its maximum capacity. As an example, the current LTE standard requires transmission of cell specific reference symbols over the whole bandwidth at all time; for this, the overhead ranges between 5 and 15 percent for 1 to 4 transmit antennas, respectively. Taking system information, control and synchronization channels into account, the overhead energy consumption may exceed 25 percent of its maximum even when no user data is transmitted. This fixed transmission of control signals contributes very significantly to the overall power consumption of a network. With the trend toward transmitters with multiple transmit antennas, the overhead in low load situations increasingly impacts on the overall energy consumed by a network.

BASEBAND SIGNAL PROCESSING

Power consumed by signal processing also constitutes a significant part of the overall power consumption of a network. Highly spectrally efficient transmission techniques have a tendency to require more complex computations with a corresponding increase of processing power. Therefore, the gains of such advanced transmission techniques on the energy efficiency may be out weighted by negative effects in other parts of the system. This is particularly true for deployments with small cell sizes, where the cell transmission power amounts only a few percent of that of a macro-cell, thus, baseband signal processing may dominate the overall energy consumption. However, such difference between power consumption components of pico/micro- and macro-cells does not determine in advance which cell type should dominate a particular network scenario.

DISCONTINUOUS TRANSMISSION AND BASE STATION SLEEP MODES

The demand for very long standby and call times of mobile terminals has resulted in a very efficient use of energy. This has been possible by employing schemes like DTX (as mentioned above), which periodically create periods in the transmission protocol where power consuming components can be switched off. Unfortunately, DTX at the base stations is not supported in the WCDMA/HSPA specifications as it requires continues pilot transmission; the situation has already improved somehow in LTE, since cell specific reference signals are no longer transmitted continuously, although frequent transmission of synchronization signals and broadcast channel remain. However, there is still potential for fur-

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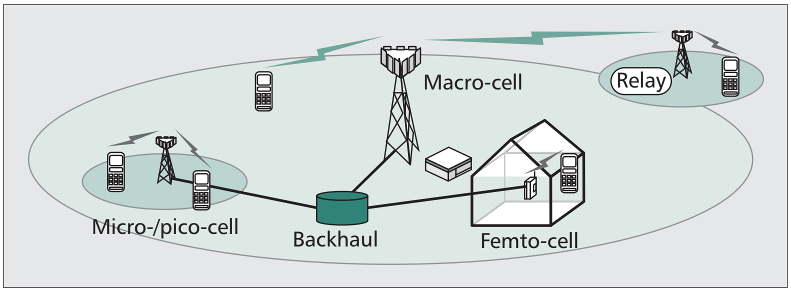

Figure 3. *Heterogeneous network deployment, consisting of micro-/pico-cells serving hot spot areas, femto-cells for indoor users, and relays for coverage extension.*

ther exploiting downlink DTX schemes as well as various kinds of base station sleep modes in future standards:

- Micro sleep modes, where base stations suspend transmission in the order of milliseconds
- Deep sleep modes, where base station transmitters are shut down for extended periods of time

While in micro sleep mode base stations are required to wake up almost immediately, in the deep sleep some transmit circuits are completely switched off, which implies that wake up times are substantially longer.

In order to utilize the potential of base station sleep modes, protocols need to be developed that allow suspending the transmission of reference symbols at low loads, hence, new protocols for handover and initial access procedures are needed that enable base stations to be on sleep mode.

POTENTIAL GAINS

In the development of radio link protocols, the focus has been on low power consumption of mobile terminals. Ignoring the power consumption of base stations in the design of the radio transmission techniques inevitably leads to energy wastage.

Current research on energy efficiency aspects of cellular radio access technologies focuses on isolated hardware aspects, hence, an embracing analysis is lacking. In order to achieve the largest energy savings, a joint optimization of spectral and power efficiency for the radio link operation is necessary. Future research must instead take the total energy consumption as optimization criterion into account, in both the radio interface and network nodes, and in different operation and deployment situations, which is expected to yield significant energy savings. The resulting new radio interface and transmission techniques will exhibit a much higher flexibility for the dynamic adaptation of the radio transmission to the dynamic traffic load situations and operation environment.

NETWORK LEVEL POTENTIALS

On network level, the potential for reducing energy consumption is in the layout of networks and in their management.

The energy consumption for maintaining network operation has to be evaluated as a function of cell size and deployment scenario, for given traffic distributions and environments ranging from dense urban to rural areas [9]. Site specific deployment options, like sectorization, antenna tilting, and distributed antennas need to be considered. Furthermore, heterogeneous networks with a hierarchical mix of base stations with different cell sizes have recently attracted increasing interest for 4G mobile communication systems [10], as they provide deployment strategies for tailored provisioning of capacity.

Despite the fact that the traffic load of mobile networks follows a daily profile of large ranges, networks are configured rather statically today. For an energy efficient operation, network management needs to take slowly changing daily load patterns into account, as well as dynamic traffic fluctuations. Moreover, research has to analyze new architectures with more disruptive approaches, including multi-hop transmission, ad-hoc meshed networks, terminal-to-terminal communications, and cooperative multipoint architectures.

NETWORK DEPLOYMENT

In heterogeneous networks, illustrated in Fig. 3, low power nodes complement the conventional macro-cellular network layout, micro-/pico-cells cover high traffic demand (hot spot) areas, while indoor base stations constitute femto-cells that provide broadband coverage to indoor users. Furthermore, relay nodes are a cost efficient means to extend outdoor coverage, since expensive backhaul links are avoided. Such heterogeneous networks potentially promise energy savings, since they shorten the propagation distance between nodes, and thereby reduce the required transmission power. On the other hand, a deployment with only small cells may be uneconomical, due to the prohibitive number of low power, and therefore short range, base stations. Moreover, this increases the number of base stations operating at low loads, which may degrade the overall energy efficiency. Hence, for each scenario (e.g., dense urban vs. rural) heterogeneous deployments with an optimal balance of macro-, micro-, pico-, and femto-cells must be found for a most energy efficient network layout.

Cooperative transmission from several base stations to one mobile device is a further enabler for enhanced energy efficient network operation; such inter-base station cooperation avoids interference, or can even turn interference into a useful signal. However, the improvement in energy efficiency at the air interface may be cancelled out by more complex signal processing and/or increased backhaul traffic. Fundamental tradeoffs among these factors need to be studied, providing the basis for designing energy efficient site cooperation protocols.

NETWORK MANAGEMENT

Figure 4 shows the daily traffic profile of a major operator, where the traffic in peak hours can be 10 times higher than the one in off-peak periods. Realizing the potential in these slow traffic variations, vendors and operators have recently started to bundle traffic of certain transceivers, and switch others off in order to save energy. Beyond these basic techniques, self-organizing networks can be exploited to adapt the network topology to slow traffic variations. Furthermore, highly dynamic load variations should be addressed by energy efficient radio resource management strategies.

Energy efficient adaptation to the daily and spatial variation of the traffic demand requires specific network management functionalities. The state-of-the-art solution is to simply reduce the number of active network elements when the traffic demand decreases [12]; however, once different energy efficient deployment scenarios are available for different traffic situations, new horizons open for network management. That is, network management can provide a seamless transition from one network configuration and topology setup to another, according to actual traffic demands, considering both slowly changing daily load patterns, as well as highly dynamic traffic fluctuations.

The transition process from one network setup to another needs the reconfiguration of particular resources, or the coordinated reconfiguration of groups of resources, or even of the whole network. When traffic demand decreases, the transition process may include, e.g., switching off particular micro-/pico-cells, transferring a sectorized base station to an omnidirectional one, or increasing cell coverage by adapting the antenna tilt. When traffic demand increases, the transition process may include, e.g., switching between various MIMO functionalities, or directing adaptive antenna arrays towards traffic hotspots. Beyond the analysis of the above options, other issues are at stake, like developing new network management concepts for dynamic reconfiguration of mobile networks, including self-optimization, self-configuration and standby-operation.

When comparing different radio access technologies, one can find that some are more energy efficient for certain types of services than others. In order to take advantage of the coexistence of different radio access technologies, new network management functions are needed to control a common resource pool. That is, radio resource management has to involve cooperative scheduling, interference coordination, and joint power and radio resource control. There is a need to investigate how to define these management functionalities to leverage the capabilities of the different technologies, and to employ multi-radio access networks in a coordinated fashion for energy savings.

CONCLUSIONS

This article addresses energy efficiency of mobile cellular networks, which is a concern of industry, operators, as well as of regulatory bodies and the society. It stresses that for fundamental improvements of the energy efficiency of wireless broadband access, joint optimizations yielding an optimum at system level need to be aimed at rather than optimizing single aspects or components. Initially, it presents a framework for energy efficiency evaluation, identifying the levels that need to be addressed, i.e., component, link and network. Metrics need to be taken for such assessment, capturing, e.g., the backhaul power

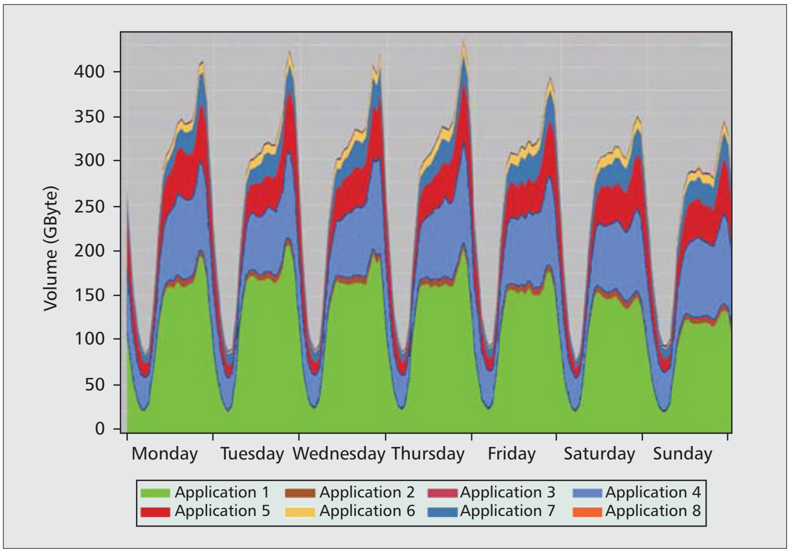

Figure 4. *Measured weekly traffic variations of a mobile cellular network [11].*

consumption, and system parameters, e.g., quality of service.

It is important to perform an assessment of the power consumption distribution of the different radio components and subsystems in typical communication scenarios. A key fraction of this consumption is observed in the power amplification stage. Digital platforms should actively support advanced power management, together with dynamic voltage and frequency scaling adapted to the workload. Energy-scalable reconfigurable transmitters and their control strategy are also key building blocks in this approach.

Radio interfaces and transmission techniques play also an important role. Aspects like spectral efficiency and information overhead need to be considered; however, more efficient techniques usually require a much more complex computation, which leads to an increase of the associated processing power, therefore, reinforcing the need for the global overview of the problem. Discontinuous transmission by base stations, where hardware components, like power amplifiers, can be switched off, can be seen as one of the directions to follow.

At the network level, the potential for reducing energy consumption lies in the layout of networks and their management. Network management needs to take slowly changing daily load patterns into account, as well as highly dynamic traffic fluctuations. Moreover, research has to analyze new architectures with more disruptive approaches, including multi-hop transmission, ad-hoc meshed networks, terminal-to-terminal communications and cooperative multipoint architectures. The use of cellular heterogeneous structures, and cooperative transmission from several base stations to one mobile device, are further enablers.

In conclusion, research on energy efficiency aspects of mobile cellular radio network has a quite extensive list of topics to be addressed, requiring an embracing analysis. The EARTH project is pursuing this vision, targeting to subdue major energy savings by exploring the approaches discussed within this article.

Research has to analyze new architectures with more disruptive approaches, including multi-hop transmission, ad-hoc meshed networks, terminal-to-terminal communications and cooperative multipoint architectures.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of the European Commission by partially funding this work, under project FP7-ICT-2009-4-247733-EARTH. We gratefully recognize the great contributions of many colleagues from EARTH; in fruitful cooperation, many people from all partners contributed with valuable insight, surveys and vision.

REFERENCES

[1] EARTH (Energy Aware Radio and neTwork tecHnologies), "EU Funded Research Project FP7-ICT-2009-4-247733-EARTH," Jan. 2010–June 2012; https://www.ict-earth.eu.

[2] J. Malmodin, "The Importance of Energy in LCA for the ICT Sector," *Proc. 14th SETAC*, Göteborg, Sweden, Dec. 2007.

[3] D. Ferling *et al.*, "Energy Efficiency Approaches for Radio Nodes," *Proc. Future Net. Mobile Summit '10*, June 2010, Florence, Italy.

[4] G. Fischer, "Future Challenges in R&D with Respect to Mobile Communication Base Stations," Bell Labs Tech. Rep., Stuttgart, Germany, Jan. 2008.

[5] Alcatel-Lucent and Vodafone Chair on Mobile Communication Systems, "Study on Energy Efficient Radio Access Network (EERAN) Technologies," Unpublished Project Report, Technical University of Dresden, Dresden, Germany, 2009.

[6] B. Debaillie *et al.*, "Energy-Scalable OFDM Transmitter Design and Control," *Proc. 43rd ACM/IEEE DAC '06*, San Francisco, CA, July 2006.

[7] E. Dahlman *et al.*, "3G Radio Access Evolution — HSPA and LTE for Mobile Broadband," *IEICE Trans. Commun.*, vol. E92-B, no. 5, May 2009, pp.1432–40.

[8] B. Hassibi and B. M. Hochwald, "How much Training is Needed in Multiple-Antenna Wireless Links?," *IEEE Trans. Info. Theory*, vol. 49, no. 4, Apr. 2003, pp. 951–63.

[9] 3GPP TR 36.814 v2.0.1, "Further Advancements for E-UTRA. Physical Layer Aspects (Release 9)," Tech. Spec. Group Radio Access Net., Mar. 2010; http://www.3gpp.org.

[10] H. Claussen, L. Ho, and F. Pivit, "Effects of Joint Macrocell and Residential Picocell Deployment on the Network Energy Efficiency," *Proc. 19th IEEE PIMRC '08*, Cannes, France, Sept. 2008.

[11] Alcatel-Lucent, "9900 Wireless Network Guardian," Tech. White Paper, 2008;http://www.alcatel-lucent.com.

[12] Ericsson, "Sustainable Energy use in Mobile Communications," White Paper, Aug. 2007;http://www.ericsson.com.

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