Approaches to Energy Efficient Wireless Access Networks

Oliver Blume, Dietrich Zeller, Ulrich Barth

Abstract—**Due to increasing data traffic rates and rollout of advanced radio transmission technologies wireless networks consume increasing amount of energy and contribute a growing fraction to the CO_2 emissions of ICT industry. Thus, climate and cost issues now shift the research focus of wireless communications to energy consumption and energy efficiency. Two approaches can be followed: Incremental improvements of existing systems or a clean slate re-design with a fundamental change of paradigms. We describe two such initiatives and discuss their differences. The EC FP7 project EARTH is a 30 month project aiming for a reduction of the overall energy consumption of 4G mobile broadband networks by 50%, regarding network aspects and individual radio components from a holistic point of view. The Green Touch Initiative is a privately financed consortium addressing fundamental research that will pave the way to much higher reductions for future systems in the order of several magnitudes, with first proof of concepts available in 5 years.**

Index Terms **— energy efficiency, mobile communication networks, radio access, small cells, energy aware management, load adaptivity, EARTH, Green Touch, fundamental research**

I. Introduction

After the COP15-event in Copenhagen in December 2009 there is at least rough consensus to limit the global temperature rise to 2°C above pre-industrialisation level. The Intergovernmental Panel on Climate Change (IPCC) stated in its latest Assessment Report [1] that a rise of 1.6°C is already inevitable and human greenhouse gas emissions need to drop 50-85% below the level of 2000 by 2050. The European Commission (EC) has reached an agreement to cut greenhouse gas emissions by 20% by 2020 and to improve energy efficiency by 20% [2]. The global information and communications technology (ICT) industry is an important and quickly growing contributor to CO_2 emissions and energy consumption. According to the SMART 2020 study [3] it accounted for 530 Megatons of CO_2 in 2002 and 830 Megatons in 2007. This is approximately 2% of global human carbon dioxide (CO_2) emissions and about equivalent to those of global aviation [4]. Acknowledging this contribution, the European Union has called on ICT industry to tackle energy efficiency of communication networks and of ICT in general [5] and is funding related research within the framework program FP7.

Within ICT, the contribution of mobile communication networks was 64 Megatons of CO_2 in 2002. This may seem a rather small fraction (12% of ICT emissions) but it is expected to grow by nearly a factor of three to 178 Megatons in 2020 (Fig. 1). With the latest projections of wireless data rates and with the rollout of additional base stations for next generation (4G) mobile networks (e.g. 3GPP LTE) the energy consumption of the network infrastructure can be expected to rise even stronger and, at growing energy prices, makes up for a significant fraction of the operational costs of operators. Therefore, energy consumption and CO_2 emissions of the mobile network infrastructure have received more and more attention in the telecommunications sector lately.

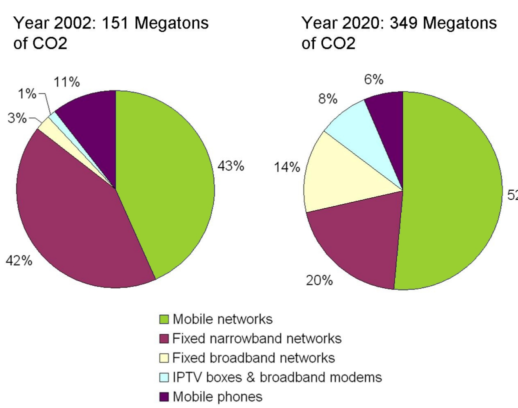

Fig. 1. Contribution of mobile communications to the CO_2 footprint of telecommunication industry in 2002 and estimated for 2020 [2].

The largest fraction of CO_2 emission from mobile communications occurs in the radio access network, i.e. in the base stations (Fig. 1). Compared to this, the energy consumption (and the according CO_2 emissions) of both the mobile devices and of the servers in the core network infrastructure are smaller by a factor of 4 or 5 [6]. Regarding only the power consumption during operation the contribution of the mobile devices is even as low as a few percent [7]. Improvements in the access network infrastructure are thus key to Green ICT.

Mobile network equipment manufacturers have already achieved big progress in energy efficiency, mainly by increasing the power efficiency of the transceivers in the base stations (Fig. 2) [8] and by replacing air conditioning of base station housings by fresh air cooling. Further improvements of energy efficiency now require more involved research and a holistic approach regarding the entire system as an ensemble.

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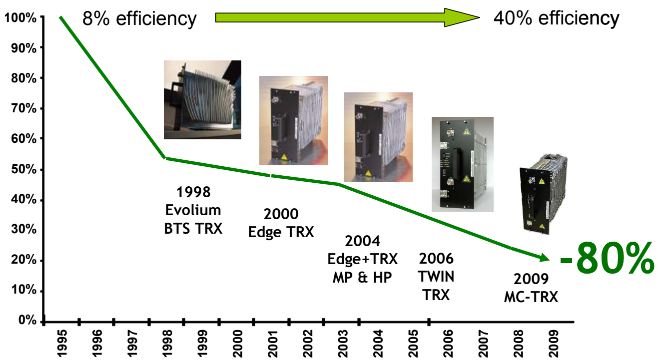

Fig. 2. Continuous improvements of power efficiency in GSM base station transceivers have resulted in an 80% reduction in energy consumption [8].

II. Metrics and Scenarios

The usual metrics for comparing different radio access technologies and equipment of different suppliers currently rather consider spectrum efficiency and consumed power per base station or component. This neglects different coverage areas, data rates, and service level. Further, the techniques adopted to improve the energy efficiency of one end of the communication system (transmitter nodes or receiver nodes) may adversely affect the energy efficiency of the other end. For example, adopting efficient multiuser scheduling techniques may reduce the transmit energy requirement, but on the other hand the receiver needs more computation energy for performing multiuser detection. A deployment of cells with smaller cell range reduces the average path loss and thus the transmission power, but this requires an increased number of sites with more standby power consumption and more equipment. Finally, the total energy consumption of the network is not limited to the energy consumed during use, but also includes the energy spent for production and deployment.

For a holistic approach it is important to define energy efficiency metrics and reference scenarios (Fig. 3) to compare the improvements on a system level. Finding such metrics is not straightforward. There are already some efforts going on in standardization bodies on metrics (e.g. [9][10]) but these different metrics still need to be combined and to find acceptance in the community.

Just like there is a well-defined driving cycle to measure the fuel consumption of cars in different situations, standardisation bodies need to agree on a set of reference scenarios that will be used to validate the progress of new solutions, e.g. made by deployment strategies with a mix of large and small cells, by cooperation schemes such as cooperative multipoint techniques and by coordination schemes between different radio access technologies.

Finally, carbon dioxide emissions are not necessarily proportional to the energy consumption of a given system since non-fossil and renewable energy sources can be used. Energy efficiency improvement for base stations can be an enabler for using locally generated wind and solar power, e.g. on off-grid base station sites [11].

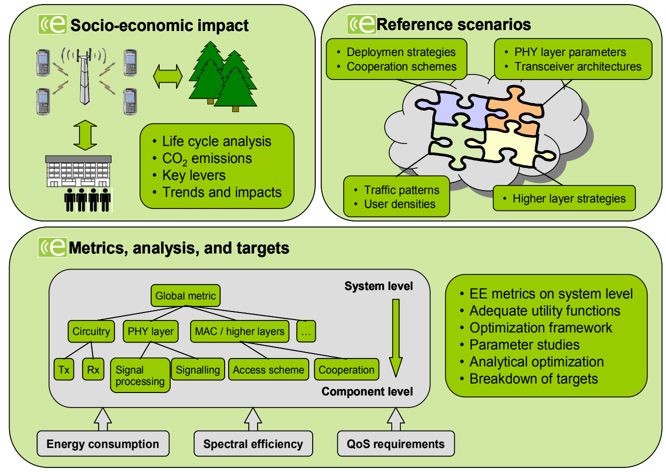

Fig. 3. Definition of energy efficiency analysis, metrics, reference scenarios and reduction targets as addressed in the EU project EARTH [12].

III. Approaches to Energy Efficiency of Wireless Communication Networks

There has been a significant interest in energy efficiency in sensor networks and multihop mesh network architectures due to the limited battery life of the communicating nodes [14][15][16]. In conventional cellular communication systems work on the energy efficiency has rather been limited to the mobile terminal with their limited battery power [17], and the energy efficiency of the infrastructure has been largely ignored.

There are several recent publications [18] that consider the issue of energy efficiency of communication systems and their components on various protocol layers. OPERA-Net [19] investigates the opportunities to improve the energy efficiency of broadband cellular networks by considering optimized cooling and energy recovery from the base stations and the optimization of the components used in communication systems. The projects PANAMA [20], ELBA [21] and Class-S [22] focus on a more efficient design of the power amplifiers in the base stations that typically still run at quite low efficiency. The Cool Silicon [23] project focuses on the optimization of individual aspects like the system architecture, communication algorithms and protocols as well as physical components in three main areas: micro/nano technology, broadband wireless access and wireless sensor networks. Mobile VCE Green Radio [24] aims at extending the efficiency studies to an energy metric for cellular and end to end communication.

However, these initiatives rather aim for selective improvements. For a rigid and systemwide solution to energy efficiency basically two approaches are possible: Either a holistic analysis of potential improvements can be undertaken based on current 4G systems or a clean slate approach with a completely disruptive redesign of wireless systems. Two such lately started approaches with leading involvement of Alcatel-Lucent researchers, EARTH [12][13] and Green Touch [25][26], will be discussed in the following.

IV. EARTH.

A consortium consisting of 15 partners from industry, academia and small and medium enterprises (SMEs) has started the EU FP7 project "Energy Aware Radio and Network Technologies" (EARTH) in January 2010 to find appropriate solutions to the energy efficiency challenge. EARTH follows a unified approach to target the whole system from an energy efficiency perspective.

The EARTH is focussing on mobile broadband networks with the future key technologies LTE (3GPP Long Term Evolution) and LTE-Advanced. Its objective is to provide tangible results such as enhanced network architectures and deployment strategies, e.g. with small indoor and outdoor cells, energy aware management mechanisms, and innovative component designs, all with respect to optimized energy efficiency. EARTH has set itself the ambitious goal to reduce the overall energy consumption of mobile broadband networks by a factor of 50% and to significantly reduce carbon dioxide emission and operating cost. A major part of the reduction will be reached during low load situations, by ensuring that the energy consumption of access networks is proportional to the traffic load. All results will be integrated into one system solution and will be validated in a real operator testbed and system simulations.

A. *NETWORK LEVEL*

Fig. 4 shows the scope of the network level oriented system work packages of EARTH.

EARTH targets significant energy savings by using new deployment strategies of radio access networks. Because of the strong decrease in signal strength with increasing distance from the base station the energy efficiency generally increases with decreasing cell size. This is limited by the fact that each base station must permanently support some basic functionality and that the effort to deploy very large numbers of small base stations may be uneconomical. A crucial task of EARTH will be to determine the ideal cell size that is expected to be significantly smaller than in conventional macro cell deployments. Furthermore, the role of repeaters and relays for energy efficient operation will be analyzed in detail, because these techniques have been introduced for capacity increase but also bring the transmitters closer to the receivers and therefore benefit from the effect discussed above.

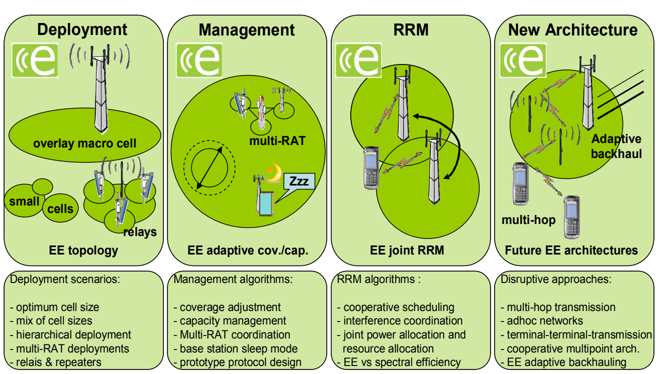

Fig. 4. Green network management tasks in EARTH.

An unavoidable consequence of reducing the cell size or of using repeaters is the stronger inter-cell interference. Avoiding interference with a frequency reuse scheme results in lower spectral efficiency. Therefore it is preferable either to coordinate the interference or to manage it at the receiver end by deploying multiuser detection strategies. These cooperation strategies are well studied for their spectral efficiency ([28] and references therein) and can provide starting points to evaluate the energy efficiency of these deployments. As already mentioned, this comes with an associated cost of higher computation energy at the receiver end and in terms of increased energy for control message signalling.

Small cell deployments and hierarchical deployments with overlay macro cells may lead to a situation where many cells are hardly loaded. In particular, this applies to situations where the load varies over different times of the day. In high load situations the best solution may be to provide coverage using many small cells, whereas in low load situations cells with only few users can be turned off by the network management. Self-organizing mechanisms and signalling protocols are required to detect such situations in order to redirect users and to adjust the network coverage, e.g. by changing antenna tilt angles.

EARTH will also analyze and exploit the potential arising from cooperation of radio access technologies, where one technique is more energy efficient for certain types of services than others. From an algorithmic point of view, multi-RAT radio resource management involves cooperative scheduling and interference coordination algorithms. A relative decrease in quality of service can be traded off against a decrease in energy consumption without jeopardizing the user experience. Some initial studies on cooperative scheduling [29], power and radio resource management [30][31] are available for specific systems and simplified scenarios.

The project also includes new architectures such as networks with multi-hop transmission or ad-hoc mesh networks. Finally, adaptive provisioning of backhaul capacities depending on the momentary needs can reduce the energy consumption.

B. *COMPONENT LEVEL*

A huge potential for energy saving is related to the power amplifiers, which consume the largest part of power in the base station (Fig. 5).

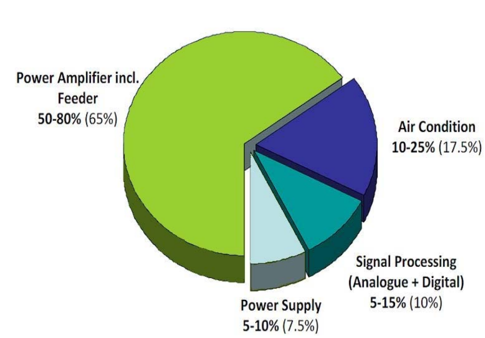

Fig. 5. Breakdown of power consumption in radio base stations [32].

Also on the component level (Fig 6) EARTH follows an integrated approach, addressing advanced transceiver architectures that interface to the resource and network management. Next to the optimization of the transceiver power efficiency itself, this enables power savings defined on the network level such as a change of the radio frequency band as well as dynamic changes of the mobile radio standard by supporting cognitive radio approaches.

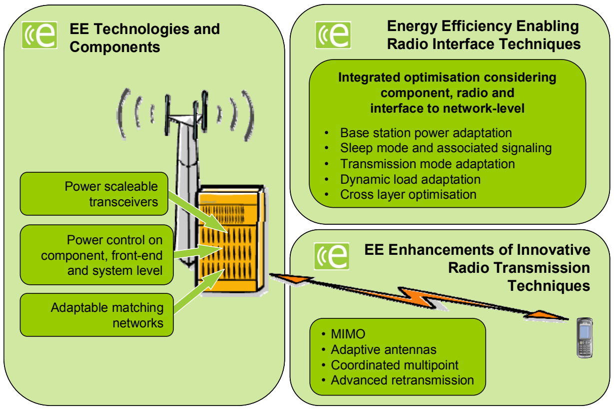

Fig. 6. Green radio.

The recent evolution of mobile communication systems from GSM to the Long Term Evolution of 3GPP leads to a continuous rise of the peak-to-average power ratios (PAPR), which will further increase by using multicarrier and multi-standard solutions. The undistorted transmission of such signals requires operating the power amplifiers on average levels far below their maximum signal output power and thus strongly limits their power efficiency.

To be up to the requirements of an energy efficient system, future power efficient transceivers need more complex amplifier architectures with improved energy efficiency combined with measures to reduce the signal PAPR parameter. By implementing new interfaces and an algorithmic intelligence, the transceiver can adapt to the system load by analyzing the incoming base band signals For example, the average signal power can be estimated in advance and an adjustment of supply voltages can be performed. Also it is possible to switch off some of the several baseband boards or other components. This capability of the transceiver allows it to follow energy saving measures on a system level with a minimum of signalling between different layers.

Another source of energy wastage is due to reflections at the antenna back to the transceiver. These reflections depend on the impedance matching of the amplifier, which in turn depends on the power level and the antenna environment. Active tuning of the matching network can cancel these reflections.

Finally, a number of new transmission techniques can be exploited for energy efficiency transmission of the data over the air, such as MIMO (multiple input multiple output), adaptive antennas, coordinated multipoint transmission mechanisms, and advanced retransmission techniques. On the lower layers, physical parameters such as the amount and frequency of broadcasted pilot signals will be addressed to minimise the system overhead in the radio transmission.

V. Green Touch

A different approach to energy efficiency is taken by the Green Touch Initiative that has recently been announced [27]. Starting from principles of information theory and computer sciences Green Touch has analyzed the fundamental limits of global communication systems [26]. It turns out that fundamental physical limits would allow designing a system that is several orders of magnitude more efficient than today's systems. However, downwards compatibility, deployed infrastructure and performance of available technology hinder the realization. Alcatel-Lucent Bell Labs have taken the initiative to shift these barriers to unprecedented energy efficiency and has formed a consortium of equipment manufacturers, network operators and leading academia. The aim is to completely rethink communication systems, to analyze the theoretical potentials, to tackle fundamental research in information theory and electronic devices. Within five years the consortium, that is still open to further members, wants to demonstrate proof-of-concept to build confidence in ICT industry in such completely new system designs.

A. NETWORK LEVEL

The potential of base stations with smaller cell size has been discussed above. But already today it is critical for operators to acquire new sites and a deployment with one or two order of magnitude higher density of sites seems impossible from management and configuration as well as from economic point of view. Fundamental research is required to provide highly scalable architectures and management systems.

Following the introduction of MIMO into the 4G system standards, the next level of complexity in wireless transmission must be addresses for future systems. Cooperative network-MIMO [33] is an example for such approaches. Basic information theoretical and radio engineering issues need to be solved.

B. COMPONENT LEVEL

In traditional systems the power demand of the power amplifier is dominating the energy consumption (fig 6). This makes improvements of amplifier efficiency the most obvious lever for energy savings, e.g. in the EARTH project. However, for future systems with very small cells or with cooperative multi-point transmission the required transmit power per base station will be orders of magnitude smaller than for today's macro cells. This implicitly reduces the energy consumption of DC power supply and dispenses air conditioning. At the same time, the computation demand increases for cooperative transmission, e.g. in advanced MIMO algorithms. Both effects lead to a situation where the weights in figure 5 are changing fundamentally and signal processing is dominating the power consumption. While the scaling of Silicon based processor efficiency with the help of Moore's law is approaching physical limits, wireless communication demands for new low-power and high-speed electronics with new processor designs and break-throughs in material technology.

Finally, future systems may overcome the limits of fixed infrastructure and be based on highly distributed and meshed autonomous devices. Only a concerting push towards fundamental limits will enable affordable and deployable solutions, that seem out of reach today.

VI. CONCLUSION

Future mobile telecommunication systems have to contribute to reductions in energy consumption and greenhouse gas emissions of ICT and to enable massive increase of utilisation and data rates. Quite some progress has already been achieved in the last decade, but there is a big need for a holistic approach and research on system level innovations. EARTH is a European research project that has set to improve 3G and 4G systems and to provide metrics and design rules for energy efficient deployments. On the component level, strategies will be developed to dynamically adapt the energy consumption to the actual system needs.. The ambitious goal of EARTH is to provide within 30 months solutions that cut the energy consumption of mobile broadband networks by 50%.

While this approach aims to drastically improve state-of-the-art systems, the Green Touch Initiative has detected that much higher potentials are available for a clean slate redesign. Complexity, economic reasons and limited features of electronic devices hinder the development and economic deployment of innovative systems close to the fundamental limits. Green Touch is tackling these barriers to deliver new concepts and first demonstrations within five years time. It is expected that such proof of concept will create an impulse in ICT industry to pursue these break-through results and design deployable products by the end of the decade.

Both approaches share the metrics and the overall aim of energy efficient wireless access systems. They follow different time limes and different constraints determine the possible solutions. Thus they are complementary and the simultaneous effort on both research approaches will enable a sustainable deployment of future broadband mobile communication systems with respect to carbon dioxide emissions as well as to operational costs.

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