Energy Savings in Mobile Networks Based on Adaptation to Traffic Statistics

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The traffic load in mobile networks is very unevenly distributed both over time and over cells. Excessive waste of energy occurs in low traffic situations since the radio system is optimized for maximum load. Drastic improvements can be achieved by adapting to the actual traffic demand. The solutions we introduce below rely on automatically switching off unnecessary cells, modifying the radio topology, and reducing the radiated power with methods such as bandwidth shrinking and cell micro-sleep. The challenge is to maintain reliable service coverage and quality of service (QoS) in the related area, while simultaneously consuming the lowest energy. The self-organizing network (SON) supports proper selection of the appropriate energy saving mechanism and automatic collaborative reconfiguration of cell parameters with the neighbor cells. © 2010 Alcatel-Lucent.

Introduction

Traditionally, mobile communication networks have been designed for maximum throughput and maximum spectral efficiency. With the introduction of new access technologies, such as Universal Mobile Telecommunications System (UMTS), High Speed Packet Access (HSPA), and Long Term Evolution (LTE), and with notably rising data volumes in mobile communication networks, operators have deployed more and more equipment in the field. Today, the energy demand for a major mobile network is on the order of several thousand gigawatts per hour per year; e.g., Vodafone's global energy consumption was about 3000 GW/h in 2007/8 [21]. With rising energy prices, this has led to a situation where energy expenses equal around 18 percent of network operational cost in European markets and even more in developing countries, where diesel fuel is used to power off-grid radio base stations [21].

Besides this operator cost issue, the rising energy consumption of mobile networks also contributes to the global emission of greenhouse gases and to global warming. Mobile network infrastructure (without mobile devices) emitted 64 Mtonns of CO_2 in 2002 and increases are projected through 2020 to 178 Mtonns [9]. Both cost and climate issues of mobile networks have recently drawn significant attention to the improvement of their energy efficiency in research initiatives [12, 16, 24] and conferences [18, 26]. Network operators have announced reduction plans for their energy usage [27] and equipment manufacturers have reported a significant increase in base station power efficiency [6, 8].

The major source of power consumption in mobile networks stems from the radio base stations [20]. Therefore, power saving methods developed and deployed today mainly focus on three areas:

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Panel 1. Abbreviations, Acronyms, and Terms

3D—Three-dimensional
3GPP—3rd Generation Partnership Project
64-QAM—Higher order quadrature amplitude modulation scheme
AC/DC—Alternating current/direct current
CDF—Cumulative density function
E^3—End-to-end efficiency
EARTH—Energy Aware Radio and Network Technology
eNB—Enhanced NodeB (i.e., 3GPP LTE base station)
EV-DO—Evolution data optimized
GSM—Global System for Mobile Communications
HSPA—High-speed packet access
IEEE—Institute of Electrical and Electronics Engineers
LTE—Long Term Evolution mobile communication standard
LTE-advanced—Enhancement of the Long Term Evolution mobile communication standard
OAM—Operations, administration, and maintenance
OFDM—Orthogonal frequency division multiplexing
QAM—Quadrature amplitude modulation
QoS—Quality of service
RF—Radio frequency
RRM—Radio resource management
SINR—Signal-to-interference-plus-noise ratio
SON—Self-organizing networks
UMTS—Universal Mobile Telecommunications System
WLAN—Wireless local area network

1) increasing the power amplifier efficiency [15], 2) minimizing the up to 50 percent feeder losses in the radio frequency (RF) cable between the power amplifier and the antenna (e.g., by using remote radio heads), and 3) avoiding air conditioning in the cabinet (e.g., by employing fresh air cooling). All of these methods limit improvements to individual components. However, future approaches for energy efficiency that also take aspects of system and network management into account are currently still at the research level [14, 17].

In this paper, we discuss the energy saving potential of network adaptations to traffic demands. Currently, networks are designed for maximum expected throughput and are optimized for operation at full load. However, it is well known that real networks are seldom fully loaded. Both over time and from base station to base station, there are significant variations in traffic load. The power consumption of installed base stations today is only weakly dependent on the amount of data transmitted [11]. Only very recently have power saving mechanisms been introduced that partially adapt to low traffic demand, allowing power to be reduced by around 25 percent [7]. Special capacity cells or sectors that are deployed to take over peak traffic load can be turned down completely in low traffic conditions, e.g., during the night, but this requires a great deal of network management and manual interaction of trained personnel to avoid coverage holes in the network.

In the following section we will discuss typical traffic statistics and the related energy saving potential. Different methods can be applied to dynamically adapt the networks to the actual traffic load and service demands. The next section describes four selected approaches. On the one hand, traditional radio resource management (RRM) can be extended to a new resource management paradigm that schedules resources in an energy efficient manner and can turn off parts of the base station hardware to implement a power saving mode with a fast wake-up response. On the other hand, parts of the network can be reconfigured; e.g., a sectorization or coverage scheme may be adapted. Such concepts require coordination between neighboring base stations and thus require deployment on a longer-term time scale. Further, these concepts demand a paradigm shift for operations, administration, and maintenance (OAM) towards dynamic and automatic network management with self-organizing network (SON) functionality, self-learning, and intelligent decision making. In the last section of the paper we present RRM-based concepts for energy savings, as well as concepts for energy aware and self-organized dynamic radio network

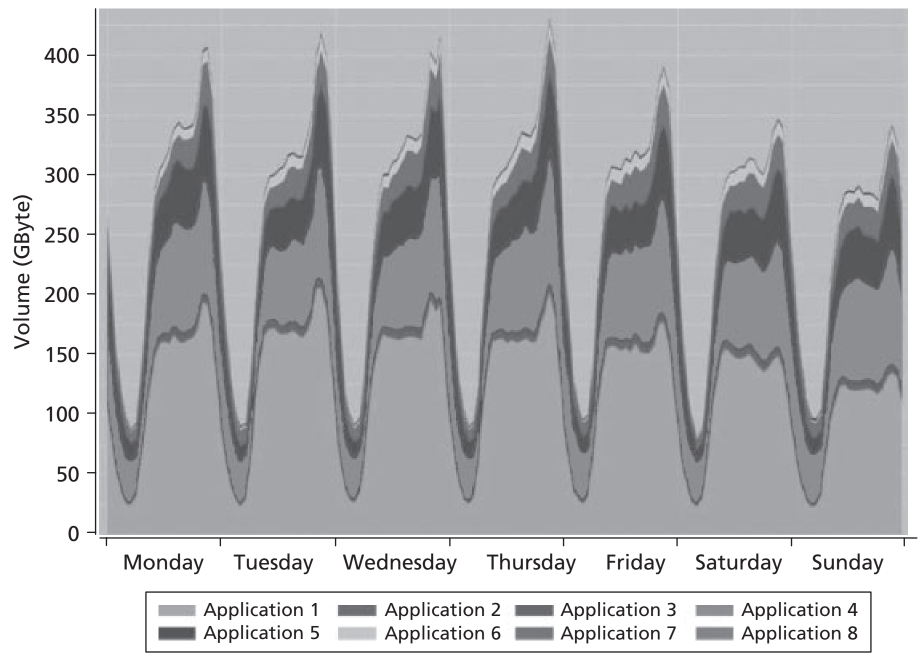

Figure 1.
Weekly traffic variations of a real mobile network, measured by a network monitoring tool.

reconfiguration including simulation results. Finally, a conclusion summarizes the potential of the presented energy saving methods.

Energy Saving Potential in Network Traffic Characteristics

Network operators observe strong variations in traffic patterns at their network base stations. Traffic load has by nature a stochastic characteristic and reveals variations in time over days and weeks. In addition, the traffic demand varies strongly by location and requires different cell site planning. In urban areas, typical cell site distances are around 500 meters to provide high capacity, and are limited by site rental cost and interference. In rural areas, population density is low and one base station can cover several square kilometers, limited by path loss and noise rather than by traffic capacity. All of these non-uniformities and their impact on energy consumption and the potential for energy savings will be analyzed.

Temporal Network Traffic Characteristics

Traffic is subject to fast stochastic variations superimposed with typical changes in user behavior over hours and days. **Figure 1** shows traffic volumes for voice and data applications [5] as measured by a network monitoring tool during a one week period. The traffic volume shows a regular pattern over the day with low traffic periods during night hours and a peak during evening hours when people are at their leisure using their mobile devices for phone calls and for surfing the Internet. Traffic variations hold also on a weekly time scale, as the weekends have different traffic demands from workdays. Network capacity is designed to provide a good user experience and therefore must guarantee a low probability of call blocking and call dropping. This design leads to the situation where cells and networks are seldom under full load. But today, most base station hardware is not able to adapt to changing traffic patterns. Power amplifiers and signal processing boards operate continuously, and even without any user traffic, power demand is only fractionally lower than at full load [17]. **Figure 2** demonstrates that about a third of the time the load is very low and on average the load is about 50 percent of the maximum load (which in turn is typically 30 percent to 50 percent of the installed hardware capacity).

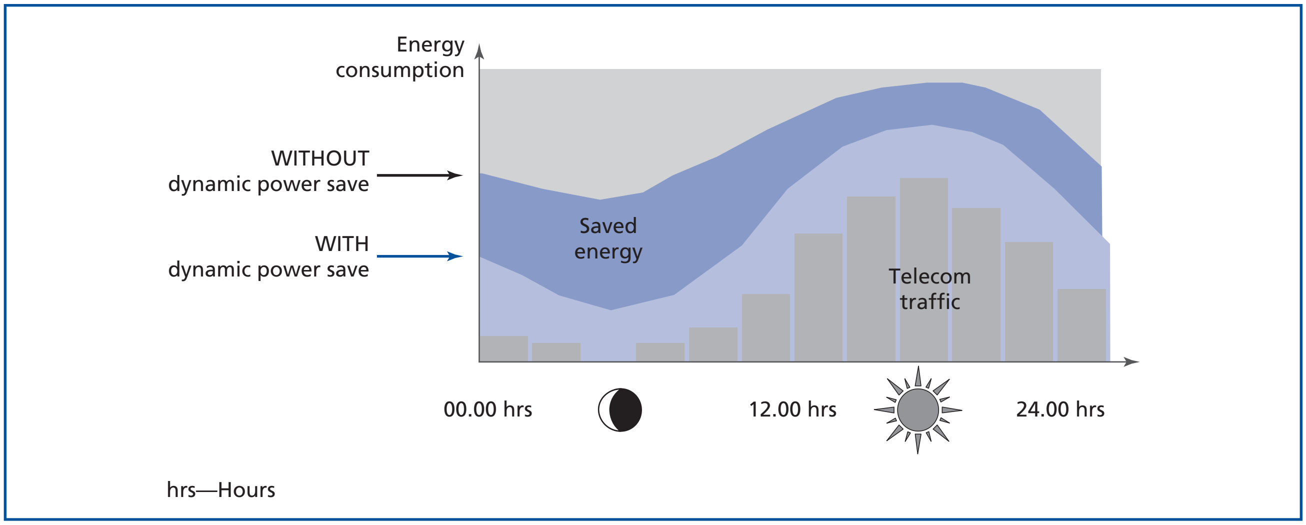

Figure 2.
Energy saving potential of mobile base stations that can adapt their power demand to the actual traffic load.

When power amplifiers [15] and other hardware components are introduced that can be operated at different power levels, or parts of the hardware can be shut down temporarily according to the traffic load, obviously a high power saving potential can be addressed. Figure 2 shows the potential energy savings when adapting the power consumption to the actual traffic load. It is estimated that the average base station energy demand can be reduced by at least 50 percent by such methods [14]. Strategies to utilize this potential, both on short time scales of milliseconds to minutes as well as on longer time scales of hours and days, are discussed in dedicated sections of this paper.

Spatial Network Traffic Characteristics

As previously mentioned, traffic demand per unit area is much lower in rural areas than it is in cities. Within cities traffic patterns are distributed further, with high volume in "hot spots," such as shopping areas and squares. **Figure 3** provides an overview of traffic distribution in a metropolitan Canadian evolution data optimized (EV-DO) network [22]. In the example, 80 percent of the cell sectors carry only 20 percent of the total traffic, and only 10 percent of the base station sectors carry more than 500 MByte per day (based on data from [22]). For example, Vodafone reports that only 5 percent of its sites in Europe have more than 90 percent utilization even during busy hours [10].

From the point of energy efficiency, it is thus beneficial to deploy different categories of base station hardware, matched to local traffic demand. In Global System for Mobile Communications (GSM) and UMTS networks, operators have already deployed large overlay macrocells for the basic coverage of urban areas in addition to small capacity cells (outdoor microcells and indoor picocells). In future deployments, such as LTE and LTE-advanced, wireless repeaters and relay nodes with wireless backhauling will also be deployed.

In these deployments, the system capacity can be designed to serve the local traffic demand without overprovisioning the surrounding area with macrocells. While this design allows for energy efficient network operation during high local load, these additional small cells and relays in a hierarchical deployment each add to the power demand of the network. However, due to the daily variations of traffic as previously described, we can expect significant potential savings from completely switching off capacity-cells or sectors of cells during low load times, when the macrocells can take over the remaining local traffic, or even from switching off sectors in the macro layer. Such reconfigurations of the coverage scheme will be analyzed in the detailed section on energy saving mechanisms.

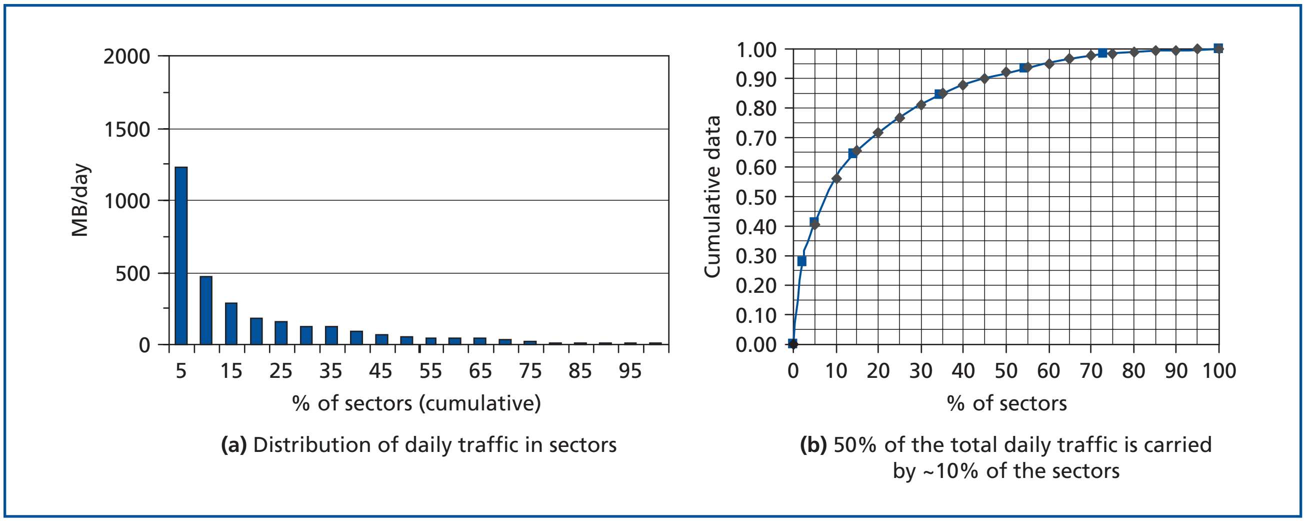

Figure 3.
Traffic distribution in a metropolitan network. For the cumulative distribution in the diagrams, sectors have been sorted by decreasing amount of traffic.

Energy Savings Strategy and Approaches

To save energy, different strategies can be applied. They differ by their reaction time and complexity with respect to the impact on neighboring cells. Here we distinguish short-term strategies that can be decided and executed based on a local scope, from long-term strategies that will require reconfigurations in the network. The latter implies workflows for the negotiations with the neighbors and adaptations of the operational parameters in them and is hence the slower and the more signaling-intensive of the two approaches. Existing mechanisms for radio resource management and self-optimizing networks are used as support functions for the long-term strategies; e.g., handover and load balancing mechanisms can be leveraged for emptying cells, and tilt and power optimization techniques can be used for maintaining coverage, since both mechanisms are transparent to the users.

The amplifier power supply uses 60 percent to 80 percent of the energy consumed by base stations [20]. In conventional amplifiers this power is independent of the amplifier input signal, i.e., of the current traffic load. With current implementations, base station energy consumption is only moderately correlated to traffic load: i.e., in the best scenario, energy consumption is reduced by 25 percent in low load (<10 percent load). The key approach to saving energy is to make the power consumption proportional to the traffic load, either by implementing a partial shut down of amplifiers as discussed in this article, or by employing enhanced power amplifiers. An overview of the latter is provided in [15]. During power-off of the amplifiers, further power savings can be achieved by also switching off the baseband signal processing, and indirectly, in the AC/DC power conversion and in the cooling fans.

From the energy consumption point of view, low loads should be avoided. Instead, two types of mechanisms should be applied to reduce idle and unused capacities. As a first step, all energy-consuming equipment should implement power-reduction mechanisms while in operational mode, adapting to the actual load (short-term strategies). Second, the traffic should be reshuffled to a smaller number of highly loaded sectors or processing entities, and the others should be switched-off (long-term strategies). However, the coverage and the quality of service must not be degraded.

Two short-term and two long-term approaches and the support provided by SON are further detailed in this document.

Short-Term Approaches

The first short-term approach, called micro-sleep, works in the time domain and switches off a sector on a time scale of milliseconds. The energy savings are applied very frequently for a short time by scheduling the load over time in a fully loaded period followed by a non-loaded period. This approach is bounded by the real-time constraints of the services and the switch-on time of the equipment. See the section on micro-sleep for details.

The second short-term approach, called dynamic spectrum reduction, works in the frequency domain. This approach reduces the width of the emitted spectrum depending on the current load situation. This reduction is beneficial because a smaller spectrum can be emitted with greater energy efficiency by suppressing the pilots in the outer parts of the spectrum. Dynamic spectrum reduction is also detailed in a later section.

Long-Term Approaches

The third and fourth approaches discussed here are long-term approaches. They save energy by switching-off whole sectors or cells for longer periods of time, e.g., overnight. During these times, the neighbor cells and sectors must provide sufficient service to the affected area and carry the load from the sectors that have been switched off. This frequently requires adaptations and compensating mechanisms in the neighbors, e.g., for optimizing coverage and capacity by automatic antenna tilting or for updating the neighbor cell list. These adaptations must be at least partly negotiated and coordinated. Also, algorithms are required to detect rising capacity needs. For example, such mechanisms could be based on traffic load within the compensating neighbor cells or on a statistical traffic forecast. They have to trigger a wake-up mechanism that must remain operable in the switched-off cells.

Switching off a whole sector or cell has a significant impact on saving energy. It releases the baseband processing entities and the power amplifier since no system information and pilots need to be transmitted. Indirectly, the energy consumption for air conditioning and DC power conversion is also reduced. Before switching-off a cell, its current load needs to be shifted to another cell. This shift is not restricted to cells of the same technology. If available, supported by the terminals, and if the services can be supported there, a handover to another radio access technology is also possible.

This third approach is detailed in the section on turning-off individual sectors.

The fourth approach applies different changes to the sector topologies for saving energy. The frequency reuse scheme is reorganized for low load situations, including the mapping of antennas to amplifiers, towards topologies with less mutual interference. This scheme is detailed in the section on different radio topologies.

All long-term approaches benefit from self-organizing mechanisms as described in the following section.

Support of Long-Term Approaches by SON

Greater benefit with respect to energy consumption can be obtained by the mechanisms described above if they are combined with several required self-organization mechanisms integrated into a distributed system. An overview on SON mechanisms will be provided in a subsequent issue of this journal [25]. Here we just briefly introduce the required components and system architecture and the application of SON to energy saving, e.g., forcing mobile handover to neighbor cells or to cells of other available radio technologies in order to empty a sector or cell before switching it off, or unbalancing the load between cells in order to enable short-term energy saving mechanisms in the low-load sector. The distributed system approach chosen follows the concept of autonomously acting network nodes, where nodes communicate to make the best decision for the network [19, 28]. Such a system, with a distributed node configuration, process control, and database, enjoys a lot of natural advantages. For example, a flat hierarchy eliminates a long communication path between network elements and OAM. In addition, network management requirements and manual intervention by trained personnel is sharply reduced. Furthermore, distributed data storage and prediction mechanisms can shorten decision times, thus allowing greater exploitation of long- and short-term energy savings measures. Also, single points of failure are avoided and network management scalability is improved. Ergo, the described approach implies a system architecture that is capable of supporting all benefits for energy savings, as well as guaranteeing a scalable,

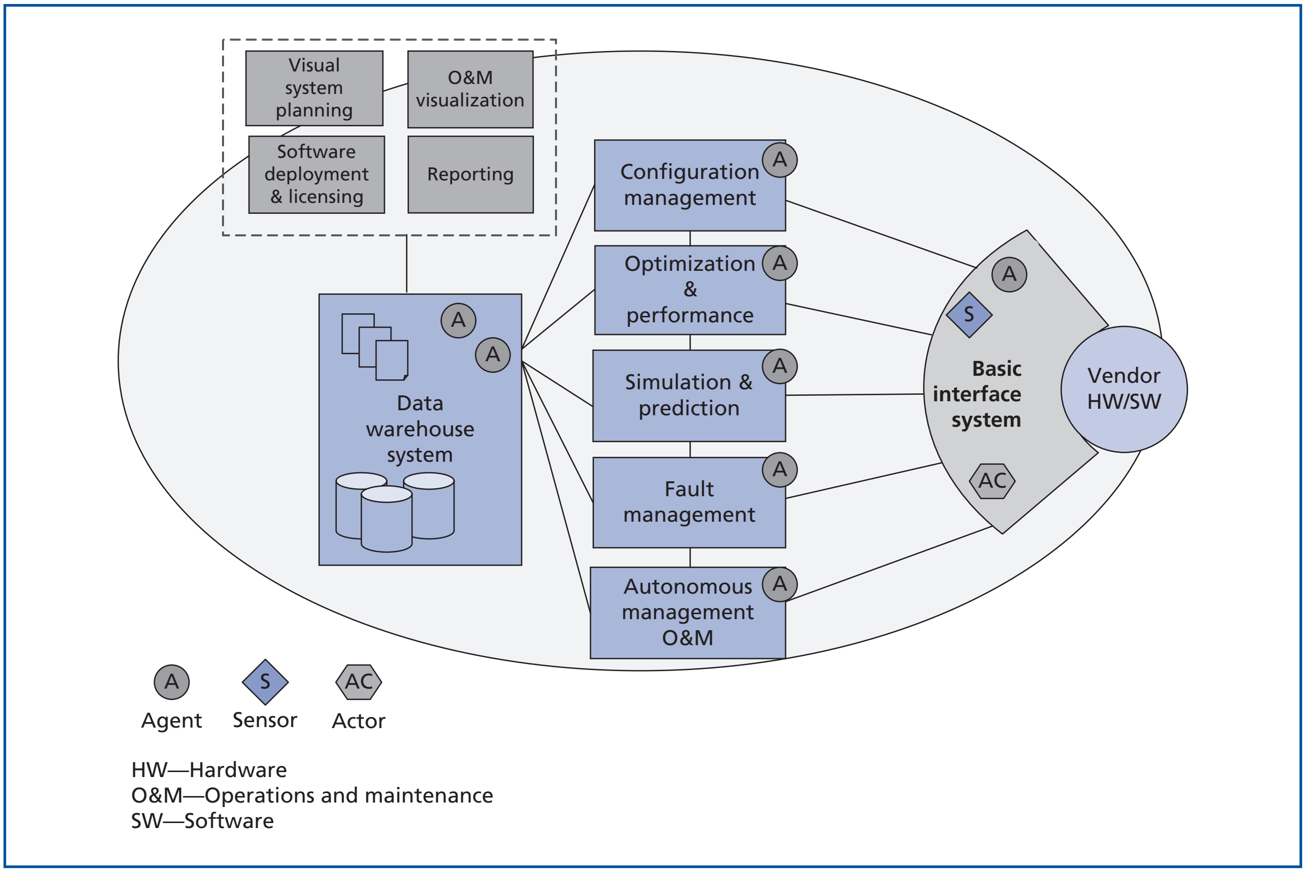

Figure 4.
Subsystems of the proposed architecture.

secure, and reliable system. The corresponding software architecture is sketched out in **Figure 4**. The primary building blocks for energy saving mechanisms are configuration management, optimization and performance, prediction and simulation, and a data warehouse subsystem.

The configuration subsystem revises the enhanced NodeB (eNB) hardware configuration with respect to energy saving mechanisms, sets the radio parameters based on a chosen traffic profile, informs neighbor eNBs, and coordinates the changeover between old and new values of configuration parameters. The optimization and performance subsystem recognizes energy optimization issues and chooses the best time for the application of an energy saving mechanism. To do so, a set of intelligent algorithms and agent-based approaches are used for performance calculation and performance optimization across neighbors. The prediction and simulation subsystem is responsible for prediction of traffic, for prediction of system parameters and system behavior, and for simulation by predefined stimuli. It estimates which hardware entities can be made superfluous and informs the configuration subsystem that, in turn, reconfigures the chosen entities. The distributed data warehouse subsystem provides necessary information about the neighbor network nodes. It consists of dedicated *fact databases* where traffic measurements and traffic and configuration profiles are collected and *intelligence database* supporting self-learning algorithms and parameter adaptation. All of the subsystems mentioned above operate in a coordinated manner executing the loop for energy optimization. The loop consists of these five steps:

1. *Preparation.* Collect and analyze terminal measurements, including location information. Describe the

traffic in a traffic profile as a function of time and density in the context of the topology of the area. The traffic profiles are then applied by SON detection algorithm for energy saving.

2. *Detection.* Identify the system state that is relevant for energy saving purposes. In this step, the traffic profiles, the short time cell load, and performance indicators such as radio link failures and call drops are examined and determined. Rule-based intelligent algorithms are used, which are supported by the *expert database*.
3. *Decision.* Select an appropriate energy saving scheme and means to execute the chosen scheme. (Examples are provided in the next section.) Before the chosen energy saving schema is put into operation, some cell preparation must be done, for example, active terminals must be passed to the neighbor cells. In this step, a communication with related neighbors is initiated, which seeks a collaborative and synchronized reconfiguration of the system.
4. *Execution.* The energy saving scheme is implemented.
5. *Feedback and learning functionalities.* The success of the energy saving activities is measured and stored for later reuse, together with the context of where and when it was applied. Using this feedback, the models contained in the detection and the decision logic are also adjusted to achieve the best fit between prediction and real evolution.

The workflow of this mechanism and its application in the subsystems is illustrated in **Figure 5**.

Detailed Description of the Selected Energy Saving Mechanisms

This section assesses concrete measures to save energy in cellular mobile networks. We first describe two energy aware resource management approaches for base stations that do not require system level reconfiguration. Afterwards, we analyze the energy saving potential of two SON operated reconfiguration schemes by means of simulations. The first investigates removal of individual sectors or cells from a network, while the other examines the effect of larger modifications to the radio cell topology. Radio topological modifications in this context refer to changes in the frequency reuse schemes and the number of sectors per cell.

Micro-Sleep

Sleep modes are well known in today's wireless telecommunication systems. In an IEEE 802.11 wireless local area network (WLAN), the access points (i.e., base stations) periodically indicate to mobile terminals if buffered data is available for transmission. This notification enables the mobile terminals to fall into a sleep mode and enter the power consuming transmission mode only once during each "delivery traffic indication message" period. In 3rd Generation Partnership Project (3GPP) systems, idle mode procedures are used to reduce signaling and signal processing when no data service is running and paging signaling is used to wake up the mobile terminal. In both cases, the power save mode is used to maximize the uptime of battery-driven mobile devices while the base station is permanently active, sending beacons and system information to maintain the connection between the mobile terminal and base station, to synchronize them, and to enable moving terminals to detect fading channels and to scan for neighboring base stations.

Next-generation energy efficient systems will also have to introduce power save modes for the base station when the system load is low. The base station scheduler is modified to aggregate downlink traffic and uplink grants, so that the length of gaps between transmissions is increased to enable micro-sleep for the signal processing and power amplifier. Also, the sending of system information can be reduced or only sent on request. But such approaches require changes in standardization and are limited to micro-sleep of up to 100 milliseconds by the speed of mobility mechanisms. Ongoing real time services with high quality of service requirements force the base station into even shorter sleep modes, with transmission of data packets at least every 20 milliseconds. Furthermore, uplink signaling in the random access channel needs to be restricted to the times when the base station is not in sleep mode and this requires additional signaling and synchronization. Backwards compatibility requirements of existing mobile devices hinder such approaches for radio access technologies that are

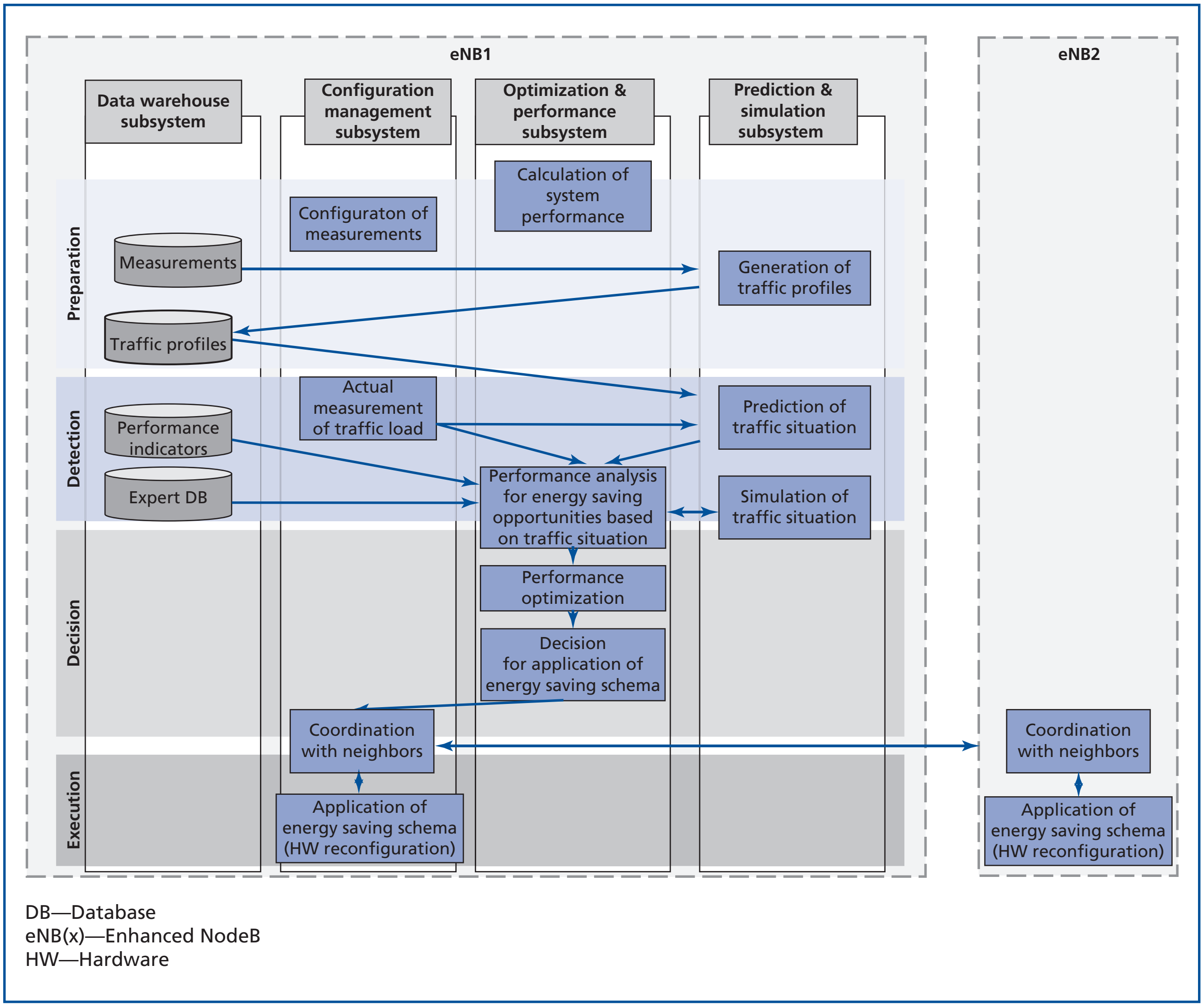

Figure 5.
Simplified workflow of applied energy saving mechanism.

already on the market. LTE-advanced is therefore a first candidate for deployment of base station micro-sleep. These developments and standardization contributions [4] are one of the objectives of research projects such as Energy Aware Radio and Network Technology (EARTH) [14].

Dynamic Spectrum Reduction

As an alternative to time-based micro-sleep, energy consuming resources can be managed on the frequency axis. The data capacity of transmission systems has been increased by the introduction of broadband systems with channel width of 5 MHz for UMTS, 20 MHz for LTE, and up to 100 MHz for LTE-advanced. To achieve a high data modulation mode (e.g., 64-quadrature amplitude modulation [QAM]) in a multipath propagation environment, a comprehensive and dynamic knowledge of the channel response is required. Especially for orthogonal frequency division multiplexing (OFDM) systems, this challenge is solved by using pilot signals that are spread over the time and spectrum resources. The diagram in **Figure 6**, based on data from [3], illustrates usage of resource blocks for system channels and pilots. 10 percent to 20 percent [3] of the full load transmission power is used by system information channels and by these pilot

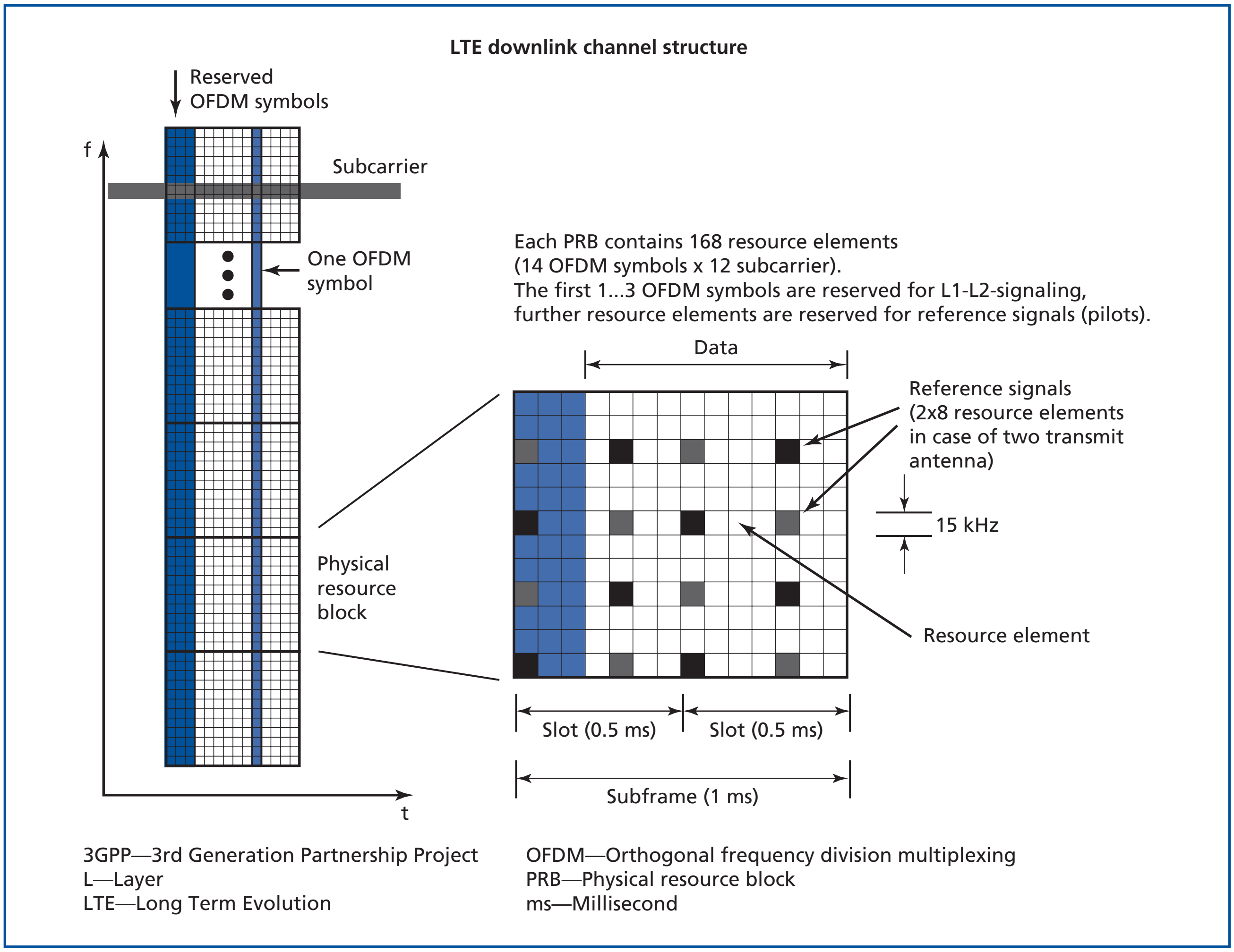

Figure 6.
Usage of resource blocks for system channels and pilots in 3GPP LTE system.

signals that need to be sent even when no user data is transmitted.

Basically, the power used for pilot signals is increasing linearly with the system spectral bandwidth. Cognitive radio approaches such as end-to-end efficiency (E^3) [13] and LTE-advanced standards allow for the adaptation of bandwidth, but these approaches require a system reconfiguration and are meant for long-term changes only. Instead, we propose to make the base station scheduler energy aware and to concentrate the traffic on a fraction of the full bandwidth during low traffic situations, typically around the central part of the system spectrum where the system channels are located. For interoperability and backward compatibility, we must assure that any reduction of the spectrum is also respected by radio resource management. One approach is to reduce the power of some of the pilot signals stepwise, so that the conventional RRM algorithms assume a fading of these channels and refrain from their usage both in uplink and downlink. This approach will be further studied in the EARTH [14] project to quantify the savings potential and to study the implications of standardization. We estimate that power consumption in low load situations can be reduced by 50 percent and by 20 percent on average.

Turning Off Individual Sectors

This approach examines the idea of switching-off appropriate radio cells or sectors in order to save energy at times of low network load. Analytical studies of this concept reveal savings on the order of 20 percent without using antenna tilting [23]. Here, we provide results of a simulation study including antenna tilt angles. The main challenge of this approach is to maintain at least a basic capacity over the whole coverage area of the cell or sector that is being switched-off. This area is termed the compensation area in the rest of this section. As a metric for coverage and capacity, we use the "geometry" in dB, which is defined as the long-term ratio of signal to noise and interference. The geometry is calculated for the compensation area. In order to facilitate the comparison of multiple simulated scenarios, all geometry statistics are condensed to their mean value (representing the average situation of the sector) and to the 5th percentile (representing the situation at the cell edge). A geometry of –3dB and above is assumed to be sufficient for basic coverage.

This study assesses the effect of a cell or sector being switched-off and compensation occurring through the tilting of antennas in the neighboring cells. For a simulation scenario, we use the usual hexagonal 3GPP configurations [1, 2], referred therein as "case 1 3D antenna." This is a simulation scenario consisting of 19 three-sectorized cells arranging themselves in two concentric circles around a center cell. A technique called wrap around pretends each individual cell is a center hexagon, and thereby prevents border effects in interference modeling. Between any receiver/transmitter pair, a channel is modeled. This channel consists of a propagation model, a 3D antenna model, and an optional shadow-fading model. A virtual mobile terminal is used to collect information within the simulated network. For that purpose, a channel is set up between any sector and any mobile device. Based on its list of channels, each mobile device calculates the signal of each sector and selects the sector with the strongest signal as the server. After the serving sector is identified, the geometry and the Shannon capacity are calculated. The term Shannon capacity refers to the Shannon Hartley theorem, which describes the theoretical upper limit of the capacity of a communication channel. The simulator was constructed based on simulation libraries provided by Bell Labs Germany and the University of Stuttgart. **Table I** summarizes the most important parameters of the simulation model.

Table I. Important simulation parameters.

Parameter	Assumption
Cell type	3-sector cloverleaf or 1-sector omni-directional
Number of cells/sectors	19/57 or 19/19
Propagation model	148.1 + 37.6 * log10(d) (distance d in km)
Carrier frequency	2 GHz
Minimum UE-BS distance	35 m
BTS height	32 m
UE height	1.5 m
UE antenna gain	0 dBi
Antenna horizontal pattern	70 degree 3 dB beam width, 25 dB backward attenuation
Antenna vertical pattern	10 degree 3 dB beam width, 20 dB backward attenuation
Antenna combined backward attenuation	25 dB
Antenna maximum gain	15 dBi for 3 sector, 9 dBi for omni-directional
Peak SINR	16.85 dB (allows maximum Shannon capacity of 6 bps/Hz) or unlimited
Handover margin	1 dB

BS—Base station
BTS—Base transceiver station
SINR—Signal-to-interference-plus-noise ratio
UE—User equipment

Simulator extensions have been implemented to allow switching individual cells or sectors on or off within the scenario to manipulate their tilt angles and to collect geometry data for statistical evaluation. A typical simulation run, which creates a single data point in a simulation study, selects a cell or sector of the simulated radio network, switches it off, and then reconstructs the radio network coverage by setting the tilt angles of neighboring cells. **Figure 7** depicts symmetries in a sector and in a cell. Due to the symmetries of the hexagonal network, some sectors are prominent candidates for compensation, namely,

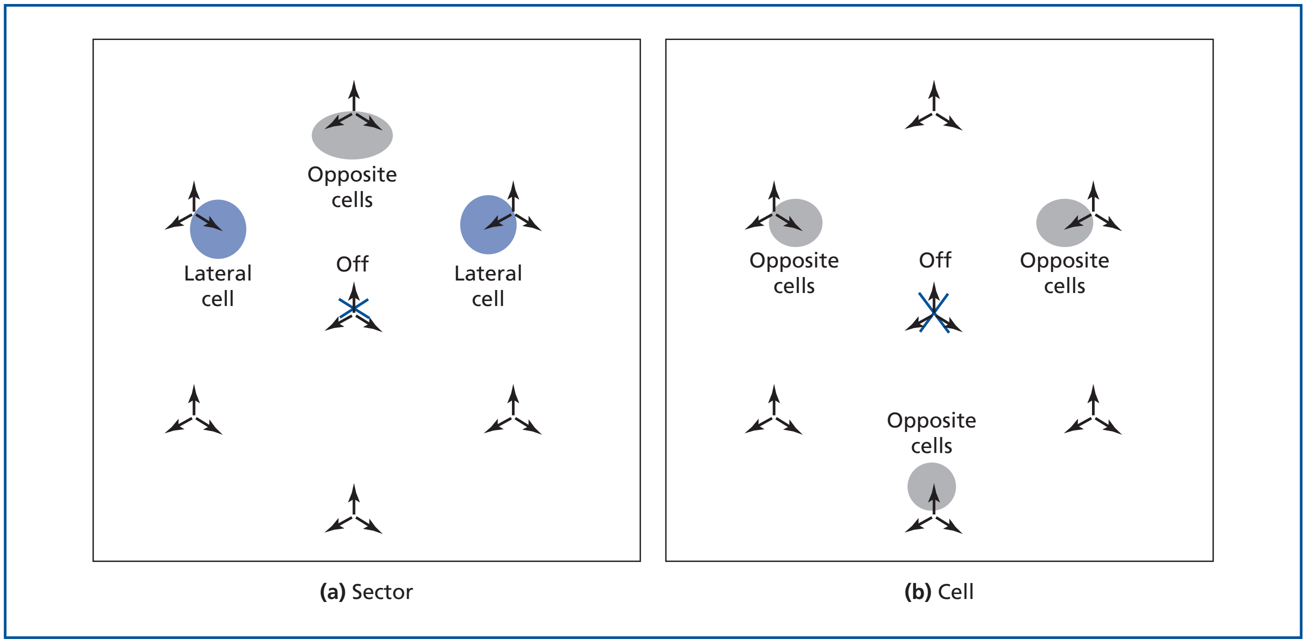

Figure 7.
Symmetries in hexagonal simulation scenarios.

the lateral and opposite sectors. Based on carefully selected combinations of these input parameters, multiple simulation runs were triggered and evaluated. Due to limited space, only a brief summary of the simulation results can be provided in this paper.

The results of the simulation study clearly indicate that network coverage can be kept intact when an individual cell or sector is switched off. **Figure 8** shows three data points referring to the outage of a sector and three more data points referring to the outage of a cell. Each data set represents the coverage of the compensation area of a fully operational network, the coverage of the same area with a single sector or cell being turned off, and the compensation achieved by variations of opposite and lateral sectors. These simulation results indicate that switching-off radio cells or sectors can be compensated by neighbor sectors in the radio network. The amount of power saved in the given scenario can be calculated from the remaining number of active cells. In our simulation scenario, a single cell switched off among 19 cells represents a savings of more than 5 percent in power consumption. More detailed studies and investigations of real deployment scenarios are required to assess the full potential of power saving with this method. Moreover, it should be noted that switching-off cells or sectors is of practical interest, as it can be readily applied to save energy in existing radio networks.

Different Radio Topologies of the Network

This section discusses modifications of the radio cell topology that go beyond switching-off single cells or sectors. The simulations here compare different network configurations against their radiated power and capacity. The goal is to assess the benefit of adaptations of the network radio topology to the network load: i.e., in times of low load, the network is reconfigured to a topology with a lower capacity and radiated power. The power consumption of different network configurations is compared against their Shannon capacity with the help of the simulator introduced in the previous section.

In urban areas, radio networks such as UMTS and LTE are typically configured to maximize their capacity. Therefore, the complete frequency spectrum is used in all sectors, which leads to clear cell edges at the cost of a high signal-to-noise ratio. Interference

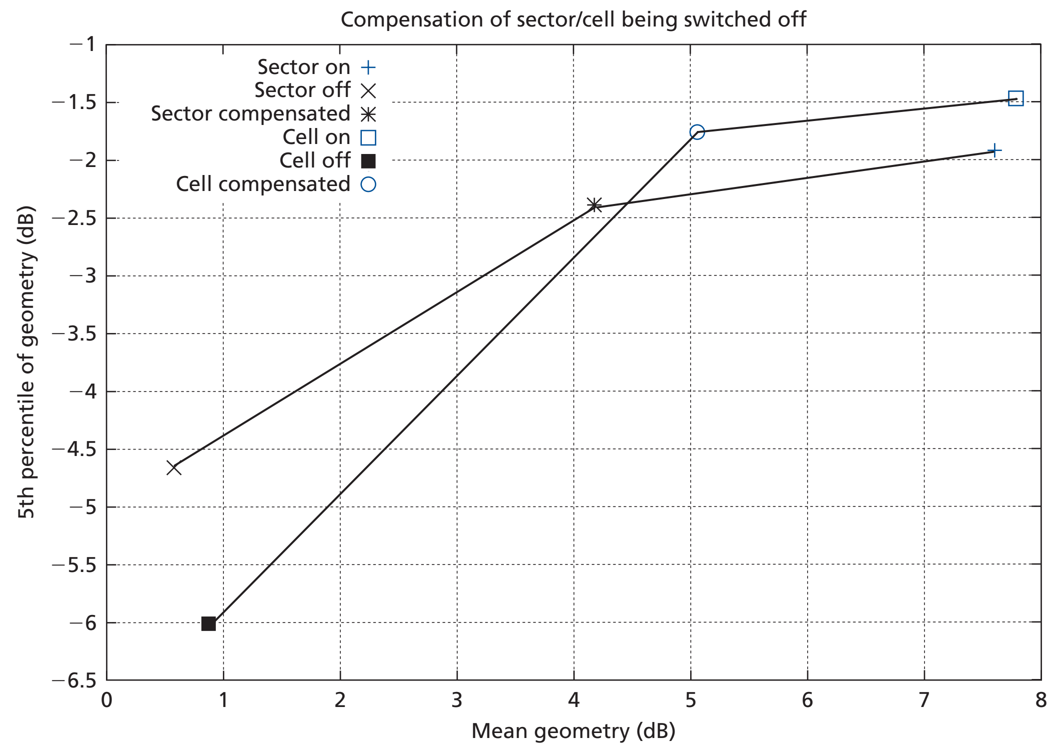

Figure 8.
Compensation of cell/sector being switched off. The compensation can achieve nearly the same cell edge performance (only 0.5 dB below the value before switch-off). The average cell geometry is reduced by 3 dB (cell-off) to 3.5 dB (sector-off).

coordination, i.e., the reduction of interfering power from neighboring sectors, aims to improve service to mobiles devices that are located close to the cell edge. If the interference a given mobile device experiences is much higher than the thermal noise, then a coordinated reduction of the mutual interference in sub-bands will lead to a direct gain in the signal-to-interference-plus-noise ratio (SINR) in some of the sub-bands. As the mobile device calculates an SINR for each sub-band individually, it will find a wider range of SINR values in the presence of interference coordination and will report these values back to the cell scheduler, which preferably serves the mobile device in the sub-band with the highest reported SINR value. Because the channel's Shannon capacity depends on its SINR, interference coordination enables a reduction of transmit power, and thus plays an important role in saving power.

Two approaches are presented here for improving mobile interference situations with the specific target to reduce radiated power: sectorization and frequency reuse. Sectorization defines the number of sectors within a cell, and therefore affects radiated power and network capacity. If the number of sectors of a cell is increased, then the usable resources, e.g., bandwidth and time, can be re-employed at each sector, and, as a consequence, the network's total capacity increases at the cost of the increased interference produced by the additional sectors. In low load situations, stepping back from multi-sector cells to single-sector cells results in a reduction of radiated power and energy consumption. The other approach, frequency reuse, splits the available spectrum into equally sized parts whose number is defined by the reuse factor. In hexagonal cell layouts, a reuse factor of 3 is optimal for 3-sectorized cells, because the frequency of cells

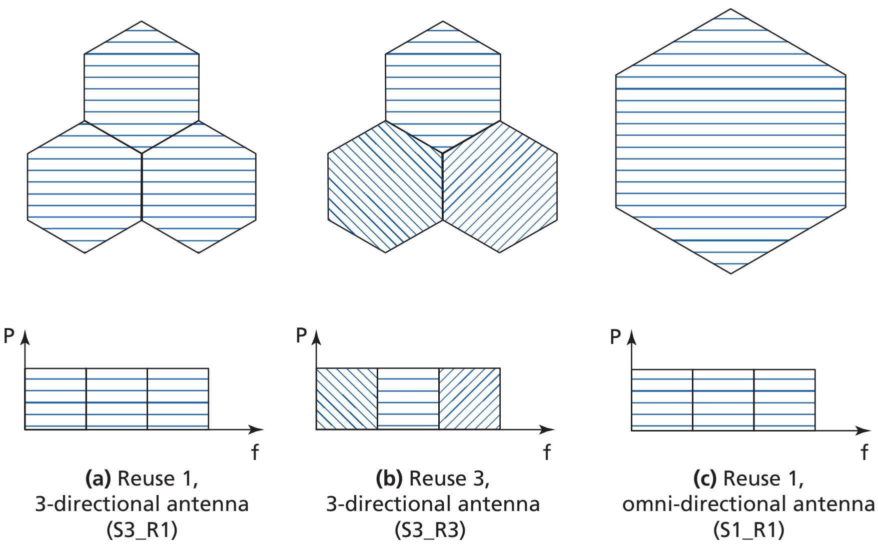

Figure 9.
Radio topologies of the network.

can be arranged to avoid neighboring sectors using the same spectrum. In this way, the critical SINR conditions at the cell border can be resolved. **Figure 9** provides an overview of the three radio topologies examined in this study. In the figure, each radio topology is identified by a shorthand of the form "Sx_Ry," which identifies the associated number of sectors x and the reuse factor of the cell, y. In Figure 9a, a radio topology with three sectors and reuse 1 is shown and is abbreviated with S3_R1. Above this title, the frequency reuse in the different sectors of the cell, each represented as a hexagonal shape, is illustrated. As all sectors of the cell use the entire spectrum, all hexagons are shown in the same color/hatching. At the bottom of Figure 9a, a diagram shows the power spectral density as a function of the frequency. In this special case, all sectors are using the entire bandwidth to serve mobiles. In Figure 9b, the radio topology "three sectors with reuse three" is shown (S3_R3). This case differs from S3_R1 in that each sector only uses one-third of the available bandwidth and thereby reduces the radiated power to the same ratio. The radio topology in Figure 9c uses single sector sites with omni-directional antennas and frequency reuse 1. This approach reduces the radiated power by decreasing the number of sectors in the coverage area of the radio network. Please note that all three radio topologies described here have a different spatial reuse: i.e., their respective sectors cover a different area.

Network radiated power and network capacity form the criteria for the comparison of the radio topology. The network radiated power is calculated by summing up the transmission power of all sectors, correcting it by the reuse factor (as the power in the unused spectrum of each sector is not radiated) and is finally normalized to square kilometers. The same calculation approach, i.e., division by the reuse factor and normalization to square kilometers, also holds for the calculation of the network capacity. All simulation results are compared in **Figure 10**, which shows the network capacity per square kilometer on the x-axis and the radiated power per square kilometer on the y-axis. The data points shown in the figure indicate the network capacity to power ratio, which can be interpreted as an efficiency measure with unit (bit/s/Hz/W). The following values were recorded during simulation: (S1_R1; 0.092), (S3_R3; 0.138), and (S3_R1; 0.075). S3_R3 achieves the best efficiency in the sense of (bit/s/Hz/W).

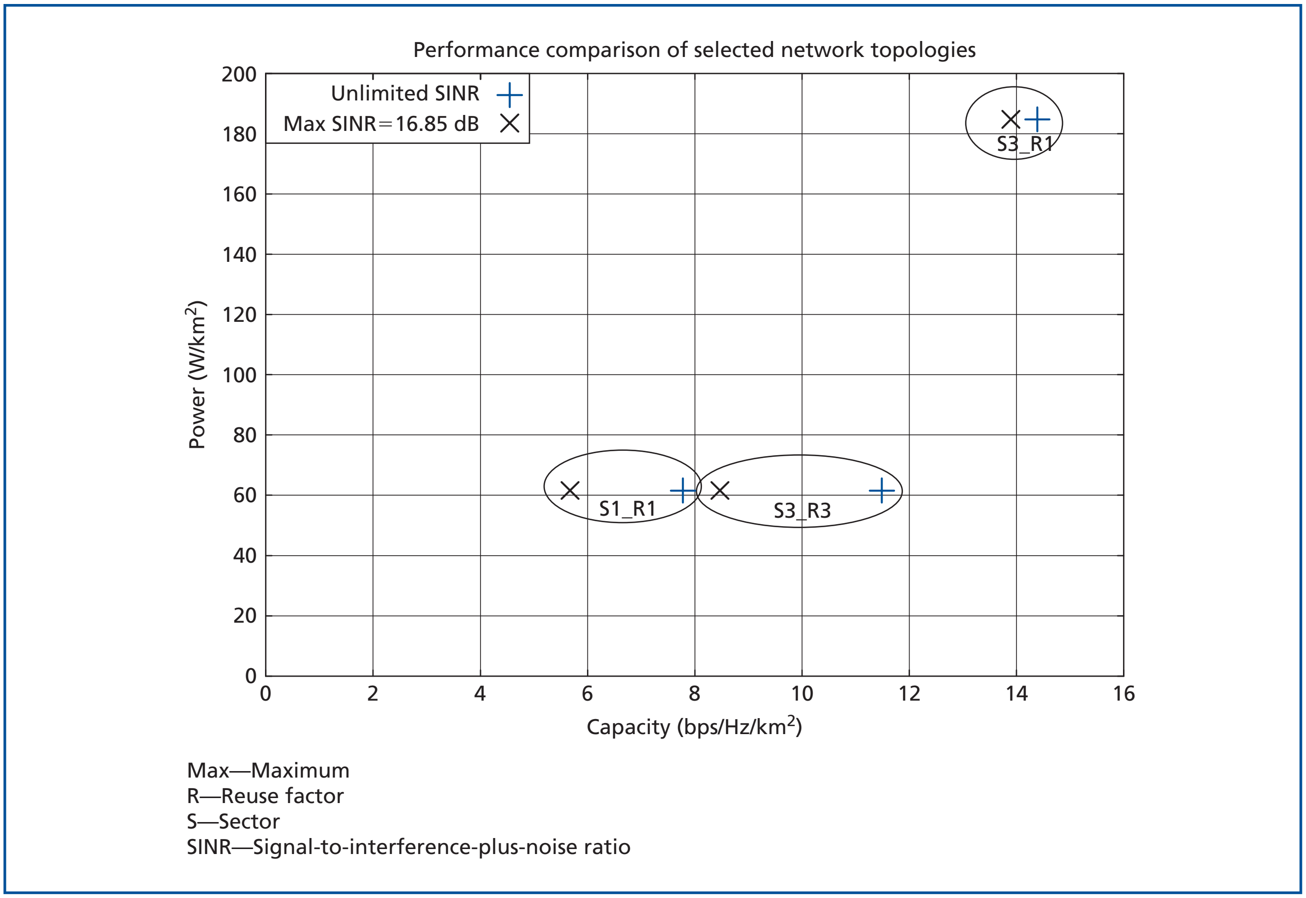

Figure 10.
Performance comparison of selected network topologies.

Figure 11 shows that radio topologies S1_R1 and S3_R3 achieve high SINR values, due to the low interference within these topologies. Unfortunately, such a high SINR would require modulation schemes above 64-QAM (6 bits/symbol), which are currently not available due to limits in the power amplifier technology. Therefore, in order to provide a reasonable comparison, SINR values have been truncated at a value of 16.85 dB, which corresponds to the Shannon capacity of 5.6 bit/s/Hz (the theoretical maximum of the LTE system).

Coverage is also an important topic for radio networks. The cumulative density function (CDF) of geometry in Figure 11 can be used to provide a basic gauge of coverage. As indicated previously, a geometry level of –3 dB and above is considered sufficient for signaling. It can also handle a simple data connection, though at the cost of high resource usage. All radio topologies examined in this section provide this minimum requirement. In Figure 11, the S3_R1 radio topology, which is common for LTE deployments, exhibits the lowest cell edge performance, because this scenario has the highest spatial reuse and hence the highest capacity, but also the most difficult interference situation.

These simulation results, especially those in Figure 10, provides a clear indication that adapting the radio network topology to the actual traffic situation leads to a high gain in radiated power. The alternative scenarios S1_R1 and S3_R3 only radiate a third of the power of S3_R1. Of course, switching the network topology is not possible with today's radio networks, as it has impact on the radio access network, the base station controllers, and many more components in the radio

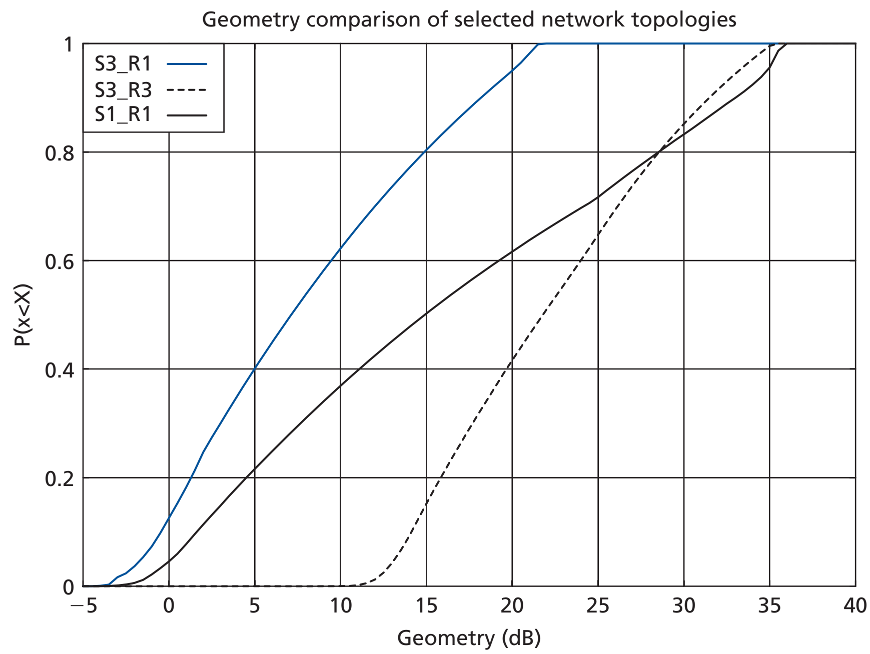

Figure 11.
Comparison of geometry for different network radio topologies (CDF of geometry).

access network and hence needs to be standardized. Still, the technologies are available and can be adapted with limited effort.

Conclusions

In this paper, various potential methods for saving energy in mobile systems were discussed. We focused on forward-looking mechanisms targeting the radio system. It has been shown that a significant decrease in power consumption can be achieved at low load situations by making the power consumption more proportional to the traffic load. RRM-based short-term mechanisms as well as SON-based long-term mechanisms turned out to be promising candidates.

The two proposed RRM-based mechanisms concentrate traffic in time and on the frequency axis. They enable energy savings by reducing radiated power through the introduction of micro-sleep, or by dynamic spectrum reduction. Both methods require standardization. Therefore, for backward compatibility, they are best suited for deployment when a new radio standard is introduced. An advantage of these methods can be seen in their applicability at the local site, i.e., without any coordination, synchronization, and signaling overhead between cells and sectors. The energy saving potential has been roughly estimated at 50 percent in low load situations and 20 percent on average. Further research and development of these methods will be conducted within the EARTH project [14], which in parallel also investigates the required hardware enhancements.

Concerning the long-term energy saving mechanisms, two approaches were assessed through system simulation. The first, switching-off an entire sector or cell, is of particular interest as it is also feasible in existing radio networks. Simulations in hexagonal scenarios provide a strong indication that the radio coverage can be kept intact by appropriate neighbor cell reconfiguration, which is of course a precondition for applicability. The second approach evaluates different radio topologies with respect to their transmission efficiency. We show that a reconfiguration of the radio system, with respect to the reuse factor at low traffic load, clearly has the potential to save a significant amount of energy.

The benefit of self-organizing mechanisms is manifested in recognition of short-term energy saving opportunities, as well as in carrying-out proper reconfiguration procedures required for long-term energy saving mechanisms. Intelligent self-learning algorithms improve decision logic to achieve the best fit between expectations and real gains in energy saving.

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