
Energy Efficiency in Cellular Networks

In this chapter, we discuss recent energy efficiency techniques and solutions that have been proposed and deployed in cellular networks. We focus mainly on the energy-efficient cellular network hardware systems that include a base station (BS) system and energy-efficient cellular network design and deployment strategies.

1.1. Overview of cellular communication networks

The world has seen an exponential growth in the number of mobile subscribers and the number of portable devices (six billion cell phones worldwide [ERI 12]). In addition, data rates for mobile broadband access are improving and several projects have been initiated to address energy efficiency in cellular networks. The Green Radio project, formulated in 2007, aims to secure 100-fold reductions in energy requirements for the delivery of high data rate services in the cellular network industry [MOB 12]. The members of the project are pursuing energy reduction from two different perspectives [MOB 12]. The first perspective is to investigate design alternatives for reducing energy consumption in the existing cellular network infrastructures. The second perspective is to study the novel techniques that can be used in BSs or handsets to reduce energy consumption. To address the challenge of increasing energy efficiency in future wireless communication networks and thereby maintain profitability, it is crucial to consider various paradigm-shifting technologies such as energy-efficient wireless architectures and protocols, efficient BS redesign, opportunistic network access or cognitive radio, cooperative relaying and heterogeneous network deployment based on smaller cells.

We have seen the evolution of mobile communication from the first-generation mobile communication networks in the early 1990s to the current fourth-generation mobile communication networks. Almost all the mobile service providers now strive

to deliver 3G and 4G services that are based on packet-switching systems, whereas in some areas the popular second-generation (2G) network, Global System for Mobile Communications (GSM), is still extensively used. Services advertised as 3G are required to meet the International Mobile Telecommunications-2000 (IMT-2000) technical standard, including standards for reliability, speed (data transfer rates) and offer voice, data and multimedia applications (3D gaming, video calls and video conferencing), specified by the International Telecommunications Union (ITU) [CHE 10]. Many services advertised as 3G provide higher speeds than the minimum technical requirements for a 3G service. Recent 3G releases, often called 3.5G and 3.75G, also provide mobile broadband access of several megabits per second to smartphones and mobile modems on laptop computers. The following standards are typically branded 3G: Universal Mobile Telecommunications Systems (UMTS), Time Division-Synchronous Code Division Multiple Access (TD-SCDMA) radio interfaces, Wideband Code Division Multiple Access (WCDMA) radio interface, High-Speed Packet Access+ (HSPA) and Code Division Multiple Access 2000 (CDMA2000). The first release of the Third-Generation Partnership Project (3GPP) Long-Term Evolution (LTE) standard does not completely fulfill the ITU 4G requirements called IMT-Advanced. The first LTE release is not backward compatible with 3G, but is a pre-4G or 3.9G technology, however, sometimes branded as “4G” by the service providers. LTE-Advanced, which is an incremental version of LTE, is a 4G technology. WiMAX is another technology marketed as 4G.

Most of these developments in wireless communication systems have been driven by the need for high-speed and data-oriented networks, which cater for bandwidth-hungry applications and services without much consideration for quality of service (QoS) and energy efficiency.

Figure 1.1 shows all the network components of a mobile cellular network. A typical cellular network consists of three main elements:

- a core network that takes care of switching,
- BSs that provide radio frequency interface, and
- mobile terminals (handsets), which are used to make voice or data connections.

Figure 1.2 shows a breakdown of power consumption in a typical cellular network and gives us an insight into the possible research avenues for reducing energy consumption in wireless communications.

Figure 1.2 illustrates the fact that a reduction in energy consumption of the BS system will lead to significant energy improvements for wireless cellular networks. The radio network itself contributes 80% to the network operator’s entire energy

consumption. Several studies have also shown that the power drain per user of the mobile handset is much lower than that of the BS component, making the latter a major focus of research [HAN 11].

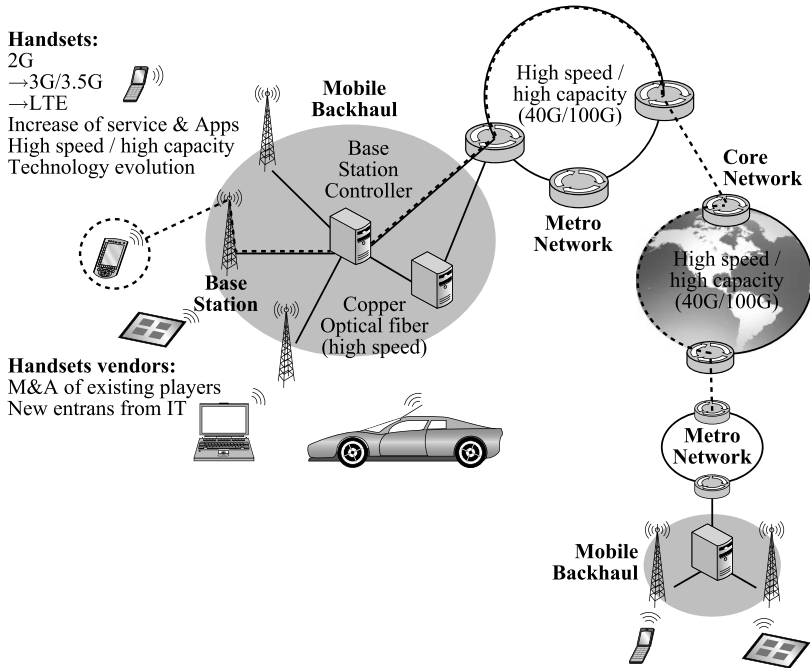


Figure 1.1. Mobile cellular networks

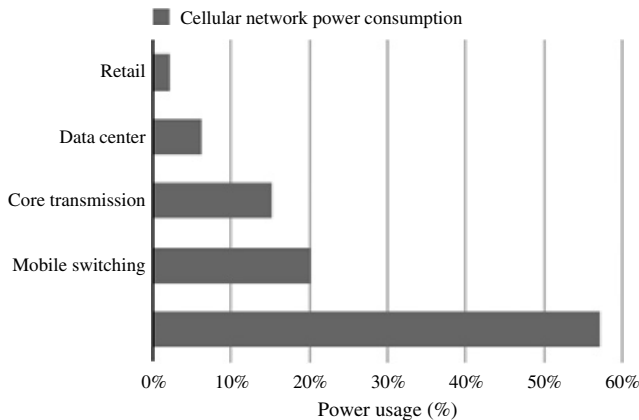


Figure 1.2. Power consumption of a typical wireless cellular network [HAN 11]

1.2. Metrics for measuring energy efficiency in cellular wireless communication systems

It is important to understand the meaningful metrics that identify the gains achieved through the introduction of energy-efficient strategies in cellular communication networks. A more comprehensive taxonomy of energy efficiency metrics is presented in [CHE 10], but there are two important metrics that are mainly used for comparison in communication systems. These metrics are the energy consumption rating (ECR) and energy consumption gain (ECG). ECR measures the consumed energy per information bit that is successfully transported over the network and is measured in joules per bit [CHE 10]. ECG is a relative measure mostly used for comparing two different systems and is the ration of energy consumed by the baseline systems and the energy consumed by the system under test [CHE 10].

Although the energy efficiency metrics at the component and equipment level are fairly straightforward to define, it is more challenging to define metrics at a system or network level [CHE 10]. Due to the intrinsic difference between various communication systems and performance measures, it is important to have different metrics. In the future, energy efficiency metrics must also consider deployment costs such as site construction, backhaul and QoS requirements such as transmission delay along with spectral efficiency in order to assess the true efficiency of the system. Once a consensus is reached on a set of standard energy metrics, there will not only be an acceleration of the research activities in energy-efficient communication, but also a way toward standardization.

The specific objectives of various projects [ICT 12a, FP7 12, ICT 12b] are to investigate and develop innovative methods to reduce the total energy needed to operate a radio access network (BS) and to identify appropriate energy-efficient radio architectures. To minimize the energy consumption of cellular architectures and networks and keep the emission of CO₂ to a minimum level, further investigations are required. In the following sections, some of the strategies and techniques that have been recently proposed to improve energy efficiency in cellular networks are presented. The focus is on energy efficiency in various components of a cellular network.

1.3. Energy efficiency in base stations

The number of BSs worldwide has increased to many millions in recent years and has led to a large increase in the energy consumption for cellular operators. BS equipment manufacturers have begun to offer a number of eco- and cost-effective solutions to reduce the power demands of BSs and to support off-grid BSs with renewable energy resources. Radio Resource Management (RRM) is a system-level

approach that controls parameters such as transmit power, channel allocation, data rates, handover criteria, modulation schemes and error coding schemes. The objective is to utilize the limited radio spectrum resources and radio network infrastructure as efficiently as possible. Traditionally, RRM did not consider system energy efficiency, but it is now being enhanced to take into consideration the energy aspect. Nokia Siemens Networks Flexi Multiradio Base Station, Huawei Green Base Station and Flexenclosure Esite Solutions [CHE 11, HUA 09, FLE 12] are a few examples of efforts to reduce the energy consumption of BSs. The overall efficiency of the BS, in terms of power drawn from its supply in relation to its radio frequency (RF) power output, depends on the power consumption of its various components including the core radio devices. Figure 1.3 shows the power consumption distribution in a BS system.

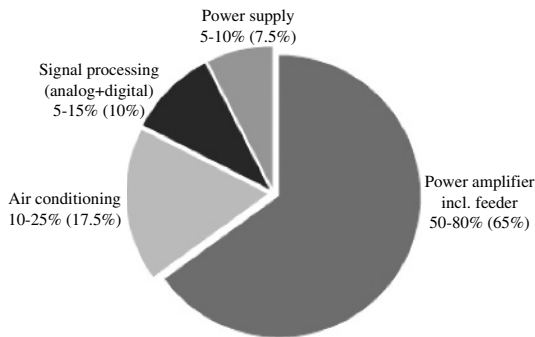


Figure 1.3. Power consumption distribution in base stations [HAN 11]

A BS typically consists of the following components that are shown in Figure 1.4:

- Radio transceivers: the equipment that transmits signals to and decodes signals from mobile terminals.
- Power amplifiers (PAs): these devices amplify the transmit signals from the transceiver to a power level high enough for transmission, typically around 5–10 W.
- Transmit antennas: these antennas are responsible for physically radiating the signals and are typically directional to deliver the signal to users without radiating the signal into the ground or the sky.

BSs also contain some other ancillary equipment, providing facilities such as connection to the service provider's network and *climate control system*. A *climate control system* is a system that is used to control the weather conditions (usually temperature) within an infrastructure where the BS equipment is stored. The system is composed of an air-conditioning and ventilation system. The energy consumption of a typical BS can be reduced by improving the BS hardware design, and by

including additional software and system features to optimize between energy consumption and performance. To make the BS design more energy efficient, all the BS components need to operate efficiently.

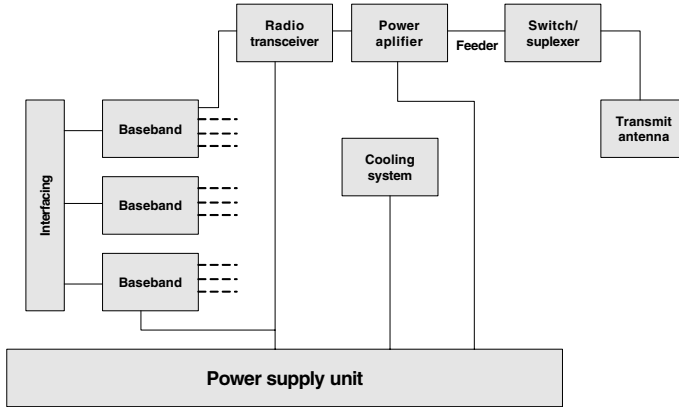


Figure 1.4. Base station architecture

Some of the techniques used to improve the BS energy efficiency are given in the following:

a) Energy-efficient power amplifiers

PAs are used to increase the power level of an input signal without altering the content of the signal. A PA dominates the energy consumption of a BS. Its energy efficiency depends on its operating frequency band, the type of modulation technique in use and its operating environment [LOU 07]. A PA consumes almost 50% of the energy in the BS. Approximately 80–90% of this consumed energy is wasted as heat, which, in turn, requires air conditioners, thereby adding even more to the energy costs. The total efficiency of a currently deployed amplifier, which is the ratio of AC power input to generated RF output power, is generally in the range from 5% to 20%, depending on the standard (i.e. GSM, UMTS, CDMA) and the equipment's condition [CLA 08].

Modern BSs are inefficient because of their need for PA linearity and high peak-to-average power ratios (PAPR). PA linearity is the linear relationship between input power and output power, which, in an ideal amplifier, would be precisely related by the gain of the amplifier. The modulation schemes used in communication standards such as WCDMA/HSPA and LTE are characterized by strongly varying signal envelopes with PAPR that exceeds 10 dB. To achieve high linearity, PAs need to operate well below saturation in order to maintain the quality of radio signals, and

this results in low power efficiency [COR 10]. Depending on their PA technology (e.g. Class-A/B amplifiers with digital predistortion) and implementation, the component-level efficiency of modern amplifiers for CDMA and UMTS systems is in the order of approximately 30–40% [CLA 08]. Because cellular technologies have reached their limits with Class-A/B power amplifiers, PAs based on special architectures such as digital pre-distorted Doherty-architectures and aluminum gallium nitride (GaN)-based amplifiers are now used to deliver higher power efficiency levels [CLA 08].

Additional improvements in energy efficiency can be done by shifting to switch-mode PAs from the traditional analog RF-amplifiers. Compared to standard analog PAs, switch-mode PAs use less electric current and dissipate less energy. While amplifying a signal, a switch-mode amplifier turns its output transistors on and off at an ultrasonic rate [CLA 08]. The switching transistors produce no electric current when they are switched off and produce no voltage when switched on, which results in highly efficient power supply. It is expected that the overall component efficiency of these energy-efficient devices could be approximately 70% [CLA 08].

b) Energy-aware cooperative BS power management

One way to improve BS energy efficiency is to shut down BS during low traffic or cell zooming [NIU 10, MAR 10]. Cell zooming is a technique through which BSs can adjust the cell size according to the network or traffic situation, in order to balance the traffic load, while reducing the energy consumption. When a cell gets congested with an increased number of users, it can zoom itself in, whereas the neighboring cells with the less amount of traffic can zoom out to cover those users that cannot be served by the congested cell. Cells that are unable to zoom in may even go to sleep to reduce energy consumption, whereas the neighboring cells can zoom out and help serve the mobile users cooperatively.

Traffic load in cellular networks causes significant fluctuations in space and time because of various factors (e.g. user mobility). During daytime, traffic load is generally higher in office areas compared to residential areas, while it is the other way around during the night. Therefore, a static cell size deployment is not optimal with the fluctuating traffic conditions. For next-generation cellular networks based on multi-hop and relay strategies, limited cell size adjustment called “cell-breathing” is currently used in CDMA networks. With cell breathing, a cell under heavy load or interference reduces its size through power control and the mobile user is handed off to the neighboring cells [NIU 10]. More network-level power management is required where multiple BSs can coordinate each other. As the operation of a BS consumes a considerable amount of energy, selectively letting BSs go to sleep based on their traffic load can help save a significant amount of energy. When some cells are switched off or in sleep mode, the radio coverage can be guaranteed by

the remaining active cells by filling in the gaps created. Such concepts of self-organizing networks (SONs) have been introduced in the 3GPP standard (3GPP TS 32.521) [NIU 10] to add network management and intelligence features so that the network is able to optimize, reconfigure and repair itself in order to reduce the costs and improve the network performance and flexibility [3G 09].

The concept of SONs can be applied to achieve various objectives. For instance, in [SCH 09], different use cases for SONs in cellular networks are discussed, e.g. load balancing, cell outage management, and management of relays and repeaters. In the context of power efficiency, the performance of these self-organizing techniques was initially explored in [MAR 10] and [MAR 09]. From the performance results obtained, the authors found that substantial amounts of energy savings can be achieved (approximately 20%, and above) by selectively reducing the number of active cells that are under low-load conditions. In contrast, a distributed algorithm is proposed in [VIE 09] in which BSs exchange information about their current level of power and take turns to reduce their power. Recently, authors of [SAM 10a] and [SAM 10b] introduced the notion of energy partitions, which relies on the cooperation between powered-on and powered-off BSs to reconfigure the energy status. Powered-on BSs provide a wider coverage to serve users on behalf of the reduced network elements by forming a type of energy subset or partition as illustrated in Figure 1.5. Such energy partitions are associated with powered-on and powered-off BSs defined within the coverage limits of the operating site. The association follows an SON paradigm by enabling autonomous configuration.

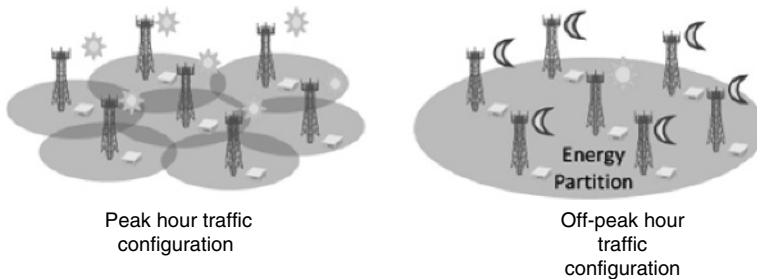


Figure 1.5. *Energy partitions configurations [SAM 10]*

c) Using renewable energy resources

In several remote locations of the world such as Africa and South America, electrical grids are not available or are unreliable [GSM 12]. Cellular network operators in these off-grid sites constantly rely on diesel-powered generators to run BSs, which is not only expensive, but also generates CO₂ emissions. One generator consumes an average of 1,500 L of diesel per month, resulting in a cost of

approximately \$30,000 per year to the network operator [GSM 12]. Moreover, the fuel has to be transported to the site and sometimes it is even transported by helicopter to remote places, which adds further to the diesel cost. In these remote locations, renewable energy resources such as sustainable biofuels, solar and wind energy seem to be more viable options to reduce the overall network operating expenditure. Hence, the adoption of renewable energy resources could save cellular companies' recurrent costs. In addition, renewable energy is derived from resources that are regenerative and renewable energy resources do not generate greenhouse gases such as CO₂. Powering BSs using renewable energy would save up to 2.5 billion liters of diesel per annum globally (0.35% of global diesel consumption of 700 billion liters per annum) and cut annual carbon emissions by up to 6.8 million tons [HAN 11]. Recently, a project called "Green Power for Mobile", which advocates for the use of renewable energy resources for BSs, was launched by 25 leading telecommunication companies in Africa under the Global System for Mobile Communications Association (GSMA) [GSM 12].

d) *Power-saving protocols*

A fairly intuitive way to save power is to switch off the transceivers whenever there is no need to transmit or receive. The LTE standard uses this concept by introducing power-saving protocols such as discontinuous reception (DRX) and discontinuous transmission (DTX) modes for the mobile handset [3G 09]. DRX and DTX are methods to momentarily switch off cellular devices in order to save power while still connected to the network, but with reduced throughput. Because continuous transmission and reception in WCDMA/HS-PA consumes a significant amount of power even if the transmit power is far below the maximum level, power savings due to DRX and DTX have become attractive options. IEEE 802.16e or Mobile WiMAX also has similar provisions for sleep mode mechanisms for mobile stations [CHA 10]. The portable device negotiates with the BS and the BS will not schedule the user for transmission or reception when the radio is off. There are a number of power-saving classes with different on/off cycles for the WiMAX standard, which are discussed in [CHA 10].

e) *Architectural site-level considerations*

Besides hardware redesign and new system-level features, there are various site-level solutions that can be used to save energy. For example, outdoor sites can be used and thus less cooling would be required. Another solution is to use more fresh air-cooling rather than power consuming air conditioners for indoor sites. Another way to improve the power efficiency of a BS is to bring some architectural changes to the BS. Currently, the connection between the RF-transmitter and antenna is done by long coaxial cables that add almost 3 dB to the losses in power transmission. To alleviate the losses, low-power RF-cables should be used and the RF-amplifier

should be kept closer to the antenna [CLA 08]. This will improve the efficiency and reliability of the BS.

In [BAS 09], the authors suggested an all-digital transmitter architecture for an energy-efficient BS that uses a combination of envelop elimination and restoration (EER) and pulse width modulation (PWM)/pulse position modulation (PPM). EER can be achieved using Kahn's technique. The Kahn's technique [BAS 09] uses the idea that high-efficiency power supply (envelope amplifier) could be used to modulate the envelope of high-efficient nonlinear power amplifiers (classes D or E). In addition, RF heads and modular BS design can be implemented to reduce power loss in feeder cables [LOU 07].

1.4. Energy-efficient cellular network design

The tremendous growth in demand for higher data rates and other services over wireless networks requires a more dense deployment of BSs within network cells. Conventional macrocellular network deployments are less energy efficient. Therefore, it may not be economically feasible to modify the current network architectures to support this increasing demand from mobile cellular users. Macrocells are generally designed to provide large area coverage and are not efficient in providing high data rates. One way to make the cellular networks more energy efficient in order to sustain high-speed data traffic is to reduce the propagation distance between nodes, which results in a reduction in the transmission power without complex infrastructure modifications. In fact, early research has shown that relaying techniques extend the battery life [LAN 00] and increase data rates, which is the first step toward energy-efficient networks. In particular, multi-hop communication divides a direct path between mobile terminals and BS into several shorter links [LI 08]. Consequently, the effect of wireless channel impairments such as path loss is less destructive; hence, lower transmission power can be assigned to the BS and relays. From this context, cellular network deployment solutions based on smaller cells such as micro-, pico- and femtocells are very promising. These smaller cells may be deployed in streets or buildings to provide improved signal quality to locations that might otherwise experience low QoS.

A micro/picocell is a cell in a cell phone network served by a low-power cellular BS that covers a small area with dense traffic such as a shopping mall, residential areas, a hotel or a train station. While a typical range of a micro/picocell is in the order of a few hundred meters, femtocells are designed to serve much smaller areas such as private homes or indoor areas. The range of femtocells is typically only of a few meters and they are generally wired to a private owners' cable broadband connection or a home digital subscriber line (DSL). Due to the sizes of the smaller cells, they are more power efficient in providing broadband coverage. For example,

a typical femtocell might only have a 100 mW PA, and draws 5 W total compared to 5 KW that would be needed to support a macrocell. An analysis by OFCOM (UK regulator) and Plextek concluded that femtocell deployment could have a 7:1 operational energy advantage ratio over the expansion of the macrocell network to provide approximately similar indoor coverage [FOR 09]. Simulations show that with only 20% of customers with picocells, a joint deployment of macrocell and picocell can reduce a network's energy consumption by up to 60% compared to a network with macrocells only [LOU 07]. Another advantage of smaller cells is that they can use higher frequency bands that are suitable for providing high data rates and they also offer localization of radio transmissions. However, deploying too many smaller cells within a macrocell may reduce the overall energy efficiency of the macrocell BS because it will have to operate under low-load conditions. Therefore, careful investigation of various deployment strategies should be done in order to find how to deploy such smaller cells in an energy-efficient manner. Calin *et al.* [CAL 10] provided insight into possible architectures/ scenarios for joint deployment of macro- and femtocells with an analysis framework for quantifying potential macro-offloading benefits in realistic network scenarios. Richter *et al.* [RIC 09] investigated the impact of different deployment strategies on the power consumption of mobile communication networks. They considered layouts featuring varying number of micro BSs per cell in addition to conventional macrosites.

1.5. Interference management and mitigation

Interference cancellation schemes are needed to mitigate interference effects in any practical communication systems where multiple BSs share the same spectrum. The impact of interference is more severe when users move closer to the boundary region between two cells, leading to significant signal to interference plus noise ratio (SINR) and data rate reduction. Most existing interference cancellation schemes have been designed to increase the spectral efficiency and data rates without much consideration given to energy efficiency. However, research efforts in the Green Radio project [MOB 12] have been focusing on developing energy-efficient interference cancellation schemes. If the level of interference can be reduced at mobile terminals, it will allow BSs to reduce the wireless transmission energy without compromising the SINR of the wireless link. One way to reduce the interference in cellular systems is to coordinate the multiple antennas of the adjacent BSs to form a distributed antenna system (DAS) [HAN 11]. In this case, each and every cell-edge user is collaboratively served by all of its surrounding BSs rather than by only a single BS with strong signal strength. DAS enables the interference experienced by users on the cell edge to be better controlled and mitigated through a coordinated transmit beamforming at all of the participating BSs. Coordinated transmit beamforming is a scheme that transmits a fixed number of data streams for each user regardless of the instantaneous channel states. The scheme ensures that all

the users, irrespective of the channel conditions, have the same number of data streams.

An alternative scheme to DAS is the implementation of interference cancellation techniques at a multiple-antenna receiver. The performance of different interference cancellation algorithms has been compared in [KU 11] for different numbers of transmitting antennas. Linear zero forcing (ZF) and minimum mean square error (MMSE) techniques were compared, along with nonlinear successive interference cancellation (SIC) variants of these methods. It was found that more transmission energy is required as the number of transmitting antennas increases. This is expected because intracell interference increases with the number of transmitting antennas. As a result, higher transmission energy is required to maintain the same SINR during transmission. In the absence of co-channel interference from neighboring BSs, it is observed that the MMSE weight optimization approach provides better transmission energy savings than the ZF approach at the desired BS, with the SIC structure performing better in energy savings than the linear receiver structure [HAN 11]. An explanation for this observation is that the ZF criterion not only cancels intracell interference, but also amplifies adjacent-cell interference and noise. However, in contrast, MMSE techniques minimize the intracell interference and noise with the adjacent-cell interference and noise components.

1.6. Enabling technologies

Recently, research on technologies such as cognitive radio and cooperative relaying has received significant attention by both industry and academia. While cognitive radio is an intelligent and adaptive wireless communication system enabling the utilization of the radio spectrum in a more efficient manner, cooperative relays provide a lot of improvement in throughput and coverage for future wireless networks. In addition, developments in these technologies enable us to address the problem of energy efficiency via smart radio transmission and distributed signal processing.

1.6.1. *Energy-efficient communication via cognitive radio*

Cognitive radio technology can play an important role in improving energy efficiency in radio networks [SCH 11]. The cognitive techniques have a wide range of properties, including spectrum sensing, spectrum sharing and adaptive transmission, which are beneficial for the improvement of the trade-off between energy efficiency, spectrum efficiency, bandwidth and deployment efficiency in wireless networks [HAY 05]. Actually, in the original definition of cognitive radio

by J. Mitola [MIT 99], it is stated that every possible parameter measurable by a wireless node or network is taken into account (cognition) so that the network intelligently modifies its functionality (reconfigurability) to meet a certain objective. One of these objectives can be power saving. It has been shown in recent works that infrastructures and techniques based on cognitive radio can reduce energy consumption, while maintaining the required QoS, under various channel conditions [HE 09, HE 08]. Nevertheless, due to the complexity of these proposed algorithms, commercial vendors of wireless products have not yet implemented these techniques.

Bandwidth efficiency has always been an important concern for wireless communication engineers. Over the years, an extensive literature on this topic has been published with the goal of improving the bandwidth efficiency in systems, but not considering power efficiency. In addition, it has been acknowledged that the allocated spectra are highly underutilized [FED 02], and cognitive radio promises to improve the spectrum utilization. Cognitive radio collects information on the spectrum usage and tries to access the unused frequency bands intelligently to compensate for this spectrum underutilization [MIT 99]. With Shannon's capacity formula [SHA 49], the capacity increases linearly with bandwidth, but only logarithmically with power. This means that in order to reduce power, we need to increase the bandwidth [GRA 09], or in other words, we need to manage the spectrum optimally and dynamically as cognitive networking supports. In fact, it has been shown in [HOL 10] that up to 50% of power can be saved if the operator dynamically manages its spectrum by activities such as dynamically moving users into particularly active frequency bands from other bands, or the sharing of the spectrum to allow channel bandwidths to be increased.

1.6.2. Using cooperative relays to support energy-efficient communication

The extension of the coverage area of a BS is an important issue for wireless networks. Considering the well-known properties of a wireless channel such as large path losses, shadowing effects and different types of signal fading, covering distant users via direct transmission becomes very expensive in terms of the power required to establish a reliable connection. This high-power transmission requirement further translates into the high-power consumption and also introduces high levels of interference to nearby users and BSs. In recent years, cooperative communication techniques have been proposed to create virtual multiple input multiple output (MIMO) systems, where installing large antennas on small devices such as mobile units (MUs) is not possible. Hence, using cooperative communication techniques, significant improvements of MIMO systems including increasing coverage and capacity enhancement can be achieved [PAB 04].

Cooperative communication techniques also combat shadowing by covering coverage holes [PAB 04]. Shadowing is the reduction in the strength of an ultra-high-frequency signal caused by some object (such as a mountain or a tall building) between the points of transmission and reception. Relays can reduce network energy consumption without complex infrastructure modifications.

Delivering energy-efficient communications via cooperative communication techniques can be achieved by two different approaches. The first approach is to install fixed relays within the network coverage area in order to provide service to more users using less power. The second approach is to exploit the users to act as relays. A relay can be defined as one of the network elements that can be fixed or mobile. It is more sophisticated than a repeater, and has capabilities for storing and forwarding data, and is also involved in scheduling and routing procedures. Although the second approach eliminates the cost of installing relay nodes, it increases the complexity of the system, mostly because centralized or distributed algorithms must be designed to dynamically select relays among the users. New mobile terminals also have to be designed such that they can support relaying. In the two following sections, we discuss these two scenarios.

1.6.2.1. *Enabling energy-efficient communication via fixed relays*

The use of many BSs leads to less energy consumption for each BS because they spread the load and increase the coverage, and lead to higher spatial reuse [ROS 10]. In fact, this is the key point that makes fixed relays a good choice for delivering energy-efficient communication as well as a general improvement in network performance. Installing new BSs can be very expensive. However, relays can be installed instead of new BSs. Some of the benefits of installing relays are as follows:

- a) Relays are economically advantageous and do not introduce much complexity to the network.
- b) Relays need not be as high as BSs because they are supposed to cover a smaller area with a lower power [SEN 03].
- c) Relays can be wirelessly connected to a BS instead of being attached to the backhaul of the network by wire using a complex interface [SEN 03].
- d) Finally, in cellular systems, unlike *ad hoc* and peer-to-peer networks, complex routing algorithms are not necessary [SEN 03].

All these benefits make the use of relays a potential solution for energy-efficient cellular networks.

1.6.2.2. *Communications in cellular networks via user cooperation*

User cooperation was first introduced in [SEN 03]. It has been shown that user cooperation not only increases the data rate, but also makes the system more robust (i.e. the achievable rates are less sensitive to channel variations). Despite all these advantages, energy efficiency issues with user cooperation make this technique unappealing in wireless mobile networks. The reason is that the increased rate of transmission for one user is achieved at the expense of the energy consumed by another user acting as a relay. The limited battery lifetime of mobile users in a mobile network leads to selfish users who do not have an incentive to cooperate. In fact, in a recent work by Nokleby and Aazhang [NOK 10], the authors explored whether user cooperation is advantageous from an energy efficiency perspective. A game-theoretic approach is proposed to give users incentives to act as relays when they are idle, and it is shown that such an approach has the potential to improve the user's bits per energy efficiency under different channel conditions [SEN 03].

From the discussion in this chapter, we can conclude that there are various types of strategies and techniques that have been proposed and implemented recently to increase energy efficiency in cellular networks. However, more research still needs to be done as cellular networks' service providers do not find these techniques economically viable to implement. Since implementing an energy-efficient network may add some operational cost, no matter how small, one question that remains with the cellular network service providers is *should we pass the cost down to the subscribers?* Cellular service providers will be motivated to implement cost-effective "energy-efficient techniques".

