ENERGY-EFFICIENT WIRELESS COMMUNICATIONS: TUTORIAL, SURVEY, AND OPEN ISSUES

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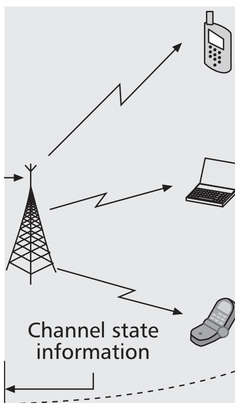

The authors introduce basic concepts of energy-efficient communications, and summarize existing fundamental works and advanced techniques for energy efficiency.

With explosive growth of high-data-rate applications, more and more energy is consumed in wireless networks to guarantee quality of service. Therefore, energy-efficient communications have been paid increasing attention under the background of limited energy resource and environmental-friendly transmission behaviors. In this article, basic concepts of energy-efficient communications are first introduced and then existing fundamental works and advanced techniques for energy efficiency are summarized, including information-theoretic analysis, OFDMA networks, MIMO techniques, relay transmission, and resource allocation for signaling. Some valuable topics in energy-efficient design are also identified for future research.

INTRODUCTION

Information and communication technology (ICT) is playing a more and more important role in global greenhouse gas emissions since the amount of energy for ICT is increasing dramatically with the explosive growth in service requirements. It is reported that the total energy consumed by the infrastructure of cellular wireless networks, wired communication networks, and the Internet takes up more than 3 percent of the worldwide electric energy consumption nowadays [1], and the portion is expected to increase rapidly in the future. As an important part of ICT, wireless communications are responsible for energy saving. On the other hand, mobile terminals in wireless systems necessitate energy saving since the development of battery technology is much slower than the increase of energy consumption. Therefore, pursuing high energy efficiency (EE) is a trend for the design of future wireless communications.

During the past decades, much effort has been made to enhance network throughput. Different network deployments have been well investigated to improve area spectral efficiency (ASE), such as optimization of the number of base stations (BSs) in cellular networks and the placement of relay nodes in relay systems. Numerous resource allocation schemes have been proposed to ensure the quality of service (QoS) of each user and fairness among different users by exploiting multi-user diversity. Many advanced communication techniques, such as orthogonal frequency-division multiple access (OFDMA), multiple-input multiple-output (MIMO) techniques, and relay transmission, have been fully exploited in wireless networks to provide high spectral efficiency (SE). However, high network throughput usually implies large energy consumption, which is sometimes unaffordable for energy-aware networks or energy-limited devices. Figuring out how to reduce energy consumption while meeting throughput requirements in such networks and devices is an urgent task.

Recently, energy-efficient system design has received much attention in both industriy and academia. In the industrial area, both vendors and operators are expecting more energy-saving devices to reduce manufacturing or operating cost. Several projects and organizations, such as Energy Aware Radio and Network Technologies (EARTH), have been set up to develop more energy-efficient architectures and techniques. On the other hand, some valuable papers have been published, and workshops on green radio have been organized at many international conferences, such as ICC and GLOBECOM. Various energy-efficient methods have been proposed for different layers of wireless networks. For network planning, the impact of cell sizes on EE in cellular networks has been studied [2]. It has been shown that reducing cell size can increase the number of delivered information bits per unit energy for given user density and total power in the service area. If a sleep mode is introduced, the EE can be further enhanced. In addition, mixed cell deployment (e.g., using microcells at the edge of a macrocell), is also an efficient way to save energy as well as to enhance the performance of cell edge users. For the medium access control (MAC) layer, protocols have been designed to efficiently utilize resources (e.g., power, time slots, and frequency bands) to reduce energy consumption. For the physical layer, different transmission techniques have been reconsidered from the EE point of view instead of traditional SE. Some

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cross-layer approaches have also been developed to obtain more gain over the independent layer design [3].

In this article, we mainly focus on techniques in physical and MAC layers. Cross-layer EE optimization in time, frequency, and spatial domains was discussed in [3] while four fundamental trade-offs, including deployment efficiency–EE, spectral efficiency–EE, bandwidth–power, and delay–power, were studied in [4]. Different from them, we discuss these topics from the perspective of how to develop specific energy-efficient techniques. Specifically, fundamentals of energy-efficient communications are first introduced, including the information-theoretic bounds and the impact of some practical issues. Multiple access techniques considering EE are discussed, where the design of energy-efficient OFDMA systems is emphasized since a comprehensive survey on EE in code-division multiple access (CDMA) networks was presented in [5]. Next, some advanced techniques, including MIMO and relay, are elaborated. Although these techniques can improve SE significantly, it comes at significant cost, including additional configuration of antennas or relay stations and additional energy consumption. How to design energy-efficient MIMO and relay systems is covered, respectively. We discuss signaling design considering EE and focus on the resource allocation between signaling and data symbols. We then conclude the article.

Fundamentals

SE is a widely used performance indicator for the design of wireless communication systems. SE-oriented systems are designed to maximize SE under peak or average power constraints, which may lead to transmitting with the maximum allowed power for a long period and thus deviate from energy-efficient design.

During the past decades, EE, which is commonly defined as information bits per unit of transmit energy, has been studied from the information-theoretic perspective for various scenarios [6]. For an additive white Gaussian noise (AWGN) channel, it is well known that for a given transmit power, P, and system bandwidth, B, the channel capacity is

$$R = \frac{1}{2}\log_2\left(1+\frac{P}{N_0 B}\right)$$

bits per real dimension or degrees of freedom (DOF) [7, Ch. 5], where N_0 is the noise power spectral density. According to the Nyquist sampling theory, DOF per second is $2B$. Therefore, the channel capacity is $C = 2BR$ b/s. Consequently, EE is [4, 8]

$$\eta_{EE} = \frac{C}{P} = \frac{2R}{N_0(2^{2R}-1)}. \quad (1)$$

From Eq. 1, it is obvious that η_{EE} decreases monotonically with R, with $(\eta_{EE})_{max} = 1/(N_0 \ln 2)$ as $R \to 0$, and $(\eta_{EE})_{min} = 0$ as $R \to \infty$.

The result in Eq. 1 is obtained by assuming an infinite size of information block and infinite number of DOF. However, the system behavior is totally different in the finite case. It is shown

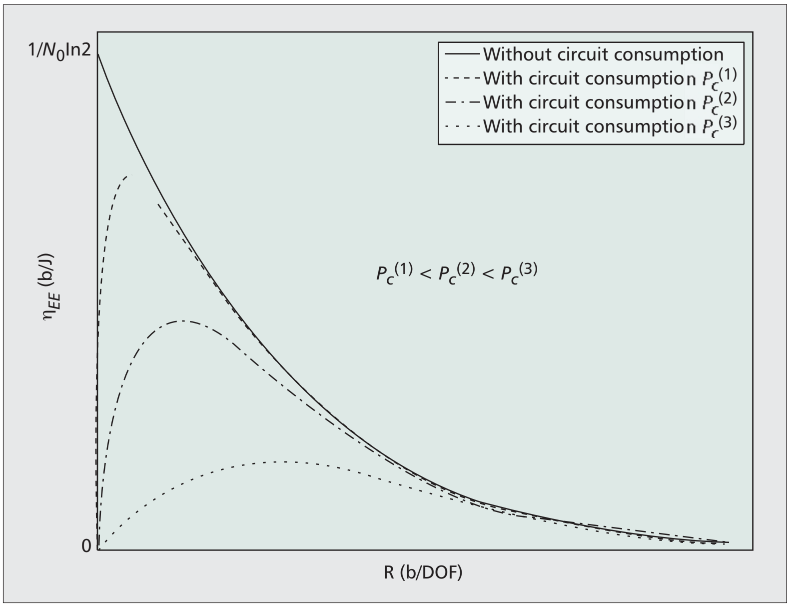

Figure 1. *Trade-off between EE (η_{EE}) and* R *in an AWGN channel.*

in [8] that noiseless feedback leads to much better EE in this case, while availability of noiseless feedback does not improve EE in the infinite case. Moreover, bounds on EE for the finite case have been derived in [9] for a given transmission rate. Results on EE in the wideband regime for many other types of channels can be found in [6].

The EE bounds derived from the information-theoretic analysis might not be achieved in practical systems due to performance loss of capacity-approaching channel codes, imperfect knowledge of channel state information (CSI) [10], cost of synchronization [11], and transmission associated electronic circuit energy consumption [12–16]. Among these factors, electronic circuit energy consumption changes the fundamental trade-off between EE and data rate. Taking circuit energy consumption into consideration, EE needs to be redefined as information bits per unit of energy (not only transmit energy), where an additional circuit power factor, P_c, needs to be added in the denominator of Eq. 1. Accordingly, the η_{EE} vs. R curve will turn from a cup shape to a bell shape, as shown in Fig. 1 from [4]. It is obvious that EE will decrease with the circuit power. As a result, circuit consumption may change our view of conventional energy saving techniques like MIMO [13], discussed later. To analyze the impact of circuit power on EE quantitatively, detailed modeling of equipment-level energy consumption of devices such as base stations (BSs) and mobile terminals is very helpful. Circuit power is usually modeled as a constant, which is independent of data transmission rate [12, 15]. Recently, it has been found that it is more accurate sometimes to model it as a linear function of data rate [16]. In [12], a detailed circuit model has been established for a 2.5 GHz radio band energy-limited transceiver. From there, it can be seen that the circuit energy consumption of a transmitter adds up to 50 mW, while the peak transmit power is 250 mW. As shown in [17], the

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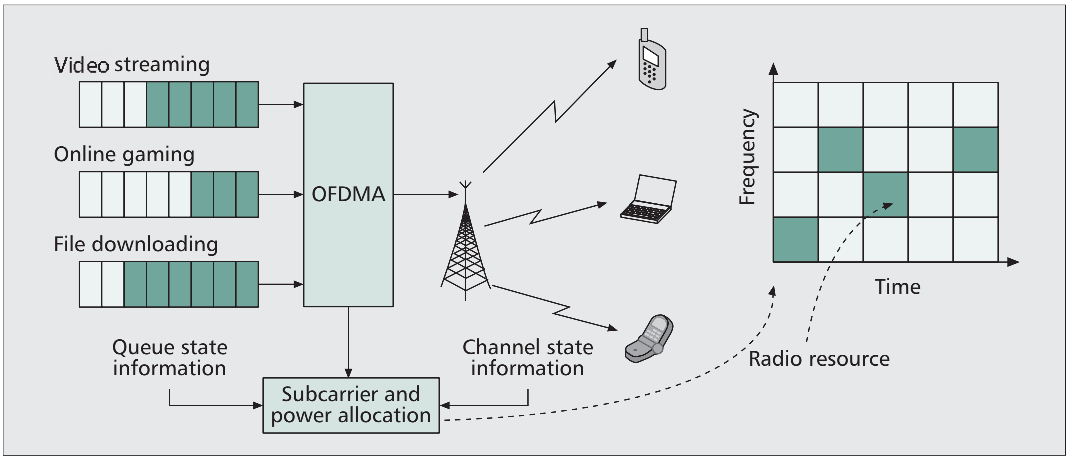

Figure 2. *Resource allocation in OFDMA [3].*

power consumption of a commercial 802.11g transceiver consumes 990 mW at the idle mode and 1980 mW at the transmit mode. These two examples also corroborate that the circuit energy consumption is not always negligible compared to the transmit power.

OFDMA Networks

OFDMA has been extensively studied for next-generation wireless communication systems, such as Worldwide Interoperability for Microwave Access (WiMAX) and the Third Generation Partnership Project (3GPP) Long Term Evolution (LTE). In OFDMA, system resource, such as subcarriers and transmit power, needs to be properly allocated to different users to achieve high performance. Figure 2 illustrates the resource allocation of a downlink OFDMA network, where subcarriers and power are allocated based on users' CSI and QoS requirements by the BS. The two most commonly used classes of dynamic resource allocation schemes are rate adaptation (RA), which maximizes throughput, and margin adaptation (MA), which minimizes total transmit power [18]. Therefore, RA aims at SE, while MA targets on transmit power efficiency. However, neither of them is necessarily energy-efficient. While OFDMA can provide high throughput and SE, its energy consumption is sometimes large. In this section, we focus on energy-efficient resource allocation schemes for OFDMA systems.

Energy-efficient orthogonal frequency-division multiplexing (OFDM) systems, a special case of OFDMA, have been first addressed with consideration of circuit consumption for frequency-selective fading channels [14]. In contrast to the traditional spectral-efficient water-filling scheme that maximizes throughput under a fixed overall transmit power constraint, the new scheme maximizes the overall EE by adjusting both the total transmit power and its distribution among subcarriers. It is demonstrated that there is at least a 15 percent reduction in energy consumption when frequency diversity is exploited.

Energy-efficient design has also been extended to general OFDMA networks [19]. For uplink transmission with flat fading channels, it is shown that using adaptive modulation, the EE increases as the user moves toward the BS, and the closer the user is to the BS, the higher the modulation order should be.

In an interference-free environment, a trade-off between EE and SE exists, for increasing transmit power always improves SE but without guarantee of EE improvement. However, in multicell interference-limited scenarios, increasing transmit power even does not necessarily benefit SE due to the associated higher interference to the network. In [20], energy-efficient design in multicell scenarios with intercell interference is studied. As shown there, energy-efficient power distribution not only boosts system EE but also refines the EE-SE trade-off due to the conservative nature of power allocation, which sufficiently restricts interference from other cells and improves network throughput. The existing research on energy-efficient OFDMA has mainly focused on uplink scenarios or mobile terminal sides. More effort should be put on the downlink or BS sides for the green design target. In addition, the impact of knowledge of traffic statistics has not been investigated. Moreover, the general EE-SE trade-off is not addressed yet. Further research on the following aspects is desired.

Energy-efficient transmission in the downlink: In many situations, downlink EE is also very important. For example, it might be desired that the construction of BSs in cellular networks have environment-friendly behavior and less expenditure for energy consumption. Also, the downlink OFDMA energy-efficient communication is different from the uplink; subcarrier allocation, power allocation, and rate adaption need to be jointly addressed. Thus, it may not be directly extended from the uplink case.

The role of traffic statistics: It is crucial in energy-efficient broadband communications. Existing approaches should be modified to incorporate traffic statistics, which may be acquired from queue status of each user. Depending on the traffic, the lengths of the active and sleep periods can be dynamically assigned, and the power, modulation order, and coding can be adjusted jointly to achieve desirable EE.

Trade-off between EE and SE: Since EE

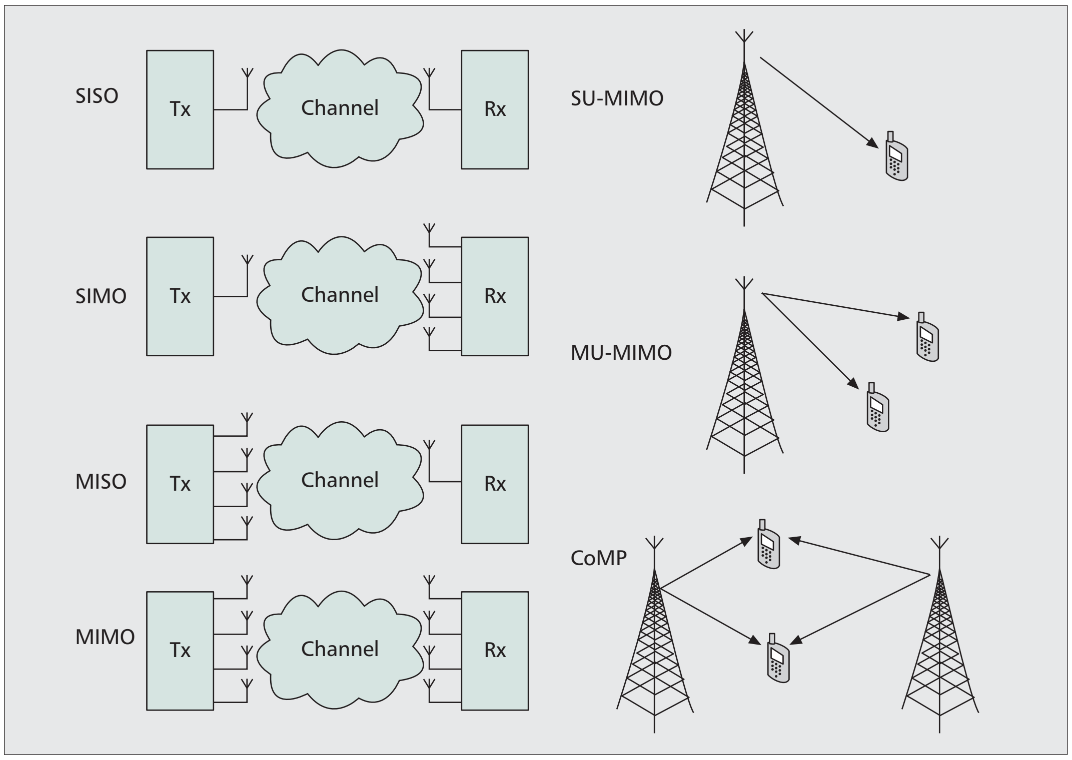

Figure 3. *Diagram of MIMO schemes.*

Since the number of channel coefficients increases with the product of the number of transmit antennas and that of receive antennas, much more signaling overhead is required for MIMO systems. The EE of MIMO systems is still unknown if all the overhead is considered.

and SE are two important system performance indicators, the trade-off between EE and SE for general OFDMA networks should be exploited to guide system design. The bounds and achievable EE-SE regions for downlink OFDMA networks are important for the system designer. Meanwhile, proper utility function should be investigated for locating the optimum operating point on the boundary of EE-SE region.

MIMO Techniques

MIMO techniques have been widely adopted in wireless networks nowadays. As shown in Fig. 3, single-input single-output (SISO), single-input multiple-output (SIMO), and multiple-input single-output (MISO) can be regarded as special cases of MIMO. MIMO can also be used with single users or multiple users to form single-user MIMO (SU-MIMO), multi-user MIMO (MU-MIMO), and coordinated multipoint (CoMP) transmission. It has been demonstrated in these specifications that spatial DOF from configuration of multiple antennas enhances both reliability and capacity. For example, in the downlink of 3GPP LTE, both SU-MIMO and MU-MIMO modes are supported, and different modes can be selected according to the specific requirement. In 3GPP LTE-Advanced, CoMP techniques have been proposed to further improve the throughput of cell edge users and the coverage.

Although MIMO techniques have been shown to be effective in improving capacity and SE of wireless systems, energy consumption also increases. First of all, more circuit energy is consumed due to the duplication of transmit or receive antennas. Depending on the ratio of the extra capacity improvement and the extra energy consumption, the EE of a multiple-antenna system may be lower than that of a single-antenna system. Moreover, more time or frequency resources are spent on the signaling overhead for MIMO transmission. For example, in most of MIMO schemes, CSI is required at the receiver or at both the transmitter and the receiver to obtain good performance. In order to estimate the CSI and feed it back to the transmitter, some training symbols need to be sent before the data transmission. Since the number of channel coefficients increases with the product of the number of transmit antennas and that of receive antennas, much more signaling overhead is required for MIMO systems. The EE of MIMO systems is still unknown if all the overhead is considered.

Some preliminary results on this topic have been presented in the literature. Adaptively changing the number of active antennas at the BS is proposed for 3GPP LTE to address the large traffic variation issue in cellular networks [21]. According to statistics, the number of active users at night is much lower than that in the day. Switching off some radio frequency (RF) amplifier units at night can save energy significantly while maintaining QoS of active users. In [22], adaptive switching between MIMO and SIMO is addressed to save energy at mobile terminals. The characteristic of dynamic user population is well exploited for joint MIMO mode switching and rate selection. The EE of Alamouti diversity schemes has been discussed in [13]. It is shown that for short-range transmission, MISO decreases EE compared with single-antenna transmission if they are not combined with