Energy-Efficient Wireless Communications: Tutorial, Survey, and Open Issues

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Abstract

With explosive growth of high-data-rate applications, more and more energy is consumed in wireless networks to guarantee *quality-of-service* (QoS). 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* (EE) are summarized, including information-theoretic analysis, *orthogonal frequency division multiple access* (OFDMA) networks, *multiple-input multiple-output* (MIMO) techniques, relay transmission, and resource allocation for signaling. Some valuable topics on energy-efficient design are also identified for future research.

Index Terms

Energy efficiency (EE), orthogonal frequency division multiple access (OFDMA), multiple-input multiple-output (MIMO), relay, signaling

I. 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 increases dramatically with explosive growth of service requirement. It is reported that the total energy consumed by the infrastructure of cellular wireless networks, wired communication networks, and internet takes up more than 3% 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 compared with the increase of energy consumption. Therefore, pursuing high *energy efficiency* (EE) will be the 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), e.g., 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 assure *quality-of-service* (QoS) of each user and fairness among different users by exploiting multiuser 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. How to reduce energy consumption while meeting throughput requirements in such networks and devices is an urgent task.

Recently, energy-efficient system design has been received much attention in both industrial and academic fields. In the industrial area, both vendors and operators are expecting more energy-saving devices to reduce manufacturing or operating cost. Several projects and organizations, e.g. *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 are organized in 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 micro-cells at the edge of a macro-cell, 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 resource, such as 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 cross-layer approaches have also been developed to obtain more gain over the independent layer design [3].

In this article, we will mainly focus on techniques in physical and MAC layers. Cross-layer EE optimization in time, frequency, and spatial domains has been discussed in [3] while four fundamental tradeoffs, including deployment efficiency - energy efficiency tradeoff, spectral efficiency - energy efficiency tradeoff, bandwidth - power tradeoff, and delay - power tradeoff, have been studied in [4]. Different from them, we will discuss these topics from the perspective of how to develop specific energy-efficient techniques. Specifically, in Section II, fundamentals on energy-efficient communications are first introduced, including the information-theoretic bounds and the impact of some practical issues. In Section III, 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 has been presented in [5]. Next, some advanced techniques, including MIMO and relay, will be elaborated. Although these techniques can improve SE significantly, high expense is also paid, including additional configuration of antennas or relay stations and additional energy consumption. How to design energy-efficient MIMO and relay systems will be provided in Sections IV and V, respectively. In Section VI, we will discuss signaling design considering EE and focus on the resource allocation between signaling and data symbols. Section VII concludes the paper.

II. 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 is thus deviated from energy-efficient design.

During the past decades, EE, which is commonly defined as information bits per unit 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 $C = 2BR$ bits per second. Consequently, EE is [4], [8]

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

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

The result in (1) is obtained by assuming an infinite size of information block and infinite number of DOF. However, the system behavior is totally different in finite case. It is shown 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 tradeoff between EE and data rate. Taking circuit energy consumption into consideration, EE needs to be redefined as information bits per unit energy (not only transmit energy), where an additional circuit power factor, P_c, needs to be added in the denominator of (1). Accordingly, the η_{EE}-versus-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], which will be discussed later. To analyze the impact of circuit power on EE quantitatively, detailed modeling of equipment level energy consumption of devices such as BS 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 is 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 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 with the transmit power.

III. 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. Fig. 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. And two most commonly used classes of dynamic resource allocation schemes are *rate adaptation* (RA) that maximizes throughput and *margin adaptation* (MA) that 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 large sometimes. 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% reduction in energy consumption when frequency diversity is exploited.

Energy-efficient design has been also 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 towards the BS, and the closer the user is to the BS, the higher the modulation order should be.

In an interference-free environment, a tradeoff between EE and SE exists for increasing transmit power always improves SE but without guarantee of EE improvement. However, in multi-cell 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 multi-cell scenarios with inter-cell interference is studied. As shown there, energy-efficient power distribution not only boosts system EE but also refines the EE-SE tradeoff 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 tradeoff is not addressed yet. Further research on the following aspects is desired.

- *Energy-Efficient Transmission in Downlink:* In many situations, downlink EE is also very important. For example, the construction of base stations in cellular networks might desire more environment-friendly behavior and less expenditure for energy consumption. And 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.
- *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 length 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.

- *Tradeoff between EE and SE:* Since EE and SE are two important system performance indicators, the tradeoff 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 system designer. Meanwhile, proper utility function should be investigated for locating the optimum operating point on the boundary of EE-SE region.

IV. 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 *multiple-input multiple-output* (MIMO). MIMO can also be used with single user or multiple users to form *single-user MIMO* (SU-MIMO), *multi-user MIMO* (MU-MIMO), and *coordinated multipoint transmission* (CoMP). 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 modes 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 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 as compared with single antenna transmission if they are not combined with adaptive modulation. However, by adapting modulation order to balance transmit energy and circuit energy consumption, MISO systems outperform SISO systems. Different MIMO schemes may have different EE in different scenarios. In [23], adaptive switching strategy among different MIMO modes is investigated. Spatial division multiplexing, space-time coding, and SISO transmission are adapted based on the CSI. It is shown that smart adaptation can achieve better EE-SE tradeoff compared with single MIMO mode and the improvement of EE is up to 30% compared with non-adaptive systems.

Existing research on the EE of MIMO techniques mainly focuses on the open-loop SU-MIMO schemes. A lot of potential research can be developed in other aspects of MIMO schemes to further improve EE. Some possible topics are as follows.

- *Closed-Loop MIMO Schemes:* Closed-loop MIMO schemes, such as beamforming and precoding, are shown to enhance SE efficiently. However, the overhead for CSI feedback will consume additional radio resources, including time, bandwidth, and power. Whether or when closed-loop MIMO schemes are more helpful than open-loop ones to save energy is still an open issue.
- *Energy-Efficient MIMO Schemes in Multi-User and Multi-Cell Scenarios:* In multi-user and multi-cell environments, the existence of inter-user and inter-cell interference complicates the design of energy-efficient MIMO systems. How to utilize the spatial resource to maximize EE while suppressing the interference is well worth investigating.
- *Energy-Efficient MIMO-OFDMA Systems:* MIMO schemes are usually incorporated into OFDMA systems. The spatial and frequency resource can be jointly allocated to improve EE. However, the complexity of the joint design may be prohibitive. Effective but simple algorithms need to be developed to obtain a tradeoff between complexity and performance.

V. Relay Transmission

Relay in wireless networks provides another way to improve performance and potentially save energy. By deploying relay nodes, more connections between the source node and the destination node are built and data from the source node can be delivered through multiple wireless links. Due to independence among different fading channels/links, diversity gain can be obtained and SE can be consequently improved. Therefore, the time to transmit a fixed amount of data reduces and so does the consumed energy. If advanced resource allocation schemes are applied, energy can be further saved.

In a typical relay system, a transmission period consists of two phases: broadcasting and multiple access. During the broadcasting phase, the source node sends data to the air, which may be received by the relay nodes or both the relay and the destination nodes. During the multi-access phase, the relay nodes or both the source and relay nodes transmit data to the destination nodes. Note that the nodes to transmit and to receive in these two phases depend on the specific protocols. The transmission schemes at the relay nodes can be *amplify-and-forward* (AF) or *detect-and-forward* (DF) transmission methods.

As shown in Fig. 4, two kinds of relay systems are considered in the literature, pure relay systems and cooperative relay systems [24]. For the pure relay systems, the role of the relay nodes is only to help the source node to transmit data while in the cooperative relay systems, all the nodes act as information sources as well as relays.

A. Pure Relay Systems

For pure relay systems, a critical problem is how to use the relay nodes efficiently, including how many relay nodes are needed for data delivery and how the relay nodes are configured. The EE-SE tradeoff of pure relay systems in AWGN relay channels has been investigated in [25], where the optimal power allocation among relay nodes is proposed to maximize EE. It has been shown that the performance (either consumed energy or data rate) depends on the transmission strategy of each node, the locations of the relay nodes, and the data rate used by each node. Two sub-optimal communication schemes, common rate and common power schemes, are proposed to capture the inherent constraints of networks, bandwidth and energy. Fig. 5, from [25], demonstrates the impact of the hop number, node locations, and data rate on EE. Although power allocation and the number and locations of nodes affect the EE significantly, such joint design is very complex and may not be suitable for some practical scenarios. Some simple and effective relay transmission strategies have been proposed. In order to simplify the relay network, only two hop communications are set up between the source and the destination nodes. Different relay selection schemes have been proposed in [26], [27]. In [26], the best relay node is selected distributively, while in [27], several relay nodes are selected for beamforming based on a simple selection strategy. It is shown that the EE may not increase with the number of relay nodes due to cooperation overhead.

B. Cooperative Relay Systems

Different from the case of pure relay systems, cooperation among users makes it more complex to optimize resource management. The first difficulty is that resource at each user should be split for transmitting data both from itself and from other users besides allocating resource among different users. The second one stems from partner selection, finding an appropriate user as a relay node. It is very complicated to find the optimal parter in a network with a large number of users since the number of possible pairings is huge.

Cooperative relay systems have been widely studied. In [28], a network with two users is considered and power is optimally allocated to maximize EE of each user in a distributed way. It is shown that user cooperation can improve users' EE. In [29], power minimization problem is formulated with constraints on each user's data rate. Cooperative user pairing, power allocation, and subcarrier mapping are jointly optimized. In [30], the EE of cooperative access with relay's data protocol is analyzed for multi-rate *wireless local area networks* (WLANs), considering transmission errors.

C. Potential Research Topics

Existing research results have shown that relay systems can improve EE significantly. However, several important issues are still open.

- *Relay Transmission Considering the Overhead:* Additional time and power may be used for resource allocation during the relay transmission . How to minimize the total energy consumption taking the additional overhead into account is not known clearly.
- *Energy-Efficient Bi-Directional Relay Systems:* Bi-directional relaying is a booming technique and provides more opportunity to save energy. How to design energy-efficient bi-directional relaying systems is an interesting topic.
- *Relay Transmission in Multi-Cell Environments:* Most existing work focuses on the single-point-to-single-point transmission, how to do resource allocation in multiple-point-to-single-point or multiple-point-to-multiple-point transmission, like in the multi-cell case, still needs further investigation.

VI. Resource allocation between signaling and data symbols

Besides data streams, signaling symbols are widely used to assist data transmission in wireless communications. The representative are the signaling for synchronization and channel estimation. In the beginning, resource allocation for signaling symbols is independent of that for data symbols. For example, the number and power of training sequences for channel estimation is only determined by the required estimation accuracy. However, the separation of signaling and data symbol designs does not optimize the system performance. Therefore, joint resource allocation between signaling and data symbols is very important for energy-efficient design.

Asynchronous EE is investigated in [11] for the scenarios that the cost of acquiring synchronization is significant. It is shown that the extent of EE reduction in the asynchronous case, compared with that in the synchronous case, depends on the measure of timing uncertainty. The EE considering training-based channel estimation is studied in [10]. By Gaussian assumption of interference incurred by channel estimation error, it is demonstrated that the EE decreases to zero as the SNR goes to zero, and the maximum EE is achieved at a nonzero SNR value as shown in Fig. 6. The figure also implies that the relationship between EE and SE is no longer a monotonically decreasing function. The EE of training-based schemes are also investigated in [10] when the channel input vector in each coherence block is subject to a peak-power constraint. Optimal resource allocation to maximize EE is obtained through numerical analysis.

In general, the study on resource allocation between signaling and data symbols is only in the initial stage. A lot of open issues need to investigate as listed below.

- *Resource Allocation between Signaling and Data Symbols in Multi-User Cases:* The EE study in the existing literature is limited to the point-to-point case. In the multi-user case, different users may suffer from different channel fading, which results in different requirement of signaling symbols. How to allocate the power and other resources between signaling and data symbols to maximize the EE is still unknown.
- *Signaling Design Considering CSI Feedback:* Although CSI at the transmitter can help to improve system capacity, the additional energy consumption on the overhead of feedback may slow down the increase of EE. The resource allocation with the feedback of CSI needs further study.

VII. Conclusion

In this article, we have comprehensively surveyed energy-efficient wireless communications from the information-theoretic and technique-oriented perspectives. As for the information-theoretic aspect, most literature about EE mainly focused on point-to-point scenarios and the impact of practical issues on EE is not fully exploited. Thus, research on EE needs to be extended to multi-user and/or multi-cell cases as well as considering the practical issues such as transmission associated circuit energy consumption, which is of great significance to the practical system design. As for the advanced techniques that will be used in the further wireless systems, such as OFDMA, MIMO, and relay, existing research has proved that larger EE can be achieved through energy-efficient design. However, most work is still in the initial stage and more effort is needed to investigate potential topics such as those listed in this article.

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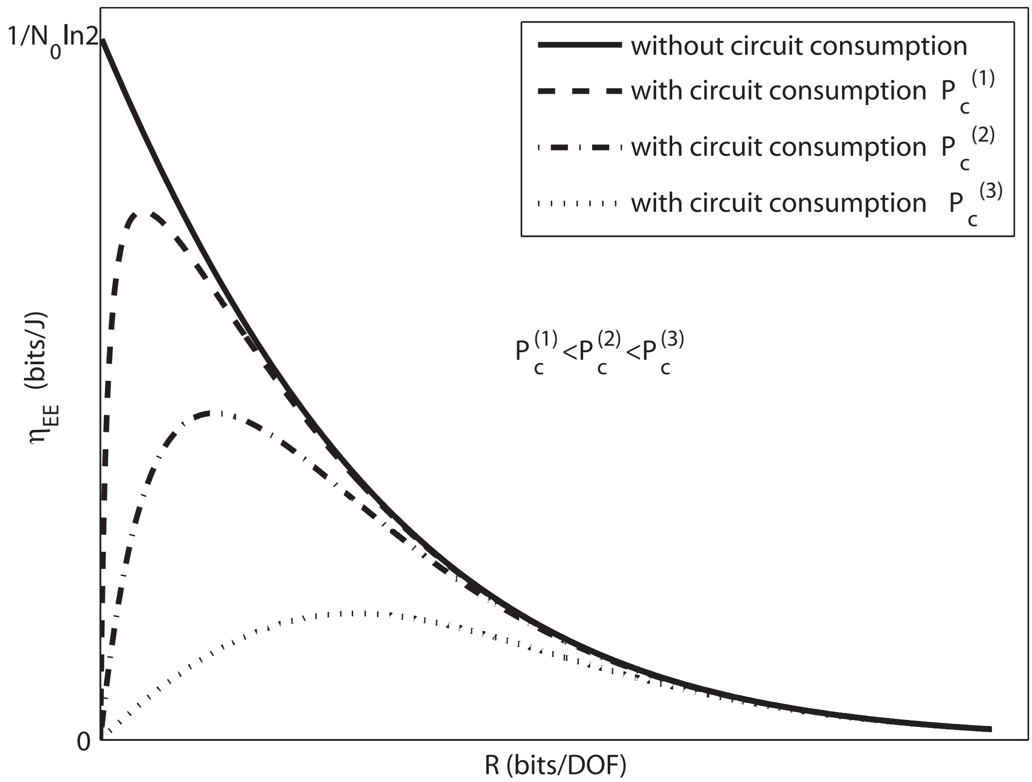

Fig. 1. Tradeoff between EE (η_{EE}) and R in an AWGN channel

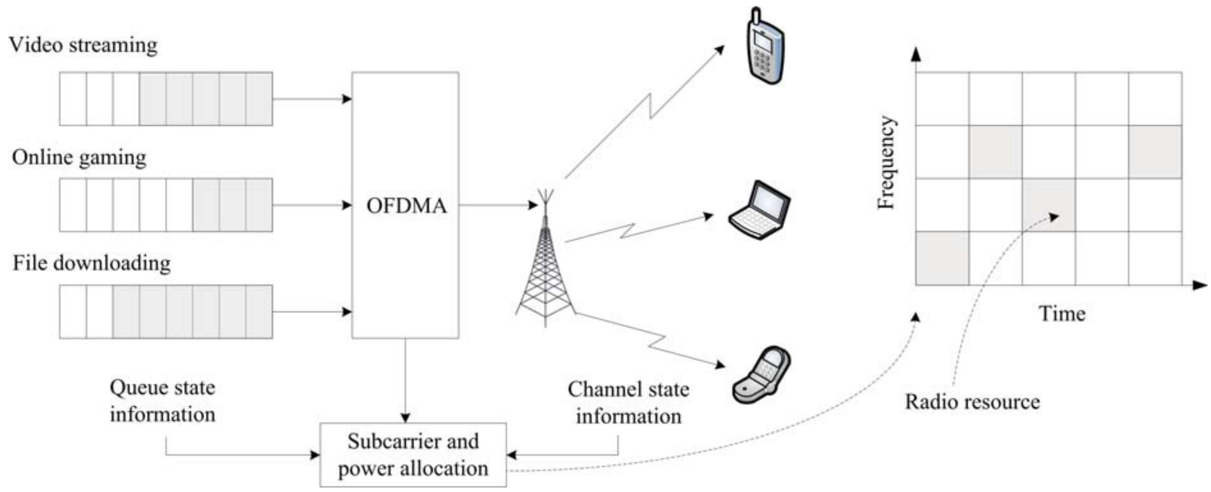

Fig. 2. Resource allocation in OFDMA [19]

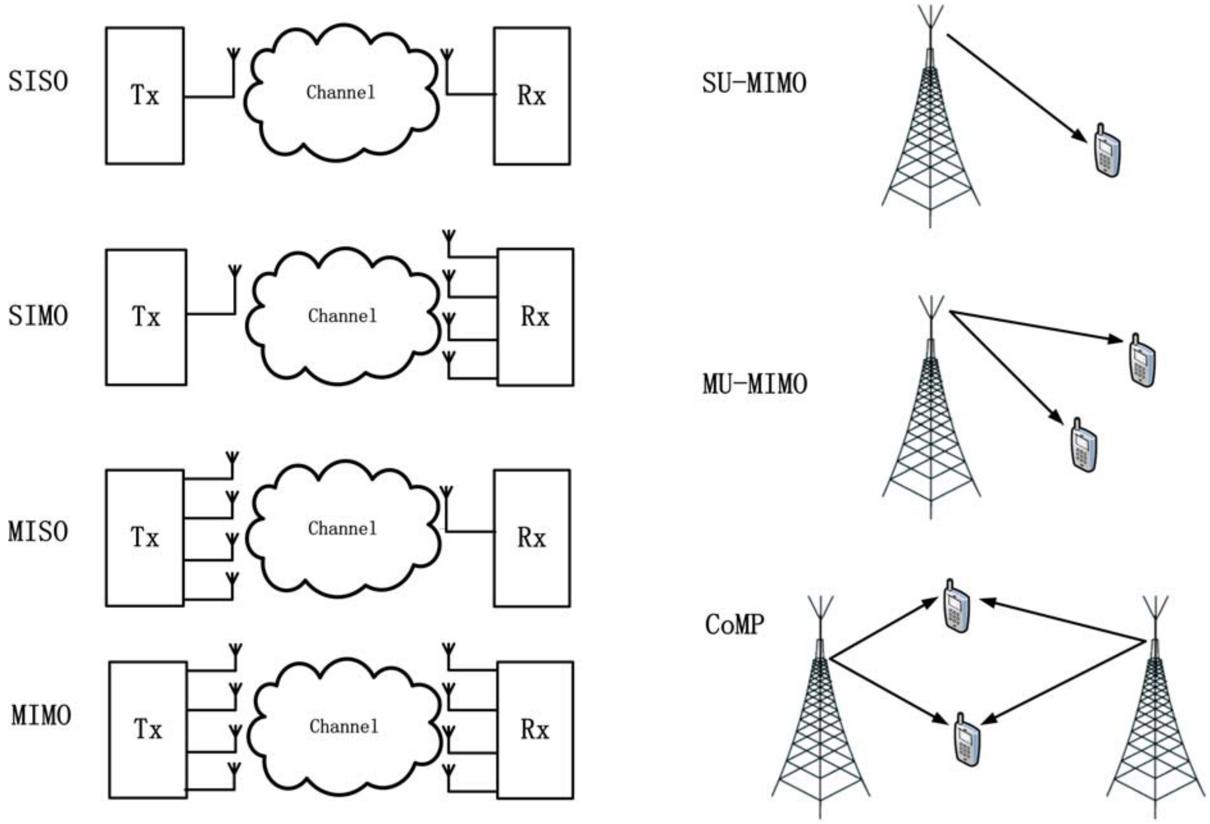

Fig. 3. Diagram of MIMO schemes

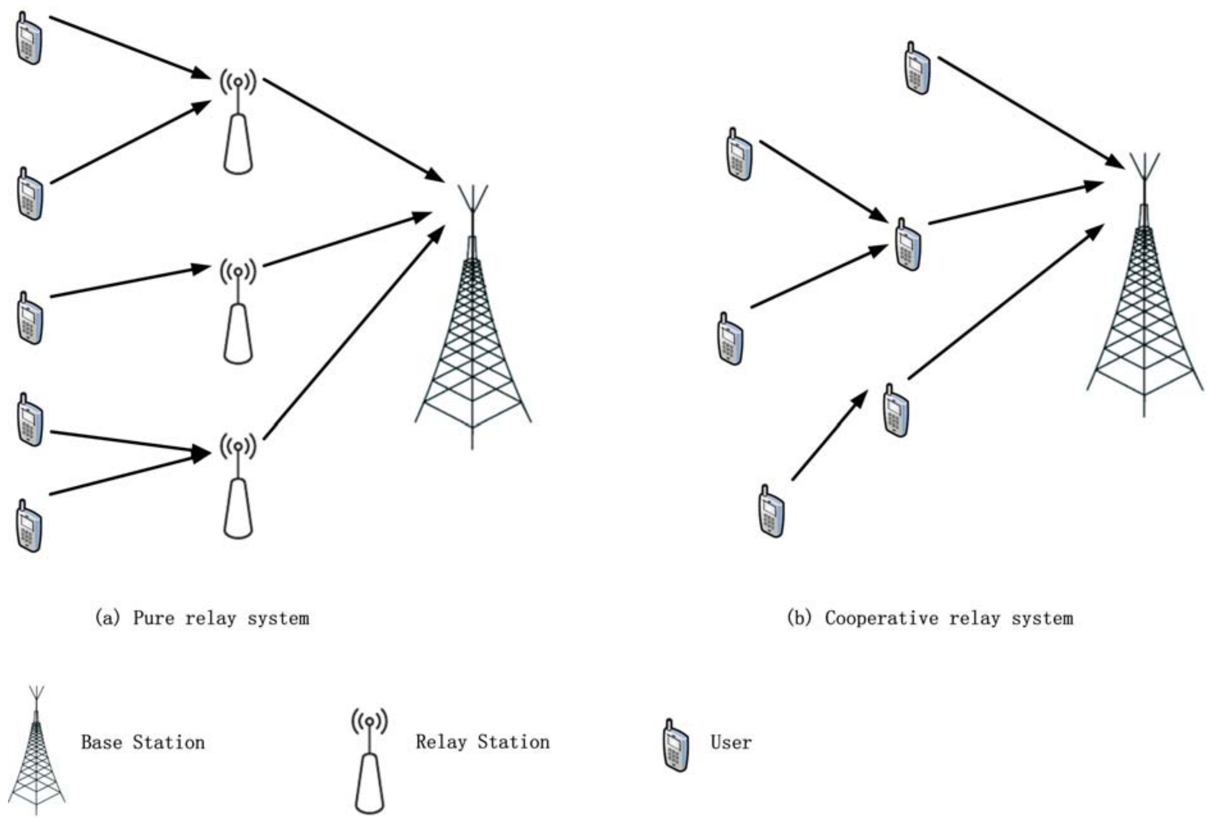

Fig. 4. Two structures of relay systems

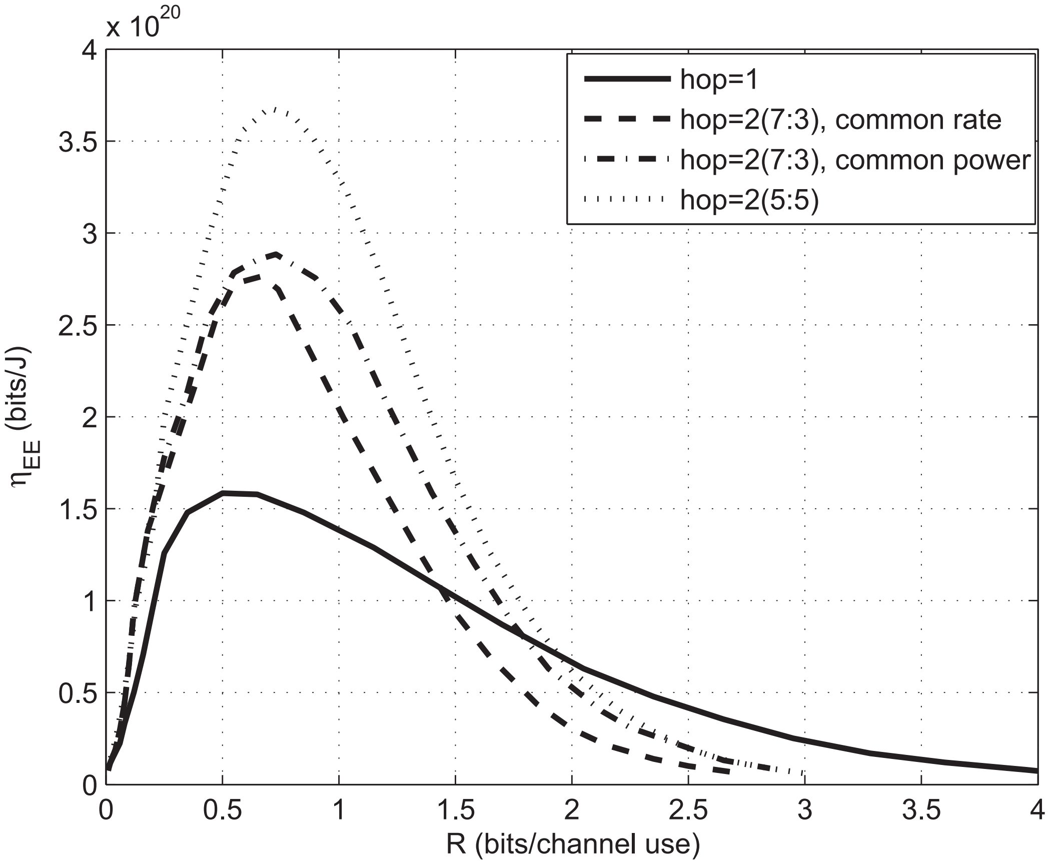

Fig. 5. EE versus data rate in a multihop relay systems when power spectral density of noise $N_0 = -174$ dBm/Hz

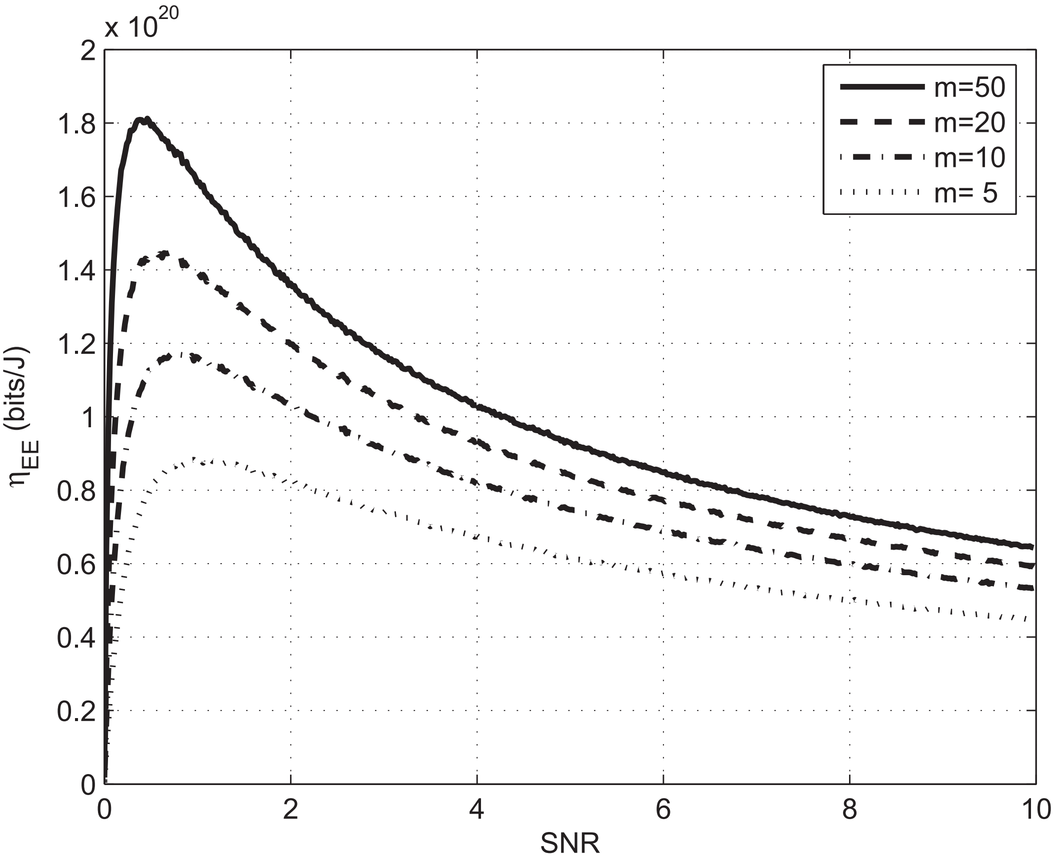

Fig. 6. EE versus SNR in the worst case scenario for block fading channels with m symbol coherence duration and unit variance when the power spectral density of noise $N_0 = -174$ dBm/Hz (Please note that SNR is just regular scale and not in dB here)