Enhancing Energy Efficiency via Cooperative MIMO in Wireless Sensor Networks: State of the Art and Future Research Directions

Yuyang Peng, Fawaz Al-Hazemi, Raouf Boutaba, Fei Tong, Il-Sun Hwang, and Chan-Hyun Youn

ABSTRACT

CMIMO is an effective approach to increase throughput and energy efficiency through the collaboration of individual antennas working together as a virtual multi-antenna system. Several CMIMO strategies have been propounded as major candidates for achieving green communications in wireless sensor networks. Compared to conventional MIMO, CMIMO provides significant gains in terms of flexibility. Recently, more advanced cooperation strategies have been proposed to improve the performance of CMIMO by using emerging techniques such as spatial modulation and coding. Although some breakthroughs have been made in this area, the problem of how to accurately adopt these emerging techniques to model CMIMO is far from being fully understood. This article surveys several state-of-the-art CMIMO models for different scenarios, including data aggregated, multihop-based, and clustered schemes. Moreover, it discusses the implementation of CMIMO techniques, which are expected to be candidate techniques for green communications in modern applications. In the implementation, the trade-offs between energy efficiency and spectral efficiency, quality of service, fairness, and security are discussed. Several simulation results are given to show how emerging techniques in CMIMO design can lead to energy efficiency enhancement. Finally, some challenges and open issues that present future research directions are discussed.

INTRODUCTION

Recently, energy consumption has become a primary performance factor in communication systems. In response, several green communication techniques have been proposed. Typically, they require the target of energy efficiency improvement, which is a near-term goal of going "green." Multiple-input multiple-output (MIMO) has been proved as a key technology to reduce the energy consumption in communication systems. Higher bit rates and energy gains are promised in MIMO systems compared to single-antenna systems. In order to achieve the objectives of MIMO, each wireless device has to be designed with multiple antennas as transmitters or receivers, where the antennas are packed together with spacing on the order of a wavelength. However, due to the small size of the sensor device, referred to as a node, it can be difficult to embed multiple antennas in such nodes. Due to this limitation, traditional MIMO systems cannot produce the expected performance, and the concept of cooperative MIMO (CMIMO) implemented by cooperation of individual antennas is explored to solve the size limitation problem.

CMIMO, also known as virtual MIMO, utilizes the benefit of MIMO elements from independent fading and is one type of cooperative communications. The major difference between MIMO and CMIMO is that in CMIMO, each node is only equipped with one antenna, and nodes are located in different areas. These distributed nodes form a virtual antenna array in order to achieve higher spatial diversity gain, which is also referred to as cooperative diversity gain [1]. The advantages of CMIMO are due to its ability to improve throughput, coverage, and capacity in a cost-effective manner. Because CMIMO offers these tremendous benefits, the research on CMIMO is an active area, and several CMIMO strategies have already been adopted in major wireless standards.

After the pioneering work of Cui *et al*. [2], significant attention has been paid to the design of CMIMO systems over the years. CMIMO has started to become important candidates for many communication networks such as wireless sensor networks (WSNs), ad hoc networks, and vehicular networks. On the other hand, some emerging technologies, such as spatial modulation (SM), have been explored to combine with CMIMO for energy efficiency improvement, and it has been shown that the combined strategy can provide significant performance in terms of energy efficiency [3]. Despite lots of research activity on CMIMO schemes over the last several years, there still remain many technical challenges in the design of CMIMO schemes. The aim of this article is two-fold:

- To present a comprehensive overview on the current state of the art in this research area
- To define open issues for future research directions

The authors survey several state-of-the-art CMIMO models for different scenarios, including data aggregated, multihop-based, and clustered schemes. They discuss the implementation of CMIMO techniques, which are expected to be candidate techniques for green communications in modern applications, as well as the trade-offs between energy efficiency and spectral efficiency, quality of service, fairness, and security.

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Reducing the energy consumption to increase energy efficiency sometimes can result in lower spectral efficiency due to the reduction of the transmission diversity. Usually, the transmission diversity is related to the modulation constellation size and dimension of the transmitted symbol. Therefore, the appropriate techniques such as adaptive modulation and index modulation techniques need to be considered.

The remainder of the article is organized as follows. We first briefly introduce the basic principle of CMIMO and its development. Following that, we discuss the energy efficiency and fundamental factors in CMIMO, and then we review some interesting recent results in CMIMO techniques. Finally, we propose some challenges and future research directions on this topic.

Overview of CMIMO

CMIMO is a novel approach of transmitting information by using collaboration of individual antennas; the idea behind of it can be traced back to the virtual antenna array as the groundbreaking work. In CMIMO schemes, the antennas are self-configured to form a cooperative network without any established infrastructure, as shown in Fig. 1. The communication between the transmitter and receiver proceeds in two phases: information sharing and cooperative transmission. Through the first phase, all the nodes get the information data from the others and enable independent data transmission. In the second phase, all the nodes or selected nodes cooperate together to form a virtual MIMO system through techniques such as distributed space time block coding or repetition. The antennas handle the necessary control and communication tasks by themselves via the use of distributed algorithms without an inherent infrastructure. CMIMO schemes are highly appealing for many reasons. In contrast to conventional MIMO schemes, which relay by packaging multiple antennas in one device, CMIMO schemes break this limitation and work in a flexible way without the performance decreasing in terms of throughput. Also, due to the distributed nature, CMIMO schemes can be rapidly deployed and reconfigured. However, these advantages should not be taken to mean that CMIMO schemes are totally flat. Indeed, many CMIMO schemes require a backbone for use by the cluster head node or assistant node to form cooperative transmissions. The cluster head node and assistant node are usually selected from distributed devices, which makes the implementation of the whole CMIMO system complex. Therefore, exploiting the good design structures of CMIMO without violating the fundamental requirements such as spectral efficiency, quality of service (QoS), fairness, and security has important value. The energy constraint is another vital concern in CMIMO schemes. Most existing applications for CMIMO are implemented by assuming that the individual antennas are embedded in the devices with limited energy, and the devices are dropped into a remote region. Therefore, conserving energy to maximize the lifetime is very important, and motivates the research focusing on energy efficiency. On the other hand, ensuring energy efficiency has an effect on the aforementioned fundamental requirements. Thus, finding the trade-off [4] between energy efficiency and the aforementioned fundamental requirements is critical to design energy-efficient CMIMO. Considering the analysis in CMIMO, we may conclude that CMIMO can be a good candidate for next generation communications if we appropriately utilize its advantages and solve its drawbacks.

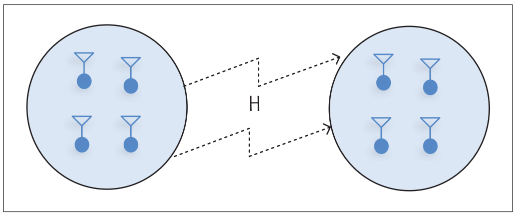

Figure 1. A cooperative MIMO scheme

Energy Efficiency in CMIMO

Since the aim of using CMIMO schemes is to tailor the CMIMO design to the appropriate application for improving energy efficiency, it is useful to discuss the energy efficiency in the CMIMO design. Several fundamental factors need to be considered in energy-efficient CMIMO design. In what follows, we consider the spectral efficiency, QoS, fairness, and security as the fundamental factors and discuss their effects on energy efficiency in CMIMO design. Reducing the energy consumption to increase energy efficiency sometimes can result in lower spectral efficiency due to the reduction of the transmission diversity. Usually, the transmission diversity is related to the modulation constellation size and dimension of the transmitted symbol. Therefore, the appropriate techniques such as adaptive modulation and index modulation techniques need to be considered. In [3, 5], the index modulation technique is taken into account in CMIMO design. The results show that significant energy efficiency is achieved compared to the traditional way under the same spectral efficiency. QoS is a factor interacting with energy efficiency and needs to be guaranteed in most cases. Apparently, the QoS improvement mechanism is contradictory to the energy efficiency requirements because good QoS usually requires big energy consumption. However, for a given QoS, energy efficiency can be achieved by adapting the modulation scheme at the cost of increasing the transmission power. Some systems are energy efficiency preferred, whereas some are power preferred. The type of reference depends on the system itself. If the system is energy efficiency preferred, the property of big power can be neglected. In [2, 6], the optimal modulation constellation sizes are derived to achieve energy efficiency under the given bit error ratio (BER) requirement. The results show that by adapting the modulation to choose the optimal modulation constellation size, the energy efficiency is obtained. Fairness for a communication system refers to the degree to which a fair share of system resources is utilized. For instance, in cognitive-radio-based wireless networks, a certain amount of spectrum should be assigned regardless of the ambient environment. In many cases, increasing energy efficiency causes unfair sharing of the system resources. Therefore, it aims to allocate resource as fairly as possible while keeping energy efficiency. The authors in [7] propose a cognitive CMIMO by considering the radio resource being fairly utilized, and the results show good performance in terms of energy efficiency. For CMIMO-based wireless sensor networks, security is usually not mandatory but desired. In a normal security-based environment, more energy is needed during the transmission due to the additional processing at both the transmitter and receiver. Spending more energy will decrease the energy efficiency. However, in some special environments such as the military environment, secure transmission can improve energy efficiency by avoiding the additional energy due to misdetection and retransmission. Hence, considering security or not to improve energy efficiency in wireless sensor networks is highly dependent on the operating environment. In the following section, we discuss more energy efficiency issues of the recent advanced techniques in CMIMO design.

RECENT ADVANCES IN CMIMO

DIVERSITY GAIN IN CMIMO SCHEMES

The first study on the CMIMO concept in WSNs dates back to 2004, in which Cui *et al.* [2] were the first to propose a CMIMO with Alamouti code in clustered WSNs. By cooperating with the neighboring wireless nodes, CMIMO can efficiently reduce the transmission energy, but this benefit comes at the cost of higher circuit energy consumption. Since the transmission energy of wireless nodes is proportional at least to the square of the distance, the transmission energy dominates the total energy consumption for a long transmission distance. On the other hand, when the transmission distance is short, circuit energy becomes the major contributor in the total energy consumption. Therefore, in the case of long transmission distance, more cooperative nodes should be used to reduce the transmission energy consumption via antenna diversity, while in the case of short transmission distance, fewer cooperative nodes are preferred to reduce the circuit energy. Moreover, the authors also show that there is an optimal modulation constellation size for each transmission distance. By considering this factor, the energy consumption performance of CMIMO can be further improved.

MULTIPLEXING GAIN IN CMIMO SCHEMES

Vertical-Bell Labs Layered Space-Time (VBLAST)-virtual MIMO [6] is yet another classical CMIMO, which provides multiplexing gain by allowing a virtual antenna array to transmit N independent data streams. The core technique of this scheme is to point a data gathering node that can cope with more computational complexity than other normal nodes at the receiver. At the transmitter, each of the nodes broadcasts its data to the other nearby nodes by means of a time-division multiple access scheme. After that, each node has data from all the others to transmit through space time coding techniques. At the receiver, the data gathering node receives data from the transmitter, which allows realization of real MIMO capability with only transmitter side local communications. Using this method, significant energy reduction is achieved.

DATA AGGREGATION GAIN IN CMIMO SCHEMES

The CMIMO with data aggregation technique is a way in which the correlated data size can be significantly reduced according to the correlation factor [8]. The underlying philosophy is to reduce the amount of redundant data depending on the data similarity at the transmitter. Specifically, the sensor nodes send the information data to their cluster head, and then the cluster head aggregates the collected data and sends them back to all the sensor nodes in that cluster. Thus, all the sensor nodes at that cluster have the same aggregated information data. After that, the sensor nodes transmit the received aggregated data to the sensor nodes that are located in the receiving cluster, and then sensor nodes at the receiving cluster transmit the received data to their cluster head for joint detection. By considering data aggregation, the transmitted data amount is significantly reduced, and so is the total energy.

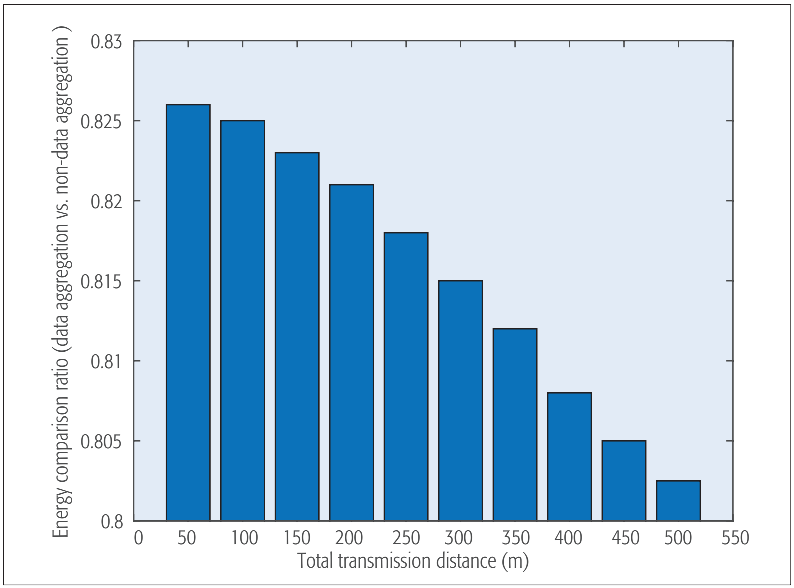

Figure 2. Energy comparison over transmission distance.

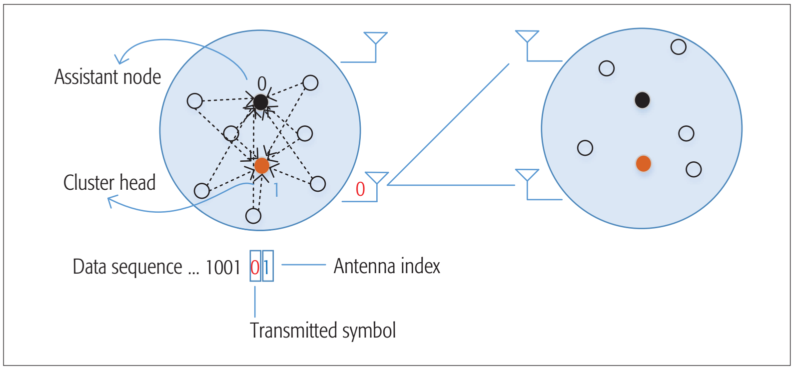

Figure 3. A CMIMO-SMR system.

Figure 2 illustrates the energy performance of data aggregation in CMIMO schemes. The comparisons are carried out under the data-aggregation-based and non-data-aggregation-based CMIMO schemes for a transmission distance of 500 m. The energy comparison ratio shows that data-aggregation-based CMIMO provides significant energy saving over non-data-aggregation-based CMIMO. We observe that although the process of data aggregation requires additional energy, this part of energy has little effect on total energy consumption. In addition, the transmission energy saving due to the small amount of data after data aggregation affects a lot of the total energy consumption. Moreover, the energy

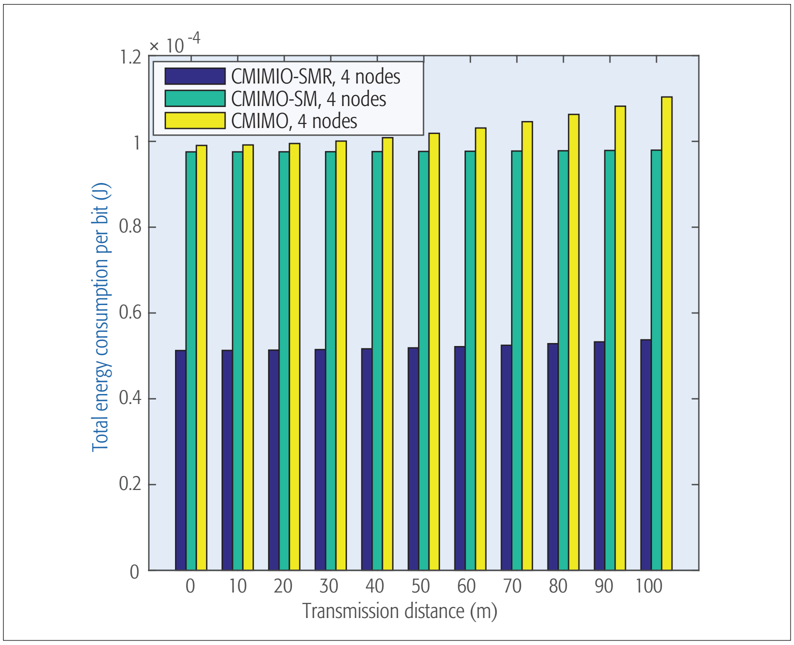

Figure 4. Energy consumption per bit over transmission distance under four-node transmission schemes.

saving performance of data aggregation becomes apparent because the transmission energy dominates the total energy consumption as the transmission distance increases.

INDEXING GAIN IN CMIMO SCHEMES

CMIMO-spatial modulation (CMIMO-SM) is a novel CMIMO transmission scheme based on the SM technique [3]. The adoption of SM makes CMIMO systems operate without inter-channel interference (ICI). In CMIMO-SM, each node at the transmitter side broadcasts its information data to all the other nodes inside the transmitting cluster using different time slots as the first stage. In the second stage, after each sensor node receives all the other information data, the data sequence is transmitted via the MIMO channel. Note that, for each time instant, the transmitted data sequence is split into two parts: the multiple quadrature amplitude modulation (MQAM)/ multiple phase shift keying (MPSK) modulated symbol part and the antenna index part. Only the modulated symbol part is transmitted, while the antenna index part is reserved for the selection of active transmit antenna and will be detected at the receiver as hidden information. Therefore, for the same spectral efficiency, fewer bits are transmitted in CMIMO-SM compared to CMIMO. Additionally, CMIMO-SM requires a single RF chain, unlike plain CMIMO. Overall, the total energy consumption, including transmission energy and circuit energy, is reduced in CMIMO-SM when compared to that in CMIMO.

CMIMO-SM with randomly distributed nodes (CMIMO-SMR), shown in Fig. 3, is a recently proposed clever modification of CMIMO-SM to improve the flexibility while maintaining its advantages such as ICI-free and energy-efficient transmission [5]. In CMIMO-SMR, the cluster head node and assistant node are jointly set up by means of a cooperative technique in each cluster to obtain diversity. Specifically, the randomly distributed nodes form clusters; and in each cluster there are a cluster head, an assistant node, and several nodes. The cluster head and assistant node have a preassigned index by use of 1 and 0, respectively, to represent them. In the cluster, each node decides if it works as a cluster head for each round according to the rounds in which the node has been a cluster head. After that, the nodes inside the cluster inform the selected cluster head that they will operate as normal nodes or the assistant node by transmitting an extra bit along with the information data. According to the received signal strength (RSS) of the acknowledgment from the other nodes, the cluster head selects the assistant node from the interested candidates. Once the formation of the cluster is done, the nodes only transmit information data to the cluster head and the assistant node. After that, the cluster head and the assistant node transmit the received information data by use of SM. Compared to CMIMO-SM, CMIMO-SMR has less operation inside the cluster and lower circuit energy consumption at the receiver due to the existence of the cluster head and assistant node. Thus, total energy reduction is achieved.

To analyze the energy consumption performance, Fig. 4 shows the total energy consumption per bit and transmission distance for the case of four nodes in one cluster. Three cooperative transmission schemes are considered in Fig. 4: CMIMO, CMIMO-SM, and CMIMO-SMR. It can be seen from Fig. 4 that the energy consumption per bit of each scheme increases as the transmission distance increases. This is because longer transmission distance requires bigger energy consumption. In Fig. 4, the case with CMIMO-SMR achieves the highest performance in terms of energy consumption due to the energy-efficient transmission.

HOP IN MULTIHOP-CMIMO SCHEMES

When the transmission distance is far, CMIMO is often presented in the context of multihop architectures. The authors in [3] derive an optimal hop length expression for multihop-CMIMO-based linear networks, where the sensor nodes form clusters using CMIMO-SM to transmit the information. The optimal length is derived mathematically by considering the transmitted load. Specifically, a cluster close to the destination forwards more load than another cluster far away from the destination; thus, the hop length for the cluster that is close to the destination should be small. The opposite way can be explained for the big hop length. In this way, for each hop length, there is a matched optimal value for it to achieve the minimum energy consumption.

When the intermediate hops act only forwarding information data rather than transmitting their own information data, an optimal number of hops that can be used to minimize the total energy consumption of the whole network can be found by solving the optimization problem. Specifically, the total energy consumption is dependent on the number of hops and can be treated as a convex function. The optimal number of hops can be achieved by taking the first-order derivative of the total energy function with respect to the number of hops and setting it to zero. Because the number of hops is defined over integer values, the adjacent value, which is with regard to the minimum total energy consumption, can be selected as the optimal number of hops. Figure 5 shows the optimal number of hops and the total energy consumption for a CMIMO-SMR-based multihop network where four different BER situations are considered. For each different BER case, a different optimal number of hops can be found to minimize the total energy consumption when both transmission energy and circuit energy are considered. It can be seen that the optimal number of hops increases as the BER performance increases. This can be explained as the truth that good link quality requires short transmission distance, namely, more hops.

COMMUNICATION MODES ADAPTATION IN CMIMO SCHEMES

In cooperative communications, it is possible to form CMIMO mode, cooperative single-input multiple-output (CSIMO) mode, and cooperative multiple-input single-output (CMISO) mode via the collaboration of nodes. In wireless sensor networks, the energy reduction can be achieved by adapting the communication modes for each transmission hop. In [9], a novel communication mode adaptation algorithm is introduced to improve energy efficiency in wireless sensor networks. For each hop, the adaptation of communication modes is considered and determined by optimizing the parameters such as the number of transmitters, receivers, and cooperation nodes to achieve the minimum energy consumption. The experiment results show that significant energy reduction can be obtained by using the communication modes adaptation algorithm.

RADIO RESOURCE MANAGEMENT IN CMIMO SCHEMES

Radio resource management is one effective way to reduce energy consumption of wireless systems [10]. The goal of the research on radio resource management is to efficiently utilize the radio resource of the whole network by use of traffic-aware and cognitive radio techniques. In [7], the authors present cognitive CMIMO where the local broadcasting phase and distributed MIMO access phase operate in the cognitive and licensed bands, respectively. In the broadcasting phase, each active node broadcasts its own message with a transmit power, whereas an inactive node becomes a participant of the CMIMO only when it can successfully decode the message transmitted from the nearest active node. It shows that the energy efficiency can be increased by tuning the bandwidth ratio for a given spectral efficiency range.

SLEEPING STRATEGY IN CMIMO SCHEMES

In CMIMO networks, it is not always reasonable to assume that all nodes simultaneously participate in the transmission or are active in certain scenarios. Therefore, sleep mode is an effective tool for energy saving. For example, Li *et al.* [11] consider the design of CMIMO schemes to decide whether a node with a single antenna should be active to become a part of CMIMO under an energy constraint requirement so as to achieve better system performance. In particular, under large-scale CMIMO-based networks, the number of cooperating nodes is high. In this case, if all the nodes participate and keep active in the cooperation stage, the local energy consumption, especially the circuit energy consumption, will increase. On the other hand, the cooperation of large active nodes makes the cooperative transmission consume less transmission energy in the long haul due to the added spatial diversity. Therefore, there is a trade-off between the number of active nodes and total energy consumption. This active nodes selection can be done via making a node sleeping strategy, and then the total energy consumption of CMIMO networks can be optimized by use of the sleeping strategy.

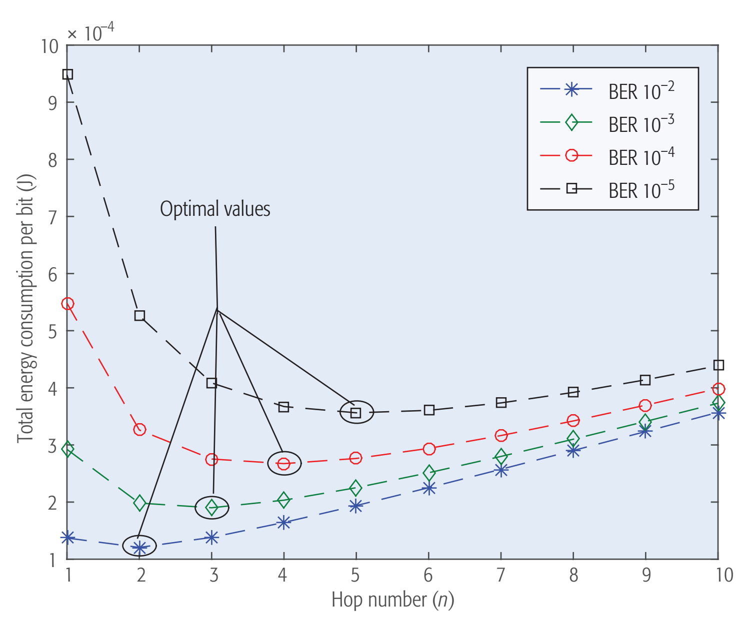

Figure 5. Optimal number of hops vs. energy consumption.

JOINT SELECTING GAIN IN CMIMO SCHEMES

Joint selection is a good candidate to reduce the energy consumption of wireless systems [12]. In multihop-CMIMO networks, the energy consumption is more complex due to the complex transmission environments. CMIMO can exploit the spatial diversity to reduce the transmission energy under a given BER. Therefore, larger hop length should be used to reduce the number of hops. On the other hand, when the hop length is large, the energy consumption of long-haul transmission will dominate the overall energy consumption. Thus, more nodes are required to enlarge the spatial diversity, which will benefit the transmission energy. This analysis means that not only the hop length, but also the number of hops influence the total energy consumption. In [13], a joint selected scheme is proposed in CMIMO systems for energy reduction. In this scheme, the hop length and the number of cooperating nodes are jointly selected under the high node density condition. The simulation results indicate that significant energy saving is obtained by using the joint selected scheme.

In Table 1, a comparison of various energy-efficient CMIMO schemes with the corresponding technologies, fundamental dimensions, and design goals are provided.

To improve the BER performance and optimize the power allocation in CMIMO systems, the channel estimation is indispensable. Although there have been many works in real MIMO channel estimation, the channel estimation in CMIMO is a challenging task because the antenna elements of CMIMO is not integrated.

Schemes	Technologies	Fundamental dimensions	Goals
CMIMO [2]	Diversity	Spectral efficiency, QoS	Reducing energy via cooperation
VBLAST-CMIMO [6]	Multiplexing	Spectral efficiency, QoS	Reducing energy via cooperation and less overhead
CMIMO-DC [8]	Date aggregation	Spectral efficiency, QoS	Reducing energy via data aggregation
CMIMO-SM [3]	Indexing, multihop	Spectral efficiency, QoS	Reducing energy via indexing
CMIMO-SMR [5]	Indexing, multihop, flexibility	Spectral efficiency, QoS	Reducing energy via indexing and flexibility
Scheme in [10]	Radio resource management	Fairness	Reducing energy via radio resource management
Scheme in [11]	Sleeping	Spectral efficiency, QoS	Reducing energy via sleeping mode
Scheme in [13]	Joint selection	Spectral efficiency, QoS	Reducing energy via joint selection

Table 1. Comparison of several CMIMO schemes.

CHALLENGES IN COOPERATIVE MIMO

Despite the significant developments that have been achieved in CMIMO, in practical environments, CMIMO still faces several challenges.

CROSS-LAYER DESIGN

Cross layer design for energy efficiency improvement is important in CMIMO-based transmission. The key design challenge is the performance guarantee when several layers are considered together. There have been many works at different layers in CMIMO networks for energy efficiency. However, their efforts mainly focus on isolated layer design, thus ignoring important interdependencies. Such isolated layer design results in poor performance, especially in real environments when energy and delay are constraints. To overcome this problem, a cross-layer design that supports integration across multiple layers of the protocol is required.

POWER CONTROL

Power control is a potent way to improve the performance of CMIMO transmissions. Due to multipath fading, the channel changes randomly. Power control can be used to compensate the random channel, reduce the transmit power, meet the delay constraint, and minimize the probability of link outage. For example, when the CMIMO transmission experiences a deep fading channel, much power should be used to maintain the required signal-to-noise ratio (SNR); when a hard delay constraint requirement is given, the power for transmission of a packet should be increased to improve the probability of successful transmission. For all these purposes, power control in the CMIMO environment needs to be investigated.

CHANNEL ESTIMATION

To improve the BER performance and optimize the power allocation in CMIMO systems, channel estimation is indispensable. Although there have been many works on real MIMO channel estimation, the channel estimation in CMIMO is a challenging task because the antenna elements of CMIMO are not integrated. Moreover, because of the frequent changing of cooperated candidates, the timing requirement of channel estimation is very strict. To achieve accurate channel estimation, there remain many open issues, such as how to utilize only partial channel state information to estimate the whole CMIMO channel, and how to characterize the relation of multiple links at the system level appropriately.

TOPOLOGY DESIGN IN MULTIHOP-CMIMO

Existing topology schemes in CMIMO are mainly developed for linear networks. Specifically, the linear network is categorized into all transmission and single-transmission networks. In these CMIMO-based networks, the optimal values such as the optimal number of hops or optimal hop lengths are calculated for the purpose of total energy saving. Their solutions mainly rely on Lagrange function or derivation. However, in fact, the nodes in CMIMO networks are usually distributed, and the linear topology may not always be suitable. Therefore, the optimal solutions in terms of hops and hop lengths for CMIMO-based random topology are needed. There have been some methods, such as energy awareness optimal relay selection (EAORS) [14], for solving the energy efficiency problem. However, it is not used in the CMIMO scenario yet. Thus, adopting such methods into CMIMO can be a good way to solve the topology problem.

ADAPTIVE RESOURCE ALLOCATION

In CMIMO systems, adaptive resource allocation can provide robust performance while meeting application-specific requirements. The working principle is to achieve better transmission performance via adaptation of the transmission schemes inlcuding constellation size, coding scheme, power level, and so on. In [2], the authors design an adaptive modulation by changing the modulation constellation size for compensating SNR variations. The transmit power can be adapted by changing the modulation constellation size to meet the BER requirements caused by the variations of SNR. However, in real CMIMO systems, how to facilitate and motivate CMIMO to be adaptive is challenging. In other words, mechanisms to facilitate the adaptation need to be investigated.

SERVICE DIFFERENTIATION

In CMIMO, energy saving should exploit not only the traffic load variations by considering the node sleeping strategy, but also the variations of QoS requirements. Specifically, in CMIMO-based wireless networks, some applications require short delay, whereas some applications are delay-tolerant. Therefore, it is reasonable to differentiate the types of traffic and make the energy consumption scale with the corresponding traffic type. Such service-differentiation-based CMIMO can be a potential candidate for energy reduction.

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CONCLUSIONS AND FUTURE WORK

CMIMO schemes are regarded as a major innovation that has potential to fundamentally increase the energy efficiency and maintain the advantages of MIMO schemes. Recently, most developments in CMIMO design target a single technique for energy efficiency. The inherent drawback of these solutions is the lack of techniques combination. For each part in CMIMO, there are different techniques for energy efficiency. Appropriate combination of these techniques will enable CMIMO to achieve significant performance improvements.

In this article, we have reviewed and discussed recent advances in CMIMO transmission schemes. Although some significant works in CMIMO schemes have been done, there is still work to be done on energy efficiency improvement. Through analyzing the characteristics of different cooperation schemes, we have given a comprehensive tutorial on CMIMO to provide a guideline for CMIMO design. In particular, we have shown the comparisons among different CMIMO schemes and the key techniques used in these schemes. To solve the energy efficiency problems in CMIMO, we have listed several challenges as future research directions in this area.

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BIOGRAPHY

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