Cooperative MIMO in Wireless Networks: Recent Developments and Challenges

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***Abstract*—Cooperative multi-input multi-output (CMIMO) is a form of cooperative communications. CMIMO emulates the functionality of multi-antenna systems by grouping wireless devices to operate as virtual multi-antenna nodes. Its main objectives are to boost network throughput, conserve energy, and improve network coverage. In this article, we discuss recent applications of CMIMO in contemporary wireless networks, including wireless sensor, mobile ad hoc, wireless LAN, cognitive, and cellular networks. We highlight several open issues that present challenges to practical deployment of CMIMO.**

***Index Terms*—Cooperative communication, virtual MIMO, MAC protocol, clustering, routing, interference management.**

I. INTRODUCTION

Multi-input multi-output (MIMO) communication is a proven technique to increase the throughput and reduce the energy consumption of a wireless network. The throughput and energy gains are, respectively, realized by having a multi-antenna node simultaneously send/receive several data streams (spatial multiplexing) or send/receive one data stream from several antennas (spatial diversity). To exploit MIMO's spatial multiplexing and diversity gains, each wireless device (henceforth, referred to as a node) has to be equipped with multiple antennas, which must be separated from each other by at least half of the operating wavelength. Small form-factor devices, e.g., mobile stations and sensors, are typically equipped with at most a few antennas. This limitation prevents such devices from taking advantage of MIMO gains efficiently.

In cooperative communications, a group of nodes that lie within a certain proximity can cooperate in sending (receiving) a signal to (from) another group of nodes. Cooperative MIMO (CMIMO), sometimes referred to as distributed, virtual, or networked MIMO, is one type of cooperative communications, whereby several nodes, each equipped with one or more antennas, cooperate to emulate a multi-antenna node, also known as a *virtual antenna array* (VAA). CMIMO allows small devices to harvest MIMO gains, and moreover, offers numerous advantages that are beyond what is typically expected from a real multi-antenna system. For instance, unlike real MIMO systems, CMIMO can flexibly select its distributed antennas to avoid having a low-rank channel gain matrix so that the spatial multiplexing gain can be better harvested (with high-rank channels).

CMIMO has been shown to improve the network lifetime, throughput, and reduce the communication delay. Network lifetime is a critical performance metric in energy-constrained systems such as wireless sensor networks (WSNs). Thanks to CMIMO's higher energy efficiency, the lifetime of a WSN can be prolonged by several times [1], compared with that of a single-input single output (SISO) approach. The throughput and communication delay of mobile ad hoc networks (MANETs) can also be dramatically improved by exploiting the higher transmission range, higher spectrum efficiency, and better interference management capability of CMIMO.

The goal of this article is to introduce the reader to recent applications of CMIMO in contemporary wireless systems. We begin with a brief history of CMIMO and highlight its theoretical gains at the physical and network layers. We then review some representative schemes, and categorize them in terms of their objectives, application contexts, and limitations. For approaches that target the same objective, we use simulations to compare their performance. The paper concludes with a discussion of some open research issues.

II. HISTORY OF CMIMO

During the late 1990s, Dohler and Said introduced VAAs [2], a MIMO-based cooperative scheme. In their model, a source node first broadcasts its data to a group of spatially adjacent nodes. These nodes then cooperate to form a VAA that forwards the signal to the next VAA. The process continues until the the last VAA sends the signal to a sink. Each element in the VAA is referred to as a *cooperating node* (CN).

Almost at the same time of introducing the VAA concept, Laneman et al. proposed distributed space-time block codes (DSTBC). As a variant of space-time block code (STBC), DSTBC is used to achieve diversity gain over a CMIMO link. DSTBC differs from STBC in that its codewords are stored separately at different nodes, which jointly encode the signal before forwarding it to the next CMIMO node. Note that the CMIMO concept was originally proposed for single-antenna nodes to exploit spatial diversity, but was later applied to multi-antenna nodes to leverage spatial multiplexing and/or interference management [3] [4] [5].

III. PERFORMANCE GAINS OF CMIMO

A. Multiplexing Gain

Similar to a MIMO system, CMIMO also offers *multiplexing gain* (MUX). This is obtained by using spatial multiplexing techniques, which allow an N_t-antenna VAA to transmit up to N_t independent *data streams*. At a receiving VAA, any stream that is not destined to that VAA is called an *interference stream*. The decoding process at an N_r-antenna VAA can be interpreted as solving a system of N_r equations, where the number of unknowns equals the number of data and interference streams. Thus, for data streams to be successfully decoded, the

number of data and interference streams must not be greater than N_r. This condition is known as the *degree constraint*. The multiplexing gain of a MIMO or CMIMO link (also known as the *degrees of freedom*) is defined as the maximum number of data streams that can be correctly decoded, and is given by $\min(N_t, N_r)$. This number can be lower if the channel gain matrix is not full-rank. Vertical Bell Laboratories Layered Space-Time Architecture (VBLAST) is a well-known approach to realize MUX in both CMIMO and MIMO.

The MUX of CMIMO is used to boost network throughput. In contrast to the MUX of a MIMO link, which is upper-bounded by the number of antennas per node, the number of antennas per VAA in CMIMO is not fixed and can be dynamically chosen (by changing the number of CNs per VAA) to suppress more interference streams and/or gain a higher MUX. However, unlike classic MIMO, the MUX in CMIMO involves some *cooperation overhead*. This overhead can be interpreted as time/delay overhead, energy for signaling packets (to coordinate CNs or to obtain channel state information (CSI) which is critical to harvest MUX), or cooperation interference incurred from creating and operating VAAs. Moreover, to guarantee the feasibility of CMIMO's decoding, signaling packets have to be exchanged among CNs to ensure the size of the receiving VAA satisfies the degree constraint and lead to a high-rank channel gain matrix (to harvest higher MUX).

B. Diversity Gain

CMIMO can also be designed to achieve *diversity gain* (DIV), which refers to the improvement in the received signal-to-noise ratio (SNR) due to the transmission of multiple, highly correlated versions of the same signal. Before the birth of the MIMO technique, spatial diversity was realized by using multiple antennas at the transmit and/or receive sides. Invention of STBCs for MIMO systems has paved the way for a new method of transmit diversity by spreading the signal onto multiple orthogonal dimensions. To exploit DIV in CMIMO, cooperation is performed smartly by employing DSTBC, which results in a maximum diversity gain of $N_t N_r$. Like MUX, DIV in CMIMO involves cooperation overhead to jointly encode/decode signals at various CNs. One key application of CMIMO's DIV is to conserve energy. As we will see later, CMIMO is of great interest to energy-constrained networks, e.g., WSNs.

C. Range Extension

Viewed as a means to improve signal quality, CMIMO's DIV can also be exploited to extend the transmission range. At a given power budget, the transmission range can be extended by a factor of $\left[\left(\sqrt{N_t}+\sqrt{N_r}\right)^2\right]^{1/\alpha}$ [6], where α is the free-space attenuation factor. Range extension can be used to enhance the network connectivity in MANETs (topology control) or to improve network coverage in WLANs and cellular networks.

D. Interference Management

Information theorists pointed out that in dense networks, due to severe interference, the capacity of each link decreases in proportion to the square root of node density. In such dense networks, CMIMO provides ample opportunity for cooperation to combat and manage interference through *interference alignment* and *interference cancellation* techniques. In interference alignment, a transmitting VAA aligns several of its data streams so that an unintended receiving VAA perceives the interference from these streams as low as one interference stream. In this case, an N_r-antenna VAA can simultaneously receive $N_r - 1$ data streams, regardless of the number of interference streams. Interference cancellation is used by receiving VAAs where several CNs exchange their decoded streams so that these streams are canceled out at unintended CNs.

IV. Applications of CMIMO in WSNs

Sensors are often powered by batteries, which are difficult or prohibitively expensive to be replaced or recharged. Hence, it is critical to design WSNs in an energy-efficient manner.

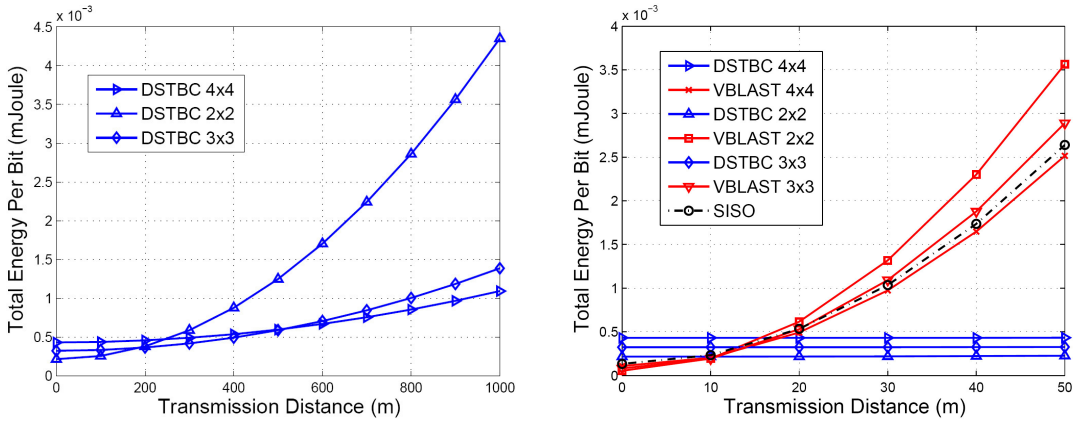
A. Diversity Gain in WSNs

In [7], the authors highlighted the energy efficiency of DSTBC in WSNs. They revealed that the reduction in the transmission energy, obtained through DIV, comes at the price of higher circuit energy consumption. The higher the DIV, the larger the number of CNs, and so the higher is the circuit energy. For long transmission distances, transmission energy dominates the total energy consumption. In this case, a CMIMO scheme should increase the size of VAAs to better exploit DIV. On the other hand, for short distances, circuit energy is the major contributor to the total energy consumption, so one should employ smaller VAAs or even operate in a SISO mode. This finding raises two key issues for protocol design: when should sensor nodes cooperate and how many of them should be used to form a VAA.

To illustrate the above tradeoff, Fig. 1(a) depicts the total energy consumption per bit for different transmit/receive combinations when the target bit error rate (BER) is 10^{-4}, the circuit power consumption per CN is 105 mW, and channel bandwidth is 1 MHz. For transmission distances less than 195 meters, the most energy-efficient configuration is to have two CNs per VAA. If the transmission distance is longer than 195 but shorter than 480 meters, three CNs per VAA is the most energy-efficient configuration. Four CNs per VAA is the best if the transmission distance increases beyond 480 meters, and so on.

B. Multiplexing Gain in WSNs

A VBLAST-based CMIMO scheme for WSNs was proposed in [8]. In this scheme, the sink is equipped with multiple antennas and is assumed to be within the transmission range of all sensors. The underlying philosophy of this scheme is to shift the cooperation burden from the transmit CNs to the sink, which is typically much more powerful in both energy and computational capability than individual sensors. A CMIMO link is formed by having sensors independently transmit their signals to the sink. At the receiver, data streams from different nodes are successively decoded in the order of their received SNR. By transmitting at a higher rate than DSTBC, the transmission duration of VBLAST-based CMIMO is significantly reduced, and so is the circuit energy.



(a) (b)

Fig. 1. a) Energy consumption per bit under DSTBC for different VAA sizes; b) energy consumption per bit vs. transmission distance for DSTBC and VBLAST.

C. Energy Efficiency of DSTBC vs. VBLAST

Using the same parameters to plot Fig. 1(a), Fig. 1(b) compares the energy consumption per bit of DSTBC and VBLAST as a function of the distance between the transmit and receive VAAs. For short communication distances (less than 10 meters), VBLAST is more energy efficient than both SISO and DSTBC. However, for longer distances, DSTBC is more energy efficient. This is because the increase in the transmission energy of VBLAST (due to the higher transmission rate) outweighs the reduction in circuit and cooperation energies.

D. CMIMO in Clustered WSNs

The application of CMIMO in WSNs is often presented in the context of clustered architectures. Neighboring nodes are often grouped into a cluster and are served by a common node, referred to as the cluster head (CH). This network structure is naturally suitable to support CMIMO, where several nodes in each cluster can act as a VAA.

The authors in [9] designed a joint clustering/routing protocol for WSNs that employ DSTBC-based CMIMO. We refer to such a protocol as "Basic-CMIMO". Each cluster is managed by two CHs, a master CH (MCH) and a slave CH (SCH). Besides coordinating with its SCH to form a VAA, the MCH is responsible for creating and maintaining its cluster and collecting sensed data from the cluster members. To reduce energy consumption between two clusters, the size (one or two) of each VAA is adapted to the inter-cluster transmission distance by controlling the transmit powers of individual CNs.

CCP (clustering and cooperative protocol) [1] is another DSTBC-based CMIMO framework for clustered WSNs. In contrast to Basic-CMIMO, CCP optimizes the number of CNs in each cluster and selects CNs so as to minimize the *energy imbalance*. This imbalance is attributed to the fact that nodes closer to the sink end up relaying more traffic than nodes farther from the sink, hence depleting the batteries of the formers much faster. When these nodes die, the network may become disconnected. CCP alleviates this phenomenon by selecting CNs so that the variance of the nodes' residual energy is minimized.

Fig. 2 compares the "network lifetime", defined as the time until the network is disconnected, under Basic-CMIMO, CCP, and a SISO-based clustered WSN (with only one CH per cluster). The simulated WSN consists of 600 nodes that are randomly placed on a square of length 1200 meters. Each node can control its power to adjust the transmission range from 180 to 720 meters. Circuit power consumption of a node is 105 mW. Three signaling packets, each of length 180 bits, are used to recruit a sensor as a CN. We observe that the lifetime of a CMIMO-based WSNs is many times longer than the lifetime of a SISO-based WSN. By optimizing the number of CNs and enforcing energy balancing, CCP dramatically improves the network lifetime over the Basic-CMIMO protocol [9].

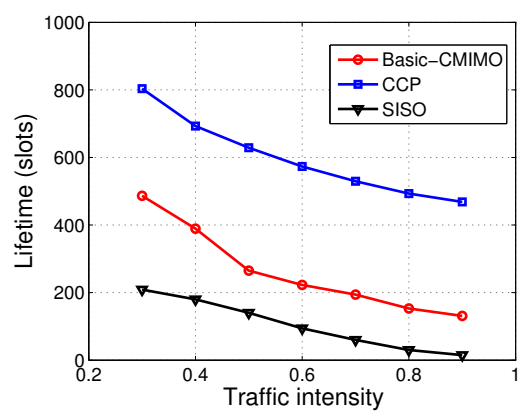


Fig. 2. Network lifetime vs. traffic intensity (normalized) for CMIMO schemes in clustered WSNs.

V. Applications of CMIMO in MANETs

A. Range Extension

The range extension of CMIMO results in a shorter multi-hop path to the sink, which consequently improves network throughput and reduces packet delay. Exploiting this fact, the

authors in [6] proposed a MAC and routing framework that improves a MANET's throughput by up to 150% and reduces the end-to-end delay by 75%. In [6] the CMIMO technique was exploited in the form of multi-input single-output (MISO) communication links, whereby a predetermined number of nodes jointly encode the signal using DSTBC before transmitting it to a single receiver. Specifically, a SISO path is initially constructed using traditional MANET routing protocols (e.g., AODV). This path is then gradually improved by replacing its SISO links with long-haul MISO ones (see Fig. 3).

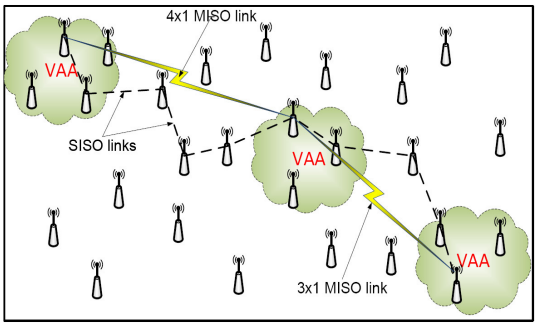


Fig. 3. 9-hop SISO path is gradually replaced by a 2-hop MISO path, improving the network throughput and delay [6].

By extending the transmission range, a MISO link is also more robust to link breakage (which is often attributed to mobility), as a node with its MISO link can reach a larger number of relay candidates, compared with SISO.

CMIMO's range extension can be leveraged to control the topology of a MANET. Topology control deals with minimizing the transmit power of nodes while keeping the network connected. To that extent, several neighboring nodes cooperate to connect to nodes that are not reachable otherwise. For instance, the transmission range of an 2×2 DSTBC-based CMIMO link under a free-space attenuation factor of 2 is 2.8 times longer than that of a SISO link [6].

B. Multiplexing Gain in MANETs with Multi-antenna Radios

So far we have examined the CMIMO concept for single-antenna devices. By combining this concept with the degrees of freedom of real multi-antenna systems, e.g., MIMO MANETs or multi-antenna base stations, CMIMO can be very instrumental in managing interference and harvesting multiplexing as well as opportunistic communication gains.

A multi-antenna transmitter can simultaneously send multiple streams to several cooperative receivers (receive VAAs). Similarly, a multi-antenna receiver can receive, at the same time, multiple streams from a set of cooperative transmitters (transmit VAAs). The cooperation to form transmit and receive VAAs must comply with the degree constraint. In [4] the authors derived an opportunistic scheduling scheme called DMUMSS for MIMO MANETs with VAAs formed by MIMO transmitters. The philosophy behind DMUMSS is to have MIMO transmitters cooperate to opportunistically activate streams with higher rates, subject to the degree constraint. Fig. 4(a) illustrates two interfering links where each node is equipped with two antennas. Under 802.11n, only one link (two streams with a total rate of 1.1) is activated. Thanks to the VAA of the two transmitters, DMUMSS schedules the two streams that have the highest rates among the four possible streams, resulting in a total rate of 1.7. DMUMSS becomes more beneficial with more links and more antennas per node.

VI. Applications of CMIMO in WLANs, CRNs, and Cellular Systems

A. CMIMO in WLANs

CMIMO operation at MIMO receivers can significantly boost the capacity of WLANs. In WLANs (e.g., 802.11n), one or more access points (APs) serve several wireless devices. Due to the degree constraint, the number of concurrent data streams on the uplink of a 802.11n WLAN is limited by the number of antennas at the AP (see Fig. 4(a)). This is also the case even if several APs are in the same proximity. The CMIMO-based scheme in [3], called interference alignment and cancellation (IAC), solves this problem by having multi-antenna APs cooperate. The cooperation among APs is realized by cables or using ultra-wide band transmission. IAC is illustrated in Fig. 4(a), where a CMIMO receiver with a four-element VAA successfully decodes three concurrent streams, compared with only two streams for 802.11n and DMUMSS. Theoretically, IAC can double the throughput of the illustrated 802.11n WLAN. Note that in IAC, the APs form a receiving VAA, in contrast to DMUMSS where a transmitting VAA is created by MIMO transmitters.

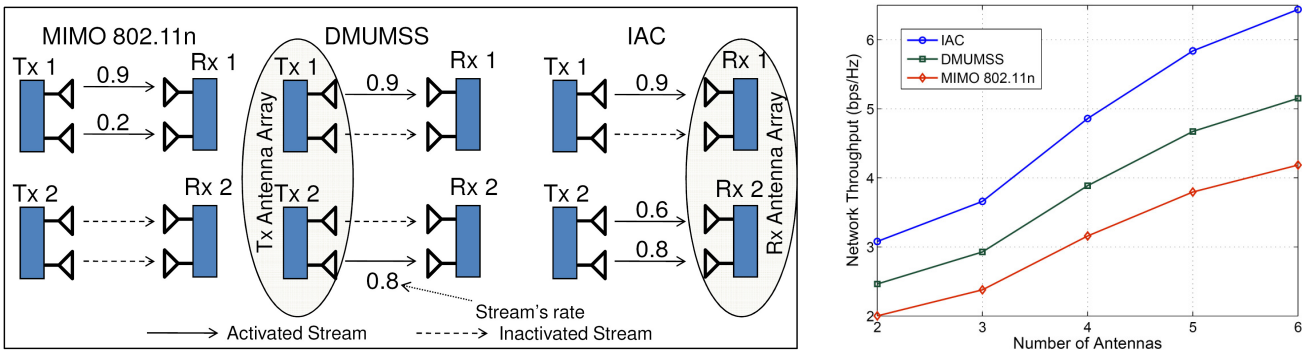
Fig. 4(b) compares the network throughput under 802.11n, DMUMSS, and IAC for the two-link scenarios in Fig. 4(a). The transmit power is 100 dBm and the noise floor is -174 dBm. The channel coefficient between any two antennas is a zero-mean, unit-variance complex Gaussian variable. It should be noted that in Fig. 4(a), after cooperation, there is only one virtual link (under either DMUMSS or IAC). Hence, it is not necessary to account for interference-related cooperation overhead. Cooperation in IAC is realized via a wire back end, so it is not subject to synchronization errors.

B. CMIMO in Cognitive Radio Networks (CRNs)

The CMIMO has also been proposed to improve network throughput and reduce the delay in MIMO CRNs [10]. In a cooperative CRN (CCRN), secondary users (SUs) relay the traffic of primary users (PUs) in exchange for time slots to transmit SUs' traffic. Assuming that SUs are equipped with multiple antennas and applying the CMIMO technique, some PU and SU transmitters (receivers) can cooperate to form a transmitting (receiving) VAA and simultaneously send (receive) PUs' and SUs' traffic to (from) an SU. This is realized by exploiting CMIMO's MUX. SUs especially benefit from this scheme, as they do not need to refrain from transmitting even when PUs are detected.

C. CMIMO in Cellular Systems

Co-channel interference among adjacent cells severely affects the capacity of a base station (BS) in cellular networks. The problem becomes more critical in smaller cells, such as femtocells. In this context, nearby BSs (often equipped with multiple antennas) can cooperate to form a VAA to function as a giant BS [5].



(a) (b)

Fig. 4. a) Two interfering MIMO links $(\mathrm{Tx}_1, \mathrm{Rx}_1)$ and $(\mathrm{Tx}_2, \mathrm{Rx}_2)$; b) their total throughput vs. number of antenna elements under 802.11n, DMUMSS, and IAC.

CoMP (Coordinated Multi-Point) is an incarnation of CMIMO, proposed for 4G Long Term Evolution (LTE). Allowing several BSs to cooperate in transmitting/beamforming a signal to (or receiving and jointly processing a signal from) mobile stations helps reduce the inter-cell interference. This technique also leverages inter-cell interference to improve the signal quality on the downlink at cell boundaries and enhance signal reception at BSs for the uplink. This leads to significant improvements in the capacity and coverage of cellular systems.

Representative CMIMO-based schemes are categorized in Table I based on the their objectives, application scenarios, and the type of CMIMO gains they exploit. Limitations of these schemes are also pointed out.

VII. OPEN ISSUEs

Despite its great promise, the application of CMIMO in practical settings faces a number of challenges, which span the physical, MAC, and network layers.

A. Optimal CMIMO Scheme and Optimal CN Selection

From a network perspective, it is desirable to develop an optimal CMIMO scheme that maximizes network metrics, e.g., energy efficiency, lifetime, throughput. Formulating such a problem is challenging and may be computationally intractable. Even if a computationally feasible solution exists, it likely requires network-wide information. Developing distributed, near-optimal solutions is significantly important. One approach is to *divide and conquer* by optimizing local performance metrics, instead of dealing with network metrics. For instance, to improve energy efficiency, a node may optimally select some neighboring CNs so as to minimize the required energy to send a packet to its destination. This problem is referred to as the *optimal CN selection*. Note that in the literature, the number of CNs is often fixed [9] [6] and/or their selection is done randomly or heuristically [1]. Furthermore, the performance metric that is selected to optimize the set of CNs should account for the conflict between the instantaneous/local gain (e.g., a given link's energy efficiency) and the long-term/global gain (e.g., network lifetime).

B. Accounting for Cooperation Overhead

Optimal CMIMO design requires accounting for the cooperation overhead. Existing protocols overlook such overhead which, indeed, is the investment for CMIMO gains. To weigh this fact, realistic models to characterize network overhead are needed. Such models are likely to be context-dependent. For example, in DIV-oriented applications, it is critical to quantify the increased interference that some nodes may experience due to CMIMO's range extension feature. The cooperation interference impacts may include wasted resources due to packet collisions (e.g., retransmission energy), the reduction in throughput and received signal quality. For MUX-oriented and interference management applications, one needs to capture the cost to acquire timely CSI among CNs and the performance degradation due to imperfect CSI.

C. CSI Estimation and Optimal Power Allocation

To align and cancel interference or optimize the power allocation among CNs, CSI has to be made available at all CNs. Although significant progress has been made on CSI acquisition in real MIMO systems, CSI estimation in CMIMO is more challenging because the antenna elements of a VAA are not co-located. Furthermore, due to possibly high mobility of CNs or fast fading, CSI's timing requirement is very strict. Thus, it is essential to develop CMIMO schemes that employ only partial CSI (e.g., channel statistics) or imperfect CSI.

Optimal resource allocation among CNs remains an open problem. Current CMIMO protocols often assume uniform power allocation among CNs [4]. However, in contrast to real MIMO systems, the elements of a VAA belong to different CNs, necessitating different transmit powers and constraints. Optimal power allocation among CNs must account for this fact.

D. Mechanisms to Facilitate Cooperation

Like any cooperative scheme, CMIMO's premise is that individual nodes are willing to cooperate. Indeed, one needs to design incentive mechanisms that motivate nodes to do so. Even if nodes are willing to cooperate, a mechanism that guarantees a

CMIMO Scheme	Cooperative MIMO Gain	Objective	Application Scenario	Signal Processing Technique	Main Limitations
Basic-CMIMO [9]	DIV	Conserve energy	Multi-hop clustered WSNs	DSTBC	Number of CNs is limitted to 2 CN selection is heuristic.
IAC [3]	MUX and interference management	Improve network throughput	Wireless LAN	Interference alignment Interference cancellation Zero-forcing	Cooperation overhead among access points is not considered.
Cui et al. [7]	DIV	Conserve energy	Single-hop WSNs	DSTBC	No MAC protocol to realize cooperation. Synchronization error is not accounted for.
MIMO-CCRN [10]	MUX	Reduce delay and improve network throughput	Cooperative CRNs	Zero-forcing	Selection of secondary radio CNs is not optimized.
Jayaweera et al. [8]	MUX	Conserve energy and reduce cooperation overhead	Single-hop WSNs	VBLAST	Less energy-efficient than DSTBC-based CMIMO schemes. Applies only to single-hop WSNs.
CCP [1]	DIV	Conserve and balance nodes' energy consumption	Multi-hop clustered WSNs	DSTBC	Selection of CNs does not consider CSI.
Jakllari et al. [6]	DIV and range extension	Reduce delay and improve network throughput	MANETs	DSTBC	Number of CNs is fixed. CNs are selected randomly. Cooperation-interference is not considered.
Cooperative BSs [5]	MUX and interference management	Mitigate co-channel interference	Cellular networks	Beamforming	Requires perfect CSI at BSs. CSI overhead not accounted for.
DMUMSS [4]	MUX	Improve network throughput	MIMO MANETs	Zero-forcing	Cooperation overhead and cooperation among receivers are not considered.

TABLE I
COMPARISON OF VARIOUS CMIMO SCHEMES.

healthy cooperation is vital. Such a mechanism should prevent a node from abusing helpers to maximize its own gain and adversely affecting network performance. Moreover, malicious users who pretend to be helpers for the purpose of intercepting ongoing communications or dropping relayed packets must be detected and excluded from the cooperation process. For all these purposes, tools from economics such as game theory and auction models, are of great interest.

E. MAC Layer Design

A MAC protocol is critical to facilitating the formation of VAAs. Such a protocol enables a node to decide to cooperate or not, how and whom it should cooperate with. In range-extension applications, a CMIMO MAC protocol has to account for collisions due to increased network interference. As mentioned in [6], extending the transmission range is accompanied with a larger interference range. One solution is to consider the interplay between the MAC and routing layers. Specifically, the selection of CNs for the next relaying CMIMO node of a data flow should not interfere with other CNs of that flow or with other flows.

To reduce the complexity of the MAC design, it is possible to cluster the network into small clusters. Clustering provides scalability in communications and processing, facilitating various functions such as data aggregation and CSI estimation. In cellular systems and WLANs, a cluster may consist of several BSs and APs, respectively. The application of CMIMO-based interference alignment/cancellation and coordinated beamforming to such clustered networks is yet to be investigated.

F. Time and Frequency Synchronization

Time synchronization among CNs, as fine as a symbol duration, should be strictly enforced to realize diversity gain and/or range extension (through DSTBC). This requirement is inherent to the spatial distribution of antenna elements in a VAA. Existing protocols (e.g., [1] [9]) were built based on the availability of this synchronization mechanism. However, maintaining such a mechanism among distributed CNs is a challenging task. Recently, there have been several asynchronous DSTBCs for CMIMO, which sacrifice some of the diversity gain. This performance degradation should be considered when selecting CNs, especially if CMIMO involves a large number of CNs.

In addition to time synchronization, frequency synchronization among CNs is also needed when combining CMIMO with OFDM, a widely-accepted technique to alleviate frequency-selective fading. How to achieve phase coherence between multiple separated transmitters is an open issue.

G. Multi-hop and Mobility Related Operation

Existing CMIMO schemes were mainly developed for single-hop networks. To provide scalable solutions, it is necessary to design CMIMO for multi-hop scenarios. Though CCP and Basic-CMIMO protocols are applicable to multi-hop clustered WSNs, their routing functionality mainly relies on existing engines developed for MANETs (e.g., AODV). Additionally, the problem of optimal resource allocation over different CMIMO hops and different CMIMO paths is yet to be explored.

Although CMIMO is most suitable for stationary networks/nodes, it can still be used in MANETs that exhibit limited mobility. For instance, in the presence of mobile sensor nodes or MANETs, reclustering has to be performed occasionally to account for topology changes. In such cases, the signaling overhead associated with reclustering and CMIMO gains have to be balanced. CMIMO operation under mobility has not been adequately addressed in the literature.

VIII. Conclusions

In this article, we overviewed the state-of-the-art application of CMIMO techniques in wireless networks, including WSNs, MANETs, WLANs, CRNs, and cellular systems. By exploiting CMIMO gains, one could dramatically improve network throughput and/or reduce energy consumption, delay, and network interference. Representative CMIMO schemes were discussed and classified based on how they exploit CMIMO gains and their application scenarios. To deploy practical CMIMO systems, it is essential to model the cooperation overhead and balance it with the resulting CMIMO gains.

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