Design and Optimization for Energy-Efficient Cooperative MIMO Transmission in Ad Hoc Networks

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***Abstract*—The need to reduce energy consumption for lowering operating costs has pushed energy efficiency to become one of the major issues of current research in the field of ad hoc networks. In this paper, a new cooperative strategy of multiple-input–multiple-output (MIMO) based on spatial modulation (SM) for the randomly distributed nodes (CMIMO-SMR) in an ad hoc network is proposed to optimize the whole energy consumption of the network. In this new strategy, the head node and the assistant node are jointly set up using a cooperative technique in each cluster to obtain the diversity. In this strategy, the effect of the amount of nodes on the energy consumption is analyzed. Moreover, the different factors such as number of hops and bit error ratio (BER) for energy savings are investigated in a CMIMO-SMR-based multihop ad hoc network where the optimal number of hops and the BER relationship are derived by taking into account the transmission energy and the circuit energy, as well as the bit-recovery situation. In the simulation, it is demonstrated that CMIMO-SMR is more energy efficient compared with the existing works. Moreover, an adaptive algorithm for choosing the appropriate number of hops to minimize the energy consumption is designed when the end-to-end designated BER is required. The results demonstrate that the minimum energy consumption can be achieved by using the proposed algorithm without compromising the designated BER requirement at the destination.**

***Index Terms*—Bit error ratio (BER), cooperative, energy efficiency, hops, multiple input multiple output (MIMO), optimal.**

I. Introduction

Ad hoc networks have become a burning issue due to the significant potential of applications such as environmental monitoring [1], military transmission, traffic control, and target tracking [2]. Consequently, many techniques in ad hoc networks have been investigated using different methods, such as designing transmission strategy and optimizing energy consumption. In the design of ad hoc networks, energy efficiency is particularly important because each node deployed in an ad hoc network has to operate without battery replacement for a long time in a harsh environment. Therefore, reducing energy consumption to achieve energy-efficient transmission plays a vital role in designing ad hoc networks. It has been proved that the multiple-input–multiple-output (MIMO) technique requires less transmission energy than single-input–single-output (SISO) technique for the same bit error ratio (BER). However, due to the small size of the node, it can be difficult to design multiple antennas in such nodes. Therefore, the concept of cooperative MIMO (CMIMO) realized by collaboration of the individual antennas is explored and shown to be energy efficient. Different forms of CMIMO, such as cooperative multiple input single output (CMISO), cooperative single input multiple output (CSIMO), and hybrid CMIMO, have been proposed to address this issue. Cui *et al.* [3] are the first to propose a CMIMO with Alamouti code in clustered wireless sensor networks (WSNs). It shows that if the transmission distance is far, CMIMO can dramatically reduce total energy consumption compared with SISO or noncooperative systems. In [4], an energy-efficient CMIMO is proposed by properly balancing power allocation between intra- and intercluster transmissions. The CMIMO considering channel estimation overhead is proposed in [5], in which the physical channel propagation parameters, the fading coherence time, and the amount of required training are investigated. In [6], the CMIMO with a data aggregation technique for energy reduction in the WSN is proposed by removing the amount of redundant data, and significant energy reduction is shown to be obtained compared with the nondata aggregation scheme.

In all of the foregoing contributions, randomly distributed nodes have not been considered. In [7], a singular-value-based adaptive modulation in CMIMO is proposed to improve the throughput. The energy efficiency of cooperative transmission under space–time block code–encode and the synchronization requirement are discussed in [8]. In [9], it is shown that to reduce energy consumption, the number of cooperative nodes at transmitter and receiver sides should be selected. In [10], the energy consumption is optimized in terms of per-unit transmit distance in a cooperative transmission. In [11], a cooperative communication scheme is designed by using a coalition formation game approach to figure out the random tradeoff between outage performance and the lifetime of the network. The cluster lifetime of a single-hop WSN with CMISO scheme is investigated in [12], in which the energy consumptions of both intra- and intercluster communications are considered, and

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the effect of cluster size on the cluster lifetime is clarified. In [13], the CMISO communication for clustered ad hoc network was analyzed, wherein the number of the cooperating nodes and hop lengths affecting the energy consumption is investigated. In [14], the CMIMO with data aggregation technique for energy reduction in WSN was proposed by using network resources through cooperative communication. However, these studies require extremely precise synchronization and suffer interchannel interference (ICI) problem.

Motivated by spatial modulation (SM) [15], a novel CMIMO transmission scheme, which is called CMIMO-SM, is proposed in [16], which is able to avoid ICI and does not require synchronization. However, since no cluster head collects the information of the nodes inside the cluster, all the nodes inside the cluster should be used as the cooperative nodes to adopt the SM technique. This requires that the number of cooperative nodes inside the cluster be 2^n (n is a positive integer). Thus, it makes the transmission scheme inflexible.

All the aforementioned literature considers the energy consumption to design energy-efficient CMIMO but fails to consider arbitrary number of randomly distributed nodes, synchronization, ICI, or flexibility issues. In fact, the nodes are usually randomly distributed in an area, and the number of nodes is arbitrary rather than fixed or formulaic. Thus, it is not reasonable to fix or formulate the number of the nodes. In addition, precise synchronization and ICI elimination usually increases system complexity and costs. Therefore, the technique such as SM in CMIMO [15] should be used as an effective way to solve synchronization and ICI problems. Moreover, after the communication is extended to the multihop scenario, the number of hops has the effect on the overall energy consumption. Consequently, the issue of finding optimal number of hops to minimize the overall energy consumption should be addressed. Another important issue is the signal quality. Due to fading, the signal becomes weak, and the quality at the source side is different from that at the destination after the signal experiences each hop; hence, construction of the relationship of the signal quality between the source to destination (end-to-end) and each single hop for energy-efficient transmission presents a challenging problem. Specifically, the mathematical expression of signal quality in terms of BER between the end-to-end and the single hop needs to be derived to check if the end-to-end BER meets the desired BER requirement. However, none of the existing studies completely consider the aforementioned issues, to the best of our knowledge.

Fully considering the preceding analysis, a new cooperative strategy of MIMO based on SM for randomly distributed arbitrary nodes (CMIMO-SMR) is proposed for energy-efficient transmission in an ad hoc network. First, the proposed cooperative strategy and working principle are introduced under the random distribution scenario with arbitrary number of nodes. In the cooperative transmission stage, the SM technique is used to solve the synchronization and ICI problems. Guided by the CMIMO-SM, the flexibility is archived to transmit the information of the arbitrary number of nodes inside the cluster by adding the assistant node along with the cluster head. After that, the energy consumption of the proposed CMIMO-SMR is compared with other conventional CMIMO schemes under the

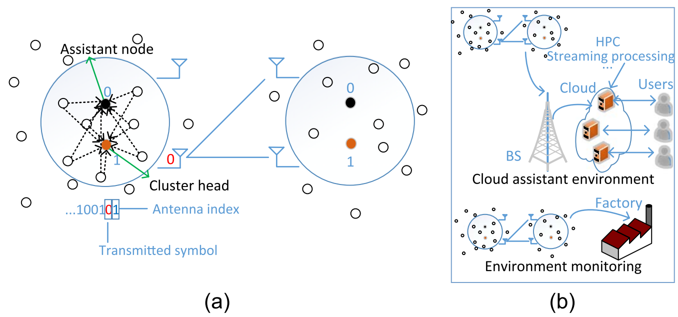

Fig. 1. (a) System model of CMIMO-SMR. (b) Possible applications.

same throughput and BER requirements, and then, the proposed scheme is extended to a multihop scenario in which the optimal number of hops is obtained by taking into account the transmission energy and the circuit energy. Moreover, in the multihop scenario, the important parameters affecting the energy consumption are investigated, and how the BER relationship between end-to-end and single hop affects the number of hops is also investigated mathematically. Results from numerical experiments indicate that energy-saving problem can be solved in addition to flexibility, synchronization, and ICI problems by using the proposed scheme. Moreover, an adaptive algorithm is designed for selecting the appropriate number of hops. The minimum energy consumption can be achieved by using the designed algorithm under the designated BER requirement in the multihop scenario. The cloud-based environment as the further issue is pointed at the end of the work. The main contributions in this paper are as follows.

- A new cooperative transmission strategy with an arbitrary number of randomly distributed nodes in an ad hoc network is proposed without ICI and synchronization requirement.
- The optimal number of hops for achieving minimum energy consumption is obtained by considering the transmission energy and the circuit energy.
- The theoretical BER relationship for designing an adaptive algorithm is derived mathematically by considering the fading and bits recovery situations.

The rest of this paper is organized as follows. Section II gives a description of the proposed scheme and energy analysis. In Section III, the energy consumption comparisons are given. The CMIMO-SMR multihop transmission scheme and related optimization results obtained under the designated BER are given in Section IV. The conclusion is given in Section V.

II. System Model and Energy Analysis

An ad hoc network with CMIMO-SMR strategy where each node is equipped with one antenna for data transmission is considered and shown in Fig. 1(a). Assume that the nodes are randomly distributed in a field and that they form clusters for convenient communication. Each cluster contains a cluster head, an assistant node, and several nodes. The cluster head and the assistant node have a preassigned index using binary numbers 1 and 0, respectively, to represent them. The data flow inside the cluster is defined as local transmission, whereas the data delivering between two adjacent clusters is defined as long-haul transmission. For the local transmission inside the cluster, each node decides whether it will be a cluster head for each round based on the number of times that the node has been a cluster head, which is similar to the LEACH protocol [17]. After that, each noncluster head node decides if it will be an assistant node or not for this round as the decision made for cluster head selection. Each node informs the selected cluster head that it will be a member of the cluster and whether it will be an assistant node by transmitting an extra bit as the overhead along with the information bits. The cluster head receives the information from the nodes that belong to the current cluster according to the received signal strength (RSS) of the acknowledgment and selects an assistant node from the interested candidates based on the maximum RSS of the acknowledgment to form cooperative communication. To obtain the full diversity gain, the cluster head can set a predefined threshold to avoid the situation in which the cluster head is too close to the assistant node. The cluster head creates a time-division multiple-access schedule and sends the schedule to the assistant node and all the normal nodes. Meanwhile, the cluster head informs the assistant node selection, and once the assistant node receives the schedule from the cluster head, it will broadcast an acknowledgment to all the normal nodes. Once the cluster formation is finished, the normal nodes always communicate with the cluster head and the assistant node of their own cluster. In addition, the neighboring clusters use different orthogonal channels to avoid interference. For the long-haul transmission, after receiving the information from all nodes, the cluster head and the assistant node transmit the received information using the cooperative approach as the long-haul transmission through the MIMO SM channel [15]. Specifically, for each time instant, the information received by the cluster head and the assistant node is composed of the multiple quadrature-amplitude modulation (MQAM)/multiple phase-shift keying (MPSK) modulated symbol part and the antenna represented part (0 or 1). Only the MQAM/MPSK modulated bits are transmitted, and the bits are represented by corresponding antennas as the hidden information will be detected at the receiver. Thus, in addition to the usual signal constellation diagram, the antenna plays the role of a second constellation diagram. For example, assume that 01 is the data sequence to transmit by using the cluster head and the assistant node after the cluster formation, as shown in Fig. 1(a), and then, only 0 will be modulated using MPSK and will be transmitted via the node having antenna index 1, whereas 1 as the antenna index will be detected at the receiver.

In the transmission, a flat Rayleigh fading channel with additive white Gaussian noise is assumed. The fading between all transmitting and receiving nodes and hops is assumed to be independent and identically distributed and to be constant during the transmission of each symbol.

According to the strategy described earlier, the total energy consumption of CMIMO-SMR is divided into local phase and long-haul phase. In other words, the energy consumption per bit E_{bt} consists of the energy consumption in the local phase E_l and the energy consumption in the long-haul phase E_{lh}, i.e.,

$$E_{\mathrm{bt}} = E_l + E_{\mathrm{lh}}. \tag{1}$$

The energy consumption of each phase can be divided into two parts: transmission energy and circuit energy.

Local phase: E_l is given by

$$E_l = E_l^t + E_l^c \tag{2}$$

where E_l^t is the transmission energy, and E_l^c is the circuit energy that happens inside the cluster.

Long-haul phase: The second term E_{lh} in (1) is given by

$$E_{\mathrm{lh}} = E_{\mathrm{lh}}^t + E_{\mathrm{lh}}^c \tag{3}$$

where E_{lh}^t is the transmission energy, and E_{lh}^c is the circuit energy that happens between clusters.

The transmission energy of E_l^t in (2) is given by

$$E_l^t = (1+\alpha)\bar{E}_{b,l} \times \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_l N_f \tag{4}$$

where $\alpha = \xi/\eta - 1$ with ξ is the peak-to-average ratio, and η is the drain efficiency of the RF power amplifiers [18]; $\bar{E}_{b,l}$ is the required energy per bit at the receiver for a given BER requirement in the local phase and can be calculated using the signal-to-noise ratio (SNR) value and the power spectral density (PSD) of the thermal noise N_0; d is the transmission distance; G_t and G_r are the transmitter and receiver antenna gains, respectively; λ is the carrier wavelength; M_l is the link margin compensating the hardware process variations; and N_f is the receiver noise. It should be noted that N_f is given by $N_f = N_r/N_0$, where N_r is the PSD of the total effective noise at the receiver input, and N_0 is the single-sided thermal noise PSD at a room temperature with a value $N_0 = -171$ dBm/Hz. The transmission energy of E_{lh}^t in (3) is given by

$$E_{\mathrm{lh}}^t = (1+\alpha)\bar{E}_{b,\mathrm{lh}} \times \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_l N_f \tag{5}$$

where $\bar{E}_{b,\mathrm{lh}}$ is the required energy per bit at the receiver for a given BER requirement in the long-haul phase.

In (2) and (3), E_l^c and E_{lh}^c are given by

$$E_l^c = E_{\mathrm{lh}}^c = \frac{P_c}{R_b} \tag{6}$$

where P_c is the total circuit power consumption [19], and R_b is the bit rate. The total circuit power P_c for an M_t transmit and M_r receive antenna system is given by

$$\begin{aligned} P_c \approx\ & M_t(P_{\mathrm{DAC}} + P_{\mathrm{mix}} + P_{\mathrm{filt}}) + 2P_{\mathrm{syn}} \\ & + M_r(P_{\mathrm{LNA}} + P_{\mathrm{mix}} + P_{\mathrm{IFA}} + P_{\mathrm{filr}} + P_{\mathrm{ADC}}) \end{aligned} \tag{7}$$

where P_{DAC}, P_{mix}, P_{LNA}, P_{IFA}, P_{filt}, P_{filr}, P_{ADC}, and P_{syn} are the power consumption values for the digital-to-analog converter (DAC), the mixer, the low-noise amplifier (LNA), the intermediate frequency amplifier (IFA), the active filters at the transmitter side, the active filters at the receiver side, the analog-to-digital converter (ADC), and the frequency synthesizer, respectively. The values of P_{DAC}, P_{ADC}, and P_{IFA} can be calculated using the model introduced in [19]–[21].

Combining (1)–(7) and considering the working principle described earlier, the total energy consumption per bit can be expressed as

$$E_{\mathrm{bt}} = \left(\sum_{i=1}^{M_t-2} K_i E_{l(i,t)} + E_{\mathrm{lh}} \sum_{i=1}^{M_t} K_i + \sum_{j=1}^{M_r-1} E_{l(j,r)} \sum_{i=1}^{M_t} K_i + E_{\mathrm{extra}} \right) \Big/ \sum_{i=1}^{M_t} K_i \quad (8)$$

where the first and third terms represent the energy consumption of data transmission inside cluster in transmitter side and the energy consumption of data collection for joint detection inside cluster in receiver side, respectively; the second term represents energy consumption between clusters; the fourth term $E_{\mathrm{extra}} = E_l M_t N_{\mathrm{extra}}$ represents the energy consumption for the overhead compensation in cluster setup procedure and cluster head and assistant node selecting procedure, with $M_t N_{\mathrm{extra}}$ being the extra bits for M_t nodes; and K_i is the number of bits to transmit for each node. $E_{l(i,t)}$, $E_{l(j,r)}$, and E_{lh} can be calculated according to (1)–(7), where $\bar{E}_{b,l}$, $\bar{E}_{b,\mathrm{lh}}$, and P_c values for local phase and long-haul phase are calculated as follows.

To obtain $\bar{E}_{b,l}$ for a given BER P_b in the local phase, the BER and SNR relationship in SISO communication needs to be determined. The average BER of a SISO binary phase-shift keying is given by [22]

$$P_b = Q\left(\sqrt{\frac{2\bar{E}_{b,l}}{N_0}}\right) \quad (9)$$

where $Q(x)$ is the Q-function, and $\bar{E}_{b,l}/N_0$ represents the SNR. $\bar{E}_{b,l}$ can be obtained by inverting (9).

SM transmission is executed in the long-haul phase. Because the closed form of BER expression is difficult to get for SM, hence, instead of inverting BER expression, the Monte Carlo simulation is carried out to find $\bar{E}_{b,\mathrm{lh}}$. Specifically, ten thousand randomly generated channel samples are taken and averaged to find the desired BER and then inverted to get the required value of $\bar{E}_{b,\mathrm{lh}}$.

E_l^c and E_{lh}^c values are calculated using (6) and (7). For local phase, P_c can be calculated according to SISO communication links by setting M_t and M_r values as one. For long-haul phase, P_c can be calculated according to SM links by setting one transmitter and two receivers since, at transmitter, only one node transmits information at each time instant, either cluster head or assistant node according to the node index and, at receiver, two nodes (cluster head and assistant node) receive the information.

III. Energy Consumption Comparisons

To evaluate the energy consumption performance of the proposed strategy, the numerical results of energy consumption under different transmission schemes are presented here. The system parameters are equivalent to those in [3] and [15] and summarized in Table I. The results of BER versus SNR for 2, 3, and 4 bit/s/Hz in the long-haul phase of CMIMO-SMR are plotted in Fig. 2. The values of $\bar{E}_{b,\mathrm{lh}}$ in the long-haul phase of MIMO-SMR are calculated using the plotted SNR values and the PSD of the thermal noise N_0 for the BER requirement 10^{-3} as an example.

TABLE I
System Parameters

f_c=2.5 GHz	η=0.35
G_tG_r=5 dBi	$N_0/2$=−174 dBm/Hz
K_i=10^4 bits	P_{syn}=50 mW
P_{mix}=30.3 mW	P_{filt}=P_{filr}=2.5 mW
N_f=10 dB	P_{LNA}=20 mW
M_L=40 dB	N_{extra}=500 bits
P_b=10^{-3}	

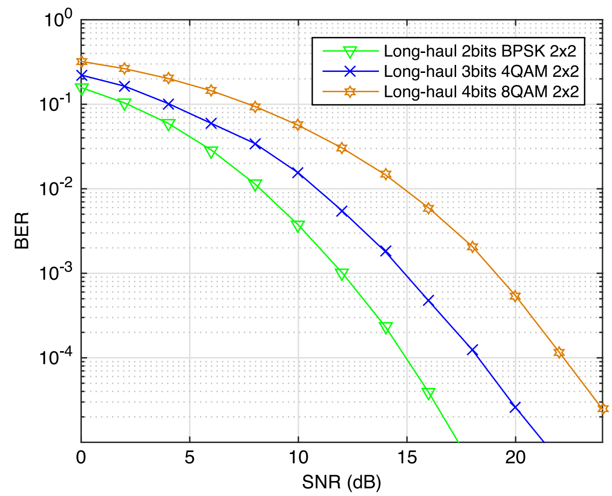

Fig. 2. Received SNR versus BER for long-haul transmission.

For comparison, the energy consumptions of CMIMO and CMIMO-SM are also plotted under different node cases. The transmission in CMIMO operates without the node antenna index, and the transmission in CMIMO-SM operates without the cluster head and the assistant node. Due to these differences, CMIMO will transmit more data and CMIMO-SM will spend more circuit energy compared with CMIMO-SMR. To better understand the performance of these cooperative transmission systems, the total energy consumptions are shown in Figs. 3–5. Specifically, Figs. 3–5 show the energy consumption per bit against transmission distance under CMIMO, CMIMO-SM, and CMIMO-SMR for two, four, and eight nodes in one cluster, respectively. As clearly shown in those plots, all the energy consumption per bit in the plots increases as the transmission distance increases due to the fact that longer transmission requires bigger energy. In addition, CMIMO-SMR outperforms all the other systems in terms of energy consumption in different nodes situations due to the efficient transmission scheme. In Fig. 3, note that, for two-node situation, only the cluster head and the assistant node participate in the cooperation; hence, CMIMO-SMR is simplified to CMIMO-SM, and they have the same energy performance. The effect of the number of nodes on the total energy consumption of CMIMO-SMR is examined, as shown in Fig. 6. It can be seen that when the number of nodes in one cluster increases, the energy consumption per bit increases correspondingly. This is because, when the number of nodes in one cluster increases, the energy consumption in the local phase increases.

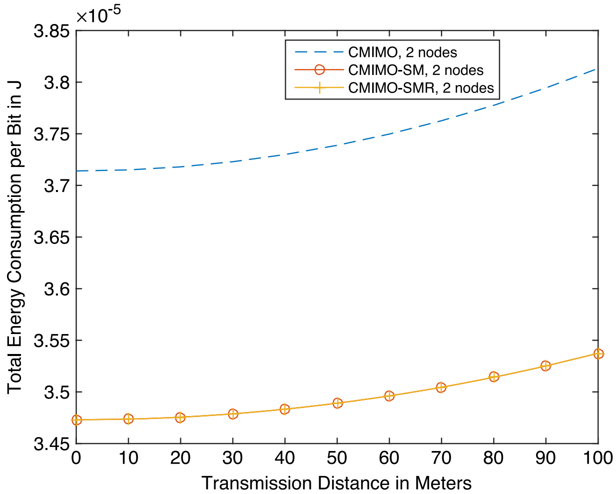

Fig. 3. Energy consumption per bit over transmission distance under different transmission schemes for two nodes. The curve of CMIMO-SM and the curve of CMIMO-SMR are superposed because of the two-node situation, where only the cluster head and the assistant node participate the cooperation; hence, CMIMO-SMR is simplified to CMIMO-SM.

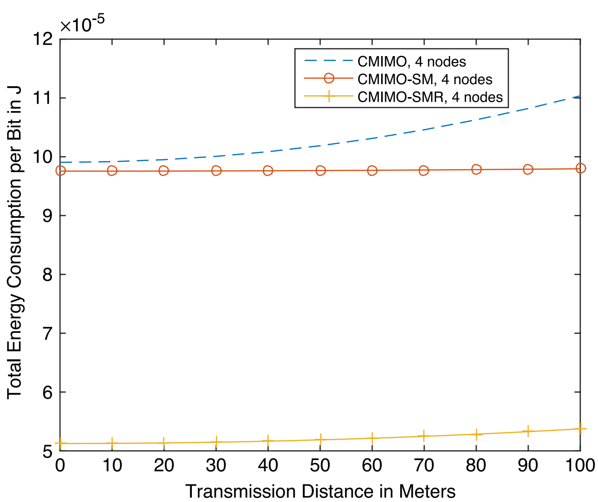

Fig. 4. Energy consumption per bit over transmission distance under different transmission schemes for four nodes.

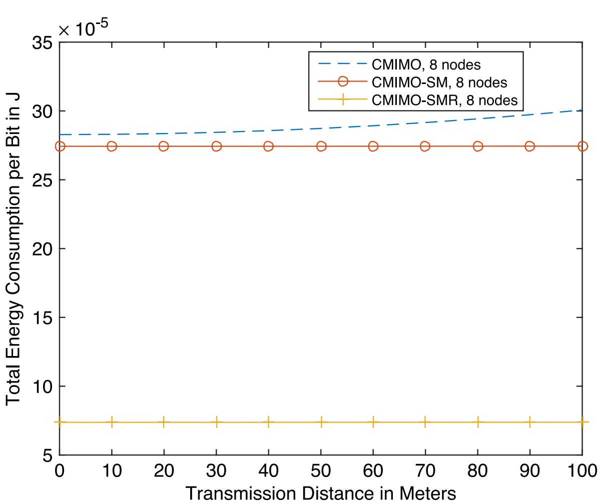

Fig. 5. Energy consumption per bit over transmission distance under different transmission schemes for eight nodes.

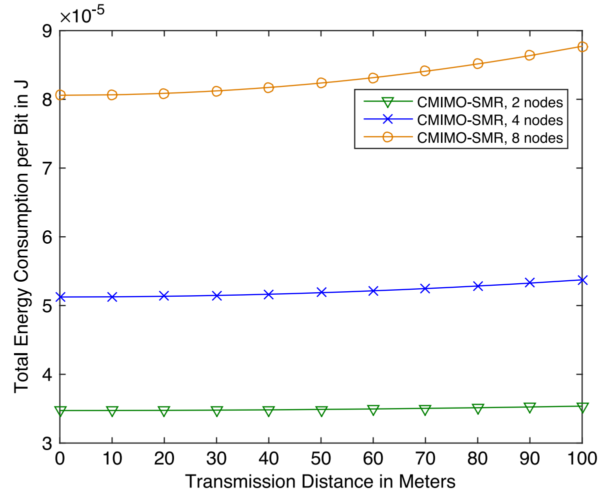

Fig. 6. Energy consumption per bit of CMIMO-SMR over transmission distance under different numbers of nodes.

IV. Cooperative Multiple-Input–Multiple-Output-Spatial Modulation for Randomly Distributed Nodes Multihop Scheme and Optimization

Here, the proposed CMIMO-SMR strategy is extended to a multihop scenario with enough nodes, as shown in Fig. 7, and the number of hops is optimized to reduce the total energy consumption of the whole network.

As shown in the preceding figure, randomly distributed nodes form clusters for transmission from source to destination. In such system, there are $n+1$ clusters, where the cluster labeled as 0 corresponds to the destination and the cluster labeled as n corresponds to the source. Assume that inside the cluster, the longest distance among the nodes is defined as d_{local}. The long-haul distance between the nearest nodes of adjacent clusters is defined as d_i $(i = 1, 2, \ldots, n)$, which is assumed to be much larger than d_{local}. According to (3), the energy consumption per bit of long haul for a transmission distance d_i is given by

$$E^i_{\text{lh}} = (1+\alpha)\bar{E}_{b,\text{lh}} \times \frac{(4\pi d_i)^2}{G_t G_r \lambda^2} M_l N_f + \frac{P_c}{R_b}. \tag{10}$$

Summing the energy consumption of all the hops and adding the local energy consumption, the total energy consumption is obtained as

$$E_{\text{total}} = \sum_{i=1}^{n} \left(\sum_{i=1}^{M_t-2} K_i E_{l(i,t)} + \sum_{j=1}^{M_r-1} E_{l(j,r)} \sum_{i=1}^{M_t} K_i + E_{\text{extra}} \right) + M_t \sum_{i=1}^{n} \left[(1+\alpha)\bar{E}_{b,\text{lh}} \frac{(4\pi)^2 \times (d_i + d_{\text{local}})^2}{G_t G_r \lambda^2} \times M_l N_f + \frac{P_c}{R_b} \right] K_i. \tag{11}$$

In (11), the minimum energy consumption can be obtained by identifying the transmission distance d_i. Since the first part of (11) is not the function of d_i, the optimization of the second

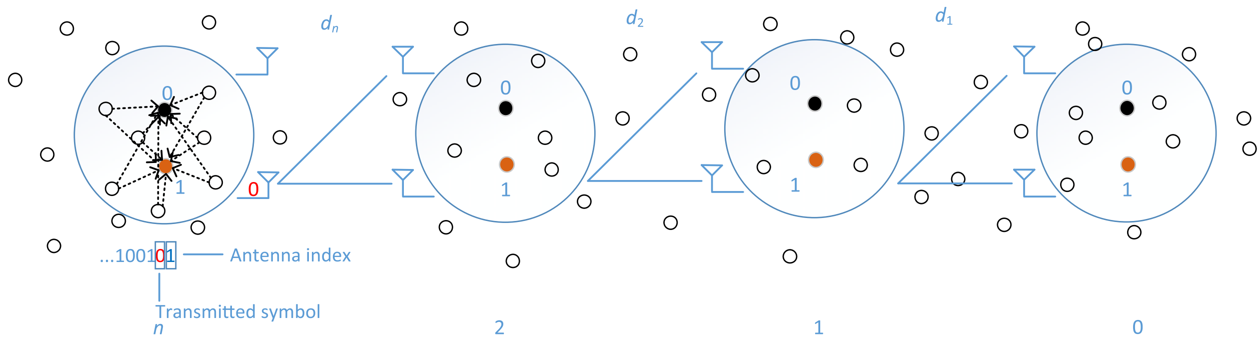

Fig. 7. Scenario of the CMIMO-SMR-based multihop network.

part can be treated as the whole optimization problem, which can be formulated as

$$\min_{d_i, i=1,2,\ldots n} M_t \sum_{i=1}^{n} \left[(1+\alpha)\bar{E}_{b,\mathrm{lh}} \frac{(4\pi)^2 (d_i + d_{\mathrm{local}})^2}{G_t G_r \lambda^2} \times M_l N_f + \frac{P_c}{R_b} \right] K_i$$

$$\text{s.t.} \quad \sum_{i=1}^{n} d_i = d - n d_{\mathrm{local}}$$

$$d_i > 0, \quad i = 1, 2, \ldots, n$$

$$n \text{ is a positive integer.} \tag{12}$$

The constraint $\sum_{i=1}^{n} d_i = d - n d_{\mathrm{local}}$ is obtained by assuming the network with enough nodes where data will be transmitted through a linear route to achieve the minimum energy consumption. This is an optimization problem of variable d_i. To solve this optimization problem, the following proposition can be obtained.

Proposition 1: Under the ad hoc transmission case, given the total distance between source and destination d, if all the hop lengths are equal (i.e., $\forall\, i : d_i = d/n - d_{\mathrm{local}}$), the minimum energy consumption can be achieved.

Proof: See Appendix A.

From Proposition 1, it is known that if all the hops are equal, i.e., $\forall\, i : d_i = d/n - d_{\mathrm{local}}$, the minimum energy consumption can be obtained for a given transmission distance under the ad hoc transmission case. However, the number of hops used for achieving minimum energy is still not clear and needs to be investigated. For an ad hoc network, multihop transmission consumes less total energy power than single-hop transmission as long as the path loss is proportional to $1/d^L$, with $L > 1$. This is also true for the proposed strategy. However, when circuit energy consumption is considered, multihop transmission may not always be more energy efficient than single-hop transmission since total circuit energy consumption also increases as the number of relay clusters (hops) increases in the case of multihop transmission. Therefore, the optimal number of hops needs to be selected to achieve the minimum energy consumption. According to (11), the expression for the total energy consumption in terms of hops n can be expressed as

$$\begin{aligned} E_{\mathrm{total}} &= \sum_{i=1}^{n} \left(\sum_{i=1}^{M_t-2} K_i E_{l(i,t)} + \sum_{j=1}^{M_r-1} E_{l(j,r)} \times \sum_{i=1}^{M_t} K_i + E_{\mathrm{extra}} \right) + M_t \sum_{i=1}^{n} \\ &\quad \times \left[(1+\alpha)\bar{E}_{b,\mathrm{lh}} \frac{(4\pi)^2 \times (d + d_{\mathrm{local}})^2}{G_t G_r \lambda^2 n^2} M_l N_f + \frac{P_c}{R_b} \right] K_i \\ &= M_t (1+\alpha)\bar{E}_{b,\mathrm{lh}} \times \frac{(4\pi)^2 \times (d + d_{\mathrm{local}})^2}{G_t G_r \lambda^2 n} M_l N_f K_i \\ &\quad + n \left(\sum_{i=1}^{M_t-2} K_i E_{l(i,t)} + \sum_{j=1}^{M_r-1} E_{l(j,r)} \sum_{i=1}^{M_t} K_i + E_{\mathrm{extra}} + \frac{M_t P_c}{R_b} K_i \right). \end{aligned} \tag{13}$$

The minimization of E_{total} can be expressed as

$$\begin{aligned} \min_{n} \; & M_t (1+\alpha)\bar{E}_{b,\mathrm{lh}} \times \frac{(4\pi)^2 \times (d + d_{\mathrm{local}})^2}{G_t G_r \lambda^2 n} M_l N_f K_i \\ & + n \left(\sum_{i=1}^{M_t-2} K_i E_{l(i,t)} + \sum_{j=1}^{M_r-1} E_{l(j,r)} \sum_{i=1}^{M_t} K_i + E_{\mathrm{extra}} + \frac{M_t P_c}{R_b} K_i \right) \\ \text{s.t.} \; & n \text{ is a positive integer.} \end{aligned} \tag{14}$$

This is an optimization problem of variable n, and the following proposition can be obtained.

Proposition 2: The total energy consumption E_{total} is dependent on the number of hops n, and the whole function is convex and has a minimum value.

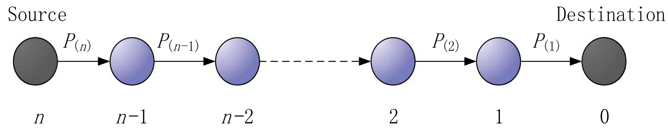

Fig. 8. Multihop scenario where single-hop BER from node n to node $n-1$ is represented by $P_{(n)}$ and end-to-end BER from source to destination is represented by P_n.

Proof: Taking the second-order derivative of (13) with respect to n, the following equation can be obtained:

$$\frac{\partial^2 E_{\text{total}}}{\partial n^2} = M_t(1+\alpha)\bar{E}_{b,\text{lh}} \times \frac{(4\pi)^2 \times (d+d_{\text{local}})^2}{G_t G_r \lambda^2 n^3} M_l N_f K_i. \tag{15}$$

Note that M_t, d, G_t, G_r, n, M_l, N_f, K_i, $\bar{E}_b$, α, and λ are all positive values. As a result, $\partial^2 E_{\text{total}}/\partial n^2 > 0$. Hence, E_{total} is convex and has a minimum value.

Taking the first-order derivative of (13) with respect to n and setting it to zero, the optimal value n^* for achieving the minimum energy is obtained as (16), shown at the bottom of the page.

Because the design variable n is defined over integer values, the aforementioned optimization issue is a nonconvex problem in integer area. Therefore, the value either $\lfloor n^* \rfloor$ or $\lceil n^* \rceil$, which is with respect to the minimum E_{total}, can be selected as the optimal number of hops n_o.

The optimal number of hops obtained earlier is the criteria used for minimizing the energy consumption of the proposed CMIMO-SMR multihop transmission strategy. However, the real value of the number of hops used may be different from the optimal one, particularly when the signal quality of the destination is required. Specifically, the signal quality is different at the source and destination since the fading exists. Usually, at the destination, the signal quality in terms of BER needs to be guaranteed. If the use of optimal number of hops cannot make the signal quality meet the BER requirement of the destination, the suboptimal value as the appropriate one needs to be determined to meet the BER requirement of the destination. To determine the appropriate number of hops, the BER relationship between end-to-end and each single hop needs to be investigated. Because the transmission distances inside the cluster are quite small compared with the transmission between clusters, each cluster in Fig. 7 can be treated as one super node at this stage for making this problem easy, and the cluster network is simplified to a single-string network, which can be treated as a virtual SISO system, as shown in Fig. 8.

Considering this scenario, single-hop BER from node n to node $n-1$ is defined by $P_{(n)}$, $n \in \{1, 2, \ldots, n\}$, and end-to-end BER from source to destination is defined by P_n. In Fig. 8, all the single hops in the route are assumed to have the same BER P_{hop} due to the equidistant hops derived earlier. These equidistant hops give each transmission the similar environments. Therefore

$$P_{(n)} = P_{\text{hop}}, \quad n \in \{1, 2, \ldots, n\}. \tag{17}$$

Usually, the expression used to determine the end-to-end BER for routes with the same value of single-hop BER is given by [23]

$$P_n = 1 - (1 - P_{\text{hop}})^n. \tag{18}$$

In fact, (18) simply accumulates the errors through the relays, not taking into account the fact that an even number of wrong single-hop transmissions in the route results in a correct end-to-end transmission. When this situation is considered, the relationship between single-hop BER and end-to-end BER will be changed, and the expression of P_n can be obtained in the following theorem.

Theorem: Let bits be transmitted from source node n to destination node 0 through n hops with identical statistical behavior and characterized by the single-hop BER $P_{(n)} = P_{\text{hop}}$, with $n \in \{1, 2, \ldots, n\}$. Then, the end-to-end BER in destination is given by

$$P_n = \frac{1}{2}\left[1 - (1 - 2P_{\text{hop}})^n\right] \quad \forall\, n \geq 1. \tag{19}$$

Proof: See Appendix B.

The relationship between single-hop BER and end-to-end BER is constructed in (19), as shown earlier. Knowing that this relationship allows the selection of the appropriate number of hops. Specifically, once the optimal number of hops is known for a given single-hop BER, the end-to-end BER can be calculated by using (19). If the calculated end-to-end BER is better than or equal to the given desired BER value, the optimal number of hops is selected. If the calculated end-to-end BER is worse than the given desired value, the suboptimal number of hops is selected to reduce the BER to meet the end-to-end BER requirement. Because (19) is an increasing function of n, therefore the small P_n requires small n as the suboptimal number of hops. Hence, finding the appropriate small value as the appropriate number of hops n_a is able to meet the end-to-end BER requirement. An algorithm for finding the appropriate number of hops n_a to meet the BER requirement is designed here. As depicted in Algorithm 1, in the case that the calculated P_n is smaller than or equal to the desired $P_{n,d}$, the optimal number of hops n_o will be selected to achieve the minimum energy consumption. In the case in which the calculated P_n is bigger than the desired $P_{n,d}$, the appropriate suboptimal number of hops n_a will be selected by iteratively updating the number of hops for each time until the calculated P_n is smaller

$$n^* = \sqrt{\frac{M_t(1+\alpha)\bar{E}_{b,\text{lh}} \times (4\pi)^2 \times (d+d_{\text{local}})^2 M_l N_f K_i}{G_t G_r \lambda^2 \left(\sum_{i=1}^{M_t-2} K_i E_{l(i,t)} + \sum_{j=1}^{M_r-1} E_{l(j,r)} \sum_{i=1}^{M_t} K_i + E_{\text{extra}} + \frac{M_t P_c K_i}{R_b}\right)}} \tag{16}$$

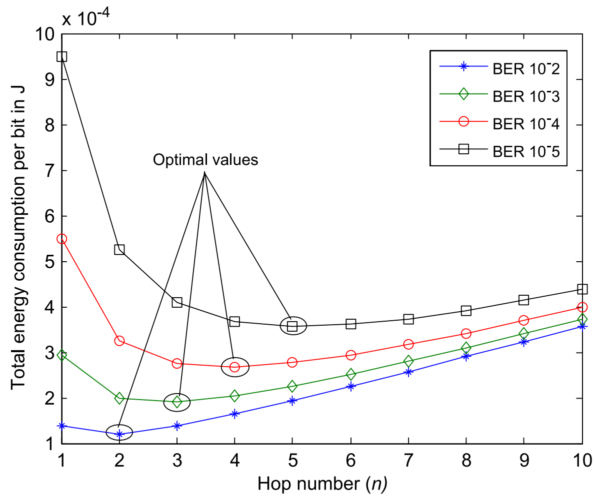

Fig. 9. Optimal number of hops versus energy consumption per bit under different BERs.

TABLE II
APPROPRIATE NUMBERS OF HOPS FOR GIVEN DESIRED BER

Single-hop BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}
Desired end-to-end BER	4×10^{-2}	4×10^{-3}	4×10^{-4}	4×10^{-5}
Optimal number of hops	2	3	4	5
Appropriate number of hops	2	3	4	4

than or equal to the desired $P_{n,d}$. Accordingly, minimum energy consumption can be obtained with such a number of hops under a given end-to-end BER requirement.

To give a numerical example, the total energy consumption versus hop numbers is investigated. In the transmission network, the total transmission distance is 2000 m long as an assumption. All the parameters used are chosen from Table I, except multiple BER value. The BER is an important parameter for evaluation of the transmission quality, and in the analysis, different BER values are applied to the multihop scenario. Note that, when different system parameters are chosen, the values of the optimal results vary accordingly. The total energy consumption per bit over number of hops under different BER environments are shown in Fig. 9, in which, for each different BER case, a different optimal number of hops can be found when both transmission energy and circuit energy are included. In addition, as the BER performance increases, the optimal number of hops increases. This is expected since the good link quality requires short transmission distance, namely, more hops. When the desired end-to-end BER values are given as the requirement, the suboptimal numbers of hops as the appropriate values calculated by using Algorithm 1 are shown in Table II. It is observed that the appropriate numbers of hops used for getting the minimum energy consumption with desired end-to-end BER are exactly the same as the optimal numbers of hops in the first three BER cases, whereas in the last BER case, the appropriate number of hops used for getting the minimum energy consumption with desired end-to-end BER is the suboptimal value. This is because, in the first three cases, with the optimal number of hops, the minimum energy consumption can be achieved under the desired end-to-end BER, whereas in the last case, although with the optimal number of hops with which the minimum energy can be achieved, the desired end-to-end BER cannot be guaranteed. To meet the desired end-to-end BER requirement, the suboptimal value needs to be selected.

Algorithm 1

Input: The single-hop BER P_{hop}
The optimal number of hops n_o
The desired end-to-end BER $P_{n,d}$
Output: The calculated end-to-end BER P_n and the appropriate number of hops n_a

1. **for** each time **do**
2. $P_n = (1/2)[1 - (1 - 2P_{\text{hop}})^{n_o}]$
3. **if** $P_n \le P_{n,d}$ **then**
4. $n_a = n_o$
5. **else**
6. $n_o = n_o - 1$
7. **end if**
8. $P_n \le P_{n,d}$
9. **end for**

V. CONCLUSION

In this paper, an energy-efficient and feasible cooperative transmission strategy, which is named CMIMO-SMR, has been proposed for an ad hoc network. Its performance in terms of energy reduction and flexibility was demonstrated by being compared with other strategies. In the CMIMO-SMR-based multihop scenario, different factors, such as number of hops and BER, were investigated for energy minimization. For a given transmission distance, by considering the transmission energy and the circuit energy, the optimal number of hops was derived using convex optimization technique. It was shown that for each different BER, an optimal number of hops can be found to minimize the total energy consumption. Later, the BER relationship was constructed and validated from a statistical point of view by considering the bits recovery situation. Furthermore, an adaptive algorithm was designed to select the appropriate number of hops when the end-to-end BER requirement is considered. Results demonstrated that with the designed algorithm, the minimum energy consumption can be achieved by selecting the appropriate number of hops without compromising the designated end-to-end BER requirement. The strengths of CMIMO-SMR were confirmed with theoretical analysis, simulations, and numerical experiments. CMIMO-SMR can be further extended to support the energy-efficient communication under the cloud environment. Specifically, the proposed strategy is expected to be applied in cloud or mobile-cloud-based ad hoc networks. In addition, to guarantee quality of service in the mobile cloud environment, which involves high mobility of devices, the proposed strategy will be extended to be applied in a dynamic environment by integrating with computing resource management schemes for high-performance computing applications.

APPENDIX A
PROOF OF PROPOSITION

To solve the problem in (12) under the constraint $\sum_{i=1}^{n} d_i = d_i - nd_{\text{local}}$, the Lagrange equation is given as

$$L = M_t \sum_{i=1}^{n} \left[(1+a)\bar{E}_{b,\text{lh}} \frac{(4\pi)^2 (d_i + d_{\text{local}})^2}{G_t G_r \lambda^2} M_l N_f + \frac{P_c}{R_b} \right] \times K_i + w \left(d - nd_{\text{local}} - \sum_{i=1}^{n} d_i \right) \quad \text{(A.1)}$$

where w is a Lagrange multiplier. According to the method of the Lagrange multiplier, the following relationship can be obtained:

$$\begin{cases} \frac{\partial L}{\partial d_i} = 0 \\ \sum_{i=1}^{n} d_i = d - nd_{\text{local}} \end{cases} \quad \text{(A.2)}$$

by taking partial derivatives on (A.1) with respect to d_i and equating to 0. Solving (A.2), each distance d_i can be determined as follows:

$$d_i = \frac{w}{M_t (1+\alpha) \bar{E}_{b,\text{lh}} \frac{(4\pi)^2}{G_t G_r \lambda^2} M_l N_f} - d_{\text{local}}. \quad \text{(A.3)}$$

Since $\sum_{i=1}^{n} d_i = d - nd_{\text{local}}$, (A.3) can be derived as

$$d_i = \frac{d}{n} - d_{\text{local}}. \quad \text{(A.4)}$$

APPENDIX B
PROOF OF THEOREM

The following relation to find the end-to-end BER under an arbitrary number of hops n is considered. When the fact that an even number of wrong single-hop transmissions in the route results in a correct end-to-end transmission is taken into account, for the case of $n = 2$, the end-to-end BER P_n can be expressed as

$$P_n = 1 - (1 - P_{\text{hop}})^2 - \binom{2}{2} {P_{\text{hop}}}^2 = 2P_{\text{hop}} - 2{P_{\text{hop}}}^2. \quad \text{(B.1)}$$

It is observed that P_n shows a behavior of a rule, as shown in the following:

$$P_n = (-2)^0 \binom{n}{1} P_{\text{hop}} + (-2)^1 \binom{n}{2} P_{\text{hop}}^2 + \cdots + (-2)^{n-1} \binom{n}{n} P_{\text{hop}}^n. \quad \text{(B.2)}$$

To demonstrate that (B.2) is right and that P_n needs to be expanded to P_{n+1} and proved. First, P_n is transformed to P_{n+1}, and then, P_{n+1} can be expressed as

$$P_{n+1} = (-2)^0 \binom{n+1}{1} P_{\text{hop}} + (-2)^1 \binom{n+1}{2} P_{\text{hop}}^2 + \cdots + (-2)^n \binom{n+1}{n+1} P_{\text{hop}}^{n+1}. \quad \text{(B.3)}$$

According to (B.1), P_{n+1} can be written as

$$\begin{aligned} P_{n+1} &= 1 - (1 - P_n)(1 - P_{\text{hop}}) - \binom{2}{2} P_n P_{\text{hop}} \\ &= P_n + P_{\text{hop}} - 2P_n P_{\text{hop}}. \end{aligned} \quad \text{(B.4)}$$

Substituting (B.2) into (B.4), P_{n+1} can be written as

$$\begin{aligned} P_{n+1} &= (-2)^0 \binom{n}{1} P_{\text{hop}} + (-2)^1 \binom{n}{2} P_{\text{hop}}^2 \\ &\quad + \ldots + (-2)^{n-1} \binom{n}{n} P_{\text{hop}}^n \\ &\quad + P_{\text{hop}} + (-2)^1 \binom{n}{1} P_{\text{hop}}^2 + (-2)^2 \binom{n}{2} P_{\text{hop}}^3 \\ &\quad + \cdots + (-2)^n \binom{n}{n} P_{\text{hop}}^{n+1}. \end{aligned} \quad \text{(B.5)}$$

P_{hop} and $(-2)^n \binom{n}{n} P_{\text{hop}}^{n+1}$ can be replaced by $(-2)^0 \binom{n}{0} P_{\text{hop}}$ and $(-2)^n \binom{n+1}{n+1} P_{\text{hop}}^{n+1}$, respectively; then, calculating (B.5) by considering that $\binom{n+1}{n} = \binom{n}{n} + \binom{n}{n-1}$, (B.3) is obtained. By assuming that $x = -2P_{\text{hop}}$ and substituting x into (B.2), this results in the following new equation:

$$\begin{aligned} P_n &= (-2)^0 \binom{n}{1} \left(-\frac{1}{2}x\right) + (-2)^1 \binom{n}{2} \left(-\frac{1}{2}x\right)^2 \\ &\quad + \cdots + (-2)^{n-1} \binom{n}{n} \left(-\frac{1}{2}x\right)^n \\ &= -\frac{1}{2} \left(\binom{n}{1} x + \binom{n}{2} x^2 + \cdots + \binom{n}{n} x^n \right) \\ &= -\frac{1}{2} [(1+x)^n - 1] \\ &= \frac{1}{2} [1 - (1+x)^n] \\ &= \frac{1}{2} [1 - (1 - 2P_{\text{hop}})^n]. \end{aligned} \quad \text{(B.6)}$$

The proof is completed.

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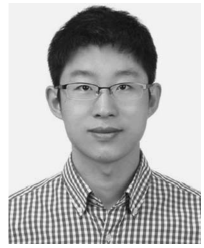

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