Energy Saving in Cluster-Based Wireless Sensor Networks through Cooperative MIMO with Idle-Node Participation

Li Fei, Qiang Gao, Jun Zhang, and Gang Wang

Abstract: **In cluster-based wireless sensor networks, the energy could be saved when the nodes that have data to transmit participate in cooperative multiple-input multiple-output (MIMO). In this paper, by making the idle nodes that have no data to transmit participate in the cooperative MIMO, it is found that much more energy could be saved. The number of the idle nodes that participate in the cooperative MIMO is optimized to minimize the total energy consumption. It is also found that the optimal number of all the nodes participating in cooperative communication does not vary with the number of nodes that have data to transmit. The proposition is proved mathematically. The influence of long-haul distance and modulation constellation size on the total energy consumption is investigated. A cooperative MIMO scheme with help-node participation is proposed and the simulation results show that the proposed scheme achieves significant energy saving.**

Index Terms: **Cooperative multiple-input multiple-output (MIMO), energy efficiency, idle nodes, wireless sensor networks.**

I. INTRODUCTION

Energy saving is a very important design consideration in wireless sensor networks, where nodes operate with small batteries for which replacement, when possible, is very difficult and expensive [1]. In cluster-based wireless sensor networks, nodes that have data to transmit in a cluster can communicate with the data sink or a relay node through cooperative multiple-input-multiple-output (MIMO), and thus, the total energy could be tremendously saved [1]–[6]. Energy efficiency of MIMO and cooperative MIMO in sensor networks is studied in [1]. The cooperative MIMO outperforms the noncooperative approach in terms of energy efficiency. If the impact of physical channel propagation parameters, fading coherence time, and extra energy overhead required for training sequence transmissions is considered, cooperative MIMO can still offer substantial energy savings in wireless sensor networks [2]. In [3], all nodes in a sensor network are divided into multiple clusters and the number of clusters is optimized to minimize the total energy consumption. In [4], the transmission energy per symbol at the source node, which determines the number of cooperative nodes, is optimized to minimize the total energy consumption. In [5] and [6], the energy consumption in multihop networks is investigated. In [5], the transmission power at the cluster head node was optimized hop-by-hop to minimize total energy consumption. In [6], the adaptive selection of cooperative nodes and the coordination between multihop routing and cooperative MIMO transmissions were analyzed to save total energy and prolong the network lifetime.

In the works above, only the nodes that have data to transmit participate in cooperative communication. However, in many sensor networks, nodes remain largely inactive for long time [7]. To save energy, generally, the idle nodes that have no data to transmit are put into a sleep state as long as possible [7]–[9]. In this paper, to get much more energy saving, we let idle nodes participate in cooperative communication. In a cluster of sensor networks, normally, some nodes have data to transmit, while others are idle. The node that has data to transmit is called data node. Some of the idle nodes, called help nodes, will participate in cooperative communication, while the rest of idle nodes, called sleep nodes, will go into a sleep state. Both data nodes and help nodes are called cooperative nodes. In a typical sensor network, information collected by multiple local sensors needs to be transmitted to a remote central processor. If the remote processor is far away, the information will first be transmitted to a relay node, and then, multihop-based routing will be used to forward the data to its final destination. If we allow cooperative transmission among multiple nodes, we can treat them as multiple antennas to the destination node such that an equivalent MIMO system (in fact, it is an equivalent multiple-input-single-output system) can be constructed. Fig. 1 shows the cooperative MIMO communication in a sensor network. Its processing consists of local communication and long-haul communication. During local communication, each data node will broadcast its data to all the other local nodes using different time slots. Both other data nodes and help nodes receive and store the broadcasted data. After each node receives all the data, they encode the transmission sequence according to the distributed space-time block codes (STBCs) [1]–[4]. During long-haul communication, both data nodes and help nodes cooperatively transmit the encoded sequence to the data sink or relay node. For the rest of this paper, unless otherwise stated, all statements about data destination will be referring to the data sink.

The total energy consumption consists of energy consumption of local communication and long-haul communication. Both of them can be divided into circuit energy consumption and transmission energy consumption. According to [1], in wireless sensor networks, the circuit energy consumption of nodes includes the energy consumed by all the circuit blocks along the signal path: The digital-to-analog converter (DAC), the mixer, the low-

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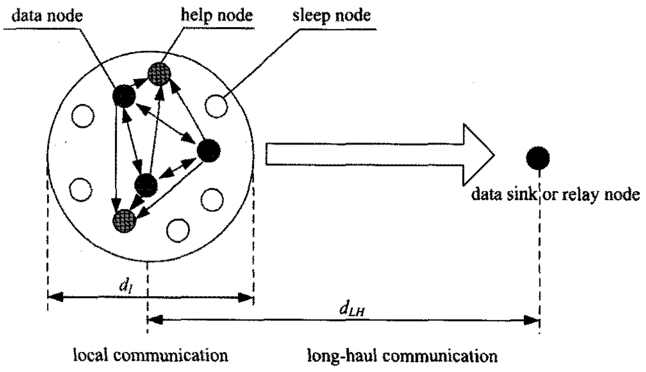

Fig. 1. System overview of cooperative MIMO in a cluster.

noise amplifier, the intermediate frequency amplifier, the active filters at transmitter side and receiver side, the analog-to-digital converter (ADC), and the frequency synthesizer. We assume that each data node has the same number of bits to transmit. If the number of data nodes is fixed, that is the number of transmission bits is fixed, the transmission energy consumption of local communication does not change whether there are help nodes participating in cooperative communication or not. However, the circuit energy consumption of local and long-haul communication will increase over the number of help nodes. On the other hand, the bit error ratio (BER) of MIMO decreases over the number of antennas due to the spatial diversity [10]; hence, the BER of long-haul communication for cooperative MIMO will decrease over the number of help nodes. An alternative view is that for the required BER, the transmission energy consumption of long-haul communication decreases over the number of help nodes. Therefore, the number of help nodes can be optimized to minimize the total energy consumption when the number of data nodes is fixed. The optimal number of help nodes will change with the number of data nodes. However, it is found that the optimal number of cooperative nodes, that is, all the data nodes and help nodes, does not vary with the number of data nodes. The influence of long-haul distance and modulation constellation size on the total energy consumption is investigated. We design a cooperative MIMO scheme with help-node participation and the simulation results show that the proposed scheme can achieve significant energy saving.

The remainder of this paper is organized as follows. In Section II, the system model of total energy consumption is established. In Section III, the number of cooperative nodes is optimized to minimize the total energy consumption. The designed cooperative MIMO scheme with help-node participation, and the simulation results are given in Section IV. Section V summarizes our conclusions.

II. SYSTEM MODEL

As shown in Fig. 1, the sensor nodes in a cluster equipped with one antenna communicate with the data sink equipped with one antenna far away from the cluster. The cluster consists of N_d data nodes, N_h help nodes, and some sleep nodes. Each data node has L bits to transmit to the data sink. The sleep nodes will not participate in cooperative communication but go into a sleep state. The energy consumption of a sleep node is very low and not comparable with the energy consumed by data nodes or help nodes for data transmission or reception [7]–[9]; hence, the energy consumption of sleep nodes is neglected in this paper.

It is assumed that quadrature amplitude modulation (QAM) is used during local and long-haul communication [1]. A square-law path loss with additive white gauss noise (AWGN) is assumed for the local communication. For the long-haul communication, a Rayleigh-fading channel with square-law path loss is assumed. The channel gain between each cooperative node and the data sink is assumed to be independent and identically distributed. The fading is assumed to be constant during the transmission of each encoded sequence. The total energy consumption E is the sum of both local communication energy consumption E_l and long-haul communication energy consumption E_{LH}; hence, E is given by

$$E = E_l + E_{LH}. \tag{1}$$

A. Energy Consumption of Local Communication

The energy consumption of local communication E_l is the sum of help nodes energy consumption E_{lh} and data nodes energy consumption E_{ld}, and it is given by

$$E_l = E_{lh} + E_{ld}. \tag{2}$$

During local communication, the help nodes do not transmit data packets but receive the data packets from the data nodes; thus, only circuit energy is consumed by the help nodes. E_{lh} is given by

$$E_{lh} = N_d \frac{L}{R_l} P_{cr} N_h \tag{3}$$

where P_{cr} denotes the circuit power of receiver. R_l denotes the bit rate for local communication and it is given by

$$R_l = b_l B \tag{4}$$

where b_l denotes the QAM constellation size of the local communication, and B denotes the modulation bandwidth.

The energy consumption of data nodes E_{ld} is the sum of circuit energy consumption E_{ldc} and transmission energy consumption E_{ldt}, and it is given by

$$E_{ld} = E_{ldc} + E_{ldt}. \tag{5}$$

The circuit energy consumed by a data node consists of the circuit energy consumed by the data node to broadcast its data and the circuit energy consumed also by the data node to receive the broadcasted data from other data nodes. The circuit energy consumption of all the data nodes E_{ldc} is given by

$$E_{ldc} = \frac{L}{R_l} P_{ct} N_d + (N_d - 1) \frac{L}{R_l} P_{cr} N_d \tag{6}$$

where P_{ct} denotes the circuit power of transmitter.

To make sure the local communication is successful, the data nodes choose the maximum separation of the cluster d_l as the transmission distance to broadcast their data during local communication. According to [1], E_{ldt} is given by

$$E_{ldt} = (1+\alpha)E_{bl}\frac{(4\pi d_l)^2}{G_t G_r \lambda^2} M_l N_f N_d L \tag{7}$$

where E_{bl} is the energy per bit at the receiver during local communication to satisfy the required BER, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, λ is the carrier wavelength, M_l is the link margin compensating hardware process variations and other additive background noise or interference, and N_f is the receiver noise figure. $1+\alpha$ is given by [3]

$$1+\alpha = \frac{3}{\eta}\left[\frac{2^{\frac{b_l}{2}}-1}{2^{\frac{b_l}{2}}+1}\right] \tag{8}$$

where η is the drain efficiency of the radio frequency power amplifier.

E_{bl} in (7) is determined by the required BER at receiver. The local communication BER at receiver P_{bl} is given by [1]

$$P_{bl} = \begin{cases} \frac{4}{b_l}\left(1-\frac{1}{2^{b_l/2}}\right) Q\left(\sqrt{\frac{3b_l}{2^{b_l}-1}\gamma_l}\right), & b_l \geq 2 \\ Q\left(\sqrt{2\gamma_l}\right), & b_l = 1 \end{cases} \tag{9}$$

where the $Q(\cdot)$ function is defined as

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-\frac{y^2}{2}}dy, \tag{10}$$

and γ_l is the signal-to-noise ratio (SNR) of local communication at the receiver. γ_l is given by

$$\gamma_l = \frac{E_{bl}}{N_0} \tag{11}$$

where N_0 is the single-sided thermal noise power spectral density.

On the basis of (9)–(11), E_{bl} can be calculated to satisfy the required P_{bl}, if N_0 and b_l are specified. With (2)–(8) and the calculated E_{bl}, the energy consumption of local communication E_l can be calculated.

B. Energy Consumption of Long-Haul Communication

During long-haul communication, both data nodes and help nodes cooperatively transmit $N_d L$ bits to the data sink on the basis of distributed orthogonal STBC, and they are the cooperative nodes whose number is denoted by N. In MIMO communication, the value of STBC spatial rate could be chosen to be 1/2 regardless how many transmitting antennas are used [10]. In this paper, to simplify the analysis and make the results comparable under different number of cooperative nodes, the spatial rate of distributed STBC R_s is chosen as 1/2 for all cases. Since the data sink is far away from the cluster, the distances from the cooperative nodes in the cluster to the data sink are assumed the same, which is called long-haul distance d_{LH}. During long-haul communication, for the proper operation of MIMO techniques, the training sequences for channel estimation need be transmitted by the cooperative nodes before data transmissions. However, the energy consumption of training sequence transmissions is not comparable with that of data transmissions and can be neglected [1], [3], [4]. The energy consumption of long-haul communication E_{LH} is the sum of the circuit energy consumption E_{LHc} and transmission energy consumption E_{LHt} of data transmission, and it is given by

$$E_{LH} = E_{LHc} + E_{LHt}. \tag{12}$$

E_{LHc} consists of the circuit energy consumption of cooperative nodes and the circuit energy consumption of data sink. Compared to local communication, extra circuit energy is consumed during long-haul communication due to distributed STBC coding and decoding. However, it is not comparable with the energy consumed by radio frequency circuit blocks and can be neglected. Therefore, the transmitter and receiver circuit power during long-haul communication can be considered as the same as that during local communication. E_{LHc} is given by

$$E_{LHc} = N_d \frac{L}{R_{LH}} P_{ct} N + N_d \frac{L}{R_{LH}} P_{cr} \tag{13}$$

where N is given by

$$N = N_d + N_h \tag{14}$$

and R_{LH} is the bit rate for long-haul communication, which is given by

$$R_{LH} = b_{LH} B R_s \tag{15}$$

where b_{LH} is QAM modulation constellation size of long-haul communication.

According to [1], the transmission energy consumption of long-haul communication E_{LHt} is given by

$$E_{LHt} = (1+\alpha)\overline{E}_{bLH}\frac{(4\pi d_{LH})^2}{G_t G_r \lambda^2} M_l N_f N_d L \tag{16}$$

where $\overline{E}_{bLH}$ is the average required energy per bit at the data sink of long-haul communication to satisfy the BER requirement on a Rayleigh channel. The average BER at the data sink on a Rayleigh channel $\overline{P}_{bLH}$ is given by

$$\overline{P}_{bLH} = \begin{cases} \varepsilon\left\{\frac{4}{b_{LH}}(1-2^{-\frac{b_{LH}}{2}})Q\left(\sqrt{\frac{3b_{LH}}{2^{b_{LH}-1}}\gamma_{LH}}\right)\right\}, & b_{LH} \geq 2 \\ \varepsilon\{Q(\sqrt{2\gamma_{LH}})\}, & b_{LH} = 1 \end{cases} \tag{17}$$

where ε denotes the expectation operator. According to [10], the SNR at the data sink γ_{LH} is given by

$$\gamma_{LH} = (\sum_{i=1}^{N}|h_i|^2)\frac{\overline{E}_{bLH}}{N N_0} \tag{18}$$

where h_i denotes the channel distributed with Rayleigh distribution between the ith transmitting node and the data sink.

On the basis of (17) and (18) and if other parameters are specified, $\overline{E}_{bLH}$ can be calculated to satisfy the required average BER $\overline{P}_{bLH}$ of long-haul communication at data sink. With (12)–(16) and the calculated $\overline{E}_{bLH}$, the energy consumption of long-haul communication E_{LH} can be calculated.

Finally, the total energy consumption E can be obtained as

$$E = (1+\alpha)E_{bl}\frac{(4\pi d_l)^2}{G_t G_r \lambda^2} M_l N_f N_d L$$

$$\begin{aligned}&+\frac{P_{cr}N_h+P_{ct}+(N_d-1)P_{cr}}{R_l}N_dL\\&+\frac{P_{ct}(N_d+N_h)+P_{cr}}{R_{LH}}N_dL\\&+(1+\alpha)\overline{E}_{bLH}\frac{(4\pi d_{LH})^2}{G_tG_r\lambda^2}M_lN_fN_dL.\end{aligned}\tag{19}$$

The first energy term of the right side in (19) represents the transmission energy consumption of local communication, which is independent of the number of help nodes N_h. The second and third energy terms represent the circuit energy consumption of local communication and long-haul communication, respectively. Both of them increase over the number of help nodes N_h. The fourth energy term is the transmission energy consumption of long-haul communication. We will demonstrate that it decreases over the number of help nodes N_h by numerical methods in the next section.

III. ENERGY CONSUMPTION MINIMIZATION

On the basis of the system model introduced in the previous section, the energy consumption of cooperative MIMO with idle-node participation is minimized.

A. Theoretical Analysis

The number of help nodes N_h can be optimized to minimize the total energy consumption. The optimization problem could be formulated as follows:

$$\begin{aligned}&\min_{N_h} E(N_h)\\&\text{s.t. } N_h \text{ is nonnegative integer.}\end{aligned}\tag{20}$$

The brute-force search method can be used to resolve the optimization problem and to find the optimal number of help nodes that minimizes total energy, which will be illustrated by the numerical results in next subsection. The energy consumption of the cooperative MIMO is related to the number of data nodes, and the optimal number of help nodes N_h^* will vary with the number of data nodes. However, we find an interesting property that the optimal number of cooperative nodes, that is, the sum of data nodes number and the optimal number of help nodes, is independent of data nodes number.

Proposition 1: The optimal number of cooperative nodes is independent of the number of data nodes.

Proof: To search for the optimal number of cooperative nodes N^* that minimizes the total energy consumption, the number of cooperative nodes N can be considered as a continuous variable, and the problem becomes a convex optimization problem. From the analysis of energy consumption in Section II, the derivative of total energy consumption with respect to N can be obtained as follows:

$$\frac{dE}{dN}=\left[(1+\alpha)\frac{(4\pi d_{LH})^2}{G_tG_r\lambda^2}M_lN_f\frac{d\overline{E}_{bLH}}{dN}+\frac{P_{ct}}{R_{LH}}+\frac{P_{cr}}{R_l}\right]N_dL.\tag{21}$$

To calculate $\frac{d\overline{E}_{bLH}}{dN}$ in (21), the BER of long-haul communication $\overline{P}_{bLH}$ can be rewritten as follows from (17) and (18):

$$\begin{aligned}\overline{P}_{bLH}&=g(N,\overline{E}_{bLH})\\&=\varepsilon\{K_1(b_{LH})Q(\sqrt{K_2(b_{LH})\gamma_{LH}})\}\\&=\int_0^{+\infty}K_1(b_{LH})Q(\sqrt{K_2(b_{LH})\gamma_{LH}})f(\gamma_{LH})d\gamma_{LH}\end{aligned}\tag{22}$$

where

$$K_1(b_{LH})=\begin{cases}\frac{4}{b_{LH}}\left(1-\frac{1}{2^{\frac{b_{LH}}{2}}}\right), & b_{LH}\geq 2\\ 1, & b_{LH}=1,\end{cases}\tag{23}$$

$$K_2(b_{LH})=\begin{cases}\frac{3b_{LH}}{2^{b_{LH}}-1}, & b_{LH}\geq 2\\ 2, & b_{LH}=1,\end{cases}\tag{24}$$

and $f(\gamma_{LH})$ is the probability density function of SNR at the data sink for long-haul communication. We denote the average SNR at data sink on a Rayleigh channel as $\overline{\gamma}_{LH}$. According to [4], $f(\gamma_{LH})$ is given by

$$f(\gamma_{LH})=\frac{1}{\Gamma(N)\overline{\gamma}_{LH}^N}\gamma_{LH}^{N-1}e^{-\frac{\gamma_{LH}}{\overline{\gamma}_{LH}}}\tag{25}$$

where $\Gamma(\cdot)$ denotes the gamma function. $\overline{\gamma}_{LH}$ is given by [4]

$$\overline{\gamma}_{LH}=\frac{\overline{E}_{bLH}}{NN_0}.\tag{26}$$

From (22)–(26), $\frac{d\overline{E}_{bLH}}{dN}$ can be obtained using implicit differentiation as follows:

$$\frac{d\overline{E}_{bLH}}{dN}=-\frac{\partial g/\partial N}{\partial g/\partial\overline{E}_{bLH}}.\tag{27}$$

Combining (22)–(27), it is found that $\frac{d\overline{E}_{bLH}}{dN}$ is a function of N and independent of the number of data nodes N_d. Substituting $\frac{d\overline{E}_{bLH}}{dN}$ in (21), $\frac{dE}{dN}$ can be obtained. Setting $\frac{dE}{dN}$ equal to zero, we have

$$\left.(1+\alpha)\frac{(4\pi d_{LH})^2}{G_tG_r\lambda^2}M_lN_f\frac{d\overline{E}_{bLH}}{dN}+\frac{P_{ct}}{R_{LH}}+\frac{P_{cr}}{R_l}\right|_{N=N^*}=0.\tag{28}$$

On the basis of (28) and the obtained $\frac{d\overline{E}_{bLH}}{dN}$, the optimal number of cooperative nodes N^* that minimizes the total energy consumption can be obtained. Since $\frac{d\overline{E}_{bLH}}{dN}$ is independent of the number of data nodes N_d, from (28), the optimal number of cooperative nodes N^* can be easily found to be independent of the number of data nodes N_d and concludes the proof. □

From the proof above, it is found that the optimal number of cooperative nodes N^* is a function of long-haul distance d_{LH}, modulation constellation size of both local communication b_l and long-haul communication b_{LH} if all the other parameters are specified.

$$N^*=h(d_{LH},b_l,b_{LH}).\tag{29}$$

The long-haul distance d_{LH} will have an impact on the optimal number of cooperative nodes and the total energy consumption. The modulation constellation size of both local communication b_l and long-haul communication b_{LH} could also be optimized to save more energy.

Table 1. Circuit and system parameters.

Parameters	Value
f_c	2.5 GHz
G_tG_r	5 dBi
B	10 KHz
η	0.35
N_f	10 dB
N_0	−134 dBm/Hz
M_l	40 dB
P_{ct}	98.2 mW
P_{cr}	112.6 mW
L	2 Kbits

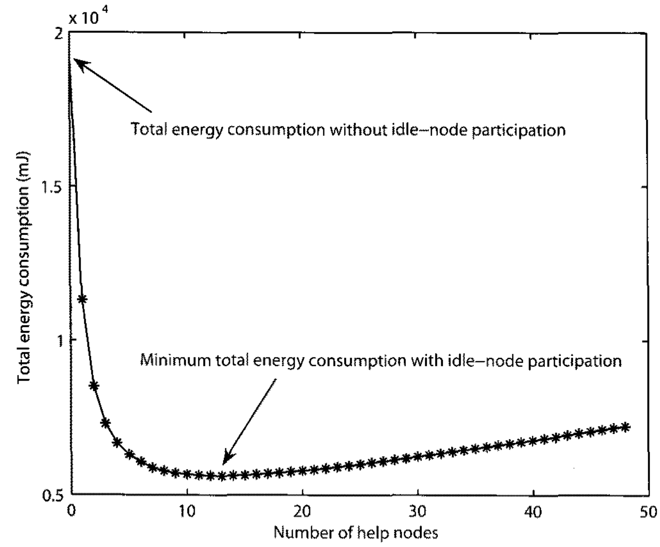

Fig. 2. Total energy consumption over number of help nodes, two data nodes.

B. Numerical Results

In this subsection the number of help nodes N_h is optimized to minimize the total energy consumption by numerical methods. The required BER for both local and long-haul communication is chosen to be 10^{-3}. The maximum separation of cluster d_l is chosen to be 10 m. The long-haul distance d_{LH} is chosen to be 100 m. The modulation constellation size of local communication b_l, and the modulation constellation size of long-haul communication b_{LH}, are both chosen to be 2. Other circuit and system parameters quoted from [1] and [6] are summarized in Table 1. In this table, f_c denotes the carrier frequency; hence, the carrier wavelength λ can be calculated on the basis of the value of f_c.

When there are two data nodes in the cluster, the total energy consumption over the number of help nodes N_h is plotted in Fig. 2. It is shown that an optimal number of help nodes can be determined to minimize the total energy consumption. The minimum total energy consumption is 5615.2 mJ, and the total energy consumption, without idle nodes participating in cooperative communication, is 19219 mJ. It can be concluded that much more energy can be saved if idle nodes participate in cooperative communication.

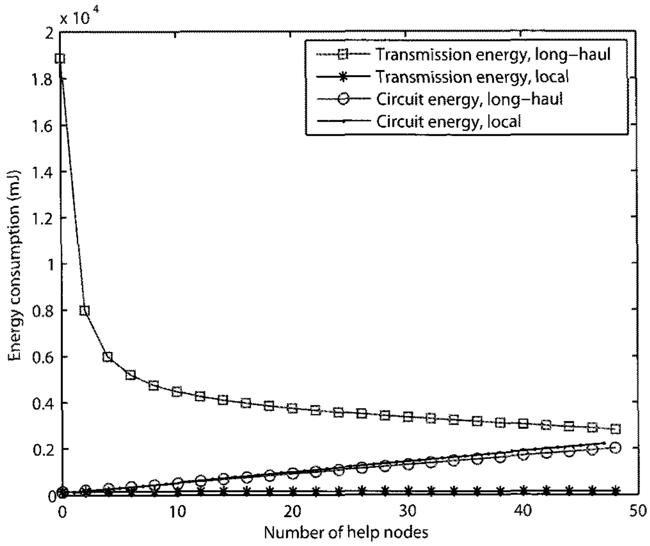

Fig. 3. Energy consumption comparison between transmission and circuitry for both local and long-haul communication, two data nodes.

Fig. 3 shows the energy consumption comparison between transmission and circuitry for both local and long-haul communication. With few idle nodes participating in cooperative communication, the transmission energy of long-haul communication is dominant in the total energy consumption, and it decreases rapidly over the number of help nodes. As more idle nodes participate in cooperative communication, the increased circuit energy consumption of local and long-haul communication becomes comparable to the transmission energy of long-haul communication and exceeds the energy saved of long-haul communication.

Table 2 illustrates that the optimal number of help nodes N_h^* varies with the number of data nodes. As the number of data nodes increases, i.e., the amount of transmitted data increases, the extra circuit energy consumption will exceed the saved transmission energy of long-haul communication due to idle-node participation in cooperative communication. Therefore, the optimal number of help nodes decreases as the number of data nodes increases. As shown in Table 2, the optimal number of cooperative nodes N^* is independent of the number of data nodes, which is theoretically proved above.

Table 3 illustrates the influence of long-haul distance on the optimal number of cooperative nodes and the saved energy over not using help nodes when there are two data nodes. As the long-haul distance increases, the transmission energy of long-haul communication is more dominant in the total energy consumption. Since it decreases as the number of cooperative nodes increases, to save more energy, the optimal number of cooperative nodes that minimizes the total energy consumption will increase over the long-haul distance.

The total energy can be further saved by jointly optimizing both modulation constellation size and the number of help nodes. When the long-haul distance d_{LH} is set as 100 m, the total energy consumption under different values of b_l and b_{LH} for the optimized number of help nodes is given in Table 4. It is clear that when $b_l = 2$ and $b_{LH} = 1$ the total energy consumption is minimum. The optimal number of cooperative nodes un-

Table 2. Optimal number of help nodes and cooperative nodes for different number of data nodes.

N_d	2	3	4	5	6	7	8	9	10	11	12	13	14	15
N_h^*	13	12	11	10	9	8	7	6	5	4	3	2	1	0
N^*	15	15	15	15	15	15	15	15	15	15	15	15	15	15

Table 3. Optimal number of cooperative nodes for different long-haul distances ($b_l = b_{LH} = 2$).

Long-haul distance (m)	100	150	200	250	300
Optimal number of cooperative nodes	15	21	27	31	42
Saved energy (mJ), 2 data nodes	13603.8	31774	57535	90862	131788

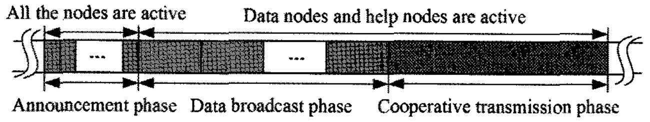

Fig. 4. The process of cooperative MIMO scheme with help-node participation.

der different values of b_l and b_{LH} is also listed in Table 4, and it varies with the chosen modulation constellation size as it is expected.

IV. COOPERATIVE MIMO SCHEME WITH HELP-NODE PARTICIPATION

To confirm the mathematical model discussed previously, a cooperative MIMO scheme with help-node participation is proposed in this section. The simulation results show that the proposed scheme can achieve significant energy saving and the energy overhead of the task assignment for help nodes can be much less than the energy consumption of data transmission with the delicate design of cooperative MIMO scheme.

A. Description of Designed Scheme

We assume that the network has been divided into clusters and sensor nodes know which cluster they belong to and how many nodes are there in the cluster, which can be achieved through a cluster-formation algorithm, such as low-energy adaptive clustering hierarchy (LEACH) [11]. In the cluster, each sensor node is assigned an unique identifier (ID). The nodes are assumed to be synchronized, which is possible by a scheme such as global positioning system (GPS). We assume that the network is relatively static and the distance from a cluster to the data sink is fixed. The optimal number of cooperative nodes N^* in the cluster is set as a parameter at each node when the network is deployed. The operation of the scheme is divided into *rounds*. As depicted in Fig. 4, each round consists of three phases.

1) Announcement phase. The announcement phase is divided into multiple time slots. The number of the slots is the same as the number of nodes in the cluster. Each node is allocated a slot. In announcement phase, each node broadcasts an announcement message during its slot and receives the announcement messages broadcasted by the others. The announcement message contains the information of the node's ID, state (is it a data node or an idle node), and residual energy. All the nodes can obtain global information of the cluster on the basis of the received messages. Each idle node will decide whether or not to participate in the succeeding cooperative communication as a help node according to the number of data nodes, the order of its residual energy among all the idle nodes, and try to achieve the optimal number of cooperative nodes.

When there is no data node in a round all the nodes will go into sleep during the rest of the round and wake up at the beginning of the next round. When the number of data nodes is equal to or more than the optimal number of cooperative nodes, all the idle nodes will go into sleep during the rest of the round and only the data nodes cooperatively transmit their data to the data sink. When the number of data nodes is less than the optimal number of cooperative nodes, some of the idle nodes will become help nodes and participate in cooperative communication and others will go into sleep during the rest of the round. The number of help nodes needed for cooperative communication N_h is given by:

$$N_h = \begin{cases} N^* - N_d, & 0 < N_d < N^* \\ 0, & \text{otherwise.} \end{cases} \tag{30}$$

Here, N_d is the number of data nodes that can be obtained after receiving announcement messages. The idle nodes are sorted in the descending order according to their residual energy. If there are two idle nodes that have the same amount of residual energy, the node with smaller ID has smaller order. If the order of an idle node is less than or equal to N_h, it will participate in the cooperative communication as a help node.

2) Data broadcast phase. The data broadcast phase consists of multiple time slots. The number of the slots is the same as the number of data nodes. Each data node broadcasts its data during one slot. The order of the slot in which the data node sends the announcement message determines which slot it uses to broadcast data. Both the data nodes and help nodes receive and store the broadcasted data.

3) Cooperative transmission phase. In this phase, both data nodes and help nodes encode the transmission sequence according to the distributed STBC and cooperatively transmit the encoded sequence to the data sink as an individual antenna in the MIMO antenna array.

B. Simulation Results

To verify the energy efficiency, we simulate the proposed scheme and compare the simulation results with the following two schemes.

Table 4. Total energy consumption and optimal number of cooperative nodes for different modulation constellation size b_l and b_{LH} (d_{LH} = 100 m).

Modulation constellation size	$b_l = 1$ $b_{LH} = 1$	$b_l = 1$ $b_{LH} = 2$	$b_l = 2$ $b_{LH} = 1$	$b_l = 2$ $b_{LH} = 2$
Total energy consumption (mJ), 2 data nodes	3878.3	5848.8	3773.8	5615.2
Optimal number of cooperative nodes	8	12	9	15

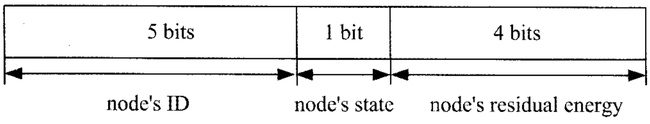

Fig. 5. The structure of an announcement message.

Cooperative MIMO scheme without help-node participation. Like the cooperative MIMO scheme with help-node participation, the operation of this scheme is divided into *rounds* and each round consists of an announcement phase, a data broadcast phase, and a cooperative transmission phase. In the announcement phase, each data node broadcasts an announcement message during its allocated slot. The structure of the announcement message is the same as that in cooperative MIMO scheme with help-node participation except without the information of the node's residual energy. The idle nodes learn how long the succeeding data transmission will last on the basis of the received announcement messages and will go into sleep during the rest of the round. In the data broadcast phase, each data node broadcasts its data during the slot decided by its announcing order. After receiving all the data from other data nodes, the data nodes will cooperatively transmit the data to the data sink in the cooperative transmission phase.

Non-cooperative scheme. In this scheme, time division multiple access (TDMA) schedule is employed. Each node directly transmits its data packet to the data sink during its allocated slot. To save energy, a node will turn off its radio during other nodes' time slots. If a node has no data to transmit during its own slot, it will turn off its radio as well.

indent In our simulations, there are 20 nodes randomly distributed in a circular region with a diameter of 10 m. The distance from the data sink to the center of the circular region is 100 m. Data packets are generated at each node following an exponential distribution with an average value of 100 s. The initial energy of each node is set to be 400 J as in [6]. The modulation of local communication is chosen to be QPSK, while the modulation of long-haul communication is chosen to be BPSK. To make the simulation results comparable, the modulation of noncooperative scheme is chosen to be BPSK. All the other parameters are set as listed in Table 1. Thus, the optimal number of cooperative nodes N^* can be calculated, which is 9. The structure of the announcement message is shown in Fig. 5. In the message, there are 5 bits to denote the node's ID, which can identify 32 nodes in the cluster. There is 1 bit allocated for the node's state. Here, we use 4 bits to indicate the residual energy, which can be quantized into 16 levels. For cooperative MIMO scheme without help-node participation, the announcement message contains 6 bits.

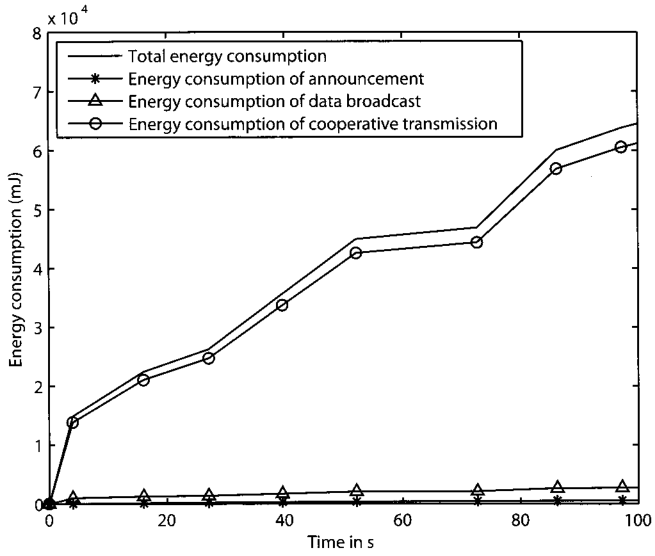

Fig. 6. Energy consumption of the cooperative MIMO scheme with help-node participation.

Fig. 6 shows the total energy consumption, energy consumption of announcement, energy consumption of data broadcast, and energy consumption of cooperative transmission when the cooperative MIMO scheme with help-node participation is employed. Note that the packet size of announcement message is much smaller than that of the data packet, and the transmission distance of local communication is much shorter than that of long-haul transmission. The energy consumption of cooperative transmission is dominant in the total energy consumption of the proposed scheme. The energy consumption of announcement, which is the scheme overhead of the task assignment for help nodes, is very small and can be neglected.

Fig. 7 shows the energy consumption of three communication schemes: Cooperative MIMO scheme with help-node participation, cooperative MIMO scheme without help-node participation, and noncooperative scheme. Compared with the other two schemes, the proposed scheme achieves significant energy saving.

Fig. 8 shows the lifetime performance of the three communication schemes. It can be seen that the lifetime of the network using the proposed cooperative MIMO scheme with help-node participation is about twice as long as that using the cooperative MIMO scheme without help nodes and is about ten times as long as that using the noncooperative scheme. Note that the energy of each node is almost exhausted at the same time for the cooperative MIMO scheme with help-node participation, which is the result of that help nodes are selected according to their residual energy.

The improvement of energy efficiency by the proposed cooperative MIMO scheme with help-node participation comes from

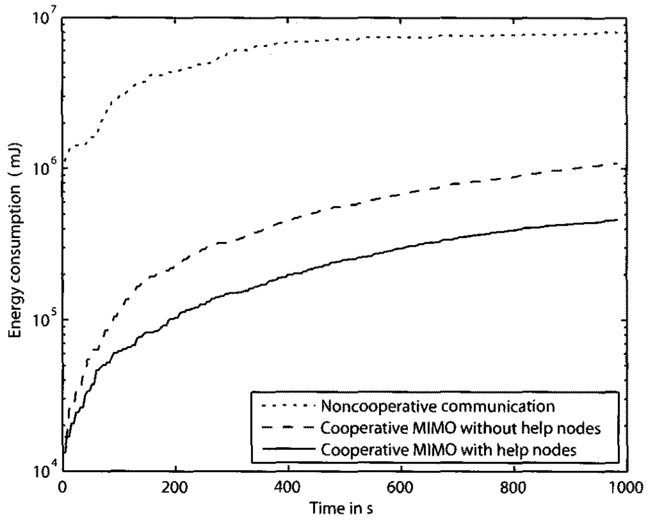

Fig. 7. Energy consumption of three communication schemes.

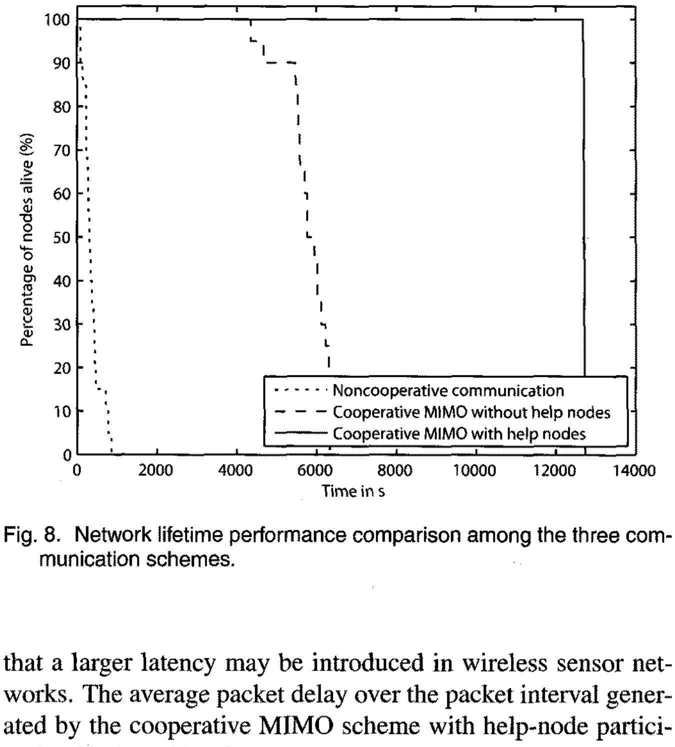

Fig. 8. Network lifetime performance comparison among the three communication schemes.

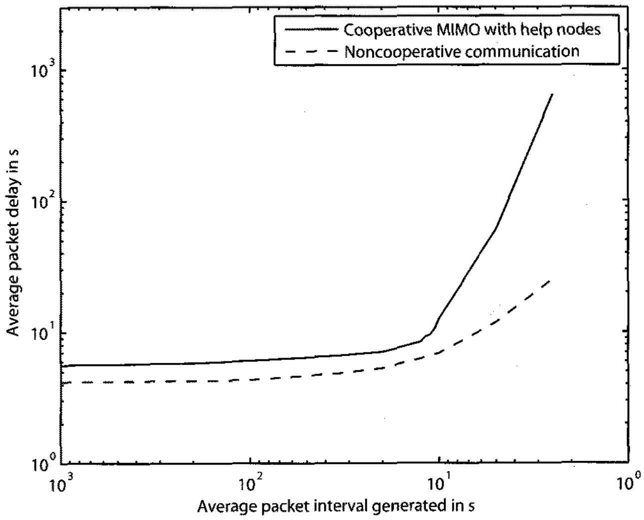

Fig. 9. Packet delay comparison between cooperative MIMO with help-node participation and noncooperative communication.

that a larger latency may be introduced in wireless sensor networks. The average packet delay over the packet interval generated by the cooperative MIMO scheme with help-node participation is plotted in Fig. 9, compared to that of the noncooperative communication scheme. We can see that when the packets interval is large (i.e., the traffic load is low) the packets take about 50% longer time to arrive at their destination for the cooperative MIMO scheme with help-node participation than that for the non-cooperative communication scheme. For the cooperative MIMO scheme with help-node participation, the duration of the announcement phase is very short and negligible and the duration of the data broadcast phase is the half of the cooperative transmission phase since QPSK is used for data broadcast, while BPSK for cooperative transmission. The data transmission time in the cooperative transmission phase of cooperative MIMO is approximately the same as that in noncooperative communication. We can also see from Fig. 9 that as the traffic load increases and approaches a threshold, the average packet delay increases sharply for the cooperative MIMO scheme and is much larger than that of noncooperative communication. This is because that the cooperative MIMO scheme with help-node participation approaches its transmission capacity first, and then, causes heavy traffic congestion. We also investigate how the packet delay vary with the number of nodes in the cluster and find that the packet delay increases with the number of nodes in the cluster for both communication schemes, but the average packet delay of the cooperative MIMO scheme with help-node participation is still about 50% larger than that of the noncooperative communication scheme.

Finally, we investigate the effect of the announcement phase on energy efficiency of the cooperative MIMO scheme with help-node participation by simulations and find that the percentage of energy consumption in the announcement phase is almost unchanged as the number of nodes in the cluster varies and decreases as the packet interval generated decreases (i.e., the traffic load increases). However, more noticeable changes in energy consumption can be seen when the length of data packet varies, and the shorter the data packet is, the more energy is consumed for announcement, as shown in Fig. 10.

V. CONCLUSIONS

In this paper, the energy consumption of cooperative MIMO in cluster-based wireless sensor networks is analyzed. Idle nodes that have no data to transmit will participate in the cooperative MIMO, and it was found that much more energy can be saved. The number of help nodes as well as the number of cooperative nodes has been optimized to minimize the total energy consumption. The optimal number of help nodes was found to be decreasing over the number of data nodes, while the optimal number of cooperative nodes was found to be independent of the number of data nodes. The influence of long-haul distance and the modulation constellation size of both local communication and long-haul communication was investigated. The results could be used as a guideline for the design of future cluster-based wireless sensor networks when cooperative MIMO is em-

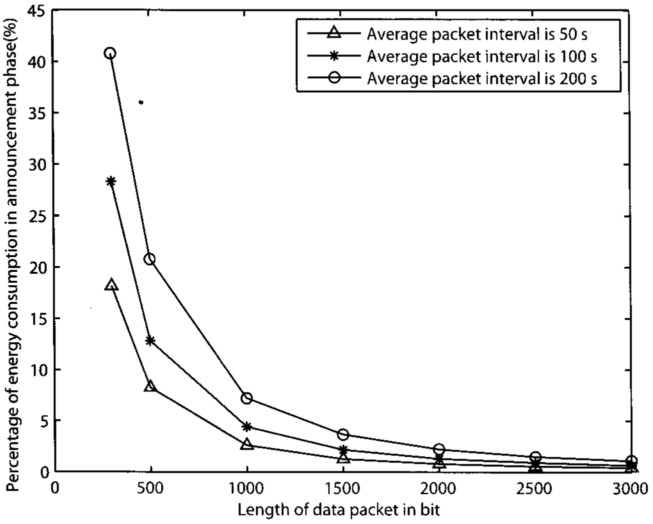

Fig. 10. Percentage of energy consumption in announcement phase of cooperative MIMO scheme with help-node participation over the length of data packet under different packet intervals generated.

ployed.

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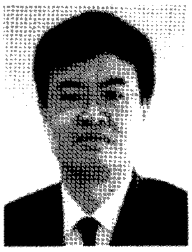

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