

# A Novel Cluster-Based Cooperative MIMO Scheme for Multi-Hop Wireless Sensor Networks

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A cluster-based cooperative multiple-input-multiple-output (MIMO) scheme is proposed to reduce the adverse impacts caused by radio irregularity and fading in multi-hop wireless sensor networks. This scheme extends the LEACH protocol to enable the multi-hop transmissions among clusters by incorporating a cooperative MIMO scheme into hop-by-hop transmissions. Through the adaptive selection of cooperative nodes and the coordination between multi-hop routing and cooperative MIMO transmissions, the scheme can gain effective performance improvement in terms of energy efficiency and reliability. Based on the energy consumption model developed in this paper, the optimal parameters to minimize the overall energy consumption are found, such as the number of clusters and the number of cooperative nodes. Simulation results exhibit that the proposed scheme can effectively save energy and prolong the network lifetime.

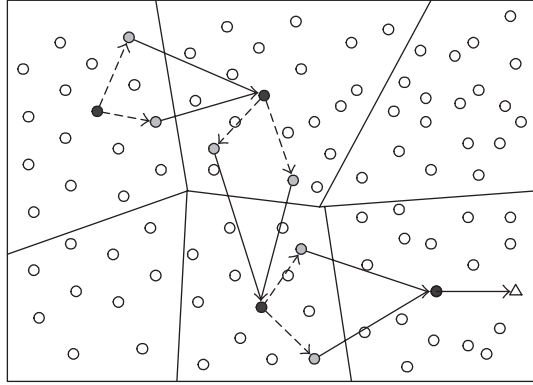
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## 1. INTRODUCTION

Due to the limited energy and difficulty to recharge a large number of sensors, energy efficiency and maximizing network lifetime have been the most important design goals for wireless sensor networks (WSNs). However, channel fading, interference, and radio irregularity pose big challenges on the design of energy efficient communication and routing protocols in the multi-hop WSNs.

As the MIMO technology has the potential to dramatically increase the channel capacity and reduce transmission energy consumption in fading channels [1], cooperative MIMO schemes have been proposed for WSNs to improve communication performance [2–5]. In those schemes, multiple individual single-antenna nodes cooperate on information transmission and/or reception for energy-efficient communications. Cui et al. [2] analyzed a cooperative MIMO scheme with Alamouti code for single-hop transmissions in WSNs. Li [3] proposed a delay and channel estimation scheme without transmission synchronization for decoding for such cooperative MIMO schemes. Li et al. [4] also proposed a STBC-encoded cooperative transmission scheme for WSNs without perfect synchronization. Jayaweera [5] considered the training overhead of such schemes.

However, in the above proposals, the multi-hop routing and distributed operations in WSNs are not taken into consideration, which limits the practical use of the cooperative MIMO schemes in WSN. In this paper we study the feasibility of a cooperative MIMO scheme in multi-hop WSNs. Radio irregularity of wireless communications and multi-hop routing is considered with the cooperative MIMO scheme. On the other hand, due to its ability of frequency reuse and efficiency in processing highly correlated data, clustering is efficient in the design of WSNs. Therefore, we incorporate the cooperative MIMO scheme with the LEACH protocol, which is an efficient clustering protocol due to its energy-efficient, randomized, adaptive, and self-configuring cluster formation. As only single-hop communications from cluster heads to the sink are considered in the original LEACH protocol, we modify the LEACH protocol to allow cluster heads to form a multi-hop backbone and incorporate the cooperative MIMO scheme into each single-hop transmission. Based on the proposed scheme, we investigate the energy consumption of each transmission/reception. Then, the overall energy consumption model is developed, and the optimal parameters of the scheme are found such as the number of clusters and the number of cooperative nodes.



△ Sink  
● Cluster header  
○ Normal node  
○ Cooperative node

FIGURE 1: Multi-hop MIMO-LEACH scheme.

The remainder of the paper is organized as follows. In Section 2 we describe the design of the proposed cluster-based cooperative MIMO scheme (multi-hop MIMO-LEACH). The overall energy consumption of the proposed scheme is analyzed in Section 3. Section 4 presents simulation results and discussions. Section 5 concludes the paper.

## 2. THE MULTI-HOP MIMO-LEACH SCHEME

In this section, we will discuss the proposed multi-hop MIMO-LEACH scheme, which is illustrated in Figure 1. First, the strategy to find appropriate cooperative nodes in the single-hop communications between cluster heads is proposed in Section 2.1. Based on the strategy, the multi-hop MIMO-LEACH scheme is presented in Section 2.2.

### 2.1. Strategy to choose cooperative nodes

To maximize the performance of single-hop communications between cluster heads, an appropriate strategy should be taken to choose the optimal cooperative nodes. Suppose that the current cluster head will use  $J$  cooperative nodes to transmit data to its neighboring cluster head  $t$  by the cooperative MIMO scheme. An AWGN channel with squared power path loss is assumed for intracluster communications. For the intercluster communications, we assume the transmission from each cooperative node experiences frequency-nonselective and slow Rayleigh fading. Furthermore, the long distance between any two nodes in the network with respect to the wavelength gives rise to independent fading coefficients for the cooperative nodes. The rationale behind such channel assumptions is that the inter-cluster transmission distance is much larger than the intra-cluster transmission distance and the transmission environments are more complex in the inter-cluster communication.

Denote the distance between node  $j$  and its current cluster head by  $d_{j1}$ . Also, denote the distance and path loss for node  $j$  to communicate with  $t$  as  $d_{jt}$  and  $k_{jt}$ , respectively. For each single-hop transmission, the current cluster head will broadcast a data packet to the cooperative nodes. Then, the cooperative nodes will encode and transmit the transmission sequence according to the orthogonal space-time block codes (STBC) to cluster head  $t$  toward the sink node. The energy consumption for these two operations in the single-hop transmission will be modeled in the remainder of this section. Then, a novel strategy will be developed to find the optimal set of cooperative nodes to minimize the overall energy consumption. In developing the strategy, we assume BPSK is adopted as the modulation scheme and the bandwidth is  $B$  Hz.

### (1) The energy consumption for the intracluster transmission

Denote by  $E_{bt}(1)$  the energy consumption for the current cluster head to broadcast one bit to the cooperative nodes.  $E_{bt}(1)$  can be broken down into two main components, the transmit energy consumption  $E_{btt}(1)$  and the circuit energy consumption  $E_{btc}(1)$ .

The BER performance for BPSK is  $P_b = Q(\sqrt{2r})$ . Here  $r$  is the signal-to-noise ratio(SNR), which is defined as  $r = P_r/(2B\sigma^2N_f)$  [6] under the assumption of AWGN channel, where  $P_r$  is the received signal power,  $\sigma^2$  is the power density of the AWGN, and  $N_f$  is the receiver noise figure.

In the high SNR regime, we can approximate the BER performance as  $P_b = e^{-r}$  by the Chernoff bound [6]. Hence, we obtain  $P_r = -2BN_f\sigma^2 \ln(P_b)$ . As the assumption of squared power path loss,  $E_{bt}(1)$  can be modelled by

$$\begin{aligned} E_{bt}(1) &= E_{btt}(1) + E_{btc}(1) \\ &= -2(1 + \alpha)N_f\sigma^2 \ln(P_b)G_1 d_{\max}^2 M_l + \frac{P_{ct} + JP_{cr}}{B}, \end{aligned} \quad (1)$$

where  $d_{\max}$  is the maximum distance from the cooperative nodes to the cluster head,  $\alpha$  is the efficiency of the RF power amplifier,  $G_1$  is the gain factor at  $d_{\max} = 1$  m,  $M_l$  is the link margin,  $N_f$  is the receiver noise figure, and  $P_{ct}$  and  $P_{cr}$  are the circuit power consumption of the transmitter and receiver, respectively [2].

Let  $f_1(P_b) = -2N_f\sigma^2 \ln(P_b)$  and  $H(d_{\max}) = G_1 M_l d_{\max}^2$ . Then, (1) can be rewritten as

$$E_{bt}(1) = (1 + \alpha)f_1(P_b)H(d_{\max}) + \frac{P_{ct} + JP_{cr}}{B}. \quad (2)$$

According to the definition,  $H(d_j)$  can be measured as follows. Let the current cluster head transmit a signal with transmit power  $P_{out}$ . Then, the power of the received signal at its cluster member, node  $j$ , is  $P_{j1} = P_{out}/H(d_j)$ . Therefore,  $H(d_j)$  can be measured as

$$H(d_j) = \frac{P_{out}}{P_{j1}}. \quad (3)$$

From (2), we can find that the energy consumption in the intra-cluster transmission,  $E_{bt}(1)$ , can be reduced by choosing the nearer cooperative nodes.

### (2) The energy consumption for the intercluster transmission

To analyze the energy consumption for inter-cluster transmissions based on the cooperative scheme, denoted by  $E_{bt}(2)$ , we refine the results in [2]. In [2] an equal transmit power allocation scheme is used as the channel state information (CSI) is not available at the transmitter. If the average attenuation of the channel for each cooperative node pair can be estimated, we can use an equal signal-to-noise (SNR) policy [7] to allocate the transmit power for its effectiveness and simplicity. The average energy consumption per bit transmission by BPSK in such a scheme can be approximated by

$$E_{bt}(2) = (1 + \alpha) \frac{N_0}{P_b^{1/J}} \sum_{j=1}^J \frac{(4\pi)^2 d_{jt}^{k_{jt}}}{G_t G_r \lambda^2} M_l N_f + \frac{(JP_{ct} + P_{cr})}{B}, \quad (4)$$

where  $N_0$  is the single-sided noise power spectral density,  $P_b$  is the desired BER performance,  $G_t$  and  $G_r$  are the transmitter and receiver antenna gains, respectively, also,  $\lambda$  is the carrier wavelength [2]. The training overhead and transmission rate are not considered in (4), which will be considered in Section 3.

The average attenuation of the channel for node  $j$  can be estimated as follows. Assume the channel is symmetric, and  $t$  transmits a signal with transmit power  $P_{out}$ , then the power of the received signal at node  $j$ ,  $P_{jt}$  can be given by

$$P_{jt} = P_{out} \frac{G_t G_r \lambda^2}{(4\pi)^2 d_{jt}^{k_{jt}} M_l N_f} = \frac{P_{out}}{G(d_{jt}, k_{jt})}, \quad (5)$$

where  $G(d_{jt}, k_{jt}) = P_{out}/P_{jt} = ((4\pi)^2 d_{jt}^{k_{jt}} / G_t G_r \lambda^2) M_l N_f$ . Therefore, (4) can be reformulated as

$$\begin{aligned} E_{bt}(2) &= (1 + \alpha) \frac{N_0}{P_b^{1/J}} \sum_{j=1}^J G(d_{jt}, k_{jt}) + \frac{(JP_{ct} + P_{cr})}{B} \\ &= (1 + \alpha) f_2(P_b) \sum_{j=1}^J G(d_{jt}, k_{jt}) + \frac{(JP_{ct} + P_{cr})}{B}. \end{aligned} \quad (6)$$

According to (6), the transmit power of node  $j$  to communicate with cluster head  $t$  can be described by

$$P_{outjt} = G(d_{jt}, k_{jt}) \frac{N_0 B}{P_b^{1/J}}. \quad (7)$$

### (3) The strategy to choose cooperative nodes

Based on (2) and (6), the overall energy consumption for the single-hop transmission can be written as (8)

$$\begin{aligned} E_{bt} &= E_{bt}(1) + E_{bt}(2) \\ &= (1 + \alpha) \left[ f_1(P_b) H(d_{\max}) + f_2(P_b) \sum_{j=1}^J G(d_{jt}, k_{jt}) \right] \\ &\quad + \frac{(J+1)(P_{ct} + P_{cr})}{B}. \end{aligned} \quad (8)$$

From (8), the energy consumption for the intracluster transmission  $E_{bt}(1)$  and intercluster transmission  $E_{bt}(2)$  should be traded off to minimize  $E_{bt}$ .  $E_{bt}$  can be minimized by choosing an appropriate set of cooperative nodes, which can minimize  $f_1(P_b) H(d_{\max}) + f_2(P_b) \sum_{j=1}^J G(d_{jt}, k_{jt})$ . In order to simplify the distributed strategy design, the cooperative nodes should be chosen as the nodes whose  $f_1(P_b) H(d_{j1}) + f_2(P_b) G(d_{jt}, k_{jt})$  are minimal. In addition, in order to balance the energy consumption, the selection criterion is defined as

$$\beta_{jt} = \frac{E_j}{f_1(P_b) H(d_{j1}) + f_2(P_b) G(d_{jt}, k_{jt})}, \quad (9)$$

where  $E_j$  is the remaining energy in the current round for node  $j$ . The rationale behind definition of  $\beta_{jt}$  is that the node, which has a good tradeoff between  $E_{bt}(1)$  and  $E_{bt}(2)$  and has more remaining energy, should have a larger chance to be selected as cooperative node. Therefore,  $J$  nodes with maximum  $\beta_{jt}$  will be chosen as the cooperative nodes to communicate with cluster head  $t$ .

## 2.2. Scheme design

In this section, we will discuss how to enable cluster heads to form a multi-hop backbone by incorporating the cooperative MIMO scheme into the LEACH protocol for each single-hop transmission. As assumed in the LEACH protocol, each node has a unique identifier (ID). The transmit power of each node can be adjusted, and the nodes are assumed to be always synchronized. Similarly, the operations of the proposed scheme are broken into *rounds*. Each round consists of three phases: (i) cluster formation phase, during which the clusters are organized and cooperative MIMO nodes are selected; (ii) routing phase, during which a routing table in each selected node is constructed; and (iii) transmission phase, during which data are transferred from the nodes to the cluster heads and forwarded to the sink according to the routing table.

### (1) Cluster formation phase

In this phase, each node will elect itself to be a cluster head with a probability  $p$  as specified in the original LEACH protocol. After the cluster heads are elected, each cluster head will broadcast an advertisement message (ADV) by transmit power  $P_{out}$  using a nonpersistent CSMA MAC protocol. The

message contains the head's ID. If a cluster head receives the advertisement message from another head  $t$  and the received signal strength (RSS) exceeds a threshold  $th$ , it will take cluster head  $t$  as a neighboring cluster head and record  $t$ 's ID. As for the noncluster head, node  $j$ , it will record all the RSSs of the received advertisement messages, and choose the cluster head whose RSS is the maximum. Then, it will calculate and save  $H(d_j)$ ,  $G(d_{jt}, k_{jt})$ ,  $\beta_{jt}$ , and  $P_{outjt}$  by (3), (5), (7), and (9). Then node  $j$  will join the cluster by sending a join-request message (Join-REQ) to the chosen cluster head. This message contains the information of the node's ID, the chosen cluster head's ID, and the corresponding values of  $\beta_{jt}$ . After a cluster head has received all join-request messages, it will set up a TDMA schedule and transmit this schedule to its members as in the original LEACH protocol. If the sink receives the advertisement message, it will find the cluster head with the maximum RSS, and send the sink-position (Sink-POS) message to the cluster head and mark the cluster head as the target cluster head (TCH).

After the clusters are formed, each cluster head will select corresponding optimal  $J$  cooperative nodes for cooperative MIMO communications with each of its neighboring cluster heads. As stated in Section 2.1,  $J$  nodes with maximum  $\beta_{jt}$  will be chosen to communicate with a neighboring cluster head  $t$ . If no such  $J$  nodes can be found for  $t$ ,  $t$  will be removed from the neighbor list, since too much energy is consumed for communicating with  $t$ . After selecting the cooperative nodes, the total energy per bit transmission for communications with  $t$ ,  $E_{bt}$ , can be derived by (4). Then,  $E_{bt}$ , the ID set of the cooperative nodes for each neighboring cluster head, will be stored. At the end of this phase, the cluster head will broadcast a cooperate-request message (COOPERATE-REQ) to each cooperative node, which contains the ID of the cluster itself, the ID of the neighboring cluster head  $t$ , the IDs of the cooperative nodes, and the index of the cooperative nodes in the cooperative nodes set for each cluster head  $t$ . Each cooperative node that receives the cooperate-request message (COOPERATE-REQ) will store the ID of  $t$ , the index, and the transmit power  $P_{outjt}$  and send back a cooperate-ACK message (COOPERATE-ACK) to the cluster head.

### (2) Routing table construction

To construct the routing table, the basic ideas of distance-vector-based routing will be used. Each cluster head will maintain a routing table, in which each entry contains *destination cluster ID*, *next hop cluster ID*, *IDs of cooperative nodes*, and *mean energy per bit*. Initially, only the neighboring cluster head will have a record in the routing table. Then each cluster head will simply inform its neighboring cluster heads of its routing table. After receiving route advertisements from neighboring cluster heads, the cluster head will update its routing table according to the route cost and advertise to its neighboring cluster heads the modified routes. After several rounds of route exchange and update, the routing table of each cluster head will be converged to the optimal one. Then, TCH will flood a target announcement message

(TARGET-ANNOUNCEMENT) containing its ID to each cluster head to enable the creation of paths to the sink.

### (3) Data transmission

In this phase, cluster members will transmit first their data to the cluster head by multiple frames as in the traditional LEACH protocol. In each frame, each cluster member will transmit its data during its allocated transmission slot specified by the TDMA schedule in *cluster formation phase*, and it will be sleep in other slots to save energy. The duration of a frame and the number of frames are the same for all clusters. Thus the duration of each slot depends on the number of members in the cluster. After a cluster head receives data frames from its cluster members, it will perform data aggregation to remove the redundancy in the data. After aggregating received data frames, the cluster head will forward the data packet to the TCH by multiple hops routing. In each single-hop communication, if there exist  $J$ -cooperative MIMO nodes, the cluster head will add a packet header to the data packet, which includes the information of source cluster ID, next-hop cluster ID, and destination cluster ID. Then the data packet is broadcasted. Once the corresponding cooperative nodes receive the data packet, they will encode the data packet by orthogonal STBC, and transmit the data as an individual antenna with transmission power  $P_{outjt}$  in the MIMO antenna array. In the cooperative MIMO scheme, the transmission delay and channel estimation scheme proposed in [3] can be used to solve the problem of imperfect synchronization in decoding.

## 3. THE ENERGY CONSUMPTION MODEL OF THE SCHEME

In this section, we will analyze the energy consumption of the scheme. Based on the result, we will develop an optimization model to find the optimal parameters in the scheme, including the number of clusters  $k_c$ , and the number of cooperative nodes  $J$ .

In analysis, we make the following assumptions. (1) There are  $N$  nodes distributed uniformly in an  $M \times M$  region. (2) An AWGN channel with squared power path loss is assumed for the intracluster communication. (3) A flat Rayleigh fading channel with  $k$ th-power path loss is assumed for the intercluster communication. (4) BPSK is used as the modulation scheme and the bandwidth is  $B$  Hz. (5) In each frame every node will send a packet with size  $s$  to the cluster head by probability  $P$ . The number of frames in each round is denoted by  $F_n$ . (6) In maintaining the routing table in each round, each cluster head will broadcast the routing table, whose size is denoted by  $R_{ts}$  for  $R_{bt}$  times. (7) The energy consumption for data processing is ignored.

Now, we are ready to model the overall energy consumption in each round, denoted by  $E(k_c, J)$ . There are four energy consuming operations in each round. (1) The cluster members transmit data to the cluster head, whose energy consumption is denoted by  $E_s(k_c)$ . (2) The cluster heads construct the routing tables, whose energy consumption is

denoted by  $E_r(k_c)$ . (3) The cluster heads transmit aggregated data to the cooperative nodes in each single-hop transmission, whose energy consumption is denoted by  $E_{c0}(k_c, J)$ . (4) The cooperative nodes transmit the data to the next cluster head in each single-hop transmission; whose energy consumption is denoted by  $E_{cs}(k_c, J)$ .

### 3.1. $E_s(k_c)$

In order to model  $E_s(k_c)$ , we will first analyze the energy consumption for the source nodes to transmit one bit to the cluster head, denoted by  $E_{bs}(k_c)$ .

Under the assumption of BPSK modulation and AWGN channel with squared power path loss,  $E_{bs}(k_c)$  can be modelled in the same manner as  $E_{bt}(1)$  in Section 2.1(1),

$$\begin{aligned} E_{bs}(k_c) &= -2(1 + \alpha)N_f\sigma^2 \ln(P_b)G_1E[d_{tc}^2]M_l + \frac{P_{ct} + P_{cr}}{B} \\ &= -\frac{1}{\pi k_c}(1 + \alpha)N_f\sigma^2 \ln(P_b)G_1M^2M_l + \frac{P_{ct} + P_{cr}}{B}, \end{aligned} \quad (10)$$

where  $d_{tc}$  is the distance from the node to the cluster head,  $G_1$  is the gain factor at  $d_{tc} = 1$  m. In (10), we use the result in [8] that  $E[d_{tc}^2] = M^2/2\pi k_c$ .

On the other hand, when the number of clusters is  $k_c$ , the average number of members for each cluster is  $\lceil N/k_c \rceil$ . Hence, the total number of bits transmitted to the cluster head for each cluster by each round is  $S_1(k_c) = \lceil N/k_c \rceil F_n P_s$ . Therefore,  $E_s(k_c) = k_c S_1(k_c) E_{bs}(k_c)$ .

### 3.2. $E_r(k_c)$

In this section, we will model the energy consumption in constructing the routing table, denoted by  $E_r(k_c)$ . When the number of clusters is  $k_c$ , the radius of each cluster can be approximated as radius =  $M/\sqrt{\pi k_c}$  [8]. Therefore, the distance between each pair of direct neighboring clusters can be approximated as  $d_{ctoc} = 2\text{radius} = 2M/\sqrt{\pi k_c}$ . We also assume the number of direct neighbors of each cluster is 4. Under the assumption of flat Rayleigh fading channel,  $E_r(k_c)$  can be approximated by [2]

$$\begin{aligned} E_r(k_c) &= k_c R_{ts} R_{bt} \left( (1 + \alpha) \frac{N_0}{P_b} \frac{(4\pi)^2 (2M)^k}{G_t G_r \lambda^2 (\pi k_c)^{k_c/2}} M_l N_f \right. \\ &\quad \left. + \frac{P_{ct} + 4P_{cr}}{B} \right). \end{aligned} \quad (11)$$

### 3.3. $E_{c0}(k_c, J)$

In this section, we will analyze the energy consumption for the cluster head to transmit aggregated data to the cooperative nodes, denoted by  $E_{c0}(k_c, J)$ . When the cluster head broadcasts the data,  $J$  cooperative nodes will receive it. Similar to the analysis of  $E_{bs}(k_c)$ , the energy per bit for this

operation, denoted by  $E_{bc0}(k_c, J)$ , can be described by

$$E_{bc0}(k_c, J) = -\frac{1}{\pi k_c}(1 + \alpha)N_f\sigma^2 \ln(P_b)G_1M^2M_l + \frac{P_{ct} + JP_{cr}}{B}. \quad (12)$$

We adopt the aggregation model in [9] to describe the aggregation operation. The amount of data after aggregation for each round is  $S_2(k_c) = S_1(k_c)/(\lceil N/k_c \rceil \text{Pagg} - \text{agg} + 1)$ , where  $\text{agg}$  is the aggregation factor. Therefore,  $E_{c0}(k_c, J) = k_c S_2(k_c) E_{bc0}(k_c, J)$ .

### 3.4. $E_{cs}(k_c, J)$

According to Section 2.1,  $J$  cooperative nodes of the current cluster will encode and transmit the transmission sequence according to the orthogonal STBC to the cluster head. In modelling the energy consumption of such operation, we need to consider the impacts of training overhead and transmission rate. Suppose that the block size of the STBC code is  $F$  symbols and in each block we include  $pJ$  training symbols, and the block will be transmitted in  $L$  symbols duration.  $F/L$  is called the transmission rate, denoted by  $R$ . Then, the actual amount of data to transmit the  $S_2(k_c)$  bits is  $S_e(k_c, J) = FS_2(k_c)/R(F - pJ)$ . Therefore,  $E_{cs}(k_c, J)$  can be described by

$$\begin{aligned} E_{cs}(k_c, J) &= S_e(k_c, J) \left( (1 + \alpha) \frac{JN_0}{P_b^{1/J}} \frac{(4\pi)^2 (2M)^k}{G_t G_r \lambda^2 (\pi k_c)^{k/2}} M_l N_f \right. \\ &\quad \left. + \frac{JP_{ct} + P_{cr}}{B} \right). \end{aligned} \quad (13)$$

Based on the above analysis, the overall energy consumption in each round,  $E(k_c, J)$  can be described as

$$E(k_c, J) = E_s(k_c) + E_r(k_c) + \bar{n}_k E_{c0}(k_c, J) + \bar{n}_k E_{cs}(k_c, J), \quad (14)$$

where  $\bar{n}_k$  is the average number of hops. In order to simplify the analysis, we assume  $\bar{n}_k = \sqrt{k_c}$ , which is just the number of clusters along each edge of the sensed region.

Based on (14), we can formulate the optimization model to choose the optimal  $k_c$  and  $J$  as

$$(k_c^*, J^*) = \text{argmin} E(k_c, J) \quad \text{s.t.} \quad J \leq 10, k_c \leq \frac{N}{3}, \quad (15)$$

where the first constraint comes from the fact that more cooperative nodes will not improve the transmission energy efficiency but cost much circuit energy, and the rationale behind the second constraint is that the size of the cluster should not be too small to make efficient aggregation. Since the search space is not large, we can use exhaustive search method to solve (15).

## 4. SIMULATION RESULTS

In the simulations, 400 nodes are randomly deployed on a  $200 \times 200$  field. The location of the sink is randomly chosen

TABLE 1: The system parameters.

$\alpha = 0.4706$	$M_l = 40$ dB	$G_1 = 30$ dB
$k \in [3, 5]$	$\sigma^2 = \frac{N_0}{2} = -134$ dBm/Hz	$N_f = 10$ dB
$f_c = 2.5$ GHz	$B = 20$ kHz	$P_b = 10^{-3}$
$P_{ct} = 98.2$ mw	$P_{cr} = 112.6$ mw	$F_n = 2$
$G_t G_r = 5$ dBi	$s = 2$ kbits	$P = 0.8$
$R = 0.75$	$F = 200$	$p = 2$
$R_{bt} = 5$	$R_{ts} = 100$	

in each round. The system parameters are summarized in Table 1.

The meanings of the entries in Table 1 are summarized as follows.  $\alpha$  is the efficiency of the RF power amplifier,  $M_l$  is the link margin,  $G_1$  is the gain factor at  $1m$ ,  $k$  is the path loss,  $\sigma^2$  is the power density of the AWGN channel in the intracluster communication,  $N_f$  is the receiver noise figure,  $f_c$  is the carrier frequency,  $B$  is the bandwidth,  $P_b$  is the desired BER performance,  $P_{ct}$  and  $P_{cr}$  are the circuit power consumption of the transmitter and receiver, respectively,  $F_n$  is the number of frames per round,  $G_t, G_r$  are the antenna gains of the transmitter and receiver,  $s$  is the packet size,  $P$  is the transmit probability of each node,  $R$  is the transmission rate,  $F$  is the number of symbols in each block,  $p$  is the number of required training symbols for each cooperative node,  $R_{bt}$  is the times for exchanging the routing table for each round, and  $R_{ts}$  is the routing table size.

To simulate the phenomena of radio irregularity, the path loss of the communication between each pair of nodes is distributed randomly from 3 to 5.

Each node begins with 400 J of energy and an unlimited amount of data to send to the sink. When the nodes use up their limited energy during the course of the simulation, they can no longer transmit or receive data.

During the simulation, we tracked the overall number of packets transferred to the sink, the amount of energy and duration required to get the data to the sink, and the percentage of nodes alive. We are interested in the transmission quality and energy saving performance of the proposed scheme. The performance of the proposed multi-hop MIMO-LEACH scheme is compared with the original LEACH and the multi-hop LEACH scheme, in which cooperative MIMO communications is not implemented. The optimal value of  $k_c$  for the original LEACH is determined by the model in [8]. We also develop a similar model to find the optimal  $k_c$  for the multi-hop LEACH scheme, which will not be discussed here due to the limited space. In the investigated scenario, it is found that the optimal  $k_c$  for the original LEACH protocol, the multi-hop LEACH scheme, and the proposed scheme are 3, 41, and 27, respectively. The optimal  $J$  for the proposed scheme is found to be 3.

Due to the aggregation operation, the number of effective received packets by sink [8] is a good application-independent indication of the transmission quality. The

effective received packets refer to the “real” packets represented by the aggregated packets. If no aggregation carries out, the number of effective received packets equals to the number of actual received packets. If the aggregation operation in transmission is *information lossless*, the number of effective received packets is just the number of total packets transferred by the source nodes.

Figures 2 and 3 show the total number of effective packets received at the sink over time and the total number of effective packets received at the sink for a given amount of energy.

Figure 2 shows that during its lifetime the LEACH protocol can obtain better latency performance compared to the multi-hop LEACH scheme and the proposed MIMO-LEACH scheme. The reason is that the multi-hop operation in the multi-hop LEACH scheme and the multi-hop MIMO-LEACH scheme will increase the latency, and thus result in a less number of data packets sent to the sink for a given period of time. However, the better latency performance of the LEACH protocol comes from the more energy consumption compared to the other two schemes. Especially, in the fading channel environment, LEACH protocol will consume much more energy due to its single-hop transmission from the cluster heads to the sink, which will result in less network lifetime and less total number of transmitted packets. Figure 3 shows that, with the same amount of energy consumption, the multi-hop MIMO-LEACH scheme can transmit much more data packets compared to the LEACH protocol and the multi-hop LEACH scheme. From these simulation results, we can find that the multi-hop MIMO-LEACH scheme is more suitable for the application scenario which has large requirements on network lifetime but little requirements on latency.

Figure 4 shows the percentage of nodes alive over time. From Figure 4, we can find that the proposed multi-hop MIMO-LEACH scheme can improve the network lifetime greatly. If we define the network lifetime of WSN as the duration of more than 70% of network nodes are alive, then we can observe that the network lifetime of WSN with the original LEACH protocol, the multi-hop LEACH scheme, and the proposed multi-hop MIMO-LEACH scheme is about  $0.7 \times 10^4$ ,  $8.2 \times 10^4$ , and  $11 \times 10^4$  s. The improvement on network lifetime obtained by the multi-hop MIMO-LEACH scheme is significant.

However, the percentage of nodes alive over time is not always a good indication to the energy saving performance of a protocol. For example, during the same time, one protocol transmits less packets than other protocols. Then, though the energy saving performance of the protocol is worse than other protocols, it will still consume less energy. In order to further investigate the energy saving performance, we also simulate the performance in terms of the percentage of nodes alive per amount of effective data packets received at the sink, which is shown in Figure 5.

From Figure 5, we find that the proposed multi-hop MIMO-LEACH scheme needs significantly less energy to transmit the same amount of data packets. Therefore, the

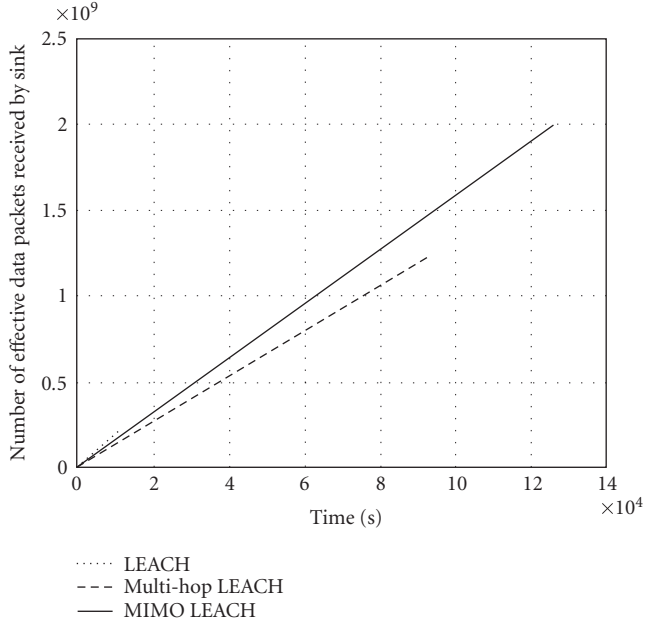


FIGURE 2: Total amount of effective packets received at the sink over time.

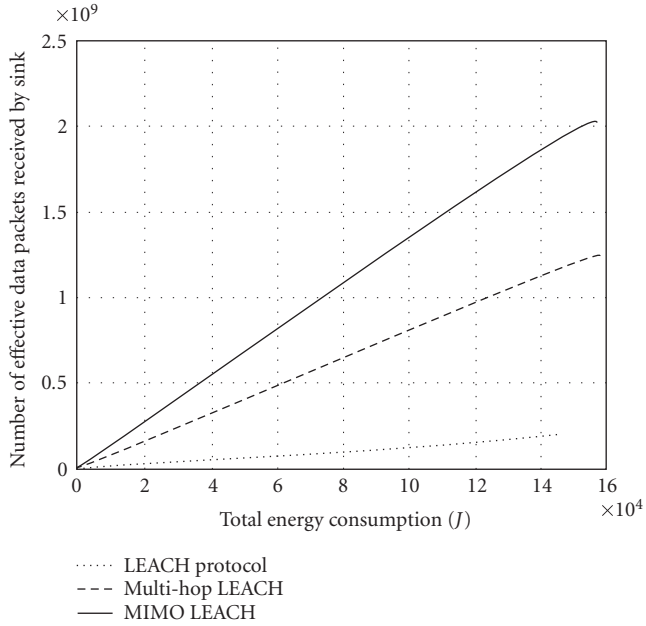


FIGURE 3: Total amount of effective packets received at the sink per given amount of energy.

improvement on network lifetime obtained by the multi-hop MIMO-LEACH scheme is significant.

On the other hand, the impacts of the parameters, including the number of cluster heads  $k_c$  and the number of cooperative nodes  $J$ , are also investigated in the simulation. Figures 6 and 7 show the percentage of nodes alive over time in different settings of  $k_c$  and  $J$ .

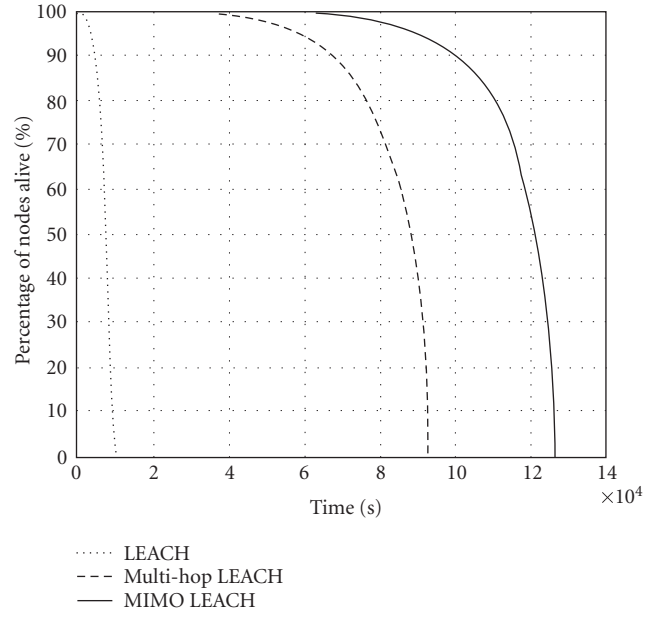


FIGURE 4: Percentage of nodes alive over time.

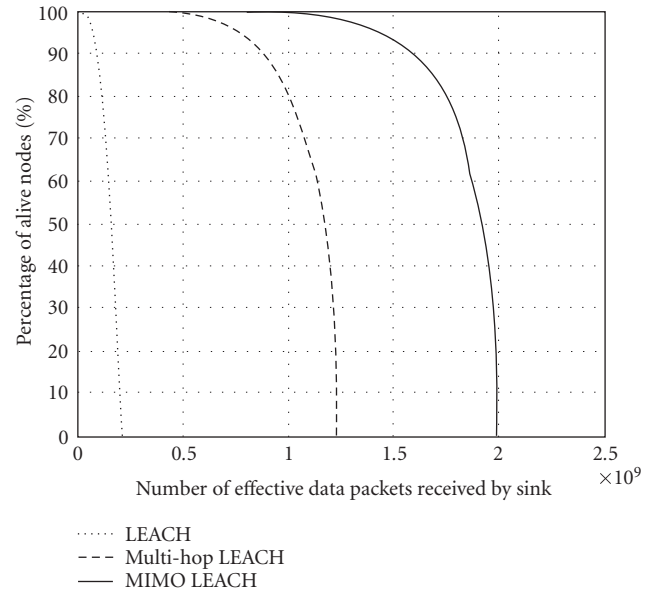


FIGURE 5: Percentage of nodes alive per amount of effective data packets received at the sink.

From the simulation results including those shown in Figures 6 and 7, we can find that the energy saving performance of the proposed scheme is impacted by the parameters. As for the number of cluster heads, too many cluster heads will reduce the distance for each single hop transmission, which will reduce the transmit energy consumption. More cluster heads will also generate a larger search space

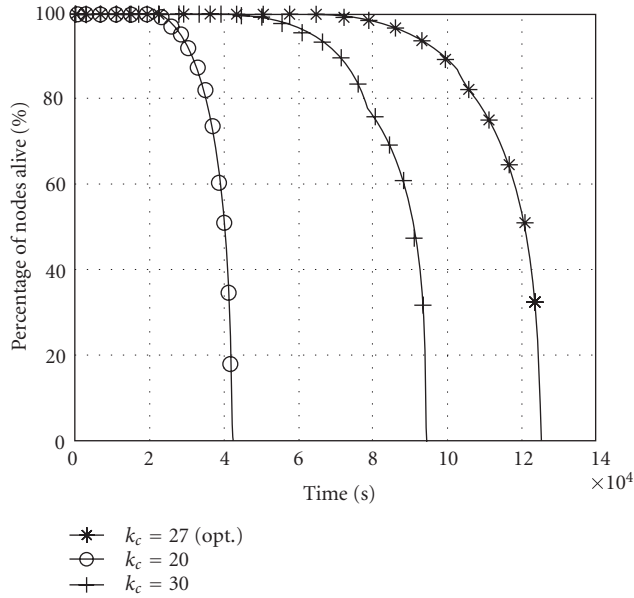


FIGURE 6: The impact of the number of cluster heads on energy saving performance.

for the routing table construction, which will also reduce the transmit energy consumption further. However, more cluster heads will result in more number of hops in transmission to the sink, which will consume more circuit energy for relaying the data packets. Therefore, the number of cluster heads should be chosen by trading off the transmit energy consumption and circuit energy consumption. As for the number of cooperative nodes, a certain number of cooperative nodes can form the effective independent multipath transmission so as to energy-efficiently combat the fading effects. However, too many cooperative nodes will result in large circuit energy consumption, which will cause large overall energy consumption. Therefore, the number of cooperative nodes should also be chosen to trade off the transmit energy consumption and the circuit energy consumption.

## 5. CONCLUSION

In this paper, we proposed a cluster based cooperative MIMO scheme to reduce energy consumption and prolong the network lifetime. A cooperative MIMO scheme is adopted to mitigate the adverse impacts of fading while clustering is used to facilitate network control and coordination. In the proposed scheme, the original LEACH protocol is extended by incorporating the cooperative MIMO communications and multi-hop routing. An adaptive cooperative nodes selection strategy is also designed. Based on the scheme, we investigated the energy consumption of each operation. Then, the overall energy consumption model of the scheme is developed, and the optimal parameters of the scheme are found such as the number of clusters and the number of cooperative nodes. Simulation results exhibit that the proposed scheme minimizes energy consumption.

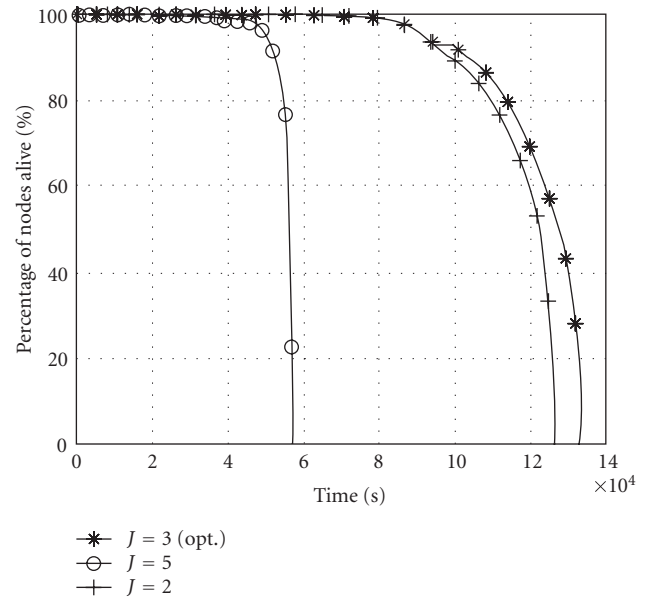


FIGURE 7: The impact of the number of cooperative nodes on energy saving performance.

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