Load-Balanced Cluster-Based Cooperative MIMO Transmission for Wireless Sensor Networks

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***Abstract*— Remote environmental surveillance by massively deployed tiny wireless sensors requires energy efficient communication and network protocols so as to prolong the network lifetime. A load-balanced cluster-based cooperative MIMO (multiple-in-multiple-out) transmission scheme for such wireless sensor networks is proposed, taking imperfect data aggregation into consideration. In this scheme, a two-layer hierarchy is formed by clustering, and the cluster heads perform local data aggregation, balance communication loads and transmit data back to the base station using cooperative MIMO techniques. Simulation results show that the proposed scheme can distribute the energy dissipation more evenly throughout the network and achieve higher energy efficiency, which leads to a longer network life span compared with other traditional schemes.**

I. Introduction

In many application scenarios of wireless sensor networks (WSNs), the sensor node can only be equipped with a limited power source which is difficult to be replenished. Therefore, improving energy efficiency so as to maximize the network lifetime is a constant design goal for energy-constrained WSNs.

Recent research on MIMO techniques shows great potential to increase the channel capacity and reduce transmission energy consumption in fading channels [1]. Energy efficiency of MIMO techniques in sensor networks has been analyzed and cooperative MIMO transmission schemes for WSNs have been proposed in [2]–[9]. In [2], Cui *et al.* proposed a cooperative MIMO scheme using Alamouti codes for WSNs and analyzed its energy efficiency. In [3], the effect of additional training overhead required by such cooperative MIMO system is studied. Li proposed a delay and channel estimation scheme without transmission synchronization for decoding of cooperative MIMO communications in [4]. Further analysis of energy efficiency of cooperative MIMO transmission with data aggregation is presented in [5]. Besides, Li *et al.* [6] also proposed a STBC-encoded cooperative transmission scheme for WSNs with low overhead.

However, [2]–[5] only focused on energy efficiency of cooperative transmission between two clusters of sensors or between one cluster of sensors and one receiver. How to effectively incorporate cooperative MIMO transmission into WSNs with a large number of wireless sensor nodes under application-specific scenarios to prolong the network lifetime remains unconsidered. Besides, although [6] proposed ways to incorporate cooperative transmission in LEACH [7], the assumption of perfect data aggregation based on ideal data correlation is not practical in most applications [8].

In this paper, we propose a new load-balanced cluster-based cooperative MIMO transmission scheme for remote environment surveillance WSNs that are typical for both civil and military applications. Without perfect data aggregation, we establish a two-layer hierarchy in the network based on clustering, and let cluster heads balance communication loads among themselves and transmit cooperatively to the base station (BS). Simulation results show that the proposed scheme can effectively prolong the network lifetime compared with LEACH and LEACH with cooperative transmission [6].

The rest of the paper is organized as follows. In Section II, the system model is described. In Section III, disadvantages of LEACH with cooperative transmission are analyzed, and then we introduce a new cooperative transmission scheme. The simulation and analysis are presented in Section IV. Finally, Section V concludes the paper.

II. System Model

A typical application that sensor networks support is the monitoring of a remote environment. Without loss of generality, we use the same assumptions about the sensor nodes and the network model as in LEACH. All sensor nodes are homogeneous and energy-constrained, and each can transmit its data to any other node and the BS. Besides, each node uses power control to vary the transmission power, and has enough computational power to perform different MAC protocols and other signal processing functions. The nodes are randomly deployed on a field and each node periodically sends the data back to the BS. Nodes that are in close proximity to each other have correlated data. The BS is fixed without energy constraint and located far from the sensors.

Regarding the data aggregation, we make a change in the assumptions used by [6], [7]. As discussed in [9], the number of cluster members in LEACH diverses greatly, which leads to a wide spread of packet numbers that are aggregated in different clusters at different time. LEACH assumed perfect beamforming data aggregation, where data are perfectly correlated, such that an arbitrary number of packets within a cluster can be compressed to one single packet, i.e., regardless of the

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amount and the correlation level of raw data, the aggregated data amount is constant. However, practically the performance of data aggregation is closely related to the various levels of data correlation [8]. Therefore, instead of perfect data aggregation, we assume that the amount of resulting aggregated data is proportional to the total amount of raw data.

In the energy consumption model, a general communication model which is the same as in [2], [3], [5] is used. The total energy consumptions are divided into the power consumptions of the power amplifiers P_{PA} and other circuits power consumptions. P_{PA} can be approximated as

$$P_{PA} = (1 + \alpha)P_{out}, \tag{1}$$

where $\alpha = \frac{\xi}{\eta} - 1$ with η being the drain efficiency of the RF power amplifier and ξ being the Peak to Average Ratio (PAR), which is dependent on the modulation scheme and the associated constellation size. P_{out} is the transmit power, and the definition can be found in [2], [3], [5]. The multiquadrature amplitude modulation (MQAM) is assumed, and the optimal constellation size is used according to the different communication distance to minimize the total communication energy.

As discussed in [2], we estimate the circuit power consumptions of the transmitter and the receiver respectively as

$$P_{ct} = P_{mix} + P_{syn} + P_{filt} + P_{DAC}, \tag{2}$$

$$P_{cr} = P_{mix} + P_{syn} + P_{LNA} + P_{filt} + P_{IFA} + P_{ADC}, \tag{3}$$

where P_{mix}, P_{syn}, P_{filt}, P_{DAC}, P_{LNA}, P_{IFA}, P_{ADC} are the power consumption values of the mixer, the frequency synthesizer, the active filters, the D/A converter, the low noise amplifier, the intermediate frequency amplifier and the A/D converter, respectively.

Then, the energy consumption per bit for the transmitter and the receiver can be formulated respectively as

$$E_{bt} = \frac{P_{PA}/M_t + P_{ct}}{R_b}, \tag{4}$$

$$E_{br} = \frac{P_{cr}}{R_b}. \tag{5}$$

where M_t is the number of virtual transmitter antennas, i.e., the number of cooperative transmission nodes, and R_b is the transmission bit rate.

III. New Load-Balanced Cluster-Based Cooperative Transmission Scheme

In [6], Li *et al.* proposed ways to incorporate cooperative MIMO techniques in LEACH to extend the network life span. The main idea in their scheme named *LEACH with cooperative transmission* is that after cluster formation, each cluster head selects the cooperative nodes in its cluster and transmit cooperatively. However, there are several drawbacks in such an approach. First, although LEACH ensures that each node becomes the cluster head exactly once within $1/P$ rounds, where P is the preset percentage of cluster heads, the chance of being selected as a cooperative node varies widely. Second, without perfect data aggregation, the volume of data that each cluster transmits also varies widely [9]. Based on these two factors, the data volume that each node transmits to the BS is location-dependent and varies widely. As a result, the energy does not dissipate evenly in the network, which adversely affects the network life span. Moreover, since the number of cluster members is a random variable, it is possible that there exists cluster head without cluster members, especially when P is high. In such situation, the cluster head can only use SISO scheme to transmit all its data directly to the BS, which consumes rather more energy than cooperative MIMO transmission especially when the BS is far away. In the following paper, we denote *LEACH with cooperative transmission* as *C-LEACH*.

In order to further prolong the network lifetime, a load-balanced scheme with reliable cooperative transmission is desired. As shown in Fig. 1, we adopt the cluster-based scheme and let cluster heads intelligently exchange data to balance communication loads and transmit cooperatively. The transmission procedure can be divided into six phases:

A. Cluster Head Advertisement

In this phase, each node decides whether to become a cluster head for the current round by a distributed algorithm. Each self-selected cluster head then broadcasts an advertisement message. This phase is the same as LEACH.

B. Cluster Set Up

In this phase, each non-cluster head node chooses one with the strongest received signal strength of the advertisement as its cluster head, and transmits a join-request message back to the chosen cluster head. The information about the node's capability of being a cooperative node, e.g., its current energy status is added into the message.

C. Schedule Creation

In this phase, each cluster head creates a TDMA schedule and broadcasts this schedule to its cluster members. This ensures that there are no collisions among data messages and allows the radio of each non-cluster head node to be turned off until its allocated transmission time to save energy.

D. Intra-cluster Transmission and Data Aggregation

In this phase, the non-cluster head node sends its packets to the cluster head, and then the cluster head performs data aggregation. At this point, each cluster head knows the volume of data it needs to transmit to the BS.

E. Data Volume Advertisement

This phase is for the cluster heads to inform each other about their data volume by broadcasting a short message that contains the node's ID and the volume of data it needs to transmit. All the messages are recorded by each cluster head. Besides, according to the received signal strength of the advertisement, each cluster head can estimate the distances to all other cluster heads and then records these information.

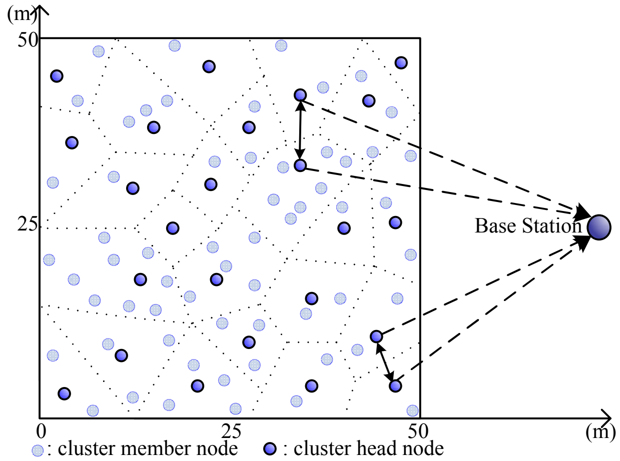

Fig. 1. Illustration of the new load-balanced cluster-based cooperative transmission scheme for wireless sensor networks

F. Data Exchange and Cooperative Transmission

In this phase, cluster heads exchange data and transmit cooperatively. We first give a multiple-in-single-out (MISO) scheme based on 2×1 Alamouti codes as an example. Schemes with more than two virtual antennas will be discussed later.

In the 2×1 virtual MISO case, each cluster head gets paired with another cluster head. They exchange data and transmit cooperatively. If the number of cluster heads is odd, one of the cluster heads selects a cooperative node within its own cluster. The detailed steps are as follows:

1) Sorting and Division: Assuming that there are k cluster heads in the current round, their IDs form a sequence $< h_1, h_2, \cdots, h_k >$, where $h_i \in G, i = 1, 2, \cdots, k$ and G is the set of cluster head nodes' IDs in the current round. We denote the volume of data of cluster head h_i as $HData\left(h_i\right), i = 1, 2, \cdots, k$. Every cluster head sorts $< h_1, h_2, \cdots, h_k >$ by $HData\left(h_i\right)$ and gets a reordered sequence $< h'_1, h'_2, \cdots, h'_k >$ such that $HData\left(h'_1\right) \le HData\left(h'_2\right) \le \cdots \le HData\left(h'_k\right)$. According to the reordered sequence, the set G is divided into two sets G_1 and G_2, where when k is even, G_1 consists of $\{h'_1, h'_2, \cdots, h'_{k/2}\}$ and G_2 consists of $\{h'_{k/2+1}, h'_{k/2+2}, \cdots, h'_k\}$, or when k is odd, G_1 consists of $\{h'_1, h'_2, \cdots, h'_{(k-1)/2}\}$ and G_2 consists of $\{h'_{(k+1)/2+1}, h'_{(k+1)/2+2}, \cdots, h'_k\}$. Note that if k is odd, $h'_{(k+1)/2}$ belongs to neither G_1 nor G_2.

2) Cooperative Node Selection and Transmission (skipped when k is even): When k is odd, the cluster head $h'_{(k+1)/2}$ will choose one cooperative node with minimal d_i/E_i in its cluster, where E_i is the energy status reported by node i and d_i is the distance between node i and the cluster head.

The cluster head $h'_{(k+1)/2}$ informs the selected cooperative node by broadcasting a short message containing the cluster head's ID, the selected node's ID and an approximate transmission time T that this pair needs to transmit data to the BS. T can be estimated by the data volume $HData\left(h'_{(k+1)/2}\right)$ and the cooperative transmission overhead. Upon receiving the message, all nodes except this pair of nodes can turn off their radio components to save energy. The cluster heads should wake up after time T, and other non-cluster head nodes can remain in the sleep state till the next round.

On the other hand, $h'_{(k+1)/2}$ sends its data to the selected cooperative node, and they encode the transmission data according to 2×1 Alamouti codes and transmit the data to the BS cooperatively. Once the transmission ends, these two nodes can go into the sleep state till the next round.

3) Cluster Head Nodes Pairing and Cooperative Transmission: In this step, each cluster head gets paired with another cluster head by the criteria that loads are well balanced in the network and simultaneously communication energy consumptions of data exchanges are as small as possible.

When k is odd, each cluster head h'_i, $i = (k+1)/2 + 1, (k+1)/2 + 2, \cdots, k$ in G_2 selects its cooperative node h'_j, $j = 1, 2, \cdots, (k-1)/2$ in G_1 by

$$\min_{p} \left[HData\left(h'_i\right) + HData\left(h'_j\right)\right] \times d^2_{h'_i h'_j}, \tag{6}$$

where p means $h'_j \in G_1$ and h'_j has not been selected before, and $d_{h'_i h'_j}$ is the distance between cluster head h'_i and h'_j.

This selection procedure is carried out from h'_k whose data volume $HData\left(h'_k\right)$ is the largest in G_2 to $h'_{(k+1)/2+1}$ whose data amount $HData\left(h'_{(k+1)/2+1}\right)$ is the smallest in G_2. At the beginning, h'_k selects its cooperative node h'_j in G_1 and broadcasts a message informing the selected node. The message contains the cluster head's ID h'_k, the selected cluster head's ID h'_j and the transmission time T which can be estimated by the total data volume of h'_k and h'_j and other cooperative transmission overhead. All the cluster heads in G_2 keep a record about the selected cluster head's ID, since this node should not be chosen as the cooperative node again. Besides, all the cluster heads except h'_k and h'_j can fall asleep and wake up in time T. On the other hand, h'_k and h'_j exchange their data, encode the data according to the 2×1 Alamouti codes and transmit the data to the BS cooperatively. Then, these two cluster heads can fall into the sleep state till the next round. After this pair finishes their transmission, other cluster heads will wake up. Then h'_{k-1} and its selected cooperative node in G_1 will perform the same transmission procedure. Such procedure is carried out pair by pair until $h'_{(k+1)/2+1}$ and its cooperative node finish the transmission.

When k is even, this step follows the Sorting and Division directly and the procedure is the same as described above.

Such 2×1 MISO scheme can be modified to support a virtual MIMO scheme with more than two antennas. Assuming that J nodes perform cooperative transmission together, where J can be more than two, we can divide G into $G_1, G_2, \cdots, G_J$ after sorting such that for cluster head $h'_i \in G_i$ and $h'_j \in G_j$, $HData\left(h'_i\right) \le HData\left(h'_j\right)$ where $i < j$. Then cluster head $h'_{k_J} \in G_J$ selects $J-1$ cooperative nodes $h'_{k_1}, h'_{k_2}, \cdots, h'_{k_{J-1}}$ from $G_1, G_2, \cdots, G_{J-1}$ respectively by

$$\min_{p} \left[HData\left(h'_{k_J}\right) d^2_{J\max} + \sum_{i=1}^{J-1} HData\left(h'_{k_i}\right) d^2_{i\max}\right], \tag{7}$$

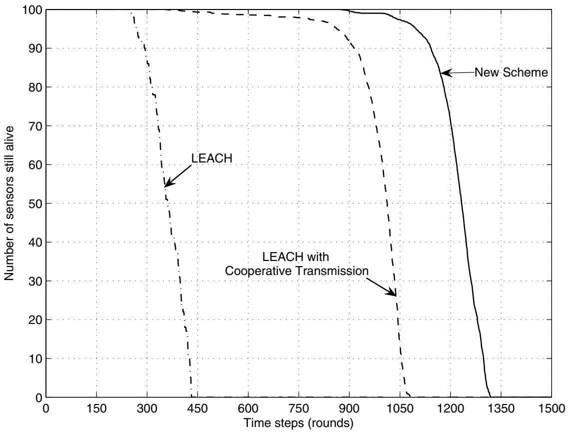

Fig. 2. Network lifetime using LEACH, C-LEACH (LEACH with cooperative transmission) and the new scheme with $15J$/node and $\gamma = 5\%$

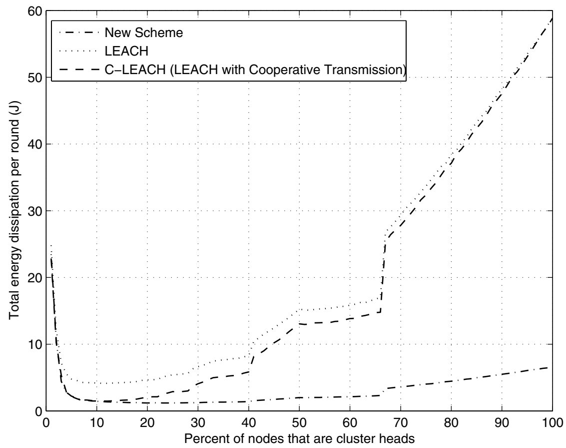

Fig. 3. The total energy dissipated in the network per round versus the percent of nodes that are cluster heads with $\gamma = 5\%$

where p means $h'_{k_i} \in G_i, i = 1, \cdots, J-1$ and h'_{k_i} has not been selected before, and $d_{i\max} = \max\{d_{h'_{k_j} h'_{k_i}}\}, j = 1, \cdots, i-1, i+1, \cdots, J$. These J cluster heads broadcast their data to each other and transmit cooperatively. Let the number of cluster heads $k = lJ + m$, where l and m are integers and $0 \leq m \leq J-1$. If $m = 0$, we can use the scheme described above directly. Otherwise, there exists one more set G_0 which consisted of m elements. These m cluster heads are located in the middle of the sorted sequence, and all the cluster heads in G_0 will perform cooperative transmission.

IV. Simulation and Analysis

A. Simulation Setup

We use the similar network settings as in [6], [7]. As Fig. 1 shows, 100 sensors are randomly deployed on a 50×50 field, and the BS is located at $(300, 25)$. Each sensor with initial energy $15J$ produces a 2000-bit packet in a round. Frequency-flat Rayleigh fading channels with additive white Gaussian noise (AWGN) and squared power path loss are assumed, and the 2×1 Alamouti MISO cooperative transmission system [2] is used. Other system parameters are the same as in [2], [5]. We compare LEACH, C-LEACH and the newly proposed scheme when the compression ratio γ is 5%, 15% and 25% respectively. γ related to the level of data correlation means that the cluster head compresses the collected data to γ of its original size, where $0 < \gamma \leq 100\%$.

TABLE I
THE NETWORK LIFETIME (ROUNDS) OF DIFFERENT SCHEMES

Compression Ratio γ	Protocol	FND	HNA	LND
5%	LEACH	253	361	432
	C-LEACH	353	1012	1081
	New Scheme	875	1232	1320
15%	LEACH	87	157	201
	C-LEACH	354	748	804
	New Scheme	640	813	889
25%	LEACH	46	98	140
	C-LEACH	323	594	647
	New Scheme	511	605	666

B. Optimum Percentage of Cluster Heads

The desired percentage of cluster heads P is crucial to the network lifetime. Fig. 3 shows the total energy dissipated per round in the three schemes as the percentage of cluster heads varies from 1% to 100%. When P is too small, the non-cluster head nodes often have to transmit data very far to reach the cluster heads. Moreover, the number of packets received by different cluster heads may vary widely leading to uneven energy dissipation. On the other hand, when P increases, the probability that cluster heads have no cluster members gets higher. As a result, there is not much local data aggregation because cluster heads with no cluster members can not find redundant data which only exists among packets with correlated data. Besides, for C-LEACH, energy consumption increases when P gets higher due to SISO transmission used by cluster heads without cluster members as cooperative nodes. As shown in Fig. 3, the optimum P for LEACH, C-LEACH and the new scheme is 10%, 10% and 25% respectively. Besides, we also notice that the optimum P hardly changes when γ varies from 5% to 25%. These schemes are compared under their optimized parameters.

In addition, Fig. 3 indicates that when P varies, in almost all cases, LEACH consumes the most energy in a round while the new scheme consumes the least. Particularly, when P is large, the new scheme is much more energy efficient than the other two schemes due to the cooperative transmissions performed by pairs of cluster heads.

C. Simulation Results

As Fig. 2 shows, the new scheme can effectively extend the network life span over LEACH and C-LEACH. When the value of γ varies, TABLE I shows that by the metric FND (First Node Dies), HNA (Half of the Nodes Alive) and LND (Last Node Dies) [10], the new scheme outperforms the other two schemes in terms of lifetime in all situations.

TABLE II

TOTAL ENERGY DISSIPATED PER ROUND IN THE WHOLE NETWORK

Compression Ratio γ	Protocol	Total Energy Dissipation $(J/round)$
5%	LEACH	4.17
	C-LEACH	1.49
	New Scheme	1.21
15%	LEACH	10.05
	C-LEACH	2.02
	New Scheme	1.84
25%	LEACH	15.92
	C-LEACH	2.54
	New Scheme	2.55

Particularly, when γ is 5% , compared with C-LEACH, the new scheme improves the network lifetime by 147.88%, 21.74% and 22.11% using the metrics FND, HNA and LND, respectively. We analyze these schemes from two aspects:

First, we compare the total energy consumptions of different schemes per round. As TABLE II indicates, the new scheme and C-LEACH are much more energy-efficient than LEACH, due to cooperative MIMO techniques. The new scheme costs less energy than C-LEACH when γ is less than 25%, and when γ is more than 25%, energy consumptions of these two schemes are approximately the same.

TABLE III

THE STATISTICAL RESULTS OF DATA AMOUNT THAT 100 NODES TRANSMIT TO THE BS IN 1000 ROUNDS

Compression Ratio γ	Statistical Results	C-LEACH	New Scheme
5%	$mean(data)$	101.87	161.03
	$std(data)$	35.97	16.83
	$\frac{std(data)}{mean(data)}$	35.31%	10.45%
15%	$mean(data)$	301.51	354.53
	$std(data)$	114.04	11.65
	$\frac{std(data)}{mean(data)}$	37.82%	3.29%
25%	$mean(data)$	501.07	546.36
	$std(data)$	190.69	25.79
	$\frac{std(data)}{mean(data)}$	38.06%	4.72%

Second, as to the energy dissipation of individual node, the new scheme can distribute transmission data loads more evenly throughout the network than C-LEACH. To show this, we eliminate energy constraint of each node so that all nodes are alive during the simulation, and accumulate the amount of data in terms of the number of packets that each node transmits to the BS as cluster heads and cooperative nodes in 1000 rounds. The accumulated data volume that node i transmits in 1000 rounds is denoted as $data_i$, $i = 1, 2, \cdots, 100$. Due to the different location of each node and random cluster formation, $data_i$ is quite different and varies widely. Then we compute the mean and standard deviation of array $< data_1, data_2, \cdots, data_{100} >$, denoted as $mean(data)$ and $std(data)$ respectively. These statistical results are listed in TABLE III. Taking results with $\gamma = 15\%$ as an example, the $mean(data)$ is 301.51 for C-LEACH while it is 354.53 for the new scheme; however, the $std(data)$ are 114.04 and 11.65 respectively. So $std(data)/mean(data)$ are 37.82% and 3.29% respectively, which indicates that the distribution of transmission data loads among all nodes is more uniform for the new scheme than that of C-LEACH. Therefore, the energy dissipates more evenly in the network.

In addition, we change the location of the BS from $(150, 25)$ to $(300, 25)$ and γ from 5% to 30%, the new scheme still performs the best in terms of network lifetime.

V. CONCLUSION

In this paper, we proposed a load-balanced cluster-based cooperative MIMO transmission scheme to improve the energy efficiency and prolong the network lifetime. We incorporate the cooperative MIMO communications into LEACH by letting cluster heads perform as a higher layer network to balance loads among themselves and transmit data to the BS cooperatively. Simulation results show that the new scheme improves the network lifetime significantly compared with LEACH. In addition, due to more even distribution of transmission data loads among cluster heads, the proposed scheme also outperforms C-LEACH (LEACH with cooperative transmission) in terms of network lifetime under different data correlation levels. Particularly, when the compression ratio is 5%, the new scheme prolongs the network lifetime by 147.88%, 21.74% and 22.11% compared with C-LEACH using the metrics FND, HNA and LND respectively.

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