

Research Article

A Cross-Layer Optimization Approach for Energy Efficient Wireless Sensor Networks: Coalition-Aided Data Aggregation, Cooperative Communication, and Energy Balancing

Qinghai Gao,¹ Junshan Zhang,¹ Xuemin (Sherman) Shen,² and Bryan Larish³

¹Electrical Engineering Department, Arizona State University, Tempe, AZ 85287, USA

²Electrical and Computer Engineering Department, University of Waterloo, Waterloo, ON, Canada N2L 3G1

³Space and Naval Warfare Systems Center, 53560 Hull Street, San Diego, CA 92152, USA

Received 29 December 2006; Revised 16 March 2007; Accepted 17 March 2007

Recommended by Jianwei Huang

We take a cross-layer optimization approach to study energy efficient data transport in coalition-based wireless sensor networks, where neighboring nodes are organized into groups to form coalitions and sensor nodes within one coalition carry out cooperative communications. In particular, we investigate two network models: (1) many-to-one sensor networks where data from one coalition are transmitted to the sink directly, and (2) multihop sensor networks where data are transported by intermediate nodes to reach the sink. For the many-to-one network model, we propose three schemes for data transmission from a coalition to the sink. In scheme 1, one node in the coalition is selected randomly to transmit the data; in scheme 2, the node with the best channel condition in the coalition transmits the data; and in scheme 3, all the nodes in the coalition transmit in a cooperative manner. Next, we investigate energy balancing with cooperative data transport in multihop sensor networks. Built on the above coalition-aided data transmission schemes, the optimal coalition planning is then carried out in multihop networks, in the sense that unequal coalition sizes are applied to minimize the difference of energy consumption among sensor nodes. Numerical analysis reveals that energy efficiency can be improved significantly by the coalition-aided transmission schemes, and that energy balancing across the sensor nodes can be achieved with the proposed coalition structures.

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1. INTRODUCTION

Wireless sensor networks have received much attention in recent years because of their great potential in many application domains, including environmental monitoring, target tracking, security, or system control (see [1] and the references therein). Depending on the specific applications, different wireless sensor networks have different traffic patterns. For example, sensors deployed for intrusion detection may only need to send very basic signal to the control center, while sensors monitoring enemy movements may need to send multimedia signals. With the increase of storage space and computing power of sensors, wireless multimedia sensor networks emerge as a very promising technology. One important example of multimedia sensor networks is a surveillance system with video cameras, which has great potential for environmental monitoring, patient care, or security. On the other hand, the multimedia data generated in such settings have a variety of different quality

of service (QoS) requirements such as stringent delay constraints for high data rate video services. Supporting multimedia applications and services puts forth great challenges on the design of wireless sensor networks to meet these QoS demands.

In wireless sensor networks, sensor nodes are often powered by batteries with limited energy. It is difficult, if not impossible, to replace or recharge the batteries in many practical scenarios. As a result, improving energy efficiency is of great importance for the design of wireless sensor networks. For sensor networks supporting multimedia applications, the energy issue becomes even more critical because of possibly larger traffic demand. Thus motivated, in this paper we study two fundamental aspects impacting the network lifetime: *energy saving for data transport* and *energy balancing across sensor nodes*. Simply put, energy saving is concerned with the total energy consumption for transporting data to the sink, and energy balancing is concerned with the difference of energy consumption among sensor nodes.

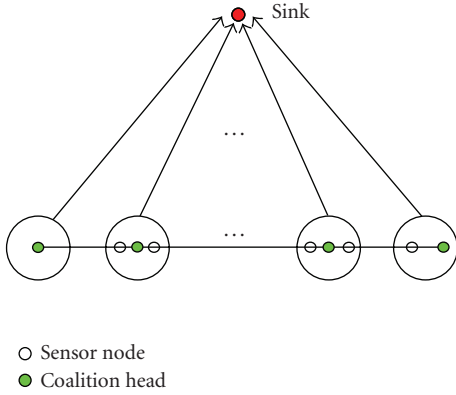


FIGURE 1: A many-to-one sensor network.

The clustering approach has proved to be one of the most effective mechanisms to improve energy efficiency in wireless sensor networks (see, e.g., [2–7]). In a cluster-based sensor network, sensor nodes are organized into groups, each with a cluster head. Traditionally, sensor nodes in a cluster send their data to the corresponding cluster head, and the cluster head forwards the data to the neighboring cluster along the route or to the sink directly. Building on the cluster-based model, we propose a coalition-aided network structure, where sensor nodes within one coalition can carry out cooperative data transmissions. This structure is motivated by the two key features of wireless sensor networks: *node cooperation* and *data correlation*, which differentiate wireless sensor networks from conventional wireless networks. In particular, the coalition head (CH) carries out data aggregation and coordinates the sensor nodes within the coalition, but not necessarily transmits the data itself. We use the term *coalition* instead of cluster to emphasize the cooperation among sensor nodes in a coalition, whereas in a traditional cluster the cluster head performs the bulk of the communication tasks.

We consider two network models in our work, that is, a many-to-one network model and a multihop network model. In a many-to-one network, data from one coalition are transmitted to the sink in one hop (see Figure 1). We propose three schemes for data transmission from each coalition to the sink. In scheme 1, one node in the coalition is selected randomly by the CH to transmit the data, implying that the energy consumption is balanced across the sensor nodes within the coalition. In scheme 2, the sensor node with the best channel condition transmits the data, yielding multiuser diversity gain. In scheme 3, all the sensor nodes within the coalition transmit as a virtual antenna array, so that cooperative diversity gain could be achieved. For the sake of fair comparison, we also take into account the energy consumption for intracoalition communications and channel contention. Our results show that significant energy saving can be achieved by the coalition-aided transmission schemes, and as expected, scheme 3 achieves the best performance.

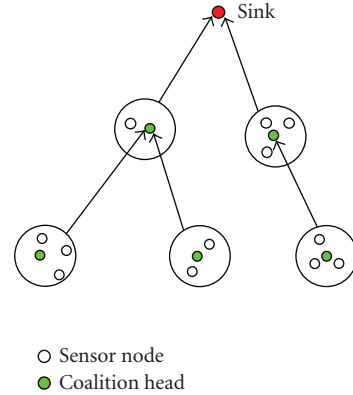


FIGURE 2: A multihop sensor network.

In some practical scenarios, some sensor nodes may not be capable of communicating directly with the sink (e.g., due to limited power), and the data need to be relayed by intermediate nodes to reach the sink. Building on the studies for the single-hop networks, we investigate coalition-based multihop networks, where one coalition sends the data to another along the route until the sink is reached, as illustrated in Figure 2. Besides using coalition-aided data transmission schemes to balance the energy consumption across the sensors within one coalition, we investigate optimal coalition planning, using unequal coalition sizes, to balance the energy consumption across different coalitions. Based on the energy consumption model for intracoalition and intercoalition communications, we treat energy balancing as an optimization problem that is targeted at minimizing the difference of energy consumption among the sensor nodes. To the best of our knowledge, our study is the first work addressing both intracoalition and intercoalition energy balancing issues in wireless sensor networks. In particular, we investigate two types of multihop network models with different traffic patterns. In a Type I network, only part of the sensor nodes have data to transmit and others serve as relays; and in a Type II network, all sensor nodes have data to transmit. Numerical examples and simulations show that energy balancing across the sensor nodes can be achieved with the proposed coalition structures.

Many methods have been developed to improve energy efficiency at individual protocol layers (see, e.g., [3, 8–11] and the references therein). Since energy consumption takes place in all layers, the methods considering layers separately leave much room for improving energy efficiency further from a cross-layer point of view. In particular, we explore the interplay between physical layer, MAC layer, and coalition planning at the routing layer. The formation of coalitions facilitates data aggregation and mitigates channel contention; and the MAC layer transmissions exploit the physical layer channel conditions. For instance, in the scheme with multiuser diversity, the channel state information is used to choose the node with the best channel condition within one coalition for data transmission. In a multihop network, the

data transmission schemes serve as the basis for the optimal coalition planning, which helps to achieve energy balancing across the sensor nodes.

The remainder of this paper is organized as follows. In Section 2 we give a brief review of the related work. Section 3 analyzes the energy efficiency of the coalition-aided data transmission schemes in many-to-one sensor networks. In Section 4, the optimal coalition planning with unequal coalition sizes is investigated for multihop sensor networks. Finally, Section 5 concludes this paper.

2. RELATED WORK

Energy efficiency of wireless sensor networks has received much attention in recent years. In particular, hierarchical protocols, in which sensor nodes are organized into clusters, have been studied extensively (see, e.g., [2–7]). In [3], the authors proposed the LEACH (low energy adaptive clustering hierarchy) protocol, in which a cluster head aggregates data from sensor nodes within the cluster and send the aggregated data directly to the sink. Furthermore, cluster head rotation scheme was proposed such that the role of cluster head is dynamically rotated among sensor nodes. It is shown that LEACH can improve the energy efficiency, at the cost of extra overhead due to dynamic clustering. As an enhancement of LEACH, Younis and Fahmy [7] proposed HEED (hybrid energy-efficient distributed clustering), where the cluster head selection is carried out periodically according to a hybrid of the node residual energy and a secondary parameter such as node proximity to its neighbors or node degree, with the assumption that multiple power levels are available at sensor nodes. It is shown that HEED prolongs network lifetime and achieves a well-distributed set of clusters. Note that in both of the protocols mentioned above, an energy consumption model is assumed such that a fixed amount of energy is needed to transmit one information bit, given the transmit distance. This model does not take into account the time varying channel condition, which can be exploited to adapt the data rate. For instance, given transmission power, if the channel condition is better, the data rate could be larger, and more information bits could be transmitted with certain energy.

Cooperative communication has also been studied in recent years (see, e.g., [12–14]). A survey about cooperative communication can be found in [14], where three cooperative methods, namely detect and forward, amplify and forward, and coded cooperation, are presented. Simply put, distributed sensor nodes can “share” their antennas in a cooperative manner to form a virtual antenna array. In this way, some benefits of MIMO (multiple input multiple output) systems can be achieved. In [12], the authors proposed cooperative MIMO in sensor networks. In their scheme, each node first broadcasts its data to other local nodes and then the nodes encode the transmission sequence according to the Alamouti diversity scheme [15]. They assume that each node has its own data to transmit and the data correlation property of sensor networks is not exploited. It is shown that both energy saving and delay reduction can be achieved.

There have been a number of studies on energy balancing in wireless sensor networks (see, e.g., [3, 16–24]). In [19], the authors proposed and analyzed four strategies that are used to balance the energy consumption of the nodes, including distance variation, balanced data compression, routing, and equalization of the end-to-end reliability. For cluster-based sensor networks, most of the existing studies focus on energy balancing across CHs, assuming that CHs take the full responsibility to forward the data. In [22], the authors proposed the routing-aware optimal cluster planning to achieve the balanced power consumption. The difference of energy consumption among cluster heads is minimized with respect to the clustering profile. Their analytical solutions and simulation results show that energy balancing across the CHs can be improved. In [21], the authors proposed a clustering scheme which takes into account the distances between the sensor nodes and the sink. Accordingly, the clusters close to the base station have smaller sizes than those farther away from the base station. In [23], the authors considered a heterogeneous network where some powerful nodes take on the cluster head role to control network operation, and an unequal clustering approach was proposed to balance the energy consumption of CHs in multihop wireless sensor networks.

3. MANY-TO-ONE SENSOR NETWORKS: COALITION-AIDED DATA TRANSPORT

3.1. System model

Following [25, 26], we consider a one-dimensional network model which consists of N sensor nodes and one sink, and the N sensors are randomly placed on a line of length L (see Figure 1). Based on the positions of sensor nodes, local neighboring nodes form coalitions. Let M be the number of coalitions and n_i the number of sensor nodes in the i th coalition. Then we have $\sum_{i=1}^M n_i = N$.

As is standard in [3], we assume that the distances between the sensor nodes and the sink are much larger than those among sensor nodes, and accordingly, we treat the distances between the sensor nodes and the sink as more or less the same (denoted as d). We assume that all the intracoalition communication channels can be modeled as AWGN (additive white Gaussian noise) channels, and this is applicable to scenarios where there exists strong line of sight (LOS) between neighboring sensor nodes in a densely deployed wireless sensor network. In contrast, we assume the communications between the sensor nodes and the sink undergo Rayleigh fading. We assume that the sink does the network training by broadcasting pilot signals periodically, so that the sensor nodes can estimate the corresponding fading channel gain. We also assume that the channels from different sensor nodes to the sink are independent.

We assume a homogeneous random field, and denote by H_0 the information entropy of each sensor node. In the i th coalition, we define the joint entropy of the n_i sensor nodes as H_i . Note that the number of information bits from different coalitions may be different.

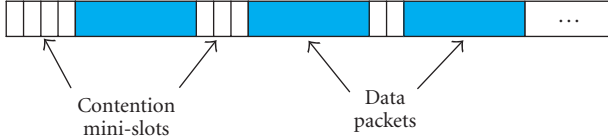


FIGURE 3: CSMA-based random access.

3.2. Coalition-aided data transmission

We assume TDMA (time division multiple access) scheduling for the intracoalition communications, which take place as follows:

- (i) the sensor nodes send their data to the CH in their time slots;
- (ii) the CH carries out data aggregation;
- (iii) the CH broadcasts the aggregated data back to the sensor nodes.

We note that some overhead may be incurred by broadcasting the data back to sensor nodes. However, since this broadcast occurs only over a short distance within a coalition, the overhead is negligible. We elaborate further on this in Section 3.3 where the energy consumption is analyzed.

We assume that the intracoalition communications of different coalitions do not interfere each other. For instance, as proposed in [3], if a unique CDMA (code division multiple access) code is used by sensor nodes within each coalition, then the neighboring coalitions' radio signals would be filtered out and not corrupt the communication in the coalition.

For the data transmissions from the coalitions to the sink, the CHs compete for the channel on behalf of the coalitions. We assume that CSMA (carrier sensing multiple access) based random access scheme is used to reserve the channel, as illustrated in Figure 3. Let the CHs probe the channel in a minislot with probability p . If the pilot packet from one CH is transmitted successfully, then an ACK signal is sent out by the sink and the channel is reserved for the coalition. We assume that the ACK signal can be received by all the sensors within the coalition, so that the data transmission can be triggered in the subsequent time slot. If collisions occur, the CHs would probe the channel again in the next contention minislot.

We study three schemes for data transmissions from the coalition with reservation to the sink. In scheme 1, one of the sensor nodes is selected randomly by the CH to transmit the data. In this scheme, the CH does not have the channel status information between the sensor nodes and the sink, but just aims to balance the energy consumption across the sensors within the coalition. In scheme 2, the sensor node with the best channel condition in the coalition transmits the data. To achieve the multiuser diversity gain, the sensor nodes need to send their channel status information (between the sensor nodes and the sink) to the CH in their time slots, (which can be simply inserted in the header of the data packets,) so that CH can choose the one with the best channel gain to send the data. In scheme 3, all the sensor nodes within the

coalition transmit in a cooperative manner to form a virtual antenna array. In this scheme, the CH also needs the channel conditions between sensor nodes and the sink to apply the transmitter beamforming across the sensor nodes [27, 28]. We illustrate these three schemes by the following example.

Example 1. As illustrated in Figure 4, there are three sensor nodes in the coalition. The channel gains in a given time slot are assumed to be $g_1 < g_2 < g_3$. The solid line indicates the data transmission from the corresponding sensor node. In scheme 1, node A is chosen “unfortunately” although it has the worst channel condition. In scheme 2, node B is chosen because it has the best channel gain g_3 . All three sensor nodes transmit the data to the sink in scheme 3.

We observe that there are benefits from at least three perspectives in a coalition-based sensor network. First, data aggregation can be carried out for the data from sensor nodes within one coalition since the data collected by neighboring nodes are typically correlated. That is, the amount of total information to be transmitted to the sink is less than that in the noncoalition case. Second, after the formation of a coalition, the coalition behaves as one metanode to communicate with the sink, and as a result, the channel contention is reduced significantly. Third, the sensor nodes within one coalition could transmit the data to the sink in a cooperative manner such that cooperative diversity gain can be achieved [14].

Needless to say, intracoalition communications are needed to carry out coalition-aided data transmissions. Specifically, channel conditions of nodes within one coalition are needed for the multiuser diversity scheme and the cooperative diversity scheme, which would incur additional message passing. Then, a natural question to ask is how much net gain the coalition-aided data transmission schemes yield, and that is the main subject of this section. In the following, we analyze the energy consumption of the proposed data transmission schemes, and compare them with the noncoalition case and the traditional cluster scheme where the CHs take the responsibility to transmit the data to the sink.

3.3. Energy consumption analysis

In what follows, we analyze the energy consumption corresponding to three parts, namely the intracoalition communications, the channel contention, and the data transmissions from coalitions to the sink.

3.3.1. Intracoalition communications

We first examine the cost of intracoalition communications. Recall that we assume an AWGN channel model and the TDMA mechanism for intracoalition communications. Each node transmits with fixed power P_t . In the i th coalition, the $n_i - 1$ sensor nodes send their information of H_0 bits to the CH and the CH broadcasts back the H_1 bits to the sensor nodes. As a result, the intracoalition communications involve totally n_i transmissions. Let R_0 be the data rate between sensor nodes and the CH.

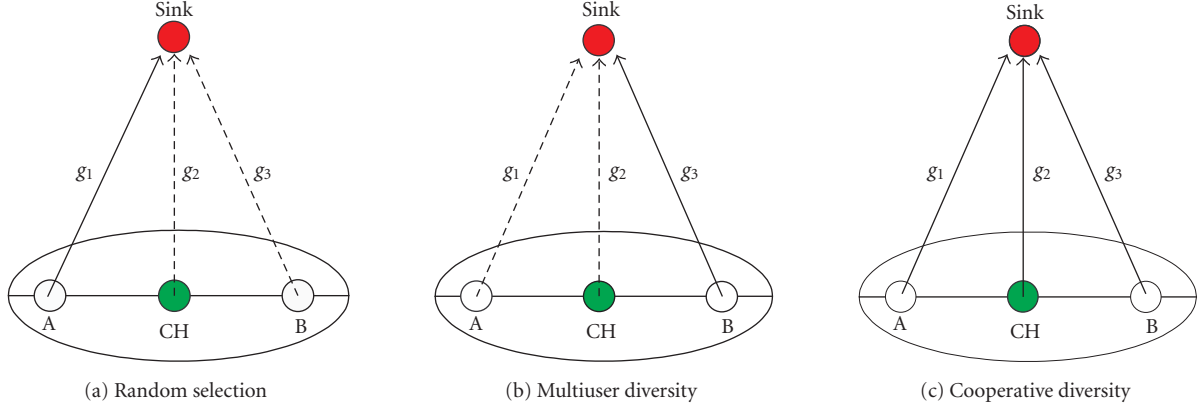


FIGURE 4: Data transmission schemes from a coalition to the sink.

The energy consumption for the intra-coalition communications is the sum of those from all the coalitions:

$$\mathcal{E}_{\text{intra}} = P_t \sum_{i=1}^M \frac{(n_i - 1)H_0 + \mathbf{H}_i}{R_0}. \quad (1)$$

Note that in traditional cluster-based sensor network, the CHs transmit the data to the sink, without sending data back to the sensors. So the intracluster energy consumption for traditional cluster-based sensor network is given by

$$\mathcal{E}_{\text{trad_intra}} = P_t \sum_{i=1}^M \frac{(n_i - 1)H_0}{R_0}. \quad (2)$$

3.3.2. Channel contention among coalitions

For the data transmissions from coalitions to the sink, CSMA is used to reserve the channel. In the coalition case, the CHs contend for the channel on behalf of the coalitions, whereas in the noncoalition case all sensor nodes with data contend for the channel. We assume that each node knows the number of contending nodes (m) and contends the channel with the optimal probability $p = 1/m$. The probability that one contending node wins the channel is $p_{\text{succ}} = (1 - 1/m)^{m-1}$. Since the number of slots needed until the successful reservation is a geometric random variable, the average total number of contending slots for the coalition case (M coalitions) is given by

$$S = \sum_{i=1}^M \frac{1}{(1 - 1/(M - i + 1))^{M-i}}. \quad (3)$$

Assuming that the time length of the contention minislot is τ , we have the energy consumption for channel contention in the coalition case:

$$\mathcal{E}_{\text{cont}} = \tau P_t \sum_{i=1}^M \frac{1}{(1 - 1/(M - i + 1))^{M-i}}. \quad (4)$$

Similarly, the energy consumption for channel contention in the noncoalition case is given by

$$\mathcal{E}'_{\text{cont}} = \tau P_t \sum_{i=1}^N \frac{1}{(1 - 1/(N - i + 1))^{N-i}}. \quad (5)$$

3.3.3. Data transmissions from one coalition to the sink: the fixed transmission power case

In this subsection, we examine the energy consumption for data transmissions from a coalition with reservation to the sink. We consider two popular transmission power allocation schemes, namely the fixed transmission power scheme and the channel inversion scheme. For the sake of fair comparison, we assume that, in the fixed transmission power case, the total transmission power from the coalition is fixed for all the data transmission schemes; and that the total received power from the coalition is a constant in the channel inversion case.

With fixed transmission power, the transmission data rate changes with the channel gain. We use Shannon capacity to approximate the transmission data rate. Let P_t be the transmission power and ρ the average received SNR in a corresponding SISO (single input single output) fading link [28]. We assume Rayleigh fading with unit average channel gain, that is, $E[g] = 1$ where g is exponentially distributed. In scheme 1, one node in a coalition is chosen randomly to transmit the data. The average transmission data rate from the sensor node to the sink is given by

$$\begin{aligned} E[W \log(1 + \rho g)] \\ = \int_0^\infty W \log(1 + \rho g) e^{-g} dg = -\frac{W}{\ln 2} e^{1/\rho} E_i\left(-\frac{1}{\rho}\right), \end{aligned} \quad (6)$$

where $E_i(\cdot)$ is the exponential integral function defined as $E_i(x) = -\int_{-x}^\infty (e^{-t}/t) dt$ [29]. Then the energy consumption for data transmission from the coalition to the sink is given by

$$\mathcal{E}_{\text{tosink}} = P_t \sum_{i=1}^M \frac{\mathbf{H}_i}{E[W \log(1 + \rho g)]}. \quad (7)$$

Note that for traditional cluster scheme, the energy consumption for data transmission from a CH to the sink is the same as above.

In scheme 2, the node with the best channel condition within the coalition is chosen to transmit the data. Denote by $g_{mi} = \max\{g_{i1}, g_{i2}, \dots, g_{in_i}\}$ the best channel gain in the i th coalition, where g_{ij} is the channel gain of the j th node in the i th coalition. The expected value of data rate is given by [30]

$$E[W \log(1 + \rho g_{mi})] = \int_0^\infty W \log(1 + \rho g_{mi}) n_i e^{-g_{mi}} [1 - e^{-g_{mi}}]^{n_i-1} dg_{mi}. \quad (8)$$

This integration can be evaluated by numerical methods. The average energy consumption of scheme 2 is given by

$$\mathcal{E}_{\text{tosink}} = P_t \sum_{i=1}^M \frac{\mathbf{H}_i}{E[W \log(1 + \rho g_{mi})]}. \quad (9)$$

The cooperative transmission technique is employed in scheme 3. More specifically, all the sensor nodes within a coalition transmit in a cooperative manner to form a virtual antenna array, that is, transmitter beamforming is applied across the sensor nodes such that the signal received at the sink can be combined coherently [27, 28]. Let $g_{ci} = \sum_{j=1}^{n_i} g_{ij}$ denote the sum of channel gains in the i th coalition. Then, the average data rate for cooperative diversity techniques can be derived as [30]

$$E[W \log(1 + \rho g_{ci})] = \int_0^\infty W \log(1 + \rho g_{ci}) \frac{1}{(n_i - 1)!} g_{ci}^{n_i-1} e^{-g_{ci}} dg_{ci} \quad (10)$$

and it can be evaluated numerically. We obtain the average energy consumption of scheme 3 as

$$\mathcal{E}_{\text{tosink}} = P_t \sum_{i=1}^M \frac{\mathbf{H}_i}{E[W \log(1 + \rho g_{ci})]}. \quad (11)$$

Combining the energy consumption for intra-coalition communications, the channel contention, and the data transmissions from coalitions to the sink, we have the total energy consumption of the three schemes:

$$\mathcal{E} = \mathcal{E}_{\text{intra}} + \mathcal{E}_{\text{cont}} + \mathcal{E}_{\text{tosink}}, \quad (12)$$

where $\mathcal{E}_{\text{tosink}}$ for scheme 1 to 3 is given by (7), (9), and (11), respectively.

For comparison, we also derive the performance of traditional cluster scheme and the non-coalition case with fixed transmission power. For the traditional cluster scheme, the energy consumption is given by

$$\mathcal{E}_{\text{trad}} = \mathcal{E}_{\text{trad,intra}} + \mathcal{E}_{\text{trad,cont}} + \mathcal{E}_{\text{trad,tosink}}, \quad (13)$$

where $\mathcal{E}_{\text{trad,intra}}$, $\mathcal{E}_{\text{trad,cont}}$, and $\mathcal{E}_{\text{trad,tosink}}$ are given by (2), (4), and (7), respectively.

For the non-coalition case, the energy consumption comes from the channel contention and the data transmission from the sensors to the sink. Then the average total energy consumption of the non-coalition case is given by

$$\mathcal{E}' = \mathcal{E}'_{\text{cont}} + P_t \frac{NH_0}{E[W \log(1 + \rho g)]}, \quad (14)$$

where $\mathcal{E}'_{\text{cont}}$ is the energy consumption for channel contention given by (5).

3.3.4. Data transmissions from one coalition to the sink: the channel inversion case

With channel inversion, the transmitter adjusts the transmission power with the channel gain, that is, $P_t = P/g$, such that the received power at the sink is a constant (P). Accordingly, the data rate R is also a constant and the time needed for data transmission is the same for all the coalition-aided data transmission schemes. We consider the energy consumption for the three data transmission schemes in the following.

In scheme 1, one node in the coalition is selected randomly to transmit the data. We assume that the sensor node does not transmit if the channel gain is below a threshold g_{th} . Then, the average energy consumption is given by

$$\mathcal{E}_{\text{tosink}} = E\left[\frac{P}{g}\right] \sum_{i=1}^M \frac{\mathbf{H}_i}{R}, \quad (15)$$

where the average transmission power $E[P/g]$ is given by [29]

$$E\left[\frac{P}{g}\right] = \int_{g_{th}}^\infty \frac{P}{g} e^{-g} dg = -E_i(-g_{th})P. \quad (16)$$

In scheme 2, the average energy consumption with multiuser diversity is given by

$$\mathcal{E}_{\text{tosink}} = \sum_{i=1}^M E\left[\frac{P}{g_{mi}}\right] \frac{\mathbf{H}_i}{R}, \quad (17)$$

where the average transmission power in the i th coalition is given by [29]

$$\begin{aligned} E\left[\frac{P}{g_{mi}}\right] &= \int_0^\infty \frac{P}{g_{mi}} n_i e^{-g_{mi}} [1 - e^{-g_{mi}}]^{n_i-1} dg_{mi} \\ &= P n_i (-1)^{n_i} \sum_{k=0}^{n_i-1} (-1)^k \binom{n_i-1}{k} \ln(n_i - k). \end{aligned} \quad (18)$$

In scheme 3, the average energy consumption with cooperative diversity is given by

$$\mathcal{E}_{\text{tosink}} = \sum_{i=1}^M E\left[\frac{P}{g_{ci}}\right] \frac{\mathbf{H}_i}{R}, \quad (19)$$

where the average transmission power in the i th coalition is given by [29]

$$E\left[\frac{P}{g_{ci}}\right] = \int_0^\infty \frac{P}{g_{ci}} \frac{1}{(n_i - 1)!} g_{ci}^{n_i-1} e^{-g_{ci}} dg_{ci} = \frac{P}{n_i - 1}. \quad (20)$$

TABLE 1: Numerical parameters.

P_t	1 mw	Transmission power of sensor nodes
d	100–200 m	Distance between sensor nodes and the sink
r	10 m	Distance between sensor nodes and CH
N	10	Number of sensors
n	2	Number of sensors within a coalition
H_0	2 k	Information bits of each sensor node
H_p	200	Number of bits in a pilot packet
W	1 MHz	Frequency bandwidth (Hz)
α	4	Path loss factor between sensors and sink
α_0	2	Path loss factor between sensors and CH
G_t	0 dB	Transmit antenna gain
G_r	0 dB	Receive antenna gain
f_c	2.4 GHz	Carrier frequency

Then we can get the total energy consumption with channel inversion by combining the energy consumption for intra-coalition communications, the channel contention and the data transmissions from coalitions to the sink.

We also consider the performance of the tradition cluster scheme and the non-coalition case for comparison. For the traditional cluster scheme with channel inversion, the energy consumption is the same as in (13) except that $\mathcal{E}_{\text{trad, to sink}}$ is given by (15) here. For the non-coalition case, the average energy consumption of the non-coalition case is given by

$$\mathcal{E}' = E\left[\frac{P}{g}\right] \frac{NH_0}{R} + \mathcal{E}'_{\text{cont}}, \quad (21)$$

where $E[P/g]$ is shown in (16) and $\mathcal{E}'_{\text{cont}}$ is given by (5).

3.4. Numerical examples

In this section, we illustrate our findings via examples. We consider a one-dimensional network where sensors are uniformly deployed. Each coalition comprises of two sensor nodes. For a transmitter-receiver separation d , the average received power is given by $P_r(d) = P_r(d_0)(d_0/d)^\alpha$, where α is the path loss factor and $P_r(d_0) = (P_t G_t G_r \lambda^2)/(4\pi)^2 d_0^2$ is the received power at the close-in distance d_0 , with d_0 normalized to 1 meter [30]. The Shannon capacity is used to approximate the data rate. The parameters for our numerical examples are summarized in Table 1.

A simple empirical model is used to model the joint entropy of two sources as a function of their distance r : $H'(r) = H_0 + [1 - 1/(r/c + 1)]H_0$, where c is a constant that characterizes the extent of spatial correlation in the data [31]. Assuming the correlation constant $c = r$, we have the joint entropy of a coalition $\mathbf{H}_i = 1.5H_0$.

We define the energy saving gain as the ratio of saved energy for each transmission scheme against the energy consumption of the non-coalition case: $\eta(E) \triangleq (\mathcal{E}' - \mathcal{E})/\mathcal{E}'$. The energy consumption with fixed transmission power are shown in Figure 5. (For the channel inversion scheme, nu-

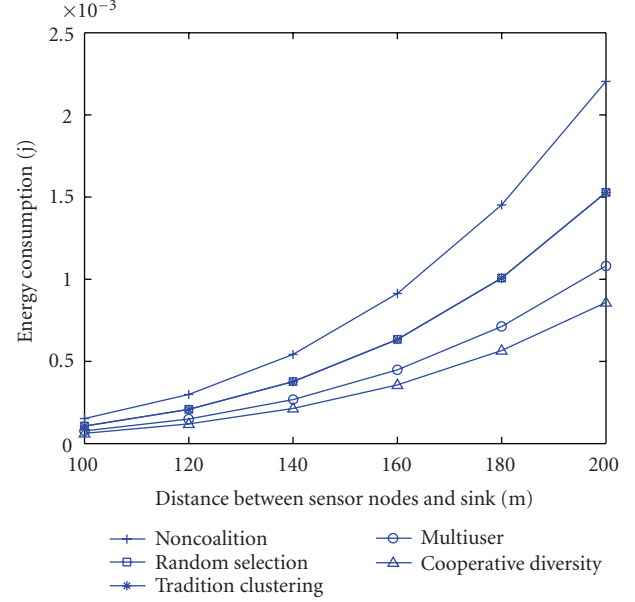


FIGURE 5: Energy consumption over fading channels.

merical examples can be achieved similarly.) From the results it can be seen that the coalition-aided data transmission schemes have better performance than the non-coalition case. Comparing with scheme 1 (random selection), the traditional cluster scheme has almost the same performance, because of the dominating energy consumption for data transmissions from coalitions to the sink. We can also see that scheme 2 and scheme 3 outperform scheme 1, and scheme 3 has the best performance. For example, when the distance between sensor nodes and the sink is 100 meters, the energy saving gain for the three data transmission schemes are 29.74%, 49.47%, and 58.84%, respectively. Note that some overhead is incurred by schemes 2 and 3 since channel status of each node should be maintained and updated from time to time. Moreover, since all the sensor nodes within a coalition transmit in scheme 3, the overhead of circuit energy consumption may become an issue which we ignore in this study.

4. MULTIHOP SENSOR NETWORKS: OPTIMAL COALITION PLANNING AND ENERGY BALANCING

In this section, we focus on energy balancing in multihop sensor networks. In a multihop network, the sensor nodes close to the sink are called in the “hot-spot,” in the sense that more traffic is forwarded by these nodes to the sink. Sensor nodes in the hot-spot may deplete their energy faster than other sensors. As a result, the network may not function properly after some nodes die, because of either network partition or insufficient field covering. Motivated by this observation, we investigate the optimal coalition planning to balance the energy consumption among the sensor nodes in the network.

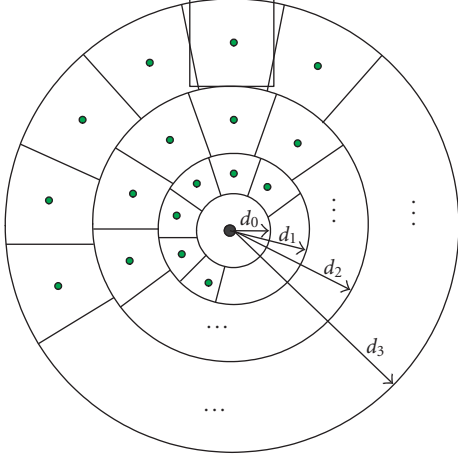


FIGURE 6: A coalition-based multihop network.

4.1. System model

4.1.1. Network model

Following [22], we consider a homogeneous circular network where the sink is located at the center and the sensors are uniformly deployed in the area $\mathcal{A}: \{(x, y) \mid d_0^2 \leq x^2 + y^2 \leq D^2\}$ with node density δ , as illustrated in Figure 6. In light of the symmetric property of this network, we assume that the sensor nodes are divided into K rings, and the i th ring denotes the sensors in the area $\{(x, y) \mid d_{i-1}^2 < x^2 + y^2 \leq d_i^2\}$, $i = 1, \dots, K$, where d_i is the distance between the outer boundary of the i th ring and the sink and $d_K = D$. The sensor nodes of each ring are grouped into multiple coalitions and the area covered by a coalition is represented by a sector within the ring. In [22], a cluster is approximated by a small circle to facilitate analysis. In this study, based on the shape of a coalition, we approximate it as a square with side length $l_i = d_i - d_{i-1}$, which we believe is more accurate than the circle approximation. (Indeed, as indicated by the simulation results in Section 4.3, the approximation has a negligible impact on network performance.) We also assume that each CH is located at the center of its coalition.

We assume AWGN channels for intracoalition communications and Rayleigh fading channels for intercoalition communications, respectively. The intra-coalition communications take place the same way as proposed in Section 3.2, except that in the Type I model the sensor nodes do not transmit data to the CH. For the intercoalition communications, data from a coalition in the i th ring is sent to the closest CH in the $(i-1)$ th ring until the sink is reached. Coalition-aided data transmission schemes can be employed for each hop.

4.1.2. Traffic model

Depending on the specific applications, different wireless sensor networks have different traffic patterns. Roughly speaking, sensor networks can be classified into four categories [32, 33]: continuous, event-driven, query-driven,

and hybrid. In the continuous delivery model, each sensor sends out data periodically. In the event-driven data delivery model, the sensors report information only if an event of interest occurs. In the query-based model, the sensors only report their results in response to an explicit request from the sink. Some networks apply a hybrid model using a combination of these models.

The aforementioned traffic patterns can be categorized into two types of traffic models:

- (i) Type I: only part of the sensor nodes have data to transmit and other sensors serve as relays;
- (ii) Type II: all sensor nodes in the area have data to transmit.

These two models represent different traffic patterns. Type I provides a good model for the event-driven (e.g., for intrusion detection) and query-based wireless sensor networks; and Type II corresponds to the periodical data transmission model (e.g., for field monitoring).

4.1.3. Energy consumption model

In this subsection we examine the transmit energy required for reliable data transmission. We consider intra-coalition communications first. Let $e_{i,\text{intra}}$ denote the transmit energy per bit and x_i the communication distance in a coalition of the i th ring. Then, the received energy per bit is given by $e_{i,\text{intra}}/x_i^\alpha$, where α is the path loss factor for intra-coalition communications. To ensure reliable reception, the received energy per bit should be no less than the threshold γ_{intra} . So the required transmit energy per bit for intra-coalition communications is given by

$$e_{i,\text{intra}} = \gamma_{\text{intra}} x_i^\alpha. \quad (22)$$

Next we turn to model the energy consumption for inter-coalition communications. Let $e_{i,\text{inter}}$ denote the transmit energy per bit and y_i the communication distance. The received energy per bit is given by $e_{i,\text{inter}}\xi/y_i^\beta$, where ξ is the Rayleigh fading gain seen by the sink and β is the path loss factor for inter-coalition communications. For reliable reception, it is assumed that the expected value of received energy per bit should be no less than a predefined threshold γ_{inter} , that is, $E[e_{i,\text{inter}}\xi/y_i^\beta] \geq \gamma_{\text{inter}}$, where the expectation is taken with respect to the channel variation seen by the receiver (γ_{inter} and γ_{intra} could but not necessarily be the same). Let n_i denote the number of sensor nodes in the coalition. For scheme 1, one sensor node is selected randomly to transmit the data. Assuming normalized channel fading, that is, $E[\xi^{(1)}] = 1$, we have

$$e_{i,\text{inter}}^{(1)} = \gamma_{\text{inter}} y_i^\beta. \quad (23)$$

For scheme 2, since the node with the best channel gain is chosen, the average channel gain is $E[\xi^{(2)}] = \sum_{j=1}^{n_i} 1/j$ [30]. Thus the required transmit energy per bit is given by

$$e_{i,\text{inter}}^{(2)} = \frac{\gamma_{\text{inter}} y_i^\beta}{\sum_{j=1}^{n_i} 1/j}. \quad (24)$$

For scheme 3, the received signal can be added coherently, so the average channel gain is given by $E[\xi^{(3)}] = n_i$ [30]. Then the required transmit energy per bit is given by

$$e_{i,\text{inter}}^{(3)} = \frac{\gamma_{\text{inter}} \gamma_i^\beta}{n_i}. \quad (25)$$

4.2. Optimal coalition planning

4.2.1. The Type I network model

In the Type I model, the data (H) need to be forwarded to the sink through K rings of coalitions. Due to the symmetry of the rings and the uniform distribution of sensors, the H information bits are evenly distributed throughout all the coalitions in the i th ring. Since the number of coalitions in the i th ring is

$$N_i \approx \frac{\pi(d_i + d_{i-1})}{d_i - d_{i-1}}, \quad (26)$$

the average amount of information bits received by a CH in the i th ring is given by

$$H_i = \frac{H(d_i - d_{i-1})}{\pi(d_i + d_{i-1})}. \quad (27)$$

After the CH receives the data, it broadcasts within the coalition. Approximating the transmission distance as $x_i = (d_i - d_{i-1})/2$, we have that the required transmit energy per bit is

$$e_{i,\text{intra}} = \gamma_{\text{intra}} \left(\frac{d_i - d_{i-1}}{2} \right)^\alpha. \quad (28)$$

So the total energy consumption for the intra-coalition communications is given by

$$\mathcal{E}_{i,\text{intra}} = H_i \cdot e_{i,\text{intra}}. \quad (29)$$

Next, we consider the energy consumption for inter-coalition communications. Denote the coordinates of the CH as $(0, (d_i + d_{i-1})/2)$ and the sink as $(0,0)$. The sensor nodes within the coalition are uniformly deployed in the area $\{(x, y) : x \in (-l_i/2, l_i/2), y \in (d_{i-1}, d_i)\}$, where $l_i = d_i - d_{i-1}$. We approximate the position of the next-hop CH as $(0, (d_{i-1} + d_{i-2})/2)$ (which actually leads the lower bound of the distance). Note that for $i = 1$, the next hop reaches the sink. Then, the average path loss for the inter-coalition communications is given by

$$\gamma_i^\beta = \begin{cases} \int_{-l_i/2}^{l_i/2} \int_{d_{i-1}}^{d_i} \frac{1}{l_i^2} [x^2 + y^2]^{\beta/2} dx dy, & \text{for } i = 1, \\ \int_{-l_i/2}^{l_i/2} \int_{d_{i-1}}^{d_i} \frac{1}{l_i^2} \left[x^2 + \left(y - \frac{d_{i-1} + d_{i-2}}{2} \right)^2 \right]^{\beta/2} dx dy, & \text{for } i = 2, \dots, K. \end{cases} \quad (30)$$

Substituting γ_i into (23), (24), and (25), we get the required transmit energy per bit of the three proposed schemes for inter-coalition communications. Then, the energy consumption for the inter-coalition communications is given by

$$\mathcal{E}_{i,\text{inter}} = H_i \cdot e_{i,\text{inter}}. \quad (31)$$

The total energy consumption of a coalition in the i th ring is given by

$$\mathcal{E}_i = \mathcal{E}_{i,\text{intra}} + \mathcal{E}_{i,\text{inter}} = \frac{H(d_i - d_{i-1})}{\pi(d_i + d_{i-1})} (e_{i,\text{intra}} + e_{i,\text{inter}}). \quad (32)$$

Since each sensor node has the same probability to transmit the data, and the average number of sensor nodes in a coalition in the i th ring is $n_i = \delta(d_i - d_{i-1})^2$, the average energy consumption of one sensor node in the i th ring is given by

$$\frac{\mathcal{E}_i}{n_i} = \frac{H}{\delta\pi(d_i^2 - d_{i-1}^2)} (e_{i,\text{intra}} + e_{i,\text{inter}}). \quad (33)$$

Then energy balancing boils down to the following optimization problem:

$$\begin{aligned} \text{P1 : } & \min_{\{d_1, \dots, d_K\}} \max_i \left\{ \frac{\mathcal{E}_i}{n_i} \right\} - \min_i \left\{ \frac{\mathcal{E}_i}{n_i} \right\} \\ & \text{s.t. } d_0 \leq d_1 \leq \dots \leq d_K. \end{aligned} \quad (34)$$

By introducing auxiliary variables $t \geq \mathcal{E}_i/n_i$ and $s \leq \mathcal{E}_i/n_i$, the optimization problem (34) can be transformed into the following equivalent form:

$$\begin{aligned} \text{P2 : } & \min_{\{d_1, \dots, d_K\}} t - s \\ & \text{s.t. } \frac{\mathcal{E}_i}{n_i} \leq t, \quad i = 1, 2, \dots, K, \\ & \frac{\mathcal{E}_i}{n_i} \geq s, \quad i = 1, 2, \dots, K, \\ & d_0 \leq d_1 \leq \dots \leq d_K. \end{aligned} \quad (35)$$

Clearly, this problem in general involves nonlinear optimization. In light of this, we turn to numerical methods to find the optimal solution. In particular, we use the nonlinear optimization solver KNITRO [34] which implements algorithms of both the interior (or barrier) type and the active-set type, and using trust regions to promote convergence [35]. We will elaborate further on this in Section 4.3.

For the sake of comparison, we also study the case that considers the energy balancing across CHs only. In this case, because the CHs always transmit the data, there is no energy consumption for intra-coalition communications. Then the energy consumption of a CH in the i th ring is given by

$$\mathcal{E}'_i = \frac{H(d_i - d_{i-1})}{\pi(d_i + d_{i-1})} (\gamma_{\text{inter}} \gamma_i^\beta). \quad (36)$$

Accordingly, the energy balancing problem can be formulated as following:

$$\begin{aligned} \text{P3 : } & \min_{\{d_1, \dots, d_K\}} \max_i \{\mathcal{E}'_i\} - \min_i \{\mathcal{E}'_i\} \\ & \text{s.t. } d_0 \leq d_1 \leq \dots \leq d_K. \end{aligned} \quad (37)$$

4.2.2. The Type II network model

In the Type II model, all the sensor nodes in the area generate information of H_0 bits. In each coalition, the CH receives the data from the coalition members and from outside rings. The CH carries out the aggregation for data from its own coalition and combine them with the relaying traffic. Let η denote the compression ratio. Then, the compressed data from its own coalition is given by

$$H_{i,\text{own}} = \eta\delta(d_i - d_{i-1})^2 H_0, \quad (38)$$

and the relaying data received by a CH in the i th ring is given by

$$H_{i,\text{relay}} = \frac{\eta\delta\pi(D^2 - d_i^2)(d_i - d_{i-1})H_0}{\pi(d_i + d_{i-1})}. \quad (39)$$

Thus the total information bits to be sent by a coalition in the i th ring is given by

$$H_i = \frac{\eta\delta\pi(D^2 - d_i^2)(d_i - d_{i-1})H_0}{\pi(d_i + d_{i-1})}. \quad (40)$$

Accordingly, the intra-coalition energy consumption is given by

$$\mathcal{E}_{i,\text{intra}} = (n_i H_0 + H_i) e_{i,\text{intra}}, \quad (41)$$

where $e_{i,\text{intra}}$ is given by (28), and the inter-coalition energy consumption is given by

$$\mathcal{E}_{i,\text{inter}} = H_i \cdot e_{i,\text{inter}}, \quad (42)$$

where $e_{i,\text{inter}}$ is given by (23), (24), and (25) for the three coalition-aided data transmission schemes, respectively. The total energy consumption of a coalition in the i th ring is given by

$$\mathcal{E}_i = n_i H_0 \cdot e_{i,\text{intra}} + H_i (e_{i,\text{intra}} + e_{i,\text{inter}}), \quad (43)$$

and the average energy consumption of one sensor node in the i th ring is given by

$$\frac{\mathcal{E}_i}{n_i} = H_0 \cdot e_{i,\text{intra}} + \frac{\eta\delta H_0 (D^2 - d_i^2)}{d_i^2 - d_{i-1}^2} (e_{i,\text{intra}} + e_{i,\text{inter}}). \quad (44)$$

Then, the energy balancing problem can be formulated the same as P1.

We also present the problem which considers the energy balancing across CHs only for the sake of comparison. The energy consumption of a CH in the i th ring is given by

$$\mathcal{E}'_i = \frac{\eta\delta H_0 \pi (D^2 - d_i^2) (d_i - d_{i-1})}{\pi (d_i + d_{i-1})} \gamma_{\text{inter}}^\beta \gamma_i^\beta, \quad (45)$$

and the energy balancing problem across CHs can be formulated the same as P3.

TABLE 2: Numerical parameters.

K	5	Number of rings
d_0	10	$X(0) = d_0$
D	200	$X(K) = D$
H_0	2000	Information bits at each node
H	5 M	Total information bits for Type I network
α	2	Path loss factor for intracoalition communications
β	4	Path loss factor for intercoalition communications
γ	10^{-15}	Received energy threshold
η	0.5	Data compress ratio
δ	0.02	Sensor node density

4.3. Numerical examples

In this section, we illustrate by numerical examples the performance of the proposed schemes, and compare them with the one considering energy balancing across CHs only. We characterize the solutions to the nonlinear optimization problems in Section 4.2. To solve the nonlinear optimization problems, we use the solver KNITRO [34] with the AMPL [36] interface. KNITRO is a powerful solver for nonlinear optimization problems, by implementing novel and state-of-the-art algorithms of both the interior (or barrier) type and the active-set type, and using trust regions to promote convergence [35]. AMPL is a comprehensive and powerful algebraic modeling language for linear and nonlinear optimization problems, in discrete or continuous variables. We convert our problems into the AMPL format and get the numerical results from the KNITRO solver. The parameters of our problem are summarized in Table 2.

First, we examine the coalition size profile in the network. Using the analytical solution, we show in Figure 7 the coalition sizes of different rings of the three transmission schemes for the Type I network model, as well as the one considering the energy balancing across CHs only (numerical studies can be carried out for the Type II network model similarly). It can be seen that the coalition size profiles of these schemes are very different. In particular, for the scheme considering CHs only and the random selection scheme, the coalition size becomes larger for coalitions farther away from the sink, while for the schemes with multiuser diversity or cooperative diversity, the middle coalitions have larger coalition sizes. This is because that the communication distance is the dominant factor for the scheme considering CH only and the random selection scheme, whereas the number of sensors becomes an important factor affecting energy consumption for the schemes with multiuser diversity or cooperative diversity. In summary, the optimal coalition structure depends on the specific data transmission scheme and therefore should be designed carefully to achieve energy balancing across nodes.

Then, we examine the energy consumption among all these schemes. The analytical results for energy consumption are shown in Table 3. From Table 3 it can be seen that the coalition-based schemes reduce the burden of the CHs a lot and hence help to prolong the life time significantly. Note that for each of the coalition aided transmission schemes, the

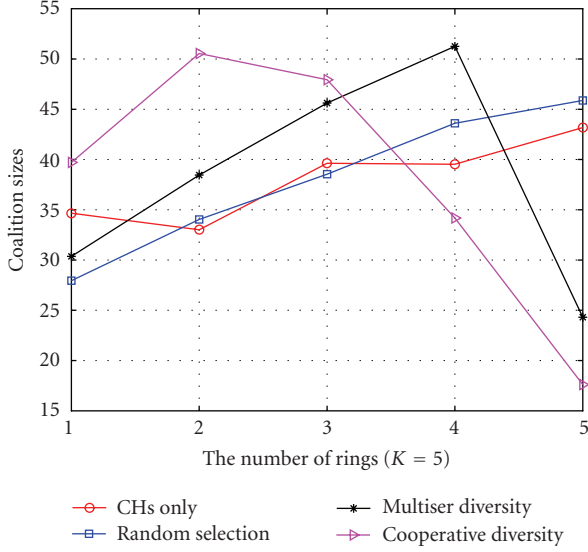


FIGURE 7: The coalition sizes.

TABLE 3: The energy consumption of all the schemes.

CHs only	Random selection	Multiser	Cooperative
521.08 μ J	18.22 μ J	5.54 μ J	0.87 μ J

result in Table 3 denotes the energy consumption of one sensor node, while for the scheme considering CHs only it denotes the energy consumption of a CH.

The analysis above is based on certain simplified assumptions (e.g., square coalitions, lower-bounded next-hop distance, etc.). To corroborate our analytical studies, we conduct simulations in a more “realistic” setting, where the sensor nodes are randomly placed in the area $\mathcal{A}$. The distances between the sink and the CHs of different rings are based on the analytical results obtained. Each sensor node joins the closest CH according to its location. The average energy consumption of one sensor node in different rings are shown in Figure 8. It can be seen that energy balancing across the sensor nodes can be achieved for all the coalition-aided data transmission schemes, and that scheme 3 has the best energy saving performance among the three schemes.

5. CONCLUSIONS

We take a cross-layer optimization approach to study energy efficient data transport in coalition-based wireless sensor networks, where neighboring nodes are organized into groups to form coalitions and data aggregation and cooperative communications can be carried out within one coalition. The interplay among data aggregation, medium access control, cooperative communication, and coalition planning are exploited. In particular, we investigate two network models, that is, many-to-one sensor networks and multihop sensor networks. In a many-to-one sensor network, data from one coalition are transmitted to the sink directly. We propose three schemes for data transmission from a coalition

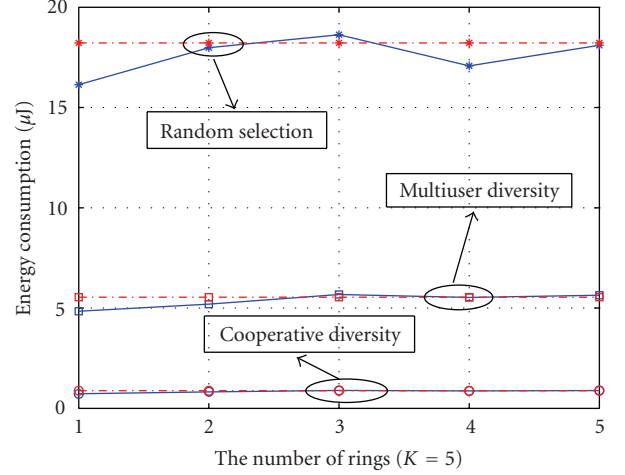


FIGURE 8: Energy balancing across coalitions.

to the sink. In scheme 1, one node in the coalition is selected randomly by the CH to transmit the data, so that each node within the coalition consumes energy in the same pace. In scheme 2, the sensor node with the best channel condition transmits the data, yielding multiuser diversity gain. In scheme 3, all the sensors within the coalition transmit as a virtual antenna array, so the cooperative diversity gain could be achieved.

Building on the coalition-aided data transmission schemes for one hop, we study energy balancing across sensor nodes in multihop networks, where data are relayed by intermediate coalitions to reach the sink. Optimal coalition planning is carried out, in the sense that unequal coalition sizes are applied to minimize the difference of energy consumption among sensor nodes. In particular, we investigate multihop networks with two different traffic patterns. In a Type I network, only part of the sensor nodes have data to transmit and others serve as relays; and in a Type II network, all sensor nodes have data to transmit. Numerical analysis shows that energy efficiency can be improved significantly by the coalition-aided transmission schemes, and that energy balancing across the sensor nodes can be achieved with the proposed coalition structures.

REFERENCES

- [1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “A survey on sensor networks,” *IEEE Communications Magazine*, vol. 40, no. 8, pp. 102–114, 2002.
- [2] S. Bandyopadhyay and E. J. Coyle, “An energy efficient hierarchical clustering algorithm for wireless sensor networks,” in *Proceedings of the 22nd Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM '03)*, vol. 3, pp. 1713–1723, San Francisco, Calif, USA, March–April 2003.
- [3] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, “Energy-efficient communication protocol for wireless microsensor networks,” in *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences (HICSS '00)*, vol. 2, pp. 3005–3014, Maui, Hawaii, USA, January 2000.

- [4] R. Krishnan and D. Starobinski, "Efficient clustering algorithms for self-organizing wireless sensor networks," *Ad Hoc Networks*, vol. 4, no. 1, pp. 36–59, 2006.
- [5] S. Lindsey and C. S. Raghavendra, "PEGASIS: power efficient gathering in sensor information systems," in *Proceedings of IEEE Aerospace Conference*, vol. 3, pp. 1125–1130, Big Sky, Mont, USA, March 2002.
- [6] A. Manjeshwar and D. P. Agrawal, "TEEN: a routing protocol for enhanced efficiency in wireless sensor networks," in *Proceedings of the 15th International Parallel and Distributed Processing Symposium (IPDPS '01)*, pp. 2009–2015, San Francisco, Calif, USA, April 2001.
- [7] O. Younis and S. Fahmy, "HEED: a hybrid, energy efficient, distributed clustering approach for ad hoc sensor networks," *IEEE Transactions on Mobile Computing*, vol. 3, no. 4, pp. 366–379, 2004.
- [8] B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris, "Span: an energy-efficient coordination algorithm for topology maintenance in ad hoc wireless networks," *Wireless Networks*, vol. 8, no. 5, pp. 481–494, 2002.
- [9] C. Schurgers and M. B. Srivastava, "Energy efficient routing in wireless sensor networks," in *Proceedings of IEEE Military Communications Conference on Communications for Network-Centric Operations: Creating the Information Force (MILCOM '01)*, vol. 1, pp. 357–361, McLean, Va, USA, October 2001.
- [10] Y. Xu, J. Heidemann, and D. Estrin, "Geography-informed energy conservation for ad hoc routing," in *Proceedings of the 7th Annual International Conference on Mobile Computing and Networking*, (MOBICOM '01), pp. 70–84, Rome, Italy, July 2001.
- [11] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient MAC protocol for wireless sensor networks," in *Proceedings of the 21st Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM '01)*, vol. 3, pp. 1567–1576, New York, NY, USA, June 2002.
- [12] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks," *IEEE Journal on Selected Areas in Communications*, vol. 22, no. 6, pp. 1089–1098, 2004.
- [13] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062–3080, 2004.
- [14] A. Nosratinia, T. E. Hunter, and A. Hedayat, "Cooperative communication in wireless networks," *IEEE Communications Magazine*, vol. 42, no. 10, pp. 74–80, 2004.
- [15] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451–1458, 1998.
- [16] J. Ai, D. Turgut, and L. Boloni, "A cluster-based energy balancing scheme in heterogeneous wireless sensor networks," in *Proceedings of the 4th International Conference on Networking (ICN '05)*, pp. 467–474, Reunion, France, April 2005.
- [17] C. Efthymiou, S. Nikolettas, and J. Rolim, "Energy balanced data propagation in wireless sensor networks," in *Proceedings of the 18th International Parallel and Distributed Processing Symposium (IPDPS '04)*, p. 225a, Santa Fe, NM, USA, April 2004.
- [18] Q. Gao, J. Zhang, B. Larish, and S. Shen, "Coalition-aided data transmissions in wireless sensor networks," in *Proceedings of IEEE International Conference on Communications (ICC '06)*, pp. 3426–3431, Istanbul, Turkey, June 2006.
- [19] M. Haenggi, "Energy-balancing strategies for wireless sensor networks," in *Proceedings of IEEE International Symposium on Circuits and Systems (ISCAS '03)*, vol. 4, pp. 828–831, Bangkok, Thailand, May 2003.
- [20] I. Howitt and J. Wang, "Energy balanced chain in distributed sensor networks," in *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC '04)*, vol. 3, pp. 1721–1726, Atlanta, Ga, USA, March 2004.
- [21] C. Li, M. Ye, G. Chen, and J. Wu, "An energy-efficient unequal clustering mechanism for wireless sensor networks," in *Proceedings of the 2nd IEEE International Conference on Mobile Ad-Hoc and Sensor Systems (MASS '05)*, pp. 8 pages, Washington, DC, USA, November 2005.
- [22] T. Shu, M. Krunz, and S. Vrudhula, "Power balanced coverage-time optimization for clustered wireless sensor networks," in *Proceedings of the 6th ACM International Symposium on Mobile Ad Hoc Networking and Computing (MOBIHOC '05)*, pp. 111–120, Urbana-Champaign, Ill, USA, May 2005.
- [23] S. Soro and W. Heinzelman, "Prolonging the lifetime of wireless sensor networks via unequal clustering," in *Proceedings of the 19th IEEE International Parallel and Distributed Processing Symposium (IPDPS '05)*, pp. 8 pages, Denver, Colo, USA, April 2005.
- [24] Y. Yu and V. K. Prasanna, "Energy-balanced multi-hop packet transmission in wireless sensor networks," in *Proceedings of IEEE Global Telecommunications Conference (GLOBECOM '03)*, vol. 1, pp. 480–486, San Francisco, Calif, USA, December 2003.
- [25] M. Dong, L. Tong, and B. M. Sadler, "Effect of MAC design on source estimation in dense sensor networks," in *Proceedings of IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP '04)*, vol. 3, pp. 853–856, Montreal, Quebec, Canada, May 2004.
- [26] D. Marco, E. J. Duarte-Melo, M. Liu, and D. L. Neuhoff, "On the many-to-one transport capacity of a dense wireless sensor network and the compressibility of its data," in *Proceedings of the 2nd International Symposium on Information Processing in Sensor Networks (IPSN '03)*, pp. 1–16, Palo Alto, Calif, USA, April 2003.
- [27] T. K. Y. Lo, "Maximum ratio transmission," *IEEE Transactions on Communications*, vol. 47, no. 10, pp. 1458–1461, 1999.
- [28] A. Paulraj, R. Nabar, and D. Gore, *Introduction to Space-Time Wireless Communications*, Cambridge University Press, Cambridge, UK, 2003.
- [29] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series and Products*, Academic Press, San Diego, Calif, USA, 2002.
- [30] T. S. Rappaport, *Wireless Communications*, Prentice-Hall, Upper Saddle River, NJ, USA, 2nd edition, 2002.
- [31] S. Pattem, B. Krishnamachari, and R. Govindan, "The impact of spatial correlation on routing with compression in wireless sensor networks," in *Proceedings of the 3rd International Symposium on Information Processing in Sensor Networks (IPSN '04)*, pp. 28–35, Berkeley, Calif, USA, April 2004.
- [32] S. Tilak, N. B. Abu-Ghazaleh, and W. Heinzelman, "A taxonomy of wireless micro-sensor network models," *ACM Mobile Computing and Communications Review*, vol. 6, no. 2, pp. 28–36, 2002.
- [33] K. Akkaya and M. Younis, "A survey on routing protocols for wireless sensor networks," *Ad Hoc Networks*, vol. 3, no. 3, pp. 325–349, 2005.
- [34] KNITRO, <http://www.ziena.com/knitro.htm>.
- [35] J. Nocedal and S. J. Wright, *Numerical Optimization*, Springer, New York, NY, USA, 1999.
- [36] AMPL, <http://www.ampl.com/>.