ENERGY-EFFICIENT COOPERATIVE COMMUNICATION IN CLUSTERED WIRELESS SENSOR NETWORKS

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ABSTRACT

We study a clustered wireless sensor network where sensors within each cluster forward the message to another cluster via cooperative communication techniques. Only those sensors that correctly decode the packet from the source can participate in the subsequent cooperative communication. Hence, the number of cooperating sensors is a random variable depending on both channel and noise realizations. We formulate a multi-variable optimization problem to minimize the overall energy consumption. With numerical methods, we investigate how the energy efficiency is affected by the transmit power allocation, the total number of sensors in a cluster, the end-to-end packet error rate requirement, and the relative magnitudes of intra-cluster and inter-cluster distances.

I. INTRODUCTION

Energy-constrained networks, such as wireless sensor networks, have nodes typically powered by batteries, for which replacement or recharging is difficult if not impossible [1]. For such networks, Minimizing the energy consumption per unit information transmission becomes a very important design consideration. It has been recently shown that multiple nodes can collaborate to achieve significant transmission power reduction via spatial diversity techniques even though each node has only one antenna [2], [3]. Such strategy is termed as cooperative communication.

In cooperative communication systems, two or more nodes form a virtual antenna array to jointly transmit information. In a relay channel context, the diversity performance and the outage behavior of cooperative communication have been analyzed in [3] under different cooperative protocols. Distributed space-time coding for a general cooperative system has been studied in e.g., [4] and [5], where clusters of nodes act as relay nodes after correctly decoding the message from the source node. Specifically, distributed space-time codes based on conventional orthogonal space-time block codes (STBC) [6] are proposed in [4]. The cases where the number of relaying nodes is unknown are also discussed in [4]. In [5], the number of relaying nodes is modeled as a random variable and each relay node randomly selects a column from an orthogonal STBC code-matrix. In such a case, full diversity can still be achieved in the high SNR regime if the total number of relaying nodes is large [5]. Energy efficiency issues in a clustered sensor network have been investigated in [2], where sensors collaborate on signal transmission and/or reception in a deterministic way. If the long-haul transmission distance (between clusters) is large enough, cooperative transmission can dramatically reduce the total energy consumption even when all the collaboration overhead is considered [2].

The performance of cooperative communication can be further improved by proper energy allocation during collaboration. With a deterministic collaboration pattern, optimal energy distribution among cooperative nodes is pursued in [7] to minimize link outage probability. For a two-node amplify-and-forward cooperation protocol, power control based on perfect channel state information is shown to achieve significant energy savings [8].

In this paper, we develop an energy-efficient cooperative communication scheme for a clustered wireless sensor network. Our work is different from existing ones in the following ways. First, the relay nodes are selected on a packet-by-packet basis, and the number of relaying nodes is random. A sensor can act as one relay node only if it can decode the packet correctly, which depends on both channel and noise realizations. Our packet-error-based analysis is more practical than existing symbol-error-based analysis, because packet errors can be detected via the cyclic-redundancy-check (CRC) bits embedded in each packet. Second, we formulate a multi-variable optimization problem to minimize the overall energy consumption, taking into account both the transmission energy and the circuit energy. Third, with numerical simulations, we thoroughly investigate how the energy efficiency is affected by the transmit power allocation, the total number of sensors in a cluster, the end-to-end packet error rate requirement, and the relative magnitudes of intra-cluster and inter-cluster distances.

II. SYSTEM MODEL

We consider a clustered wireless sensor network which is composed of multiple clusters of nodes, with each node equipped with only one antenna. A typical example is shown in Fig. 1. The nodes within the same cluster are closely spaced and can cooperate in signal transmission and/or reception. We assume that the average distance between adjacent clusters is much larger than the average distance among the nodes within each cluster. This is a typical wireless sensor network scenario, and has been widely used in the literature [2], [4], [9], [10]. Suppose that one node (the source node) in a cluster wants to send a message to another node (the destination node) in a nearby cluster. Since the transmission distance is relatively large between clusters, we can first broadcast the message to other nodes in the same cluster and then use cooperative communication to reduce the inter-cluster transmit energy. This approach has been shown to be energy-efficient relative to direct (non-cooperative) transmission [2], [9] under certain conditions. Specifically, our cooperative communication scheme works in two phases as follows:

Phase 1: Intra-cluster broadcasting. The source node broadcasts the packet with energy P_{t1}(per symbol) to the nodes within the same cluster. All the nodes in the cluster decode the received packet simultaneously. Each node knows whether the reception is successful or not based on the CRC bits embedded in the packet.

Phase 2: Inter-cluster cooperative transmission. The source node and all the nodes that receive the packet correctly will "cooperatively" transmit the packet simultaneously with the same energy P_{t2} (per symbol) to the destination node. Here we use schemes based on distributed space-time block coding [4].[1]

We choose this system model for the following reasons. First of all, this model can maximize the achievable spatial diversity by probing all available nodes in the same cluster for joint relaying [3], [4]. This can lead to more energy savings compared with the two-node cooperation strategies in [13]. Secondly, our model assumes no channel state information (CSI) at the transmitters, which makes the proposed cooperative communication scheme easier to implement.

[1]When the number of transmitters is unknown, the issues of distributed space-time code design have been previously discussed in [4], [11]. In this paper, as in [4], [12], we assume that there exists some form of central control that assigns the space-time code matrix columns to the cooperative nodes.

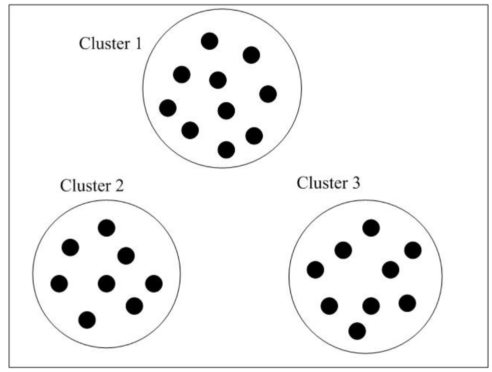

Fig. 1. A clustered wireless sensor network

Compared with those cooperative communication schemes that assume perfect intra-cluster communication and cooperative relaying by all the nodes in the cluster [2], [9], the proposed cooperative communication model considers a more realistic scenario where packet errors may occur during the intra-cluster communication. Furthermore, compared with analysis based on symbol error rate [10], the PER-based models are more practical.

Problem Statement: We are concerned with energy issues for the considered cooperative strategy, where the number of nodes that participate in the inter-cluster cooperative transmission is random. We quantify the achievable energy savings over direct (non-cooperative) strategies and investigate the effects of various parameters such as the transmit power allocation (P_{t1} and P_{t2}), the total number of sensors in a cluster, the end-to-end packet error rate requirement, and the relative magnitudes of intra-cluster and inter-cluster distances.

III. PERFORMANCE ANALYSIS AND OPTIMIZATION

A. Intra-Cluster Broadcasting

We first calculate the average PER during the intra-cluster broadcasting phase. Let r denote the distance between the source node and a receiving node. We assume that the source node is in the center of the cluster, and there are N nodes uniformly distributed in a circular area with radius R_1 around the source node. The distance r is a random variable with distribution

$$f(r) = \frac{2r}{R_1^2}, \quad 0 < r \leq R_1. \tag{1}$$

We assume a Rayleigh fading channel on top of the average path loss that is proportional to r^{α}, where α is the propagation constant. The average signal to noise ratio (SNR) $\bar{\gamma}_1$ at the receiver side is

$$\bar{\gamma}_1 = \frac{GP_{t1}}{N_0 r^{\alpha}}, \tag{2}$$

where P_{t1} denotes the average transmit-energy per symbol in the broadcasting phase, N_0 is the one-sided spectral density of the additive noise, and G is a constant that is defined by the signal frequency, antenna gains, and other parameters [2]. The instantaneous SNR γ_1 is distributed as

$$f(\gamma_1) = \frac{1}{\bar{\gamma}_1} e^{-\frac{\gamma_1}{\bar{\gamma}_1}}. \tag{3}$$

Conditional on each realization of γ_1, the instantaneous PER can be approximated by [15]:

$$\text{PER}(\gamma_1) = \begin{cases} 1 & 0 < \gamma_1 < \gamma_{pn} \\ a_n e^{-g_n \gamma_1} & \gamma_1 \geq \gamma_{pn}, \end{cases} \tag{4}$$

where a_n, g_n and γ_{pn} are parameters that depend on the packet length, modulation, coding, and other factors. The values of these parameters are provided in [15] for various modulation/coding schemes. Since exact PER is not available and the approximation in (4) is quite accurate [15], we will use (4) in our following analysis.

Averaging the PER in (4) over the Rayleigh channel γ_1 in (3), we obtain:

$$\begin{aligned} \overline{\text{PER}}_1(\bar{\gamma}_1) &= \int_0^{\infty} \text{PER}(\gamma_1) f(\gamma_1) d\gamma_1 \\ &= \frac{a_n}{1 + g_n \bar{\gamma}_1} e^{-\gamma_{pn}\left(g_n + \frac{1}{\bar{\gamma}_1}\right)} + \left(1 - e^{-\frac{\gamma_{pn}}{\bar{\gamma}_1}}\right). \end{aligned} \tag{5}$$

Substituting (2) into (5), we have

$$\begin{aligned} \overline{\text{PER}}_1(P_{t1}, r) = &\frac{a_n r^{\alpha} N_0}{r^{\alpha} N_0 + g_n P_{t1} G} e^{-\gamma_{pn}\left(g_n + \frac{N_0 r^{\alpha}}{P_{t1} G}\right)} \\ &+ \left(1 - e^{-\frac{\gamma_{pn} N_0 r^{a}}{P_{t1} G}}\right). \end{aligned} \tag{6}$$

Averaging (6) over the distance [cf. (1)] leads to

$$\begin{aligned} \overline{\text{PER}}_1(P_{t1}) &= \int_0^{R_1} \overline{\text{PER}}_1(P_{t1}, r) \frac{2r}{R_1^2} dr \\ &= \int_0^{R_1} \left[\frac{a_n r^{a} N_0}{r^{a} N_0 + g_n P_{t1} G} e^{-\gamma_{pn}\left(g_n + \frac{N_0 r^{a}}{P_{t1} G}\right)} \right. \\ &\qquad \left. + \left(1 - e^{-\frac{\gamma_{pn} N_0 r^{a}}{P_{t1} G}}\right) \right] \frac{2r}{R_1^2} dr. \end{aligned} \tag{7}$$

The probability that M nodes in the cluster can decode the packet correctly is thus

$$P(M) = \binom{N}{M} \left[1 - \overline{\text{PER}}_1(P_{t1})\right]^M \left[\overline{\text{PER}}_1(P_{t1})\right]^{N-M}, \tag{8}$$

where the mean value of M is

$$M_E = E(M) = N[1 - \overline{\text{PER}}_1(P_{t1})]. \tag{9}$$

B. Inter-Cluster Cooperative Transmission

Suppose that M nodes will correctly decode the packet during the intra-cluster broadcasting phase. Hence, $M_0 = M + 1$ nodes (including the source node) will participate in the inter-cluster cooperative transmission phase. We now derive the average PER conditional on M.

Let P_{t2} denote the transmission energy per symbol per node. The average received SNR corresponding to each relay node is

$$\overline{\gamma}_2 = \frac{GP_{t2}}{N_0 L_1^{\alpha}}, \tag{10}$$

where L_1 is the inter-cluster distance between the transmitting and the receiving clusters (from center to center). Note that we approximate the transmission distances from all the transmitting nodes to the receiving node as L_1, since L_1 is usually much larger than the intra-cluster distance.

The distributed space-time coding is built upon the orthogonal space-time block codes [11], [6], where every cooperative transmitting node is assigned a column from the space-time block code matrix. Correspondingly, the effective SNR γ_2 after decoding is [6]:

$$\gamma_2 = \left(\sum_{i=1}^{M_0} |h_i|^2 \right) \overline{\gamma}_2 \tag{11}$$

where h_i denotes the channel between the ith transmitting node and the receiving node. Assume that h_i's are independent and identically distributed with a Rayleigh distribution, γ_2 is subject to a central chi-square distribution with $2M_0$ degrees of freedom as [16]

$$f(\gamma_2) = \frac{1}{\Gamma(M_0) \bar{\gamma}_2^{M_0}} \gamma_2^{M_0 - 1} e^{-\frac{\gamma_2}{\bar{\gamma}_2}}. \tag{12}$$

The average PER with M_0 transmitting nodes is then given as

$$\begin{aligned} &\overline{\text{PER}}_2(\bar{\gamma}_2, M_0) = \int_0^{\infty} \text{PER}(\gamma_2) f(\gamma_2) d\gamma_2 \\ &= \frac{1}{\Gamma(M_0) \bar{\gamma}_2^{M_0}} \left[\int_0^{\gamma_{pn}} \gamma_2^{M_0 - 1} e^{-\frac{\gamma_2}{\bar{\gamma}_2}} d\gamma_2 \right. \\ &\qquad \left. + a_n \int_{r_{pn}}^{\infty} \left(\gamma_2^{M_0 - 1} e^{-\left(g_n + \frac{1}{\bar{\gamma}_2}\right)\gamma_2} \right) d\gamma_2 \right] \\ &= \frac{a_n \Gamma\left(M_0, \left(g_n + \frac{1}{\bar{\gamma}_2}\right)\gamma_{pn}\right)}{\Gamma(M_0)(1 + g_n \bar{\gamma}_2)^{M_0}} + \frac{\Gamma(M_0) - \Gamma\left(M_0, \frac{\gamma_{pn}}{\bar{\gamma}_2}\right)}{\Gamma(M_0)}, \end{aligned} \tag{13}$$

where $\Gamma(x,y)$ is the incomplete Gamma function. Substituting (10) into (13), we obtain

$$\overline{\mathrm{PER}}_2(P_{t2},M_0)=\frac{a_n\Gamma\left(M_0,\left(g_n+\frac{L_1^\alpha N_0}{GP_{t2}}\right)r_{pn}\right)}{\Gamma(M_0)\left(\frac{GP_{t2}}{N_0L_1^\alpha}g_n+1\right)^{M_0}}+\frac{\Gamma(M_0)-\Gamma\left(M_0,\frac{r_{pn}N_0L_1^\alpha}{GP_{t2}}\right)}{\Gamma(M_0)}. \quad (14)$$

C. Overall Energy Minimization

In Section III-A, we characterized the distribution of the number (M) of nodes that participate in the cooperative transmission. In Section III-B, we analyzed the average PER when there are M_0 nodes cooperatively transmitting. Combining (8), (14), and $M_0=M+1$, the average end-to-end PER is

$$\begin{aligned}\overline{\mathrm{PER}}(P_{t1},P_{t2})&=\sum\nolimits_{M=0}^{N}P(M)\,\overline{\mathrm{PER}}_2(P_{t2},M+1)\\&=\sum\nolimits_{M=0}^{N}\binom{N}{M}[1-\overline{\mathrm{PER}}_1(P_{t1})]^M\\&\quad\times[\overline{\mathrm{PER}}_1(P_{t1})]^{N-M}\overline{\mathrm{PER}}_2(P_{t2},M+1).\end{aligned} \quad (15)$$

We now analyze the overall energy consumption, which includes both the transmission energy and the associated circuit energy consumption. According to [2], [9], when a wireless node transmits data to another node, the overall consumed energy per symbol is

$$P_{\mathrm{total}}=P_{\mathrm{ct}}+P_{\mathrm{cr}}+P_t, \quad (16)$$

where P_{ct} is the transmitter circuit energy consumption per symbol, P_{cr} is the receiver circuit energy consumption per symbol, and P_t is the transmitting energy per symbol. Without loss of generality, we assume that all nodes have the same P_{ct} and P_{cr}.

During the first phase, the source node transmits with energy P_{t1} per symbol and N nodes receive the signal. While in the second phase, on average there are M_E+1 nodes (including the source node) transmitting with energy P_{t2} per symbol per node. The total energy consumption $\bar{P}_{\mathrm{symbol}}$ in the network per symbol is

$$\begin{aligned}&\bar{P}_{\mathrm{symbol}}\\&=P_{t1}+P_{\mathrm{ct}}+(M_E+1)(P_{\mathrm{t2}}+P_{\mathrm{ct}})+(N+1)P_{\mathrm{cr}}.\end{aligned} \quad (17)$$

The total energy consumption for a packet

$$\bar{P}_{\mathrm{packet}}=L_s\bar{P}_{\mathrm{symbol}}=\frac{1}{b}L_b\bar{P}_{\mathrm{symbol}}, \quad (18)$$

where L_s is the number of symbols in a packet, L_b is the number of bits in a packet, and b denotes how many bits a symbol conveys, which is decided by the choices on modulation and coding [15].

To minimize the overall energy consumption under a certain PER requirement, we need to solve the following optimization problem (over P_{t1} and P_{t2})

$$\begin{aligned}\min_{P_{t1},P_{t2}}\quad&\bar{P}_{\mathrm{packet}}=\frac{1}{b}L_b\Big\{P_{t1}+P_{\mathrm{ct}}+(N+1)P_{\mathrm{cr}}\\&+\left[N\left(1-\overline{\mathrm{PER}}_1(P_{t1})\right)+1\right](P_{t2}+P_{\mathrm{ct}})\Big\}\\\text{subject to}\quad&0\le P_{t1}\le P_{\max},\\&0\le P_{t2}\le P_{\max},\\&\overline{\mathrm{PER}}(P_{t1},P_{t2})\le\overline{\mathrm{PER}}_0\end{aligned} \quad (19)$$

where $P_{\max}$ is the maximum transmitting energy per symbol allowed at each node and $\overline{\mathrm{PER}}_0$ is the PER target that is stipulated by the system. For each given P_{t1}, the value of P_{t2} can be uniquely determined by the PER constraint. Hence, we can solve (19) by a one-dimensional search on P_{t1}.

The optimization problem in (19) also suggests that the energy benefit of cooperative communication is related to other system parameters, such as the number of nodes N in the cluster, the cluster size R_1, and the inter-cluster distance L_1. If some or all of these parameters are adjustable, (19) can be generalized to a multi-variable combinatorial optimization problem shown as follows:

$$\begin{aligned}\min_{\mathbf{x}}\quad&\bar{P}_{\mathrm{packet}}=\frac{1}{b}L_b\Big\{P_{t1}+P_{\mathrm{ct}}+(N+1)P_{\mathrm{cr}}\\&+\left[N\left(1-\overline{\mathrm{PER}}_1(P_{t1})\right)+1\right](P_{t2}+P_{\mathrm{ct}})\Big\}\\\text{subject to}\quad&g_i(\mathbf{x})\le 0\qquad i=1,\cdots,N_c,\end{aligned}$$

where the design vector $\mathbf{x}$ may contain variables $\{P_{t1},P_{t2},N,R_1,L_1,\overline{\mathrm{PER}}_0,L_b,b\}$, and the feasible region is defined by N_c constraints.

IV. NUMERICAL RESULTS

We now compare the proposed energy-optimal cooperative communication scheme with the non-cooperative direct communication from the source to the destination, under the same PER constraint. We consider a networking scenario that has no hard requirements on the throughput and delay (referred to as "network scenario 1"). For example, in a sensor network for ecological environment monitoring, system lifetime is of paramount importance and the requirements on the throughput and delay are much less critical. For such networks, we compare the energy consumption of cooperative communication with that of direct communication for transferring the same amount of packets; the achievable

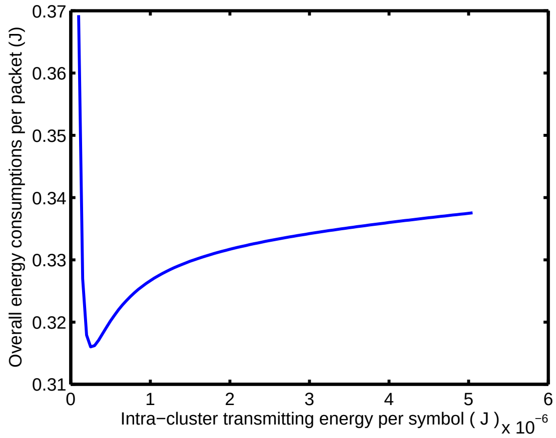

Fig. 2. Energy consumption vs. intra-cluster broadcast energy

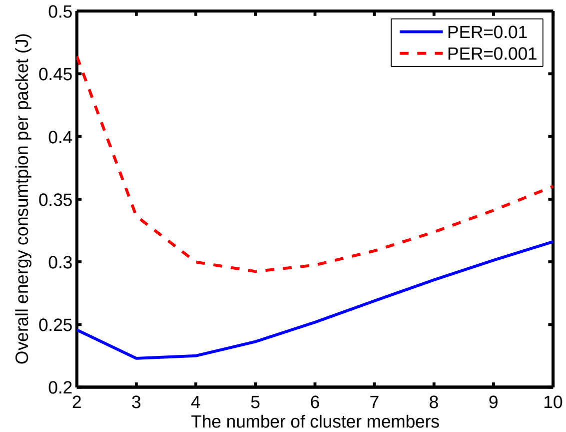

Fig. 3. Energy consumption vs. number of cluster nodes

information rates and delays are different because cooperative communication needs twice the transmission time due to the relay operation. In our related work [14], we have also studied the scenario with hard requirements on throughput and delay (referred to as "network scenario 2"), where comparisons are carried out under the same throughput and delay requirements. Due to space limitation, we only present results for network scenario 1 here.

For direct communication, the energy consumption $\bar{P}_{\text{direct}}$ is obtained from (6) with $r = L_1$ based on the PER constraint. We define an energy efficiency parameter η as the ratio of the energy consumption of cooperative communication to that of direction communication

$$\eta = \frac{\bar{P}_{\text{packet}}}{\bar{P}_{\text{direct}}}. \tag{20}$$

Throughout this section, we set the power loss constant $\alpha = 2$, $N_0 = 10^{-10}$ W/HZ, and $G = 1$. BPSK modulation method is used for both schemes. The corresponding parameters a_n, g_n and r_{pn}, are obtained from Table I of [15]. The information bit rate is set to be 10 kb/s. The packet length is of 1080 bits. Using parameters from [2], [17], the transmitter circuit power is 150 mW and the receiver circuit power is 100 mW, from which P_{ct} and P_{cr} can be computed.

Case 1: Overall energy consumption versus intra-cluster transmit power. We set $R_1 = 20$ m, $L_1 = 200$ m, $\overline{\text{PER}}_0 = 0.01$, and $N = 10$. Fig. 2 shows that an optimal P_{t1} exists to minimize the total energy consumption. In this example, if $P_{t1} = 2.5 \cdot 10^{-7}$ J, P_{packet} reaches the minimum value of $3.16 \cdot 10^{-1}$ J. If $P_{t1} < 2.5 \cdot 10^{-7}$ J, no enough nodes can correctly decode the packets, thus the energy benefit from the cooperation is limited. If $P_{t1} > 2.5 \cdot 10^{-7}$ J, too many nodes can correctly decode the packets and participate in the relay operation. The energy benefit from the cooperation is offset by the increase of P_{t1} and additional circuit energy consumed by the cooperating nodes.

Case 2: Overall energy consumption versus number of nodes in the cluster. We set $R_1 = 20$ m, $L_1 = 200$ m, $\overline{\text{PER}}_0 = 0.01, 0.001$. We change N continuously from 1 to 10. We observe from Fig. 3 that $\bar{P}_{\text{packet}}$ does not decrease monotonically with N. Instead, there exists an optimal value for N. For example, when $\overline{\text{PER}}_0 = 0.01$, the optimal N is 3. This can be explained as follows. With the increase of N, there will be more potential cooperative transmitting nodes. Although a larger N can reduce the inter-cluster transmitting energy consumption (by cooperative communication), it also introduce additional circuit energy cost. When N increases, the additional circuit energy consumption will surpass the reduction of the inter-cluster transmitting energy. This suggests that a proper sleep/wake-up mechanism can be introduced to reduce the number of active sensors at any given time if there are a large number of sensors within a cluster.

Case 3: Overall energy consumption versus intra-cluster distance. We set $L_1 = 200$ m, $\overline{\text{PER}}_0 = 0.01$, $N = 3, 5, 10$. We change R_1 from 5 m to 25 m. Fig. 4 shows that $\bar{P}_{\text{packet}}$ increases slowly with R_1, but at different rates for different N. The more cluster nodes we have, the less the impact of the intra-cluster distance on the overall energy consumption.

Case 4: Packet error rate versus overall energy consump-

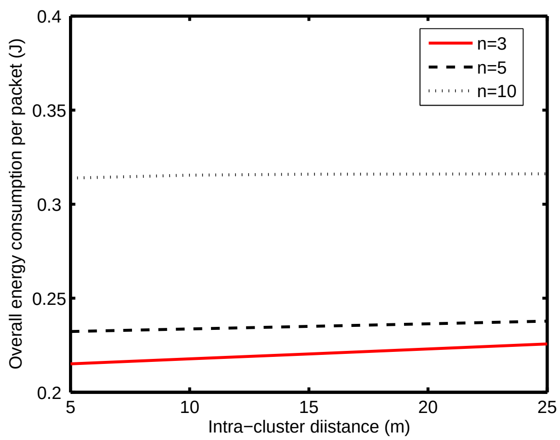

Fig. 4. Energy consumption vs. intra-cluster distance

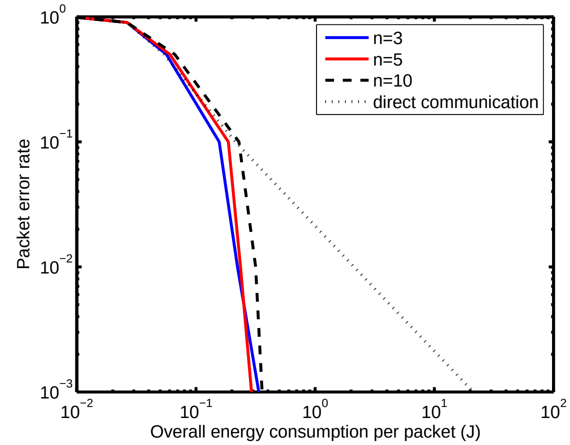

Fig. 5. PER vs overall energy consumption

tion. We set $R_1 = 20$ m, $L_1 = 200$ m, and $N = 3, 5, 10$. As shown in Fig. 5, when the required PER is relatively large, the energy advantage of cooperative communication is less significant. When the required PER is larger than 10^{-1}, cooperative communication consumes the same or more energy than direct communication. With the decrease of PER, cooperative communication becomes more and more energy efficient. Thus, cooperative communication is preferable in systems that require a small PER.

Fig. 6 depicts the energy characteristics when $\overline{\text{PER}}_0$ changes from 0.01 to 0.0001. We observe that although the minimum overall energy per packet $\bar{P}_{\text{packet}}$ derived from (19) increases when the average PER drops, the energy efficiency parameter η decreases (meaning more efficient). Hence, cooperative communication is more energy efficient when the required PER is relatively low. Fig. 6(b) demonstrates the huge energy benefit that cooperative communication can bring. For example, when $\overline{\text{PER}}_0 = 0.001$ and $N = 5$, the energy efficiency parameter of cooperative communication can be as low as 0.02; i.e., cooperative communication consumes one fiftieth of the needed energy for direct communication.

Case 5: Overall energy consumption vs. inter-cluster distance. We set $R_1 = 20$ m, $\overline{\text{PER}}_0 = 0.01$, $N = 3, 5, 10$, and change L_1 from 100 m to 300 m. Fig. 7 shows that although the overall energy consumption per packet $\bar{P}_{\text{packet}}$ increases with L_1, the energy efficiency becomes higher. Therefore, the larger the inter-cluster distance, the more energy efficient the cooperative communication becomes. From Fig. 7, we see that when $L_1 < 245$ m, the system with $N = 3$ consumes the least energy. When 245 m$< L_1 < 300$ m, the system with $N = 5$ consumes the least energy. This implies that the optimal N depends on the inter-cluster distance.

V. CONCLUSIONS

In this paper, we analyze the energy issues for cooperative communication in a clustered wireless sensor network, where the number of cooperating nodes depends on the correct packet reception within a cluster. We formulate a multi-parameter optimization problem to minimize the overall energy consumption. Through numerical results, we show that the total energy consumption can be considerably reduced by adjusting the transmit power for intra-cluster and inter-cluster transmission. We also show that having more nodes in a cluster may be less energy efficient due to the extra circuit energy consumed by relay nodes. In addition, under different requirements on PER, the optimal number of sensors in the cluster is different. Jointly optimizing multiple network parameters with efficient numerical methods is a promising future research direction.

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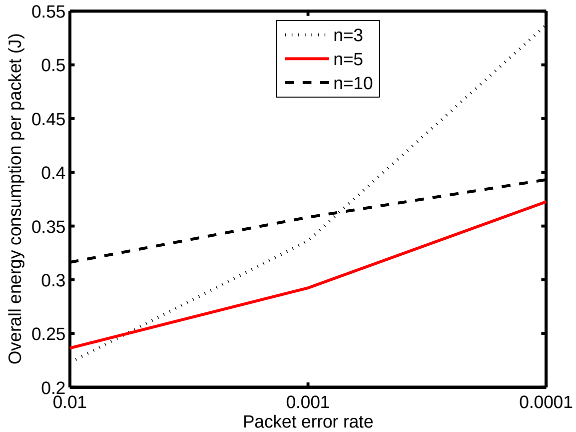
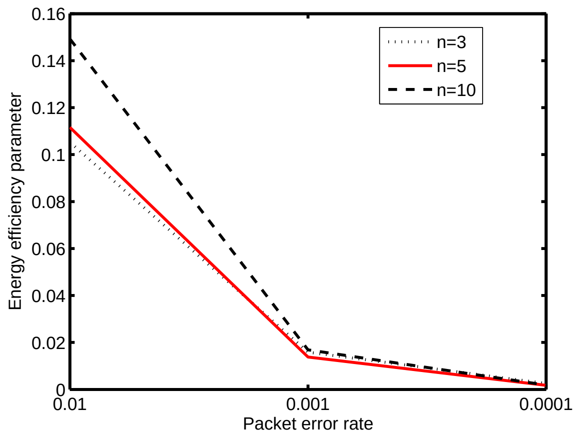


(a) Energy consumption per packet



(b) Energy consumption ratio of cooperative communication relative to direct communication

Fig. 6. Energy characteristics vs. PER

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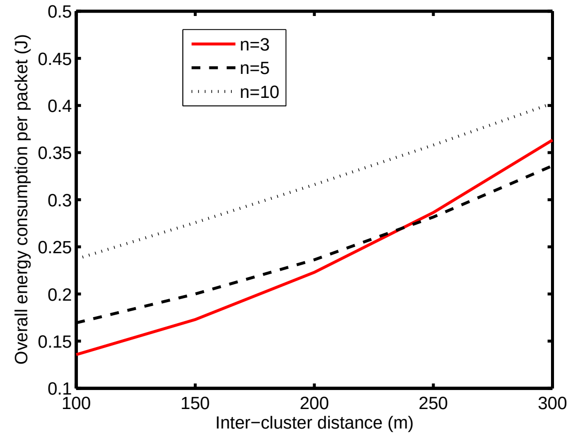
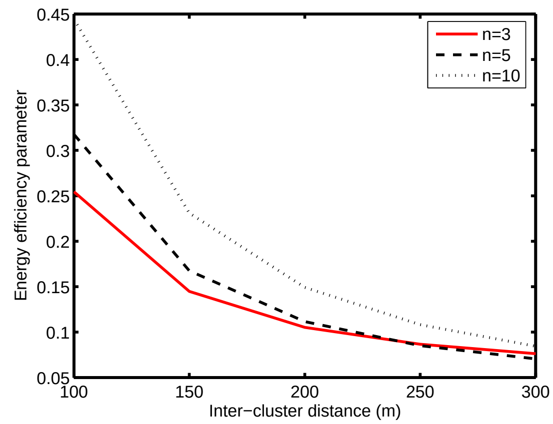


(a) Energy consumption per packet



(b) Energy consumption ratio of cooperative communication relative to direct communication

Fig. 7. Energy characteristics vs. inter-cluster distance

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