Research Article

Energy Efficiency Optimization of Cooperative Communication in Wireless Sensor Networks

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In wireless sensor networks (WSNs), cooperative communication represents a potential candidate to combat the effects of channel fading by exploiting diversity gain achieved via cooperation among the relays nodes. However, for the energy-constrained WSN, to what extent cooperative communication can save energy consumption for a successful packet transmission is still unknown. Energy efficiency of cooperation and direct transmission schemes in WSN is studied and compared in this paper. The expressions of energy efficiency of the two schemes are derived, respectively. The numerical results reveal that for the small distance separation between the source and destination nodes, the direct transmission scheme is more energy efficient than cooperation and the relay location, packet size, and modulation level have important effects on energy efficiency. At last, energy efficiency maximization for the cooperative communication system is achieved by optimizing both the packet size and modulation level jointly.

1. Introduction

Wireless sensor networks (WSNs) are composed of nodes typically powered by batteries, for which replacement or recharging is very difficult [1]. With finite energy, we can only transmit a finite amount of information. Therefore, minimizing the energy consumption for data transmission becomes one of the most important design considerations for WSN. Unfortunately, the channel fading has a great effect on the reliability of data transmission and energy consumption in WSN. Cooperative diversity represents a potential candidate to combat the effects of channel fading by exploiting diversity gain achieved via cooperation among the relays nodes [2–4].

Various cooperative schemes have been developed and proved to be highly effective in terms of throughput or capacity compared with the noncooperative scheme [5–13]. Multi-node cooperative schemes have been investigated in [5–7]. Distributed space-time coding for cooperative systems has been proposed in [5, 6], where a number of nodes transmit the different columns of a space-time coding matrix simultaneously to the destination. Distributed beamforming schemes have been also proposed in [7], which require all cooperators to be synchronized and cophased such that the signals from the cooperators can be combined constructively at the destination. Single-relay selective cooperative schemes have been investigated recently in [8–10], where only one out of a set of potential candidates is chosen to aid the communication process, and the relay selection can be based on instantaneous channel gains. Compared with multinode cooperative schemes, the single-relay selective cooperative scheme is easy to implement and incur less cooperation overhead since it requires neither distributed space-time coding nor cooperative beamforming. Moreover, it can potentially achieve the same diversity-multiplexing tradeoff as that of multinode cooperative schemes [9, 10]. Hence, the single-relay selective cooperative strategy is practically more appealing.

Compared with the noncooperative scheme named as the direct transmission (DT) scheme in this paper, the single-relay cooperative transmission (CT) scheme can mitigate the required transmission energy for the successful data transmission. However, a successful packet transmission in the single-relay CT scheme involves two transmitting nodes, the source and the relay node, transmitting an identical data packet to the destination node via relaying way, which

might increase energy consumption. Therefore, compared with DT, to what extent the single-relay CT can save energy consumption for a successful packet transmission in WSN is still unknown. For the energy-constrained WSN, it is desired that the proper design of CT scheme can conduct minimum energy consumption for the successful packet transmission between the source and the destination. Furthermore, designing energy efficient single-relay CT schemes suitable for WSN is still an open problem.

Motivated by previous researches, in order to minimize the energy consumption for the successful packet transmission in the single-relay cooperative system, the optimal incremental relaying (IR) cooperation strategy is investigated in this paper. Energy efficiency is a fair and appropriate metric to performance evaluation and comparison between the DT and CT, which can be defined as a ratio of the number of packet bits transmitted successfully to energy consumption. Specifically, the energy efficiency expressions of DT and CT are firstly derived, respectively. Then, the effects of the locations of relay nodes, the packet size, and modulation level on energy efficiency are discussed detailedly. At last, energy efficiency maximization for the single-relay cooperative communication system is achieved by optimizing both the packet size and modulation level jointly, and the performance of the optimal IR cooperative scheme is compared with that of the traditional IR cooperative scheme and the DT scheme.

2. Related Work and Paper Contributions

There is a large amount of previous works focusing on the energy efficiency optimization problem of communication in WSN. Energy efficiency based packet size optimization in WSN was investigated firstly in [14]. Energy efficiency of large-scale proactive and reactive WSN for applications involving data-centric and location-centric queries was evaluated in [15]. In [16], the authors studied the joint optimization problem of transmit power time and bit energy efficiency in CDMA WSN. Optimal transmission range for wireless sensor networks based on energy efficiency was conducted in [17, 18]. However, all the aforementioned papers focused on the energy efficiency problem of noncooperative communication scheme in WSN. Different from research of these works, energy efficiency of the multinode cooperative transmission exploiting distributed space-time codes was studied in [19–22], where cooperation was utilized for data transmission between clusters of nodes in WSN. Besides, several energy efficient transmission strategies for WSN were analyzed assuming the presence of powerful mobile agents equipped with antenna arrays and complex processors in [23]. However, few attempts have been done on the energy efficiency of the single-relay CT. In our work, we consider a single-relay CT which is more bandwidth efficient compared with multinode CT exploiting distributed space-time codes. Moreover, it is easier to implement than the multinode CT exploiting distributed space-time codes, as the later requires synchronization between the spatially separated relays performing the distributed space-time code.

Specially speaking, the CT scheme studied in this paper is different from the multihop relay transmission essentially. Due to the limited transmission ranges of nodes, the data packet of the source node needs to be relayed to the sink node via the multihop fashion, which is the final receiving node for the data packet. In this paper, the data transmission via each hop is named as the direct transmission (DT) which does not exploit the cooperative nodes. During the each-hop transmission from the transmitting node to the receiving node, due to the broadcast nature of the wireless medium, the neighbor node of the transmitting node may overhear the data packet. Then, the neighbor node can be exploited to retransmit the data packet to the receiving node, which is the so-called cooperative transmission. So, in CT, the receiving node can receive the two same data packets, with which cooperative diversity can be achieved. But, in the multihop relay transmission scheme, the receiving node can only receive one data packet from the previous transmitting node during the each-hop transmission.

Furthermore, our study is concentrated on the energy efficiency analysis and optimization of cooperative communication in two-hop fashion. Essentially speaking, multihop cooperative communication is a cooperative routing problem, which is not the solved issue in this paper. In future, our work will be generalized to multihop cooperative fashion.

We can summarize the contributions of our work as follows. The analysis approach of energy efficiency of the single-relay IR cooperative communication in WSN is proposed in this paper and expressions of energy efficiency for DT and CT are derived, respectively. The numerical results reveal that for the small distance separation between the source and the destination, DT is more energy efficient than CT. Moreover, the effect of the locations of relay nodes on energy efficiency in cooperation communication is evaluated, which can provide guidelines for relay selection algorithms in the large-scale WSN. At last, the optimal IR cooperative scheme is conducted by optimizing both the packet size and modulation level jointly. The results show that energy efficiency of the optimal IR cooperative scheme outperforms that of the traditional IR cooperative scheme. In summary, we provide important guidelines for WSN designers to decide when and how to apply the cooperative communication scheme.

The remainder of this paper is organized as follows. Section 3 introduces the system models and discusses the different aspects of the two considered communication architectures, namely direct and cooperative transmission. Energy efficiency expressions of DT and CT are derived, respectively, in Section 4. Some numerical results are given and a discrete optimization algorithm for energy efficiency maximization is proposed in Section 5. Finally, some conclusions are drawn in Section 6.

3. System Model

Consider three relevant nodes in WSN, represented, respectively, by S (source node), R (relay node), and D (destination node), and assume that S wants to send the packet to D, as
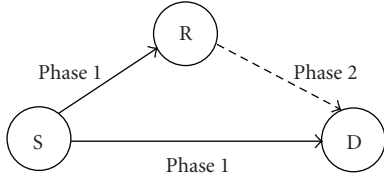
FIGURE 1: A typical scenario model in WSN.

illustrated in Figure 1. In the DT scheme, S just transmits the packet to node D directly, thus, the energy should be consumed for supporting the required SNR in node D for the successful packet transmission.

In the incremental relaying CT scheme, we consider a two-phase cooperation protocol. In the first phase, S transmits a data packet to D, and due to the broadcast nature of the wireless medium, R can overhear this data packet. If D receives the packet in this phase correctly, then it sends back an acknowledgment (ACK) and R just idles. On the other hand, if D cannot decode the received packet correctly, then it sends back a negative acknowledgment (NACK). In this case, if R was able to receive the data packet correctly in the first phase, then it forwards it to D. Otherwise, this packet will be dropped.

Compared with DT, CT can mitigate the required transmission energy of S for the successful packet transmission. However, a successful packet transmission in CT involves two transmitting nodes, S and R, transmitting an identical data packet to D via relaying way, which might increase energy consumption. Therefore, compared with DT, to what extent CT can save energy consumption for a successful packet transmission is still unknown. For the energy-constrained WSN, it is desired that the proper design of CT scheme can conduct minimum energy consumption for the successful packet transmission between the source and the destination.

Next, the wireless channel and the packet error rate (PER) models of DT and CT are described. Consider that the wireless channel between any two nodes is subject to flat Rayleigh fading and channel gains for different links are assumed to be statistically mutually independent and unchanged during the time period of a data packet. Assuming that the transmit power is constant for all nodes, denoted by P_t, path loss exponent is represented by α, and the noise components are modeled as additional white Gaussian noise (AWGN) with variance N_0, we can obtain the description of received SNR γ for a link by the probability distribution function (PDF),

$$f_{\gamma_{ij}}(\gamma) = \frac{1}{\sigma_{ij}} \exp\left(-\frac{\gamma}{\sigma_{ij}}\right) \quad ((ij) = (\text{sd}), (\text{rd}), (\text{sr})), \quad (1)$$

where (ij) denotes the different links and σ_{ij} is the average SNR and can be expressed by

$$\sigma_{ij} = \frac{P_t \left(r_{ij}\right)^{-\alpha}}{N_0}, \quad (2)$$

where r_{ij} denotes the distance of a link with nodes i and j being transmitter and receiver, respectively.

Assume that uncoded M-QAM is adapted with the modulation level $b = \log_2 M$ bit/symbol, the closed-form expression for the average symbol error rate (SER) of a link is given by [24]

$$\text{SER}_{ij} \approx 2\left(1 - 2^{-b/2}\right)\left(1 - \sqrt{\frac{3\sigma_{ij}}{2(2^b - 1) + 3\sigma_{ij}}}\right) \quad (b \geq 2). \quad (3)$$

So, the PER of a link can be obtained as

$$\text{PER}_{ij} = 1 - \left(1 - \text{SER}_{ij}\right)^{L/b}, \quad (4)$$

where L is the length of the data packet.

Apparently, the PER of DT equals to the PER of the S-D link and can be written as

$$\text{PER}^D = \text{PER}_{\text{sd}} = 1 - (1 - \text{SER}_{\text{sd}})^{L/b}. \quad (5)$$

Having the PER of all the links given by (4), the PER of CT can be evaluated by

$$\text{PER}^C = \text{PER}_{\text{sd}}\text{PER}_{\text{sr}} + \text{PER}_{\text{sd}}(1 - \text{PER}_{\text{sr}})\text{PER}_{\text{rd}}. \quad (6)$$

Equation (6) shows that the successful packet transmission from node S to node D can be carried out through the path of S-D or S-R-D, and the corresponding PER might be reduced by R's retransmission.

Noting that the entire data packet is composed of the packet header, payload and trailer, energy efficiency of the system can be expressed by

$$\eta = \frac{L_p(1 - \text{PER})}{E}, \quad (7)$$

where L_p is the payload length of a data packet, PER denotes the packet error rate of DT or CT, and E is energy consumption of transporting a data packet with the DT or CT scheme. Therefore, energy efficiency η represents the ratio of the number of packet bits transmitted successfully to energy consumption.

In the next section, we will evaluate energy efficiency of DT and CT.

4. Performance Analysis

In this section, we characterize the system performance in terms of energy efficiency for the direct and cooperative scenarios to quantify the energy savings, if any, gained by applying cooperative transmission.

Assume that the total energy consumption of the system is composed of the power consumption of the power amplifiers and all other circuit blocks of the nodes. Let β denotes the loss factor of the power amplifier ($0 < \beta < 1$) and P_{ct} and P_{cr} represent the power consumption of circuit blocks of transmitter and receiver, respectively. Moreover, the symbol rate R_s is assumed to be constant, and then, the bit rate is given by $R_s \times b$.

4.1. Direct Transmission. The total consumed energy of transmitting one data packet with the DT scheme can be expressed by

$$E^D = (P_t(1+\beta) + P_{ct} + P_{cr})\frac{L}{R_b}. \tag{8}$$

Substituting (5) and (8) into (7), energy efficiency of DT is given by

$$\eta^D = \frac{L_p(1 - \text{PER}^D)}{E^D}. \tag{9}$$

4.2. Cooperative Transmission. Different from DT, the total consumed power for CT to transmit one packet is a discrete random variable and can be statistically described as follows,

$$P_{\text{total}}^C = \begin{cases} P_t(1+\beta) + P_{ct} + 2P_{cr}, & (1 - \text{PER}_{sd}), \\ P_t(1+\beta) + P_{ct} + 2P_{cr}, & (\text{PER}_{sd}\text{PER}_{sr}), \\ 2P_t(1+\beta) + 2P_{ct} + 3P_{cr}, & (\text{PER}_{sd}(1 - \text{PER}_{sr})). \end{cases} \tag{10}$$

In the first term of the above expression, when the packet transmission over the S-D link is successful with the probability $(1 - \text{PER}_{sd})$, the consumed power is composed of the consumed power in node S $(P_t(1+\beta) + P_{ct})$ and the receiving power of the D and R $2P_{cr}$. Similarly, $(\text{PER}_{sd}\text{PER}_{sr})$ denotes the failure probability of both the transmissions over the S-D and the S-R links, and so the consumed power is still $(P_t(1+\beta) + P_{ct} + 2P_{cr})$. The last term corresponds to the event indicating the R's retransmission while the failure of transmission is over the S-D link.

So the total consumed energy of transmitting one data packet with CT is written as

$$E^C = \frac{(1 - \text{PER}_{sd})(P_t(1+\beta) + P_{ct} + 2P_{cr})L}{R_b}$$

$$+ \frac{\text{PER}_{sd}\text{PER}_{sr}(P_t(1+\beta) + P_{ct} + 2P_{cr})L}{R_b} \tag{11}$$

$$+ \frac{\text{PER}_{sd}(1 - \text{PER}_{sr})(2P_t(1+\beta) + 2P_{ct} + 3P_{cr})L}{R_b}.$$

Substituting (6) and (11) into (7), energy efficiency of CT is given by

$$\eta^C = \frac{L_p(1 - \text{PER}^C)}{E^C}. \tag{12}$$

We have derived energy efficiency expressions of DT and CT. So, the energy efficiency gain can be defined as the ratio of energy efficiency of CT to that of DT and can be obtained as

$$G = \frac{\eta^C}{\eta^D}. \tag{13}$$

When this ratio is smaller than one, this indicates that DT is more energy efficient and that the extra energy consumption induced by cooperation overweighs its gains in decreasing the packet error rate of the system.

5. Numerical Results

There are different system parameters such as the link distance, the packet size, and modulation level, which have important effects on energy efficiency. In order to understand the effect of each of these parameters, we will study the performance of CT and DT in Matlab 7.0.1 when varying one of these parameters and fixing the rest.

Without the loss of the generality, we assume that the S, R, and D nodes lie along a straight line and the R-D distance is $r_{rd} = q \times r_{sd}$ $(0 < q < 1)$.

In all of the numerical simulations, the system parameters take the following values when considered fixed: $\alpha = 4$, $\beta = 0.3$, $P_t = 0.001$ w, $P_{ct} = 10^{-4}$ w, $P_{cr} = 5 \times 10^{-5}$ w, $R_s = 10^4$ symbol/s, $N_0 = 10^{-13.5}$, $q = 0.5$, $L_p = 40$ bit, $L = 56$ bit, and $b = 4$. The values of α, β, P_t, P_{ct}, and P_{cr} are taken from the specifications of Mica2 motes [25].

5.1. Effects of the S-D Distance and the Relay Locations on Energy Efficiency. Firstly, we study the effects of the S-D distance and the relay locations on energy efficiency.

Figure 2 depicts energy efficiency of CT and DT, which are expressed by "C" and "D", respectively, and Figure 3 depicts the energy efficiency gain for different relay locations, respectively. At S-D distances below 80 m, DT is more energy efficient than CT. This is because the extra energy consumption of the relay node induced by cooperation outweighs its gain in decreasing the packet error rate of the system. However, at S-D distances above 80 m, CT is more energy efficient than DT as shown in Figures 2 and 3. Because the PER of DT deteriorates more seriously as the S-D distance increases endlessly. However, due to the benefit of cooperation, the PER of CT can keep much lower than that of DT. The analytical and numerical results reveal a distance threshold behavior that separates regions where DT is better from regions where CT prevails.

Moreover, when q equals 0.5, which means that the S-R distance equals the R-D distance, the energy efficiency gain is best among all of relay locations as shown in Figure 3. When the S-D distance is below 80 m, the relay location hardly affects energy efficiency gain. The effect of relay locations on the energy efficiency can provide guidelines for relay selection algorithms in the large-scale wireless sensor networks.

5.2. Effects of the Packet Size and Modulation Level on Energy Efficiency. Secondly, the effects of the packet size and modulation level on energy efficiency are discussed detailedly.

Based on the theoretical analysis in Sections 3 and 4, Figure 4 shows the joint effects of the packet size and modulation level on energy efficiency of CT at $r_{sd} = 140$. It can be seen that the energy efficiency plane is smooth, which indicates a good match between the local maximum and the global maximum of energy efficiency. We have conducted extensive simulation for the DT system and found that the energy efficiency plane of it is also smooth. So, energy efficiency can be maximized by optimizing the packet size and modulation level jointly.
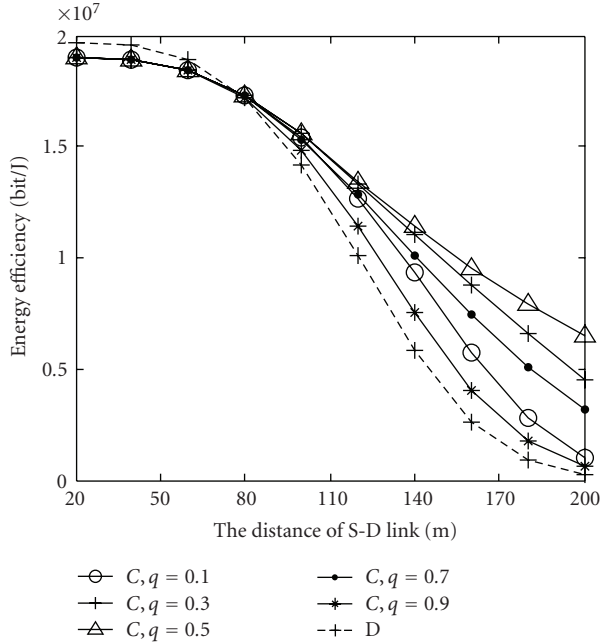
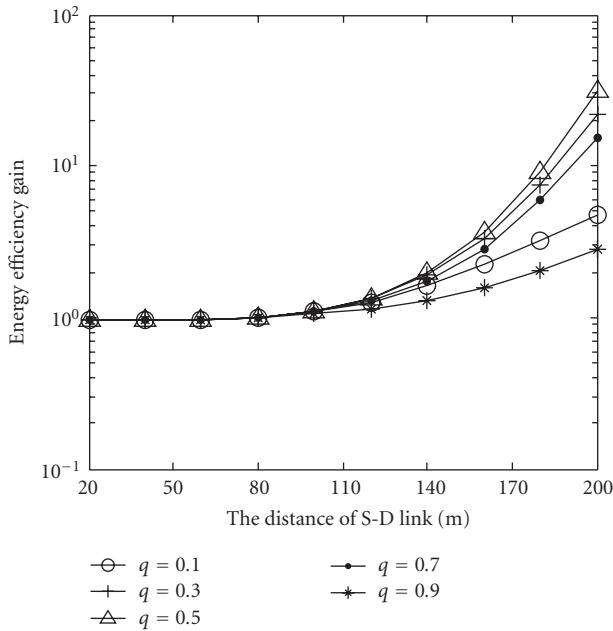FIGURE 2: Energy efficiency versus the S-D distance for different relay locations.

FIGURE 3: Energy efficiency gain versus the S-D distance for different relay locations.

5.3. Discrete Optimization Algorithm for Energy Efficiency Maximization. As discussed in Section 5.2, energy efficiency clearly depends on two important parameters: the packet length L and the modulation level b. As we know, a small packet length indicates that the packet transmission is not susceptible to errors but at the cost of a large packet overhead. A large L implies that the packet is more susceptible to errors, which may decrease energy efficiency. As for the modulation
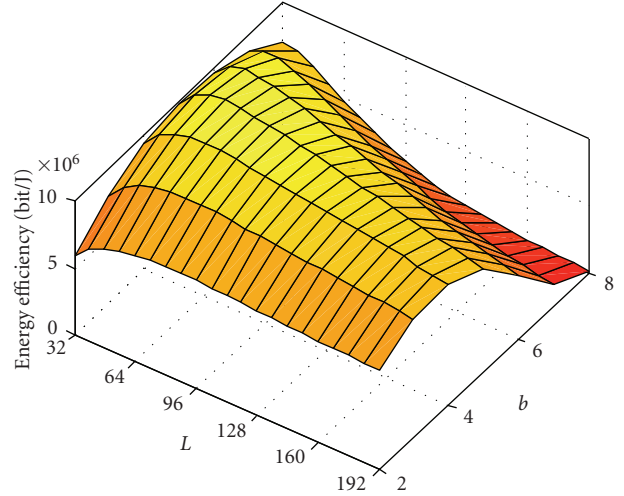

FIGURE 4: Energy efficiency versus the packet size and modulation level for the cooperation scenario ($r_{sd} = 140$).

level b, a packet with a low modulation level is more robust but may result in inefficient use of the channel and energy. On the other hand, a packet with a high modulation level is more liable to error but carries more information per symbol. Therefore, the joint optimal L and b are desired so as to maximize energy efficiency. Noting that both the packet size L and modulation level b are discrete, we propose a two-dimensional discrete optimization algorithm to find the maximum of energy efficiency for the CT and DT systems by optimizing both L and b jointly.

Let $\eta(L, b)$ represents energy efficiency with a packet length L and a modulation level b and η^* denotes the optimal energy efficiency. Assume the minimum of L equals 32 bits, the incremental step value of L equals 1 byte (8 bits), and the maximum value of b equals 8. The discrete optimization algorithm is described as shown in Algorithm 1.

In the optimization algorithm, we start searching the optimal packet size L_{opt} with a fixed $b = 2$, and for each incremental b, we compute the maximum of energy efficiency by optimizing L. The whole process will terminate when energy efficiency begins to fall. This is based on the observation that the local energy efficiency and the global energy efficiency always match perfectly when b varies and L is fixed or L varies and b is fixed as shown in Figure 4. It can be seen that with discrete optimization algorithm, the joint optimization of L and b is decoupled so that the complexity can be reduced dramatically.

Using the discrete optimization algorithm, the curves of energy efficiency for the optimal CT and DT systems, which are expressed by "Optimal C" and "Optimal D", respectively, are plotted in Figure 5. For comparison, the energy efficiency curves for CT and DT systems with fixed $L = 56$ and $b = 4$ are also given in Figure 5. The corresponding optimal values of packet size L and modulation level b are drawn in Figures 6 and 7, respectively.

It can be seen from Figure 5 that the optimal CT scheme exhibits the best performance and energy efficiency of the

Initialization: $b = 2, k = 2; \eta^* = 0$;
while $(b < 9)$ %Performing condition of the algorithm
    $L_m = 32$;   %The minimum of packet size 32 bits
    $L_t = L_m + 8$;   %Increasing the packet size with 8 bits
    %Comparing energy efficiency η for different L
    {**while** $(\eta(L_m, b) < \eta(L_t, b))$
        $L_m = L_t$;
        $L_t = L_t + 8$; %Increasing the packet size with 8 bits
    end while}
    %Saving the temporary value of energy efficiency η_k
    $b_k = b$;
    $L_k = L_m$;
    $\eta_k = \eta(L_k, b_k)$;
    {**if** $(\eta_k > \eta^*)$
        $\eta^* = \eta_k$;
        $b^* = b_k$;
        $L^* = L_k$;
    else
        $\eta_{\mathrm{opt}} = \eta^*$; %The optimal value of energy efficiency
        $b_{\mathrm{opt}} = b^*$; %The optimal value of packet size
        $L_{\mathrm{opt}} = L^*$; %The optimal value of modulation level
        stop;   %Terminating the whole loop
    end if}
    $b = b + 1$;   %Increasing the modulation level with 1
    $k = k + 1$;   %Performing the next loop
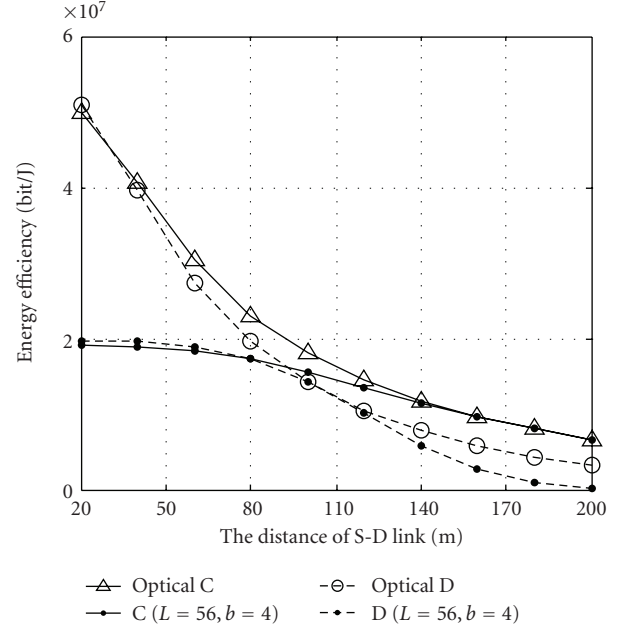**end while**

ALGORITHM 1

FIGURE 5: Energy efficiency versus the S-D distance for optimal and nonoptimal scenarios.
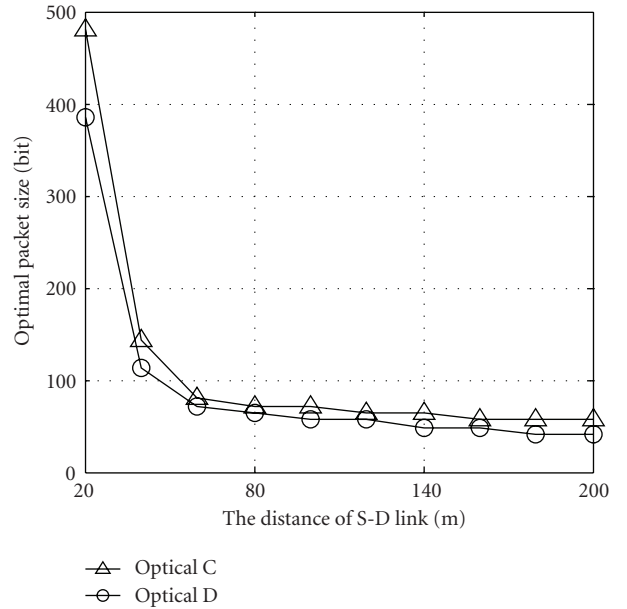

FIGURE 6: Optimal packet size versus the S-D distance for cooperation and direct transmission scenarios.

optimal DT scheme is much less than that of the optimal CT scheme, especially when the S-D distance becomes longer and longer. In addition, energy efficiency of the optimal CT scheme is better than that of the traditional CT scheme with fixed L and b.

Moreover, when the S-D distance is above 160 m, energy efficiency of the optimal CT scheme equals that of the traditional CT scheme with fixed $L = 56$ and $b = 4$. Because, at the S-D distances above 160, the optimal packet size and modulation level for the optimal CT scheme are also 56 and 4, respectively, as shown in Figures 6 and 7.

At last, specially speaking, the optimal cooperative communication scheme should use the large packet size and high modulation level when the S-D distance is shorter and adopt the small packet size and low modulation level when the S-D distance is longer, as shown in Figures 6 and 7.

6. Conclusions and Future Work

In this paper, energy efficiency of the cooperative and direct transmission schemes in WSN is studied and compared. The numerical results reveal that for small distance separation between the source and destination, direct transmission is more energy efficient than cooperation and, above the threshold distance, cooperation gains can be achieved. Moreover, when the S-R distance equals the R-D distance, energy efficiency gain is the best among all of the different relay locations. This conclusion can provide guidelines for relay selection algorithms in the large-scale wireless sensor networks. At last, a two-dimensional discrete optimization algorithm is proposed to find the maximum of energy efficiency for cooperative communication system by optimizing both the packet size and modulation level jointly. Energy efficiency of the optimal cooperative scheme is better than that of the traditional cooperative scheme with fixed L and b. In summary, we provide important guidelines for WSN designers to decide when and how to apply the cooperative communication scheme.
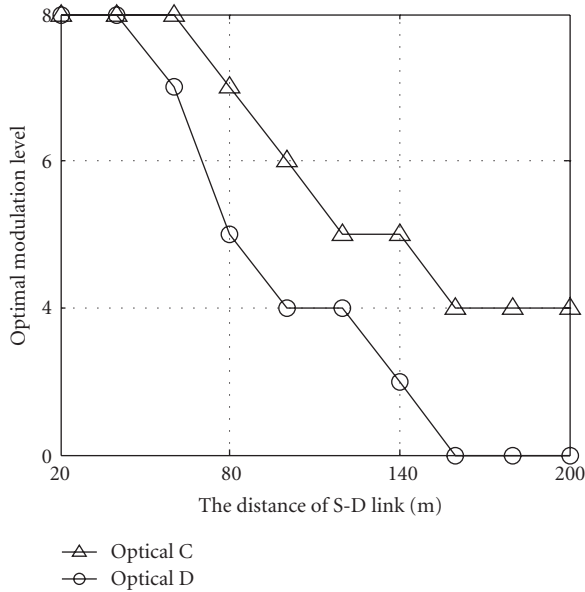
FIGURE 7: Optimal modulation level versus the S-D distance for cooperation and direct transmission scenarios.

We present the performance analysis of cooperative communication in two-hop fashion, which will be generalized to multihop cooperative fashion. Moreover, the constant transmit power is adopted at all the nodes in this paper. In future, the power control scheme can be integrated into our research.

Acknowledgment

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