ENERGY-EFFICIENT COOPERATIVE COMMUNICATION BASED ON POWER CONTROL AND SELECTIVE RELAY IN WIRELESS SENSOR NETWORKS

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ABSTRACT

Cooperative communication with single relay selection is a simple yet effective communication scheme for energy-constrained networks. In this paper, we investigate the minimum energy relay selection mechanism jointly with transmission power control. Based on the proposed MAC layer signaling, a set of potential relays determine their needed transmission power to participate in the cooperative communication, while only the "best" one is chosen to minimize the overall energy consumption. The relay selection is done in a distributed manner with minimum overhead. Numerical and simulation results confirm significant energy savings and outage improvement of the proposed scheme relative to direct transmission alternatives.

I. INTRODUCTION

Energy-constrained networks, such as wireless sensor networks, have nodes typically powered by batteries, for which replacement or recharging is very difficult, if not impossible [1]. Minimizing the energy consumption per unit information transmission becomes one of the most important design considerations for such networks.

Multi-input multi-output (MIMO) techniques based on antenna arrays can dramatically reduce the required transmission power under a certain throughput requirement due to spatial diversity. Even though each node could be limited in size to mount multiple antennas in wireless sensor networks, multiple nodes could collaborate to form a virtual antenna array to achieve spatial diversity [2], [3]. Such strategies are termed as cooperative communication schemes. Various cooperative schemes, e.g., cooperative beamforming and distributed space time coding, have been developed and proved to be highly effective in many networking scenarios [3], [4], [5].

Selective cooperative communication schemes have been investigated recently in [6], [7], [8], where a single relay or multiple relays are selected to collaborate on information transmission. In [6], the energy efficiency of cooperative communication based on a simple relay selection strategy is investigated. Since cooperative beamforming is used at the transmitter, multiple relays may be selected as the final relay set [6]. A *single* relay selection strategy based on distance estimation has been investigated in [7], where a distributed scheme always selects the cooperative relay that is closest to the destination from the set of relays that have decoded the data successfully. A selective cooperation scheme based on the instantaneous channel strength is proposed in [8], where potential relays compete with each other based on certain policies and the winner is selected to aid the communication process afterwards.

Compared with multi-node cooperative communication schemes, single-relay cooperation schemes need neither cooperative beamforming nor distributed space-time coding. Only the "best" relay will participate in the final signal transmitting procedure. Thus they incur less cooperation overhead and are much easier to implement. Besides, they can potentially achieve the same diversity-multiplexing tradeoff as that of multi-node cooperative schemes [8]. Hence, single-relay-selection cooperative strategies are practically appealing and have also been discussed in [9], [10], [11].

Most of the aforementioned papers on selective cooperation schemes focus on the multiplexing-diversity tradeoff property, where a fixed power level is usually assumed at the source and relays. Power control issues are investigated in [12] from an information theoretic point of view based on the outage probability analysis. In this paper, we develop an energy-efficient single-relay-selection cooperative communication scheme for wireless sensor networks. Our novelty is that we consider the MAC layer protocol and the power control strategy at the physical layer jointly. The power control and node selection are unified into the MAC signaling procedure, in a distributed fashion. Although we focus on the policy that minimizes the overall energy consumption per packet, other policies can be easily incorporated into the proposed scheme. Simulation results demonstrate that

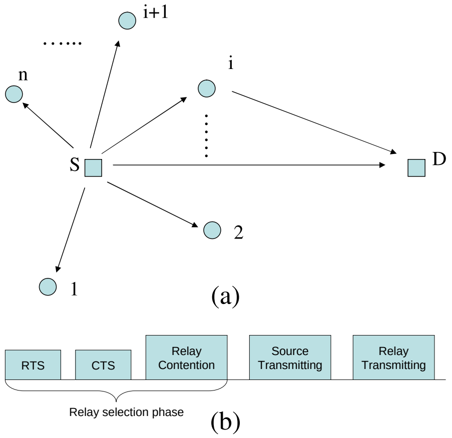

Fig. 1. (a) The "best" node from all potential candidates $(1, 2, \dots, n)$ is selected to relay the message to the destination; (b) The overall communication process for one data burst

the proposed scheme is highly energy-efficient relative to direct transmission alternatives.

The rest of the paper is organized as follows. In Section II, we describe the system setup and the cooperative transmission procedure. In Section III, we provide the power control solutions for the proposed scheme. In Section IV, numerical and simulation results are given. Conclusions are drawn in Section V.

II. SYSTEM MODEL AND COOPERATION PROCEDURE

As shown in Fig. 1(a), the single-relay-selection cooperative communication scheme selects the "best" relay from a set of potential relay nodes, and then uses this "best" relay to aid the source-to-destination communication. Before describing the specific process, we make the following assumptions.

1) The fading channels between nodes are flat in frequency, and remain constant during one burst data transmission (i.e., block-fading).
2) The reciprocal channel from node B to node A is the same as the channel from node A to node B.
3) All nodes can adjust their instantaneous transmission power within the range of $[0, P_{\max}]$, where $P_{\max}$ is imposed by certain physical constraints (e.g., by the battery). For convenience, we fix the symbol duration T_s, and use the transmission energy per symbol as the control parameter. The maximal transmission energy per symbol is then $E_{\max} = P_{\max} T_s$.

As depicted in Fig. 1(b), the overall communication process for one data burst consists of three phases.

Phase 1: Relay selection. When a source node has data to transmit, it first sends out a RTS (request-to-send) message with energy $E_{\max}$ per symbol to contend the shared wireless channel, as in the 802.11 protocol [13]. The destination node and the source's neighbor nodes (denoted as the set $\mathcal{N}_s$) hear this message, based on which the channels between them and the source are estimated (denoted by $|h_{sd}|^2$ and $|h_{sk}|^2$, $k \in \mathcal{N}_s$, respectively). After receiving the RTS message, the destination node replies a CTS (clear-to-send) message with energy $E_{\max}$ per symbol. Based on the information in CTS and the assumption A2, the source node and the destination's neighbor nodes (denoted as the set $\mathcal{N}_d$) estimate the channels from them to the destination, which are denoted as $|h_{sd}|^2$ and $|h_{jd}|^2$, $j \in \mathcal{N}_d$, respectively. After a successful RTS/CTS exchange, all neighboring nodes of both the source and the destination become aware of this transmission event and refrain themselves from transmitting data to avoid collisions [13]. The relay candidate set $\mathcal{N}_r$ is given as $\mathcal{N}_r = \mathcal{N}_s \bigcap \mathcal{N}_d + \{s\}$, where the extra s term means that we allow the source node itself to participate in the relay competition process and can act as its own relay if it is "better" than others, i.e., repetition coding may be used.

After the RTS/CTS exchange, all overhearing nodes will calculate their priorities according to some predefined policies based on the information collected from RTS/CTS packets (The policy and needed system parameters will be specified in Section III). Then they compete with each other within a time window, which is called the "relay contention period". The competition process is executed as follows. Node i will listen to the channel in the relay contention period. If it has not heard any beacon message from other nodes for time t_i (where the higher its priority is, the smaller t_i is, and the priority measure will be defined later), it will broadcast one beacon message to grab the channel. In this way, the node with the highest priority will transmit first and "win" the competition to serve as the relay for cooperative data transmission. The competition is done within a fixed competition window of length $T_{\max}$. In some cases, it is possible that no relays can support the data transmission (to meet a predefined source-to-destination data rate R) or multiple beacon messages collide. Under such circumstances, the source cannot decode beacon messages from others and no cooperative communication can be formed. If the source node cannot support the data transmission by itself, it will back off and wait for some random time before initiating another RTS.

To assist the data transmission process with a predefined source-to-destination data rate R, each relay node determines the transmission energy per symbol E_{t1} for the source and the transmission energy per symbol E_{t2}

for itself. Since the computation is done locally at the relay node, the relay node needs to inform the source node the calculated E_{t1} in its beacon message. The relationship among R, E_{t1}, and E_{t2} will be discussed in Section III.

Phase 2: Source transmission. The source node sends out data with transmission energy E_{t1} per symbol. The selected "best" relay decodes the received data. The destination stores the received signal from the source and defers the decoding to the next phase.

Phase 3: Relay transmission. The "best" relay forwards the decoded data to the destination with transmission energy E_{t2} per symbol. The destination combines the received data and the stored signal (received in Phase 2) for joint decoding. The transmitted signals in Phase 2 and Phase 3 will have the same length and format, but with different power.

The proposed protocol is fully distributed and easy to implement. Since the RTS/CTS exchange is implemented in the 802.11-like MAC protocols anyway, the additional overhead is mainly due to the relay competition. Compared with data transmission, the relay competition period is short and is usually negligible. In addition, since there is only one node selected to relay the transmission, it is much simpler than traditional distributed space-time coding or beamforming that requires multi-node cooperation.

A similar scheme has been proposed in [8], where potential relay nodes obtain the channel gains during the RTS/CTS exchange. Based on the channel pair ($|h_{si}|^2$ and $|h_{id}|^2$ for node i), the relays compete and only one is selected. Our differences from [8] are: (i) we incorporate power control at the physical layer while [8] does not; and (ii) our objective is to derive energy-efficient cooperative schemes, while [8] studies the diversity-multiplexing tradeoff of single relay selection in the high power regime.

We next detail the proposed energy-efficient cooperative communication scheme based on single relay selection and power control.

III. ENERGY-EFFICIENT COOPERATIVE SOLUTION

We now specify how each node determines its power control strategy to minimize the overall energy consumption per packet, and how the priority parameter is defined for each relay candidate.

A. Optimal power control solution

For presentation brevity, we normalize the noise variance to one and assume capacity-achieving codes over each link[1]. The minimum required transmission energy to support a data rate R (bits per symbol) from the source to the destination shall satisfy:

$$R \leq \frac{1}{2}\log_2(1 + E_{t1}\,|h_{sd}|^2 + E_{t2}\,|h_{id}|^2), \qquad (1)$$

when node i is used for relaying. The factor $1/2$ in (1) is due to equal time sharing between the source and relay transmissions. From (1), we obtain

$$E_{t1}\,|h_{sd}|^2 + E_{t2}\,|h_{id}|^2 \geq (2^{2R} - 1). \qquad (2)$$

On the other hand, node i has to decode the source signal successfully. Thus, the transmission energy must satisfy:

$$\frac{1}{2}\log_2(1 + E_{t1}\,|h_{si}|^2) \geq R, \qquad (3)$$

which translates to

$$E_{t1} \geq \frac{(2^{2R} - 1)}{|h_{si}|^2}. \qquad (4)$$

Each node will independently carry out an optimization problem; for node i, this is given as

$$\begin{aligned} \min_{E_{t1},E_{t2}} \quad & f_i(E_{t1}, E_{t2}) = \frac{N_b}{R}(E_{t1}+E_{t2}) = N_s(E_{t1}+E_{t2}), \\ \text{subject to} \quad & \frac{(2^{2R} - 1)}{|h_{si}|^2} \leq E_{t1} \leq E_{\max}, \\ & E_{t1}\,|h_{sd}|^2 + E_{t2}\,|h_{id}|^2 \geq (2^{2R} - 1), \\ & 0 \leq E_{t2} \leq E_{\max}, \end{aligned} \qquad (5)$$

where N_b is the length of the packet in bits and $N_s = N_b/R$ is the length of packet in symbols. The objective function $f_i(E_{t1}, E_{t2})$ is proportional to the overall transmission energy consumed by one data packet if node i serves as the relay. The optimization problem is formed and solved for each data burst, where the length of the data burst will be upper bounded by the channel coherence time, since we assume that the channels remain invariant during the whole cooperative communication process as depicted in Fig. 1(b).

Note that in the analysis herein, we neglect the energy consumption due to the RTS/CTS transmission and the relay competition. These energy consumption overheads are more or less fixed, regardless of which node is selected. We will present simulation results in Section IV-B that accounts for these overheads.

The optimization problem in (5) can be easily solved by linear programming. The feasible solutions for (E_{t1}, E_{t2}) form a polygon within the region

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[1] For practical codes, we could use the gap approximation of [14] that the maximum supported rate is $\log_2(1 + \mathrm{SNR}/\Gamma)$ rather than the capacity of $\log_2(1 + \mathrm{SNR})$, where Γ is the "SNR gap" [14].

$[0, E_{\max}] \times [0, E_{\max}]$, where the optimal solution is one of the corner points of the polygon [15]. For various conditions on $|h_{sd}|^2$, $|h_{si}|^2$, $|h_{id}|^2$, and R, the feasible solution regions are shown in Fig. 2, case by case. Specifically, we list the optimal power control solutions for node i ($i \in \mathcal{N}_r - \{s\}$) as follows.

Case 1:

$$\text{Conditions:} \quad |h_{sd}|^2 > |h_{si}|^2, \ E_{\max} \geq \frac{(2^{2R}-1)}{|h_{sd}|^2}$$

$$\text{Optimal solution:} \quad E_{t1} = \frac{(2^{2R}-1)}{|h_{sd}|^2}, \ E_{t2} = 0.$$

This case corresponds to Fig. 2(a), where the channel $|h_{si}|$ is weaker than $|h_{sd}|$. Hence, the source-to-relay link becomes the bottleneck such that there are no benefits to use relay i. In this case, node i will not participate in the relay competition and keep silent.

Case 2:

$$\text{Conditions:} \quad |h_{sd}|^2 \leq |h_{si}|^2, \quad |h_{id}|^2 > |h_{sd}|^2,$$

$$\frac{(2^{2R}-1)}{|h_{si}|^2} \leq E_{\max}, \frac{(2^{2R}-1)}{|h_{id}|^2}\left(1 - \frac{|h_{sd}|^2}{|h_{si}|^2}\right) \leq E_{\max}$$

$$\text{Optimal solution:} \quad E_{t1} = \frac{(2^{2R}-1)}{|h_{si}|^2},$$

$$E_{t2} = \frac{(2^{2R}-1)}{|h_{id}|^2}\left(1 - \frac{|h_{sd}|^2}{|h_{si}|^2}\right).$$

This case corresponds to Fig. 2(b), where both $|h_{si}|$ and $|h_{id}|$ are stronger than $|h_{sd}|$ such that energy efficiency can be improved by using relay i.

Case 3:

$$\text{Conditions:} \quad |h_{id}|^2 \leq |h_{sd}|^2, \ \frac{(2^{2R}-1)}{|h_{sd}|^2} \leq E_{\max}$$

$$\text{Optimal solution:} \quad E_{t1} = \frac{(2^{2R}-1)}{|h_{sd}|^2}, \ E_{t2} = 0. \tag{6}$$

This case corresponds to Fig. 2(c), in which there are no benefits to use node i as the relay due to the weak link $|h_{id}|$. In this case, node i will not participate in the relay competition and keep silent.

Case 4:

$$\text{Conditions:} \quad |h_{sd}|^2 \leq |h_{si}|^2, |h_{id}|^2 > |h_{sd}|^2,$$

$$\frac{(2^{2R}-1)}{|h_{si}|^2} \leq E_{\max}, \frac{(2^{2R}-1)}{|h_{id}|^2}\left(1 - \frac{|h_{sd}|^2}{|h_{si}|^2}\right) > E_{\max},$$

$$\frac{(2^{2R}-1) - |h_{id}|^2 E_{\max}}{|h_{sd}|^2} \leq E_{\max},$$

$$\text{Optimal solution:} \quad E_{t1} = \frac{(2^{2R}-1) - |h_{id}|^2 E_{\max}}{|h_{sd}|^2},$$

$$E_{t2} = E_{\max}. \tag{7}$$

This case corresponds to Fig. 2(d), where the power constraint limits E_{t2} to be $E_{\max}$ when node i has better channel to the destination than the source node. With the relay node reaching the maximum power, the source node also needs to contribute sufficient transmission power to support the data rate R.

Case 5:

$$\text{Conditions:} \quad |h_{sd}|^2 \leq |h_{si}|^2, |h_{id}|^2 \leq |h_{sd}|^2,$$

$$\frac{(2^{2R}-1)}{|h_{sd}|^2} > E_{\max}, \frac{(2^{2R}-1)}{|h_{si}|^2} \leq E_{\max},$$

$$\frac{(2^{2R}-1) - |h_{sd}|^2 E_{\max}}{|h_{id}|^2} \leq E_{\max},$$

$$\text{Optimal solution:} \quad E_{t1} = E_{\max},$$

$$E_{t2} = \frac{(2^{2R}-1) - |h_{sd}|^2 E_{\max}}{|h_{id}|^2}. \tag{8}$$

This case corresponds to Fig. 2(e), where the power constraint limits E_{t1} to be $E_{\max}$ when the source node has better channel to the destination than relay node i. With the source node reaching the maximum power, the relay node needs to contribute sufficient transmission power to support the data rate R.

Case 6:

For all other conditions, there is no feasible solution to (5). This means that the system cannot support reliable transmission of the end-to-end data rate R if node i is selected as the relay. For convenience, we set $E_{t1} = \infty$ and $E_{t2} = \infty$ that lead to $f_i(E_{t1}, E_{t2}) = \infty$. As such, node i will not contend during the relay competition window and keep silent.

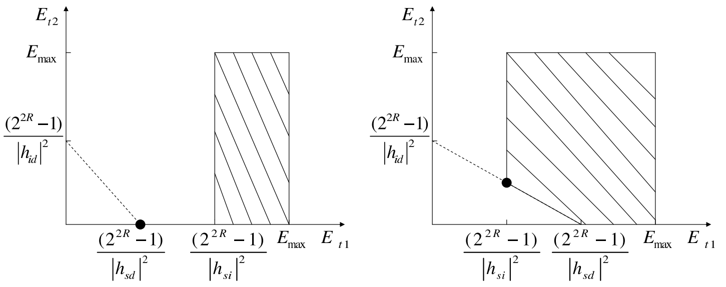
In our protocol, we also allow the source node to participate in the competition. For the source node, $|h_{si}|^2$ in (5) is replaced by $|h_{ss}|^2 = \infty$. The optimal power-control solution (E_{t1}, E_{t2}) at the source node is given as:

$$\begin{cases} \left(\frac{2^{2R}-1}{|h_{sd}|^2}, 0\right), & \frac{2^{2R}-1}{|h_{sd}|^2} \leq E_{\max} \\ \left(E_{\max}, \frac{2^{2R}-1}{|h_{sd}|^2} - E_{\max}\right), & E_{\max} \leq \frac{2^{2R}-1}{|h_{sd}|^2} < 2E_{\max} \\ (\infty, \infty), & \frac{2^{2R}-1}{|h_{sd}|^2} > 2E_{\max} \end{cases} \tag{9}$$

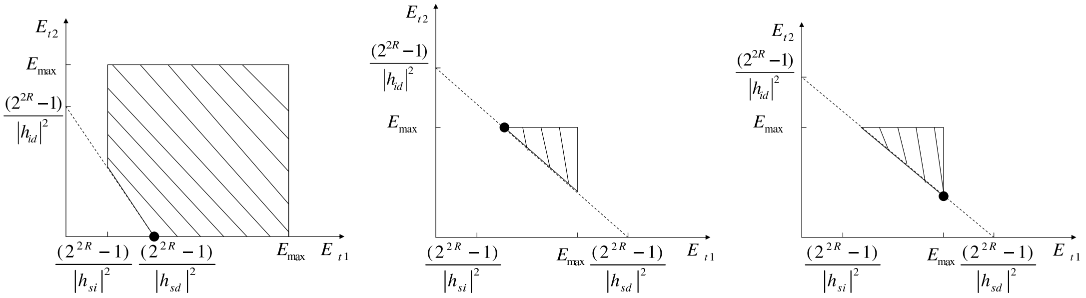
If the source node wins the competition, it will transmit with energy E_{t1} per symbol at the first time slot, and with E_{t2} per symbol at the second time slot. Note that the top part of (9) corresponds to (6) in case 3, the middle part corresponds to (8) in case 5, and the bottom part corresponds to case 6.

B. Signaling

In order to find the optimal power control solution, node i needs to know parameters $|h_{sd}|^2$, $|h_{si}|^2$, and



(a) Case 1 (b) Case 2



(c) Case 3 (d) Case 4 (e) Case 5

Fig. 2. The feasible region for power control solutions under different situations

$|h_{id}|^2$. As we have explained before, node i estimates $|h_{si}|^2$ based on the RTS message from the source and $|h_{id}|^2$ based on the CTS message from the destination. The concern is then how node i estimates $|h_{sd}|^2$. Since the destination already has h_{sd} after receiving RTS, we propose that the value of $|h_{sd}|^2$ is included in the CTS message. After the RTS/CTS exchange, node i can then find its optimal solution on (E_{t1}, E_{t2}) and the corresponding $f_i(E_{t1}, E_{t2})$.

The nodes in $\mathcal{N}_r$ will participate in the competition process according to its priority, which is reflected by a back-off time t_i. Specifically, before sending out the beacon message, the ith relay candidate delays time t_i as

$$t_i = \frac{f_i(E_{t1}, E_{t2})}{f(E_{\max}, E_{\max})} T_{\max}, \tag{10}$$

where $T_{\max}$ is the pre-defined contention window length and $f(E_{\max}, E_{\max}) = 2N_s \times E_{\max}$ is independent of i. Hence, any node that has a $f_i(E_{t1}, E_{t2})$ lower than $f(E_{\max}, E_{\max})$ gets a chance to be presented within the time window $[0, T_{\max}]$. Certainly, the node with the smallest $f_i(E_{t1}, E_{t2})$, i.e., the highest priority, will win.

Collision among beacon messages might happen if the delay time of the best relay and those of other relays are too close. A detailed analysis on the collision probability is given in [8]; it was shown that this probability is small in the scenarios considered therein. Note that this collision probability is closely related to the length of the beacon message and how the delay time t_i is defined. Here we choose (10) to compute the delay time t_i for simplicity and we argue that the collision probability can be further reduced if a more delicate (possibly nonlinear or discrete) mapping between $f_i(E_{t1}, E_{t2})$ and t_i is used. In this paper we neglect the influence of beacon message collisions just mentioned; analysis and algorithm development to reduce such collisions warrant future investigation.

IV. PERFORMANCE EVALUATION

In this section, we first present numerical results to show the benefits of our scheme. Then, we give our simulation results based on the ns-2 simulator.

A. Numerical results

We assume a random network where cooperative nodes are distributed randomly in a circular area with radius 120 meters. The source-destination pairs are randomly chosen, but with a distance of 100 m. We also assume that all nodes within the circular area can hear the RTS/CTS messages from the source and the destination nodes. The packet length is set to be 1000 bits. The symbol duration is $T_s = 10^{-4}$s.

We compare our cooperative scheme with two direct communication schemes, which support the same data rate. For direct communication scheme 1, source node transmits at rate R all the time, while for direct communication scheme 2, source node transmits at rate $2R$ half of the time and then remains idle for the other half.

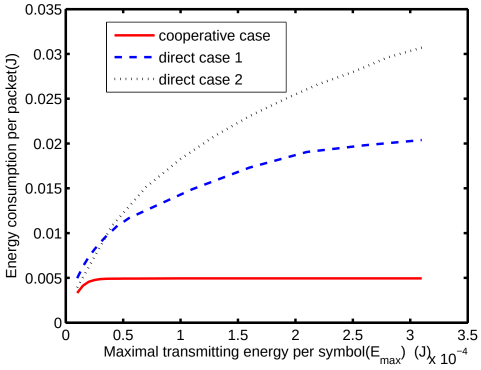


Fig. 3. Energy consumption per packet

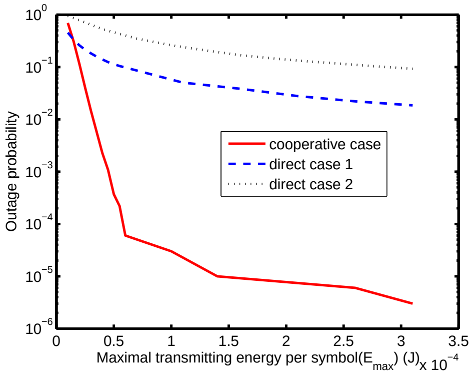


Fig. 4. Outage probability

Both schemes achieve the same average data rate as that of the cooperative case.

Case 1: Overall energy consumption and outage properties with varying $E_{\max}$. We set data rate $R = 2$ (bits per sample). A total of 10 relay nodes are randomly distributed in the whole network area. We change the maximum allowed energy consumption per symbol $E_{\max}$ (same for all the nodes) from 1×10^{-5} J to 3.5×10^{-4} J, and draw the overall energy consumption in Fig. 3, where we see clearly that compared with both direct communication schemes, cooperative communication achieves significant energy savings. For example, when $E_{\max} = 1.5 \times 10^{-4}$ J, the overall energy consumption per packet for the cooperative scheme is 0.54×10^{-2} J, while for the direct case 1, it is as high as 1.6×10^{-2} J, where a significant amount of energy is saved. Fig. 4 shows that in most cases, the outage probability of our scheme is also the smallest, where outage is declared when the source-to-destination rate R cannot be supported with the given power constraints. From this figure, we see that when the nodes are under the same maximum instantaneous transmit power constraint, our scheme outperforms direct communications in terms of both the average transmit power and the outage probability, in most situations.

Case 2: Outage probability versus energy consumption with different numbers of relay nodes. Here, we set $R = 2$ and change $E_{\max}$ to get different outage probability and energy consumption pairs. This way, we obtain the relationship between the outage probability and the average energy consumption per packet. Fig. 5 clearly shows that under the same outage probability, our scheme consumes much less energy than direct communication schemes in most situations. For example, if the required outage probability is 10^{-2}, when $n = 10$, the energy consumption per symbol is only 0.95×10^{-2} J; while for direct communication case 1, the consumed energy is about 2.3×10^{-2} J. Fig. 5 also shows that the energy benefit of our scheme increases with the number of nodes. This is reasonable since more cooperators can contribute more diversity gain that can be converted to energy efficiency.

B. Simulation results in ns-2

To test the impact of beacon collisions and energy overhead such as circuit energy consumption on our scheme, we simulate the proposed cooperative scheme by using one popular network simulator ns-2 [16]. We modify its 802.11 MAC protocol implementation to incorporate our scheme while keeping its RTS/CTS mechanism unchanged. For comparison, we have also simulated direct scheme 1. In the direct scheme, by measuring the signal strength of the CTS message from the destination, the source node gets to know the channel $|h_{sd}|^2$ and adjusts its power for data transmission accordingly.

In this set of simulations, multiple network nodes are uniformly distributed in a circular area with radius 100 meters. Every node randomly chooses a network node as its destination and generates the traffic with an average inter-packet arrival time uniformly chosen within the interval $(2s, 6s)$. The bit rate is set to be 10^4 bps, and the packet length is 1000 bits; thus one packet transmission is 100 ms. The lengths of RTS/CTS and the beacon message are set to be 10 bytes (80 bits) respectively, and the competition window of beacon message is set to be 10 ms, which is one tenth of the packet transmission time. The initial energy of every node is set to be 10 Joules. All energy consumption terms including the energy spent on RTS/CTS and in circuits are considered, where we set the transmitting circuit power as 15 mW and the receiving circuit power as 10 mW. Fig. 6 depicts the total number of packets transmitted during the network lifetime; here, the network lifetime is defined

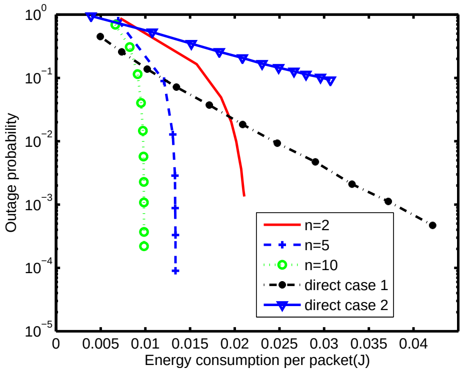


Fig. 5. Outage probability vs. energy consumption per packet

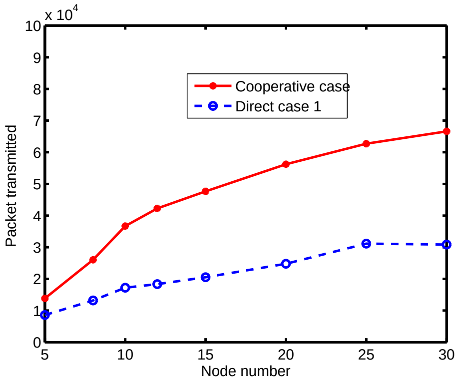


Fig. 6. The total number of packets transmitted via ns-2 simulation

as the time before the first node dies out. Compared with the direct communication scheme, we see that the total number of packets transmitted in our cooperative scheme is much larger. For example, when the number of nodes equals 10, the cooperative scheme can transmit three times more packets than the direct scheme before the first node dies.

V. CONCLUSIONS

In this paper we proposed an energy-efficient single relay selection cooperative communication scheme for wireless sensor networks, where the MAC layer protocol and the power control strategy are incorporated into the node selection process, in a distributed manner. The resulting cooperative scheme minimizes the overall energy consumption per packet. Numerical and simulation results confirmed that the energy efficiency and outage performance of the proposed scheme are much better than that of direct communication alternatives. The proposed scheme can be viewed as one example of cross-layer (MAC and physical layers) design for selective cooperative communications in the context of wireless sensor networks.

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