On the Energy Efficiency of Cooperative Communications in Wireless Sensor Networks

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Cooperative communications represent a potential candidate to combat the effects of channel fading and to increase the transmit energy efficiency in wireless sensor networks with the downside being the increased complexity. In sensor networks the power consumed in the receiving and processing circuitry can constitute a significant portion of the total consumed power. By taking into consideration such overhead, an analytical framework for studying the energy efficiency trade-off of cooperation in sensor networks is presented. This trade-off is shown to depend on several parameters such as the receive and processing power, the required quality-of-service, the power amplifier loss, and several other factors. The analytical and numerical results reveal that for small distance separation between the source and destination, direct transmission is more energy efficient than relaying. The results also reveal that equal power allocation performs as well as optimal power allocation for some scenarios. The effects of the relay location and the number of employed relays on energy efficiency are also investigated in this work. Moreover, there are experimental results conducted to verify the channel model assumed in the article.

Categories and Subject Descriptors: H.1 [**Models and Principles**]: Systems and Information Theory; C.2 [**Computer-Communication Networks**]: Network Architecture and Design—*Network communications*

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1. INTRODUCTION

Spatial diversity has been extensively studied in the context of Multiple-Input-Multiple-Output (MIMO) systems [Foschini and Gans 1998] to combat the effects of multipath fading. This is mainly because it provides a more bandwidth-efficient means to achieve diversity compared to frequency diversity schemes, besides not being prone to delay problems that might be encountered when applying time diversity schemes in case there is high temporal correlation.

However, in wireless networks, especially sensor networks, it might not be feasible to install more than one antenna on the wireless terminal because of space limitations or the required simplicity in implementation. To solve such problems, cooperative diversity has been introduced recently in Laneman et al. [2004] and Sendonaris et al. [2003b] as a means to provide spatial diversity via distributed antennas. Cooperation takes advantage of the broadcast nature of the wireless channel, in particular, two or more nodes can share their antennas to form a virtual array. For example, if we have two nodes, one acts as the source and transmits its information in one phase while the second node listens, and in a second phase the second node acts as a relay and forwards the received signal to the destination. There have been many protocols proposed in the literature to implement cooperation [Laneman et al. 2004; Laneman and Wornell 2003; Sendonaris et al. 2003b, 2003a; Sadek et al. 2006b]. Symbol error rate performance of cooperative communications and optimal power allocation are studied in Su et al. [2005] and Sadek et al. [2006a], capacity results are reported in Kramer et al. [2005], coverage extension through relaying has been investigated in Sadek et al. [2006c] and Hu et al. [2004]. These works and others have demonstrated the significant gains promised by cooperation in terms of throughput increase, energy efficiency, and coverage extension, which renders cooperation a very exciting paradigm to implement in wireless networks [Liu et al. 2008]. Some recent works also consider designing distributed space-time coding for wireless networks [Scutari and Barbarossa 2005; Seddik et al 2008].

All of the previous works study the gains of cooperative diversity under the ideal model of negligible listening and computing power. In sensor networks, and depending on the type of motes used, the power consumed in receiving and processing may constitute a significant portion of the total consumed power. Cooperative diversity can provide gains in terms of savings in the required transmit power in order to achieve a certain performance requirement because of the spatial diversity it adds to the system. However, if one takes into account the extra processing and receiving power consumption at the relay and destination nodes required for cooperation, then there is obviously a trade-off between the gains in the transmit power and the losses due to the receive and processing powers when applying cooperation. Such a trade-off between the gains promised by cooperation and this extra overhead in terms of the energy efficiency of the system should be taken into consideration in the network design.

In this article we investigate such a trade-off and characterize the gains of cooperation under such extra overhead. Moreover, we also consider some practical system parameters as the power amplifier loss, the Quality-of-Service (QoS) required, the relay location, and the optimal number of relays. We compare between two communications architectures, direct transmission and cooperative transmission. Our performance metric for comparison between the two architectures is the energy efficiency of the communication scheme. More specifically, for both architectures we compute the optimal total power consumption to achieve certain QoS requirements and we calculate the cooperation gain defined as the ratio between the power required for direct transmission and cooperation. When this ratio is smaller than one, this indicates that direct transmission is more energy efficient, and that the extra overhead induced by cooperation overweighs its gains in the transmit power. Moreover, we compare between optimal power allocation at the source and relay nodes and equal power allocation. The results reveal that under some scenarios, equal power allocation is almost equivalent to optimal power allocation. We also investigate the effect of relay location on the performance to provide guidelines for relay assignment algorithms. Finally, we generalize the these results to the case of multiple relays trying to answer the important question of how many relays should be used for cooperation given some communication setup.

Our analytical and numerical results reveal that there is a threshold below which we should implement direct transmission and above which cooperation is more advantageous. Such results can provide guidelines for wireless sensor networks designers to decide when to cooperate and when not to cooperate. In our analysis we assume a Rayleigh fading channel model where the channel gains between different links fade independently. To verify our analytical model we did some experiments to test the channel correlation, and we used wireless network cards to do that. More details on our experiments and results are provided in Section 5.

Paper Contributions and Related Work. Circuit energy consumption was modeled in Yuan et al. [2006] in which a clustered-based cooperative MIMO scheme was proposed. This energy consumption model was used to characterize the optimal parameters for cluster formation as the number of cooperative nodes and the number of clusters. Using distributed MIMO between clusters has also been addressed in Bravos and Kanatas [2007] in which the energy efficiency of multihop transmission combined with MIMO was studied. In Zhang and Dai [2007] several transmission strategies for wireless sensor networks were analyzed assuming the presence of powerful mobile agents equipped with antenna arrays and complex processors. The mobile agents are assumed to be at the receiver side and its energy consumption is excluded from the analysis.

General guidelines for selecting the transmission strategy that minimizes the total energy consumption while guaranteeing a desired quality-of-service are presented. The energy efficiency of cooperative transmission via distributed space-time codes was studied in Cui et al. [2004]. Cooperation is utilized for data transmission between a cluster of nodes. It is assumed that the intermediate hops between the source and the destination can decode correctly without errors.

In our work, we take into consideration the possibility of the wireless channel being in outage between any two nodes in the network. We also consider an incremental relaying cooperation strategy which is more bandwidth efficient compared to distributed space-time codes. Moreover, it is easier to implement than distributed space-time codes, as the latter requires synchronization between the spatially separated relays performing the distributed space-time code.

We can summarize the contributions of our work as follows.

— We consider a practical framework for analyzing the performance of cooperative transmission in sensor networks by considering the extra overhead induced by enabling cooperation. This extra overhead appears in the extra processing and receiving powers at the relays and destination.
— Our analytical and numerical results reveal an interesting threshold behavior that separates regions where direct transmission is better from regions where cooperation prevails.
— We also show that under certain scenarios, equal power allocation has very close performance to optimal power allocation.
— Moreover, we show that for small distances between the source and the destination, the performance is not sensitive to relay location, which leads to simpler relay assignment algorithms.
— Our results also reveal that cooperative communication is more robust to poor power amplifier designs compared to direct transmission.
— Our analytical framework can also be utilized to determine the optimal number of relays for any given scenario.

In summary, we provide important guidelines for wireless sensor network designers to decide when and how to apply the cooperative communication paradigm, and when is direct transmission more energy efficient.

The remainder of the article is organized as follows. In the next section we describe the system and channel model, and discuss the different aspects of the two considered architectures, namely direct and cooperative transmission. In Section 3 we formulate a constrained optimization problem which minimizes the total consumed power under the constraint of achieving a given outage probability. Section 4 generalizes the previous analysis for the multiple relay scenario. Section 5 has two parts; the first part describes the experimental results in which we verify some of the assumptions on the channel models, and the second part discusses some numerical results to give insight into our theoretical results.

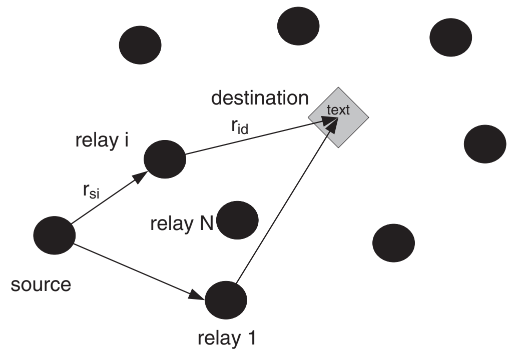

Fig. 1. System model.

2. SYSTEM MODEL

We consider a single source-destination pair separated by distance r_{sd}. The number of potential relays available to help the source is N. This is illustrated in Figure 1, where the distances between source and relay i, and relay i and destination are r_{si} and r_{id}, respectively, and $i \in \{1, 2, \ldots, N\}$. First we analyze the performance of the single relay scenario, and later we extend the results for arbitrary finite N.

We compare the performance of two communication scenarios. In the first scenario only direct transmission between the source and destination nodes is allowed, and this accounts for conventional direct transmission. In direct transmission, if the channel link between the source and destination encounters a deep fade or strong shadowing, for example, then the communication between these two nodes fails. Moreover, if the channel is slowly varying, which is the case in sensor networks due to the stationarity or limited mobility of the nodes, then the channel might remain in the deep fade state for long time (strong time correlation), hence conventional automatic repeat request (ARQ) might not help in this case.

In the second communication scenario, we consider a two-phase cooperation protocol. In the first phase, the source transmits a signal to the destination, and due to the broadcast nature of the wireless medium the relay can overhear this signal. If the destination receives the packet from this phase correctly, then it sends back an acknowledgement (ACK) and the relay just idles. On the other hand, if the destination cannot decode the received packet correctly, then it sends back a negative acknowledgement (NACK). In this case, if the relay was able to receive the packet correctly in the first phase, then it forwards it to the destination. So the idea behind this cooperation protocol is to introduce a new ARQ in another domain, which is the spatial domain, as the links between different pairs of nodes in the network fade independently. The assumptions of high temporal correlation and independence in the spatial domain will be verified through experiments, as discussed in Section 5.

Next the wireless channel and system models are described. We consider a sensor network in which the link between any two nodes in the network is subject to narrowband Rayleigh fading, propagation path-loss, and Additive White

Gaussian Noise (AWGN). The channel fades for different links are assumed to be statistically mutually independent. This is a reasonable assumption as the nodes are usually spatially well separated. For medium access, the nodes are assumed to transmit over orthogonal channels, thus no mutual interference is considered in the signal model. All nodes in the network are assumed to be equipped with single-element antennas, and transmission at all nodes is constrained to the half-duplex mode, that is, any terminal cannot transmit and receive simultaneously.

The power consumed in a transmitting or receiving stage is described as follows. If a node transmits with power P, only $P(1-\alpha)$ is actually utilized for RF transmission, where $(1-\alpha)$ accounts for the efficiency of the RF power amplifier which generally has a nonlinear gain function. The processing power consumed by a transmitting node is denoted by P_c. Any receiving node consumes P_r power units to receive the data. The values of the parameters α, P_r, P_c are assumed the same for all nodes in the network and are specified by the manufacturer. Following, we describe the received signal model for both direct and cooperative transmissions.

First, we describe the received signal model for the direct transmission mode. In the direct transmission scheme, which is employed in current wireless networks, each user transmits his signal directly to the next node in the route which we denote as the destination d here. The signal received at the destination d from source user s, can be modeled as

$$y_{sd} = \sqrt{P_s^D(1-\alpha)r_{sd}^{-\gamma}}\, h_{sd}x + n_{sd}, \tag{1}$$

where P_s^D is the transmission power from the source in the direct communication scenario, x is the transmitted data with unit power, and h_{sd} is the channel fading gain between the two terminals s and d. The channel fade of any link is modeled throughout the article as a zero mean circularly symmetric complex Gaussian random variable [Foschini and Gans 1998] with unit variance. In (1), γ is the path-loss exponent, and r_{sd} is the distance between the two terminals. The term n_{sd} in (1) denotes additive noise; the noise components throughout the article are modeled as white Gaussian noise (AWGN) with variance N_o.

Second, we describe the signal model for cooperative transmission. The cooperative transmission scenario comprises two phases, as illustrated before. The signals received from the source at the destination d and relay 1 in the first stage can be modeled, respectively, as

$$y_{sd} = \sqrt{P_s^c(1-\alpha)r_{sd}^{-\gamma}}\, h_{sd}x + n_{sd}, \qquad y_{s1} = \sqrt{P_s^c(1-\alpha)r_{s1}^{-\gamma}}\, h_{s1}x + n_{s1}, \tag{2}$$

where P_s^c is the transmission power from the source in the cooperative scenario. The channel gains h_{sd} and h_{s1} between the source-destination and source-relay are modeled as zero-mean circular symmetric complex Gaussian random variables with zero mean. If the SNR of the signal received at the destination from the source falls below the threshold β, the destination broadcasts a NACK. In this case, if the relay was able to receive the packet from the source correctly in the first phase, it forwards the packet to the destination with power P_1

$$y_{1d} = \sqrt{P_1(1-\alpha)r_{1d}^{-\gamma}}h_{1d}x + n_{1d}. \tag{3}$$

Cooperation results in additional spatial diversity by introducing this artificial multipath through the relay link. This can enhance the transmission reliability against wireless channel impairments as fading, but will also result in extra receiving and processing power. In the next section, we discuss this in more detail.

3. PERFORMANCE ANALYSIS AND OPTIMUM POWER ALLOCATION

In this article we characterize the system performance in terms of outage probability. Outage is defined as the event that the received SNR falls below a certain threshold β, hence, the probability of outage P_O is defined as

$$\mathcal{P}_O = \mathcal{P}(\text{SNR} \leq \beta). \tag{4}$$

If the received SNR is higher than the threshold β, the receiver is assumed to be able to decode the received message with negligible probability of error. If an outage occurs, the packet is considered lost. The SNR threshold β is determined according to the application and the transmitter/receiver structure. For example, larger values of β is required for applications with higher Quality-of-Service (QoS) requirements. Also increasing the complexity of transmitter and/or receiver structure, for example, applying strong error coding schemes, can reduce the value of β for the same QoS requirements.

Based on the derived outage probability expressions, we formulate a constrained optimization problem to minimize the total consumed power, subject to a given outage performance. We then compare the total consumed power for the direct and cooperative scenarios to quantify the energy savings, if any, gained by applying cooperative transmission.

3.1 Direct Transmission

As discussed before, the outage is defined as the event that the received SNR falls below a predefined threshold which we denoted by β. From the received signal model in (1), the received SNR from a user at a distance r_{sd} from the destination is given by

$$\text{SNR}(r_{sd}) = \frac{|\, h_{sd} \,|^2 \, r_{sd}^{-\gamma} P_s^D(1-\alpha)}{N_o}, \tag{5}$$

where $|\, h_{sd} \,|^2$ is the magnitude square of the channel fade and follows an exponential distribution with unit mean; this follows because of the Gaussian zero mean distribution of h_{sd}. Hence, the outage probability for the direct transmission mode P_{OD} can be calculated as

$$\mathcal{P}_{OD} = \mathcal{P}(\text{SNR}(r_{sd}) \leq \beta) = 1 - \exp\left(-\frac{N_o \beta r_{sd}^{\gamma}}{(1-\alpha)P_s^D}\right). \tag{6}$$

The total transmitted power P_{tot}^{D} for the direct transmission mode is given by

$$P_{tot}^{D} = P_s^{D} + P_c + P_r, \tag{7}$$

where P_s^{D} is the power consumed at the RF stage of the source node, P_c is the processing power at the source node, and P_r is the receiving power at the destination. The requirement is to minimize this total transmitted power, subject to the constraint that we meet a certain QoS requirement that the outage probability is less than a given outage requirement, which we denote by $\mathcal{P}_{out}^{*}$. Since both the processing and receiving powers are fixed, the only variable of interest is the transmitting power P_s^{D}.

The optimization problem can be formulated as follows.

$$\min_{P_s^{D}} P_{tot}^{D}, \qquad \text{such that } \mathcal{P}_{OD} \leq \mathcal{P}_{out}^{*} \tag{8}$$

The outage probability $\mathcal{P}_{OD}$ is a decreasing function in the power P_s^{D}. Substituting $\mathcal{P}_{out}^{*}$ in the outage expression in (6), we get after some simple arithmetics that the optimal transmitting power is given by

$$P_s^{D*} = -\frac{\beta N_o r_{sd}^{\gamma}}{(1-\alpha)\ln(1-\mathcal{P}_{out}^{*})}. \tag{9}$$

The minimum total power required for direct transmission in order to achieve the required QoS requirement is therefore given by

$$P_{tot}^{*} = P_c + P_r - \frac{\beta N_o r_{sd}^{\gamma}}{(1-\alpha)\ln(1-\mathcal{P}_{out}^{*})}. \tag{10}$$

In the next subsection we formulate the optimal power allocation problem for the cooperative communication scenario.

3.2 Cooperative Transmission

For the optimal power allocation problem in cooperative transmission, we consider two possible scenarios. In the first scenario, the relay is allowed to transmit with different power than the source and hence the optimization space is two-dimensional: source and relay power allocations. The solution for this setting provides the minimum possible total consumed power. However, the drawback of this setting is that the solution for the optimization problem is complex and might not be feasible to implement in sensor nodes. The second setting that we consider is constraining the source and relay nodes to transmit with equal powers. This is much easier to implement as the optimization space is one-dimensional in this case, moreover, a relaxed version of the optimization problem can render a closed form solution. Clearly the solution of the equal power allocation problem provides a suboptimal solution to the general case in which we allow different power allocations at the source and the relay. It is interesting then to investigate the conditions under which these two power allocation strategies have close performance.

First, we characterize the optimal power allocations at the source and relay nodes. Consider a source-destination pair that are r_{sd} units distance. Let us compute the conditional outage probability for given locations of the source and the helping relay. As discussed before, cooperative transmission encompasses two phases. Using (2), the SNR received at the destination d and relay 1 from the source s in the first phase are given by

$$\mathrm{SNR}_{sd} = \frac{|\ h_{sd}\ |^2\ r_{sd}^{-\gamma} P_s^C(1-\alpha)}{N_o}, \quad \mathrm{SNR}_{s1} = \frac{|\ h_{s1}\ |^2\ r_{s1}^{-\gamma} P_s^C(1-\alpha)}{N_o}. \tag{11}$$

While from (3), the SNR received at the destination from the relay in the second phase is given by

$$\mathrm{SNR}_{1d} = \frac{|\ h_{1d}\ |^2\ r_{1d}^{-\gamma} P_1(1-\alpha)}{N_o}. \tag{12}$$

Note that the second phase of transmission is only initiated if the packet received at the destination from the first transmission phase is not correctly received. The terms $|\ h_{sd}\ |^2$, $|\ h_{s1}\ |^2$, and $|\ h_{1d}\ |^2$ are mutually independent exponential random variables with unit mean.

The outage probability of the cooperative transmission $\mathcal{P}_{OC}$ can be calculated as follows.

$$\begin{aligned}\mathcal{P}_{OC} &= \mathcal{P}((\mathrm{SNR}_{sd} \le \beta) \cap (\mathrm{SNR}_{sl} \le \beta)) \\ &\quad + \mathcal{P}((\mathrm{SNR}_{sd} \le \beta) \cap (\mathrm{SNR}_{ld} \le \beta) \cap (\mathrm{SNR}_{sl} > \beta)) \\ &= (1 - f(r_{sd}, P_s^C))(1 - f(r_{s1}, P_s^C)) + (1 - f(r_{sd}, P_s^C)) \\ &\quad \times (1 - f(r_{1d}, P_l)) f(r_{s1}, P_s^C),\end{aligned} \tag{13}$$

where $f(x, y) = \exp(-\frac{N_o \beta x^{\gamma}}{y(1-\alpha)})$. The first term in the preceding expression corresponds to the event that both the source-destination and the source-relay channels are in outage, and the second term corresponds to the event that both the the source-destination and the relay-destination channels are in outage while the source-relay channel is not. The previous expression can be simplified as follows.

$$\mathcal{P}_{OC} = \left(1 - f\left(r_{sd}, P_s^C\right)\right)\left(1 - f(r_{1d}, P_l) f\left(r_{s1}, P_s^C\right)\right) \tag{14}$$

The total average consumed power for cooperative transmission to transmit a packet is given by

$$\begin{aligned}E\left[P_{tot}^C\right] &= \left(P_s^C + P_c + 2P_r\right)\mathcal{P}(SNR_{sd} \ge \beta) \\ &\quad + \left(P_s^C + P_c + 2P_r\right)\mathcal{P}(SNR_{sd} < \beta)\mathcal{P}(SNR_{s1} < \beta) \\ &\quad + \left(P_s^C + P_1 + 2P_c + 3P_r\right)\mathcal{P}(SNR_{sd} < \beta)\mathcal{P}(SNR_{s1} > \beta),\end{aligned} \tag{15}$$

where the first term in the right-hand side corresponds to the event that the direct link in the first phase is not in outage, therefore, the total consumed power is only given by that of the source node, and the 2 in front of the received power term P_r is to account for the relay receiving power. The second term in the summation corresponds to the event that both the direct and the source-relay links are in outage, hence the total consumed power is still given as in the first term. The last term in the total summation accounts for the event that the source-destination link is in outage while the source-relay link is not, and hence we need to account for the relay transmitting and processing powers, and the extra receiving power at the destination. Using the Rayleigh fading channel model, the average total consumed power can be given as follows.

$$\begin{aligned} P_{tot}^C = & \left(P_s^C + P_c + 2P_r\right) f\left(r_{sd}, P_s^C\right) \\ & + \left(P_s^C + P_c + 2P_r\right)\left(1 - f\left(r_{sd}, P_s^C\right)\right)\left(1 - f\left(r_{s1}, P_s^C\right)\right) \\ & + \left(P_s^C + P_1 + 2P_c + 3P_r\right)\left(1 - f\left(r_{sd}, P_s^C\right)\right) \times f\left(r_{s1}, P_s^C\right) \end{aligned} \tag{16}$$

We can formulate the power minimization problem in a similar way to (8) with the difference that there are two optimization variables in the cooperative transmission mode, namely, the transmit powers P_s^C and P_1 at the source and relay nodes, respectively. The optimization problem can be stated as follows.

$$\min_{P_s^C, P_1} P_{tot}^C\left(P_s^C, P_1\right), \qquad \text{s.t. } \mathcal{P}_{OC}\left(P_s^C, P_1\right) \le \mathcal{P}_{out}^*. \tag{17}$$

This optimization problem is nonlinear and does not admit a closed form solution. Therefore we resort to numerical optimization techniques in order to solve for this power allocation problem at the relay and source nodes, and the results are shown in the simulations section.

In the preceding formulation we considered optimal power allocation at the source and relay node in order to meet the outage probability requirement. The performance attained by such an optimization problem provides a benchmark for the cooperative transmission scheme. However, in a practical setting, it might be difficult to implement such a complex optimization problem at the sensor nodes. A more practical scenario would be that all the nodes in the network utilize the same power for transmission. Denote the equal transmission power in this case by P_{CE}; the optimization problem in this case can be formulated as

$$\min_{P_{CE}} P_{tot}^C(P_{CE}), \qquad \text{s.t. } \mathcal{P}_{OC}(P_{CE}) \le \mathcal{P}_{out}^*. \tag{18}$$

Besides being a one-dimensional optimization problem that can be easily solved, the problem can be relaxed to render a closed form solution. Note that at sufficiently high SNR the following approximation holds $\exp(-x) \simeq (1 - x)$; where x here is proportional to $1/SNR$.

Using the preceding approximation in (16), and after some mathematical manipulation, the total consumed power can be approximated as follows.

$$P_{tot}^C \simeq P_{CE} + P_c + 2P_r + (P_{CE} + P_c + P_r)\frac{k_1}{P_{CE}} - (P_{CE} + P_c + P_r)\frac{k_1 k_2}{P_{CE}^2}. \tag{19}$$

Similarly, the outage probability can be written as0

$$\mathcal{P}_{OC} \simeq \frac{k_1 k_2}{P_{CE}^2} + \frac{k_1 k_3}{P_{CE}^2} - \frac{k_1 k_2 k_3}{P_{CE}^3}, \tag{20}$$

where $k_1 = \frac{\beta N_o r_{sd}^\gamma}{1-\alpha}$, $k_2 = \frac{\beta N_o r_{s1}^\gamma}{1-\alpha}$, and $k_3 = \frac{\beta N_o r_{1d}^\gamma}{1-\alpha}$. This is a constrained optimization problem in one variable and its Lagrangian is given by

$$\frac{\partial P_{tot}^C}{\partial P_{CE}} + \lambda \frac{\partial \mathcal{P}_{OC}}{\partial P_{CE}} = 0, \tag{21}$$

where the derivatives of the total power consumption P_{tot}^C and the outage probability $\mathcal{P}_{OC}$ with respect to the transmit power P_{CE} are given by

$$\begin{aligned}\frac{\partial P_{tot}^C}{\partial P_{CE}} &= 1 + \frac{k_1 k_2 - (P_c + P_r)k_1}{P_{CE}^2} + \frac{2k_1 k_2 (P_c + P_r)}{P_{CE}^3};\\ \frac{\partial \mathcal{P}_{OC}}{\partial P_{CE}} &= \frac{-2(k_1 k_2 + k_1 k_3)}{P_{CE}^3} + \frac{3k_1 k_2 k_3}{P_{CE}^4},\end{aligned} \tag{22}$$

respectively. Substituting the derivatives in (22) into the Lagrangian in (21), and doing simple change of variables $1/P_{CE} = x$, the Lagrangian can be written in the following simple polynomial form

$$1 + (k_1 k_2 - (P_c + P_r)k_1)x^2 + 2(k_1 k_2 (P_c + P_r) - \lambda(k_1 k_2 + k_1 k_3))x^3 + 3\lambda k_1 k_2 k_3 x^4 = 0 \tag{23}$$

under the outage constraint

$$(k_1 k_2 + k_1 k_3)\,x^2 - k_1 k_2 k_3 x^3 = \mathcal{P}_{out}^*. \tag{24}$$

The constraint equation given before is only a polynomial of order three, so it can be easily solved and we can find the root that minimizes the cost function.

4. MULTIRELAY SCENARIO

In this section, we extend the protocol described in Section 2 to the case when there is more than one potential relay. Let N be the number of relays assigned to help a given source. The cooperation protocol then works as an N-stage ARQ protocol as follows. The source node transmits its packets to the destination and the relays try to decode this packet. If the destination does not decode the packet correctly, it sends a NACK that can be heard by the relays. If the first relay is able to decode the packet correctly, it forwards the packet with power P_1 to the destination. If the destination does not receive correctly again, then it sends a NACK and the second candidate relay, if it received the packet correctly, forwards the source's packet to the destination with power P_2. This is repeated until the destination gets the packet correctly or the N trials corresponding to the N relays are exhausted.

We model the status of any relay by 1 or 0, corresponding to whether the relay received the source's packet correctly or not, respectively. Writing the status of all the relays in a column vector results in a $N \times 1$ vector whose entries are either 0 or 1. Hence, the decimal number representing this $N \times 1$ vector can take any integer value between 0 and $2^N - 1$. Denote this vector by S_k where $k \in \{0, 1, 2, \ldots, 2^N - 1\}$.

For a given status of the N relays, an outage occurs if and only if the links between the relays that decoded correctly and the destination are all in outage. Denote the set of the relays that received correctly by $\chi(S_k) = \{i : S_k(i) = 1, 1 \le i \le N\}$, and $\chi^c(S_k)$ as the set of relays that have not received correctly, that is, $\chi^c(S_k) = \{i : S_k(i) = 0, 1 \le i \le N\}$. The conditional probability of outage given the relays status S_k is thus given by

$$\mathcal{P}_{OC|S_k} = \mathcal{P}\left(SNR_{sd} \leq \beta \bigcap_{j\in\chi(S_k)}^{N} \left(SNR_{jd} \leq \beta\right)\right). \tag{25}$$

The total outage probability is thus given by

$$\mathcal{P}_{OC} = \sum_{k=0}^{2^N-1} \mathcal{P}(S_k)\mathcal{P}_{OC|S_k}. \tag{26}$$

We then need to calculate the probability of the set S_k, which can then be written as

$$\mathcal{P}(S_k) = \mathcal{P}\left(\bigcap_{i\in\chi(S_k)} (SNR_{si} \geq \beta) \bigcap_{j\in\chi^c(S_k)} \left(SNR_{sj} \leq \beta\right)\right). \tag{27}$$

The average outage probability expression can thus be given by

$$\mathcal{P}_{OC} = \sum_{k=0}^{2^N-1} \left(1-f\left(r_{sd}, P_s^c\right)\right) \prod_{j\in\chi(S_k)} (1-f(r_{jd}, P_j)) f(r_{sj}, P_s^c) \prod_{j\in\chi^c(S_k)} \left(1-f\left(r_{sj}, P_s^c\right)\right) \tag{28}$$

where P_j, $j \in \{1, 2, \ldots, N\}$, is the power allocated to the jth relay.

Next we compute the average total consumed power for the N-relays scenario. First we condition on some relays' status vector $\chi(S_k)$.

$$E\left[P_{tot}^c\right] = E\left[E\left[P_{tot}^c|\chi\left(S_k\right)\right]\right] = \sum_{k=0}^{2^N-1} P\left(\chi(S_k)\right) E\left[P_{tot}^c|\chi(S_k)\right] \tag{29}$$

For a given $\chi\,(S_k)$, we can further condition on whether the source get the packet through from the first trial or not. This event happens with probability $f(r_{s,d}, P_s^c)$, and the consumed power in this case is given by

$$P_{tot}^{c,1} = P_s^c + (N+1)P_r + P_c. \tag{30}$$

The complementary event that the source failed to transmit its packet from the direct transmission phase happens with probability $1 - f(r_{s,d}, P_s^c)$, and this event can be further divided into two mutually exclusive events. The first is when the first $|\ \chi(S_k)\ | -1$ relays from the set $\chi(S_k)$ fails to forward the packet and this happens with probability $\prod_{i=1}^{|\chi(S_k)|-1}(1 - f(r_{i,d}, P_i))$ and the corresponding consumed power is given by

$$P_{tot}^{c,2} = P_s^c + (N+1+\mid \chi(S_k)\mid)P_r + (\mid \chi(S_k)\mid +1)P_c + \sum_{n=1}^{|\chi(S_k)|} P_{\chi(S_k)(n)}. \tag{31}$$

And the second is when one of the intermediate relays in the set $\chi(S_k)$ successfully forwards the packet and this happens with probability $\prod_{m=1}^{j-1}(1 - f(r_{m,d}, P_m)) f(r_{j,d}, P_j)$ if this intermediate relay was relay number j, and the corresponding power is given by

$$P_{tot}^{c,3,j} = P_s^c + (N+1+j)P_r + (1+j)P_c + \sum_{i=1}^{j} P_{\chi(S_k)(i)}. \tag{32}$$

From (29), (30), (31), and (32), the average total consumed power can be given by

$$E\left[P_{tot}^{c}\right] = \sum_{k=0}^{2^N-1} P\left(\chi(S_k)\right)\Bigg\{ f(r_{s,d}, P_s^c)P_{tot}^{c,1} + \left(1 - f(r_{s,d}, P_s^c)\right)\left[\prod_{i=1}^{|\chi(S_k)|-1}(1 - f(r_{i,d}, P_i))P_{tot}^{c,2} + \sum_{j=1}^{|\chi(S_k)|-1}\prod_{m=1}^{j-1}(1 - f(r_{m,d}, P_m))f(r_{j,d}, P_j)P_{tot}^{c,3,j}\right]\Bigg\}. \tag{33}$$

The optimization problem can then be written as

$$\min_{\mathbf{P}} P_{tot}^{C}(\mathbf{P}), \qquad \text{such that } \mathcal{P}_{OC}(\mathbf{P}) \leq \mathcal{P}_{out}^{*}, \tag{34}$$

where $\mathbf{P} = [P_s^c, P_1, P_2, \cdots, P_N]^T$.

5. EXPERIMENTAL AND SIMULATION RESULTS

5.1 Experimental Results

In our system model we have assumed the channel independence between the following links: the source-relay link, the source-destination link, and the relay-destination link. Moreover, a strong motivation for applying cooperative transmission instead of ARQ in the time domain is the assumption of high temporal correlation which results in delay and requires performing interleaving at the transmitter side. In this section, we have conducted a set of experiments to justify these two fundamental assumptions.

The experiments are set up as follows. We have three wireless nodes in the experiments, one of them acts as the sender and the other two act as receivers. Each wireless node is computer equipped with a IEEE 802.11g wireless card, specifically, we utilized three LINKSYS wireless-G USB network adaptors. The sender's role is to broadcast data packets with a constant rate, while the two receivers' role is to decode the packets and record which packet is erroneous. The traffic rate is 100 packets per second, and the size of each packet is 554 bytes (including packet headers). The two receivers are placed together, with the distance between them being 20cm. The distance between the transmitter and the receiver is around 5 meters. The experiments have been mainly conducted in office environments. The experiments results, which are illustrated next, have revealed two important observations: the channels exhibit a strong time correlation for each receiver, while there is negligible dependence between the two receivers. Figure 2 illustrates one instantiation of the experiments. The first figure illustrates the results obtained at the first receiver and the second figure is for the second receiver.

For each figure, the horizontal axis denotes the sequence number of the first 100000 packets, and the vertical axis denotes whether a packet is erroneous or not. First, from these results we can see that packet errors exhibit a strong correlation in time. For example, for the first receiver, most erroneous packets cluster at around 22^{nd} second and around 83^{rd} second. Similar observations

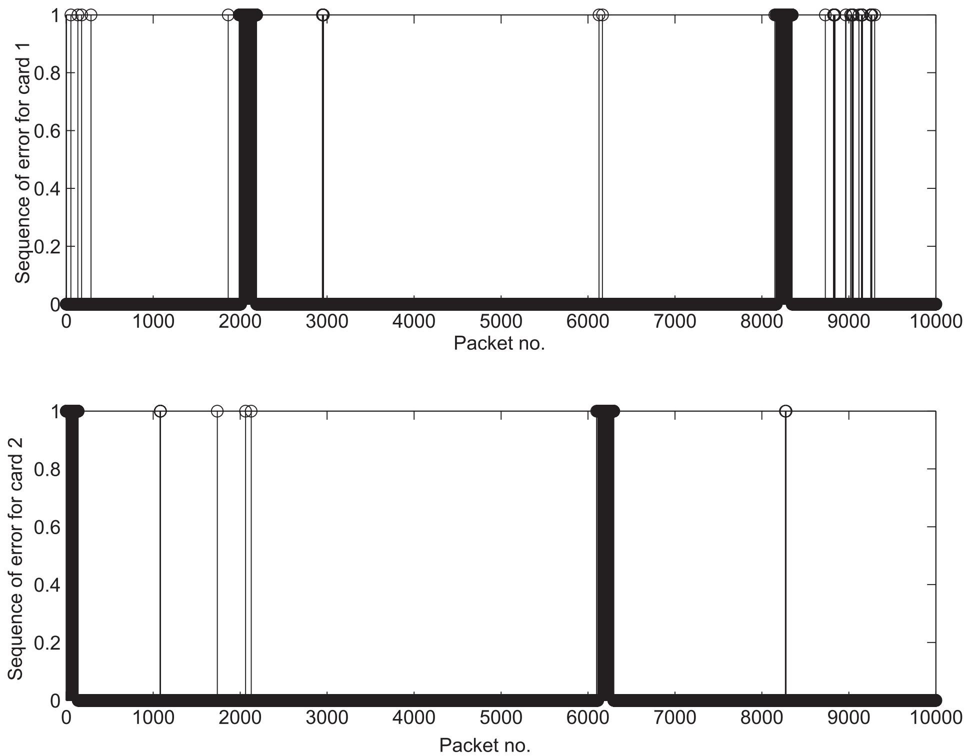

Fig. 2. Sequence of packet errors at the two utilized wireless cards.

also hold for the second receiver. If we take a further look at the results we can see that in this set of experiments the duration for the cluster is around 2 seconds. To help better understand the time correlation of erroneous packets, we have also used a two-state Markov chain to model the channel, as illustrated in Figure 3. In this model "1" denotes that the packet is correct, and "0" denotes that the packet is erroneous. $P_{i|j}$ denotes the transition probability from state i to state j, that is, the probability to reach state j given the previous state is i. The following transition probabilities have been obtained after using the experimental results to train the model: $P_{1|0} = 0.03$, $P_{1|1} = 0.999$, $P_{0|0} = 0.97$, $P_{0|1} = 0.001$. These results also indicate a strong time correlation. For example, given that the current received packet is erroneous, the probability that the next packet is also erroneous is around $P_{0|0} = 0.97$.

Now we take a comparative look at the results obtained at the two receivers. From these results we can see that although there exists slight correlation in packet errors between the two receivers, it is almost negligible. To provide more concrete evidence of independence, we have estimated the correlation between the two receivers using the obtained experiment results. Specifically, we have measured the correlation coefficient between the received sequences at the two receivers and we found that the correlation coefficient is almost 0, which indicates a strong spatial independence between the two receivers.

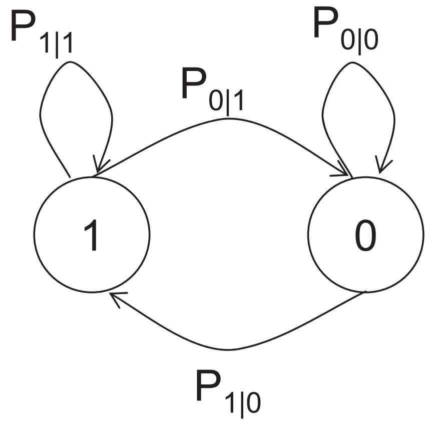

Fig. 3. Modeling the channel by a two (on-off) state Markov chain to study the time correlation.

5.2 Simulation Results

As discussed in the previous sections, there are different system parameters that can control whether we can gain from cooperation or not, among which are the received power consumption, the processing power, the SNR threshold, the power amplifier loss, and the relative distances between the source, relay, and destination.

In order to understand the effect of each of these parameters, we are going to study the performance of cooperative and direct transmission when varying one of these parameters and fixing the rest. This is described in more detail in the following. In all of the simulations, the aforementioned parameters take the following values when considered fixed: $\alpha = 0.3$, $\beta = 10$, $N_o = 10^{-3}$, $P_c = 10^{-4}$ Watt, $P_r = 5 \times 10^{-5}$, $QoS = \mathcal{P}^*_{out} = 10^{-4}$. We define the cooperation gain as the ratio between the total power required for direct transmission to achieve a certain QoS, and the total power required by cooperation to achieve the same QoS.

First, we study the effect of varying the receive power P_r as depicted in Figure 4. We plot the cooperation gain versus the distance between the source and the destination for different values of receive power $P_r = 10^{-4}, 5 \times 10^{-5}, 10^{-5}$ Watt. At source-destination distances below 20m, the results reveal that direct transmission is more energy efficient than cooperation, that is, the overhead in receive and processing power due to cooperation outweighs its gains in saving the transmit power. For $r_{sd} > 20m$, the cooperation gain starts increasing as the transmit power starts constituting a significant portion of the total consumed power. This ratio increases until the transmit power is the dominant part of the total consumed power and hence the cooperation gain starts to saturate.

In the plotted curves, the solid lines denote the cooperation gain when utilizing optimal power allocation at the source and the relay, while the dotted curves denote the gain for equal power allocation. For $r_{sd} \leq 100$m, both optimal power allocation and equal power allocation yield almost the same cooperation gain. For larger distances, however, a gap starts to appear between optimal

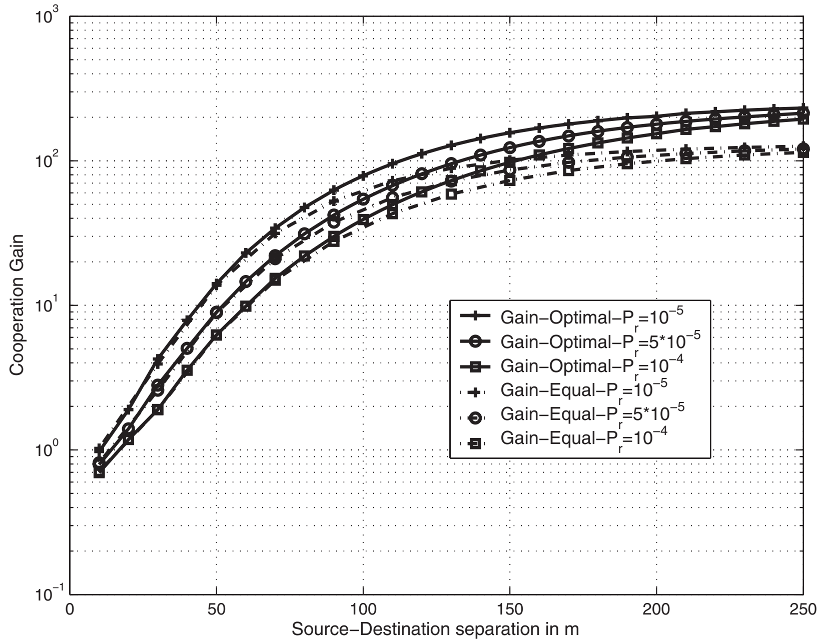

Fig. 4. Cooperation gain versus the source-destination distance for different values of received power consumption.

and equal power allocation. The rationale behind these observations is that at small distances the transmit power is a small percentage of the total consumed power and hence optimal and equal power allocation almost have the same behavior, while at larger distances, transmit power plays a more important role and hence a gap starts to appear.

In Figure 5 we study the effect of changing the SNR threshold β. The distance between source and destination r_{sd} is fixed to 100m. It is clear that the cooperation gain increases with increasing β, and that for the considered values of the system parameters, equal power allocation provides almost the same gains as optimal power allocation. In Figure 6 we study the effect of the power amplifier loss α. In this case, we plot the total consumed power for cooperation and direct transmission versus distance for different values of α. Again below 20m separation between the source and the destination, direct transmission provides better performance over cooperation. It can also be seen from the plotted curves that the required power for direct transmission is more sensitive to variations in α than the power required for cooperation. The reason is that the transmit power constitutes a larger portion in the total consumed power in direct transmission than in cooperation, and hence the effect of α is more significant. The QoS, measured by the required outage probability, has similar behavior and the results are depicted in Figure (7).

Next we study the effect of varying the relay location. We consider three different positions for the relay: close to the source, in the middle between the source and the destination, and close to the destination. In particular, the relay

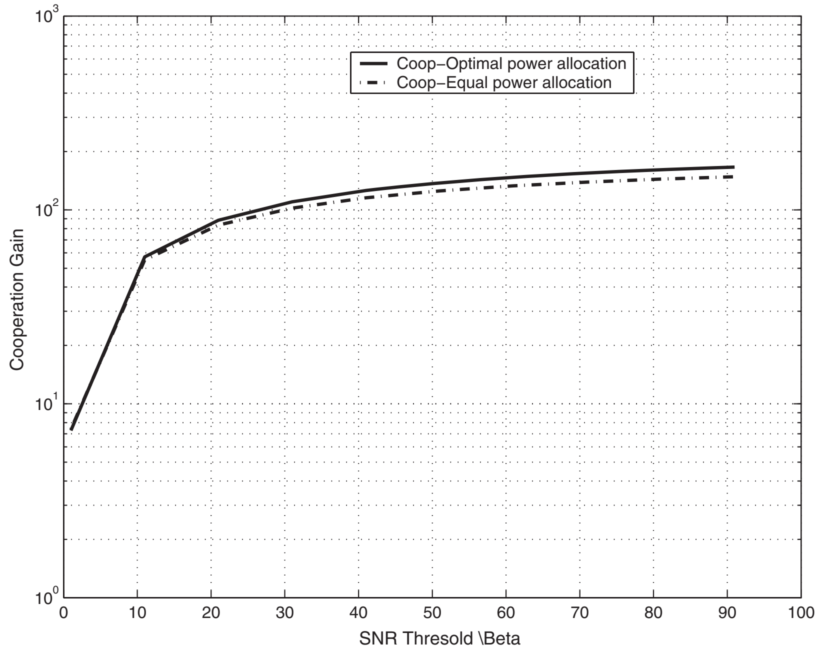

Fig. 5. Cooperation gain versus the SNR threshold β.

position is taken equal to ($r_{s1} = 0.2r_{sd}, r_{1d} = 0.8r_{sd}$), ($r_{s1} = 0.5r_{sd}, r_{1d} = 0.5r_{sd}$), and ($r_{s1} = 0.8r_{sd}, r_{1d} = 0.2r_{sd}$).

Figures 8 and 9 depict the power required for cooperation and direct transmission versus r_{sd} for equal power and optimal power allocation, respectively. In the equal power allocation scenario, the relay in the middle gives the best results, and the other two scenarios, relay close to source and relay close to destination provide the same performance. This can be expected because for the equal power allocation scenario the problem becomes symmetric in the source-relay and relay-destination distances. For the optimal power allocation scenario depicted in Figure 9, the problem is no longer symmetric because different power allocation is allowed at the source, and relay. In this case, numerical results show that the closer the relay to the source, the better the performance. The intuition behind this is that when the relay is closer to the source, the source-relay channel is very good and almost error free.

From both figures, it is also clear that for small source-destination separation r_{sd}, equal and optimal power allocation almost provide the same cooperation gain while for larger r_{sd} optimal power allocation provides more gain. Another important observation is that at small distances below 100m, the location of the relay does not affect the performance much. This makes the algorithms required to select a relay in cooperative communications simpler to implement for source-destination separations in this range. Finally, the threshold behavior below 20m still appears where direct transmission becomes more energy efficient.

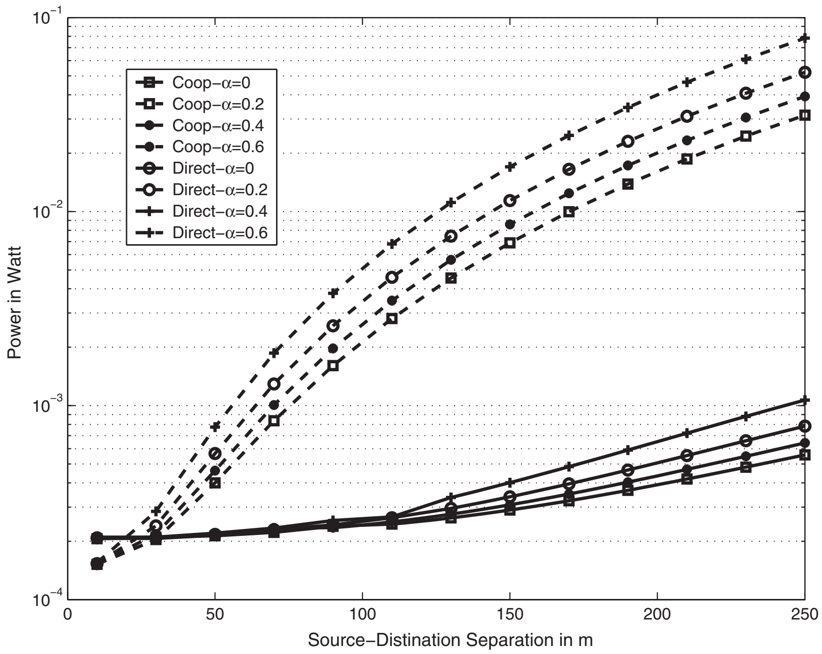

Fig. 6. Optimal power consumption for both cooperation and direct transmission scenarios for different values of power amplifier loss α.

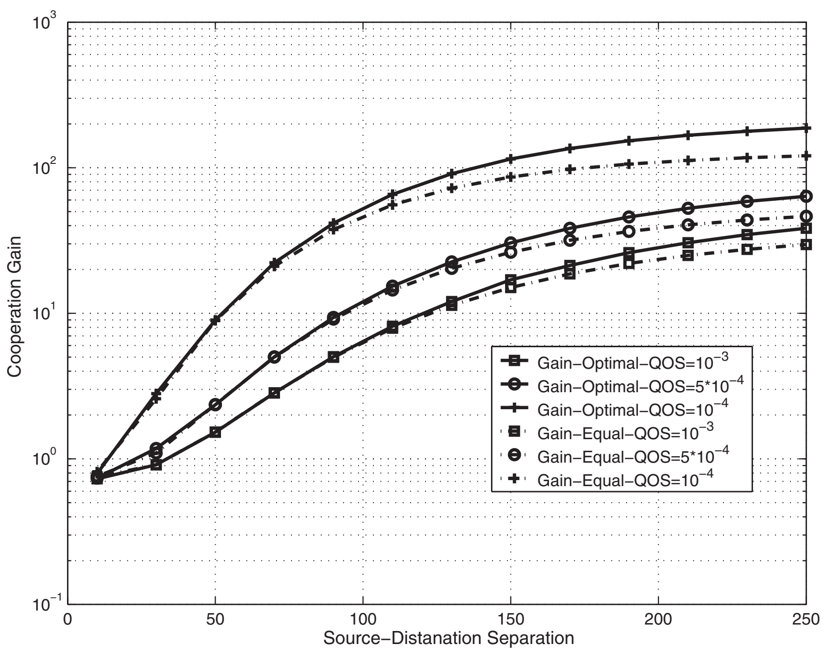

Fig. 7. Cooperation gain versus the source-destination distance for different values of QOS.

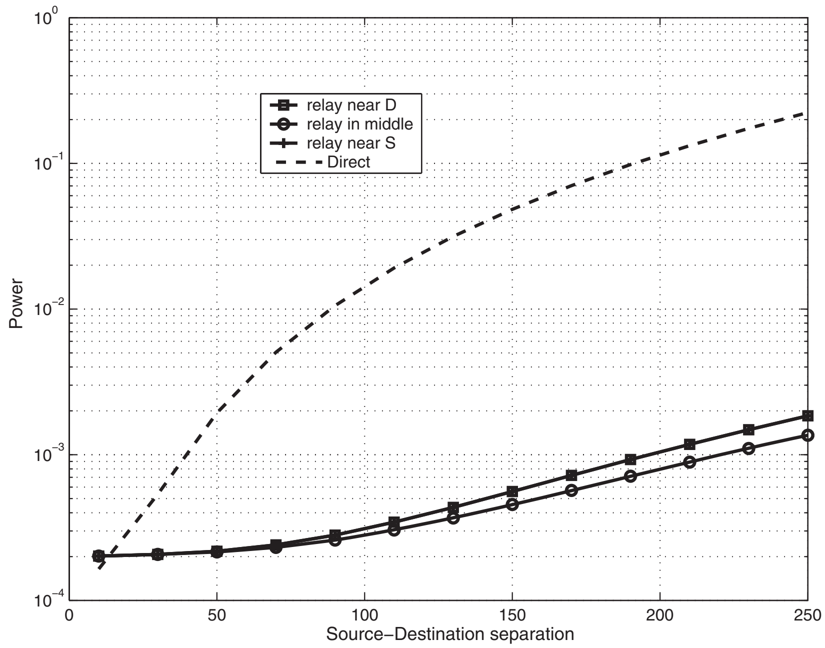

Fig. 8. Optimal consumed power versus distance for different relay locations for equal power allocation at source and relay.

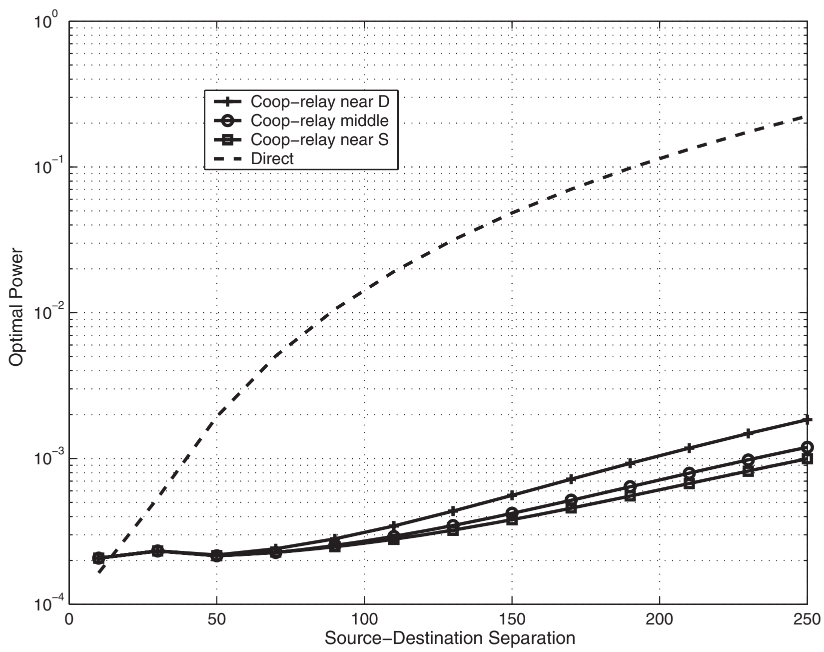

Fig. 9. Optimal consumed power versus distance for different relay locations for optimal power allocation at source and relay.

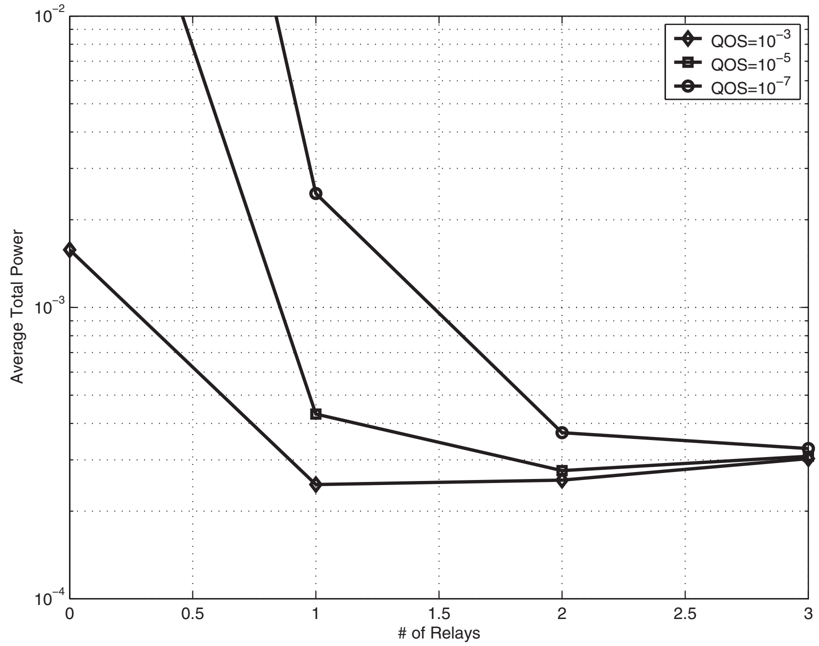

Fig. 10. Optimal consumed power versus number of relays for different values of required outage probability.

Figure 10 depicts the multiple relays scenario for different values of outage probability $\mathcal{P}_{out}^{*}$. The results are depicted for a source-destination distance of 100m, and for $N = 0, 1, 2, 3$ relays, where $N = 0$ refers to direct transmission. As shown in Figure 10, for small values of required outage probability, one relay is more energy efficient than two or three relays. As we increase the required QoS, reflected by $\mathcal{P}_{out}^{*}$, the optimal number of relays increases. Hence, our analytical framework can also provide guidelines to determining the optimal number of relays under any given scenario.

6. CONCLUSIONS

We have investigated the gains of cooperation in sensor networks under a practical setting where the extra overhead of cooperation is taken into account. A constrained optimization problem was formulated to minimize the total consumed power under a given QoS requirement. Our results reveal that for short distance separations between the source and the destination, for example, below a threshold of 20m , the overhead of cooperation outweighs its gains and direct transmission is more efficient. Above that threshold, cooperation gains can be achieved. It was also shown that simple equal power allocation at the source and the relay achieves almost the same gains as optimal power allocation at these two nodes for distances below 100m, for the specific parameters used.

Furthermore, choosing the optimal relay location for cooperation plays an important role when the source-destination separation exceeds 100m, and the best relay location depends on the power allocation scheme, whether optimal or equal. Our results can also be used to provide guidelines in determining the optimal number of relays for any given communication setup, as we show that increasing the number of relays is not always beneficial. In summary, caution must be taken before applying cooperative communications to sensor networks, in particular whether we should apply cooperation or not, whether equal power allocation is good enough, how to choose a partner or a relay for cooperation, and how many relays should be assigned to help the source.

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