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When Does Cooperation Have Better Performance in Sensor Networks?

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Abstract—**The gains of cooperative communications in wireless networks have been explored recently under the ideal assumption of negligible receiving and processing power. In sensor networks, the power spent for listening and computing can constitute a significant portion of the total consumed power, and such an overhead can reduce the gains promised by cooperation. In this paper, cooperation gains are investigated by taking into consideration such overheads in the analytical framework. The performance metric considered is the energy efficiency of the system measured by the total power required to achieve a certain quality of service requirement. The analytical and numerical results reveal very interesting threshold behavior below which direct transmission is more energy efficient, and above which cooperation provides more gains. Such a tradeoff is shown to depend on many parameters such as the relative locations of the source and destination, the values of the receive and processing powers, the application, and many other factors. Moreover, there are experimental results conducted to verify the channel model assumed in the paper.**

I. Introduction

Spatial diversity has been extensively studied in the context of multiple-input-multiple-output (MIMO) systems [1] 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 [2], [4] 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 [2], [3], [4], [5], [6], [7], and they have all shown a significant gain in network throughput, capacity [8], coverage [10], and energy efficiency which renders cooperation a very exciting paradigm to implement in wireless networks. Some recent works also consider designing distributed space-time coding for wireless networks [9].

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 can be of the same order as the transmit 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 tradeoff between the gains in the transmit power and the losses due to the receive and processing powers when applying cooperation. Hence such a tradeoff between the gains promised by cooperation and this extra overhead in terms of the energy efficiency of the system must be taken into consideration in the network design.

In this paper we investigate such a tradeoff 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, and the relay location. We compare between two communications architectures, direct transmission and cooperative transmission using one relay node. 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 the ratio is smaller than one, this indicates that direct transmission is enough and that the extra overhead from cooperation is more significant than the gains in the transmit power.

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 IV

The remainder of the paper 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 III we formulate a constrained optimization problem which minimizes the total consumed power under the constraint of achieving certain outage probability. Section IV 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

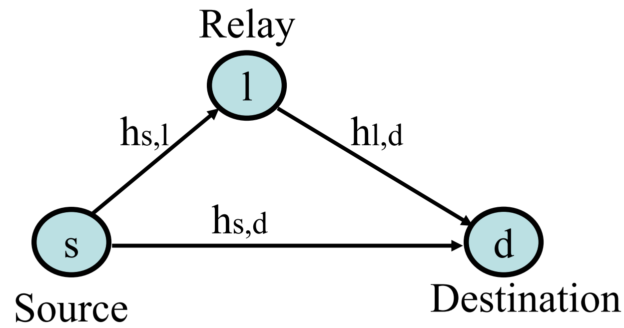

Fig. 1. System Model.

II. System Model

For the simplicity of illustrating how our communication protocol works, we consider a single hop in the network between two nodes; one being the source and the second being the destination. In addition, we have a third node that acts as a relay in the cooperation mode. It is easy after that to extend this to a multihop scenario in which our three node model acts as a new virtual single hop in the complete route. This is more illustrated in Fig. 1 where we have three nodes: source, relay, and destination. The distances between the source-destination, source-relay, and relay-destination pairs are denoted by r_{sd}, r_{sl}, and r_{ld}, respectively.

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 can not 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 dimension, which is the spatial dimension, as the links between different pairs of nodes in the network fade independently. The two assumptions of high temporal correlation and independence in the spatial domain will be verified through experiments as shown in Section IV

In this paper 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,

$$\mathcal{P}_O = \mathcal{P}(\text{SNR} \leq \beta). \quad (1)$$

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.

Our proposed cooperative protocol can be thought of as a modified version of the incremental relaying protocol proposed in [2]. Our protocol employs decode-and-forward at the relay node while the protocol in [2] employs amplify-and-forward at the relay. A second difference between our modified protocol and the conventional incremental relaying in [2], is that in case of packet failure in the first transmission from the source, the BS/AP does not store this packet to combine it later with the packet received from the relay. Storing the packet from the first transmission was assumed in most of the previous works on cooperative diversity, as it enhances the received SNR by applying a maximal ratio combiner, for example. However, a crucial implication of this assumption is that the destination has to store an analog form of the signal, which is not practical. This could be practically solved, for example, by storing a quantized version of the signal, and the quantization noise should then be taken into account in the analysis.

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, i.e., 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 non-linear 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

$$y_{sd} = \sqrt{P_s^D(1-\alpha)r_{sd}^{-\gamma}}\, h_{sd}x + n_{sd}, \quad (2)$$

where P_s^D is the transmission power from the source in the direct communication scenario, x is the transmitted data with unit power, h_{sd} is the channel fading gain between the two terminals s and d. The channel fade of any link is modeled throughout the paper as a zero mean circularly symmetric complex Gaussian random variable [1] with unit variance. In (2), γ is the path loss exponent, and r_{sd} is the distance between the two terminals. The term n_{sd} in (2) denotes additive noise; the noise components throughout the paper are modeled as white Gaussian noise (AWGN) with variance N_o.

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

$$\begin{aligned} y_{sd} &= \sqrt{P_s^c(1-\alpha)r_{sd}^{-\gamma}}h_{sd}x + n_{sd}, \\ y_{sl} &= \sqrt{P_s^c(1-\alpha)r_{sl}^{-\gamma}}h_{sl}x + n_{sl}, \end{aligned} \tag{3}$$

where P_s^c is the transmission power from the source in the cooperative scenario, and P_l is the transmitting power from the relay in the cooperative mode. The channel gains h_{sd} and h_{sl} 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

$$y_{ld} = \sqrt{P_l(1-\alpha)r_{ld}^{-\gamma}}h_{ld}x + n_{ld}. \tag{4}$$

Cooperation provides a new means to achieve signal reliability via spatial diversity. Significant gains in the system throughput, energy efficiency, capacity, and other aspects have been shown in a lot of works on cooperation, for example, [2], [3], [4], [8]. These works, however, did not consider the overhead introduced by cooperation. The drawback of the cooperation mode is obviously the extra processing and receiving power required at the relay and destination. Hence there is a tradeoff between the losses due to this overhead and the gains promised by cooperation. Many factors can play a role in deciding whether this tradeoff will favor cooperation over direct transmission or the opposite. Among these factors is the application considered, the required QoS, the relative positions of source and destination, the value of the listening and processing powers, the power amplifier loss, and others. The criteria that we consider to decide when to cooperate is the total power required to achieve certain QoS. In the next Section, we discuss this in more details.

[1] We denote the relay by l not to confuse with r that denotes distance.

III. Performance Analysis and Optimum Power Allocation

In this section, we provide outage performance analysis for the two communication scenarios considered in this paper, namely, direct transmission and cooperative transmission. Then, 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.

A. Direct Transmission

As discussed before, the outage is defined as the event that the received SNR is lower than a predefined threshold which we denoted by β. From the received signal model in (2), the received SNR from a user at a distance r_{sd} from the BS/AP 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

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

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 quality of service requirement that the outage probability is less than a given outage requirement, which we denote by 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

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

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

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

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

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

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

B. 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.

First, we characterize the optimal power allocations at the source and relay nodes. Consider a source-destination pair that are r_{sd} units distance apart as depicted in Fig. 1. Let us compute the conditional outage probability for given locations of the user and the helping relay. As discussed before, cooperative transmission encompasses two phases. Using (3), the SNR received at the destination d and the relay l from the source s in the first phase are given by

$$\begin{aligned} \text{SNR}_{sd} &= \frac{|\, h_{sd} \,|^2 \, r_{sd}^{-\gamma} P_s^C (1-\alpha)}{N_o}, \\ \text{SNR}_{sl} &= \frac{|\, h_{sl} \,|^2 \, r_{sl}^{-\gamma} P_s^C (1-\alpha)}{N_o}. \end{aligned} \tag{11}$$

While from (4), the SNR received at the BS/AP from the relay in the second phase is given by

$$\text{SNR}_{ld} = \frac{|\, h_{ld} \,|^2 \, r_{ld}^{-\gamma} P_l (1-\alpha)}{N_o}. \tag{12}$$

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 $|\, h_{sd} \,|^2$, $|\, h_{sl} \,|^2$, and $|\, h_{ld} \,|^2$ are mutually independent exponential random variables with unit mean.

The outage probability of the cooperative transmission P_{OC} conditioned on the fixed topology of the user s and the relay l, as in Fig. 1, can be calculated as follows

$$\begin{aligned} &\mathcal{P}_{OC} = \mathcal{P}\left((\text{SNR}_{sd} \leq \beta) \cap (\text{SNR}_{sl} \leq \beta)\right) + \\ &\mathcal{P}\left((\text{SNR}_{sd} \leq \beta) \cap (\text{SNR}_{ld} \leq \beta) \cap (\text{SNR}_{sl} > \beta)\right) = \\ &\left(1 - f(r_{sd}, P_s^C)\right)\left(1 - f(r_{sl}, P_s^C)\right) \\ &+ \left(1 - f(r_{sd}, P_s^C)\right)\left(1 - f(r_{ld}, P_l)\right) f(r_{sl}, P_s^C), \end{aligned} \tag{13}$$

where $f(x,y) = \exp(-\frac{N_o \beta x^{\gamma}}{y(1-\alpha)})$. The first term in the above 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 above expression can be simplified as follows

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

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

$$\begin{aligned} &P_{tot}^C = (P_s^C + P_c + 2P_r)\mathcal{P}(SNR_{sd} \geq \beta) \\ &+ (P_s^C + P_c + 2P_r)\mathcal{P}(SNR_{sd} < \beta)\mathcal{P}(SNR_{sl} < \beta) \\ &+ (P_s^C + P_l + 2P_c + 2P_r) \\ &\times \mathcal{P}(SNR_{sd} < \beta)\mathcal{P}(SNR_{sl} > \beta), \end{aligned} \tag{15}$$

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 reception 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. Using the Rayleigh fading channel model, the total consumed power can be given as follows

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

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_l at the source and relay nodes respectively. The optimization problem can be stated as follows

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

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 above 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

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

Beside 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 enough high SNR the following approximation holds $\exp(-x) \simeq (1-x)$; where x here is proportional to $1/SNR$.

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

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

and similarly, the outage probability can be written as follows

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

where $k_1 = \frac{\beta N_o r_{sd}^\gamma}{1-\alpha}$, $k_2 = \frac{\beta N_o r_{sl}^\gamma}{1-\alpha}$, and $k_3 = \frac{\beta N_o r_{ld}^\gamma}{1-\alpha}$.

This is a constrained optimization problem in one variable and its Lagrangian is given by

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

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

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

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

$$\begin{aligned} &1 + (k_1 k_2 - P_c k_1) x^2 + 2\left(k_1 k_2 P_c - \lambda(k_1 k_2 \right. \\ &\left. + k_1 k_3)\right) x^3 + 3\lambda k_1 k_2 k_3 x^4 = 0, \end{aligned} \tag{23}$$

under the outage constraint

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

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

IV. Experimental and Simulation Results

A. 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. Meanwhile, we have also assumed that the channel errors exhibit strong time correlation. In other words, if the channel errors happen independently, there will be no performance gain by applying cooperative communication comparing to direct transmission. In this work 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 strong time correlation for each receiver, while exhibit negligible dependence among the two receivers. Fig. 2 illustrated one instantiation of the experiments. The first figure illustrates the results obtained in 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 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 observation also holds for the second receiver. If we take a further look at the results we can see that in this set

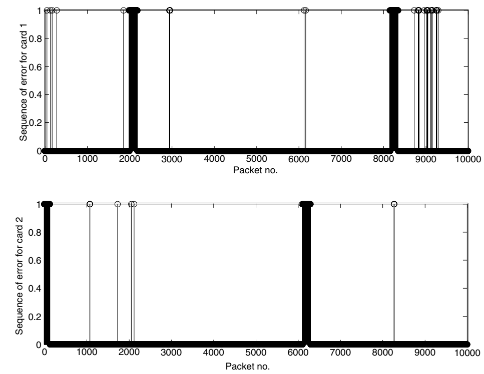

Fig. 2. Sequence of packet errors at the two utilized wireless cards.

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 Fig. 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 strong time correlation. For example, given the current received packet is erroneous, the probability that the next packet is also erroneous is around $P_{0|0}$.

Now we take a comparative look at the results obtained in the two receivers. From these results we can see that although there exist 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.

B. 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,

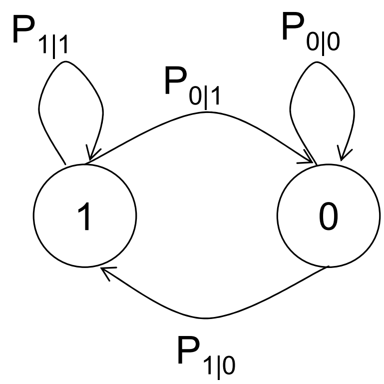

Fig. 3. Modelling the channel by a two (on-off) state Markov chain to study the time correlation.

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 details 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, $P_r = 5 \times 10^{-5}$, $QoS = 10^{-4}$. These values are taken from the specifications of Mica2 and Micaz motes. 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 P_r as depicted in Fig. 4. We plot the cooperation gain versus the distance between the source and the destination for different values of receive power $P_r = 10^{-4}, 5 \times 10^{-5}, 10^{-5}$. At source-destination distances below 20m, the results reveal that direct transmission is more energy efficient than cooperation, i.e., 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 almost yield the same cooperation gain. For larger distances, however, a gap starts to appear between optimal and equal power allocation. The intuition 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 Fig. 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 parameter, equal power allocation provides equal gains as optimal power allocation. In Fig. 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 Fig. (7).

In Fig. 8 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 position is taken equal to ($r_{sl} = 0.2r_{sd}, r_{ld} = 0.8r_{sd}$), ($r_{sl} = 0.5r_{sd}, r_{ld} = 0.5r_{sd}$), and ($r_{sl} = 0.8r_{sd}, r_{ld} = 0.2r_{sd}$).

Figs. 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

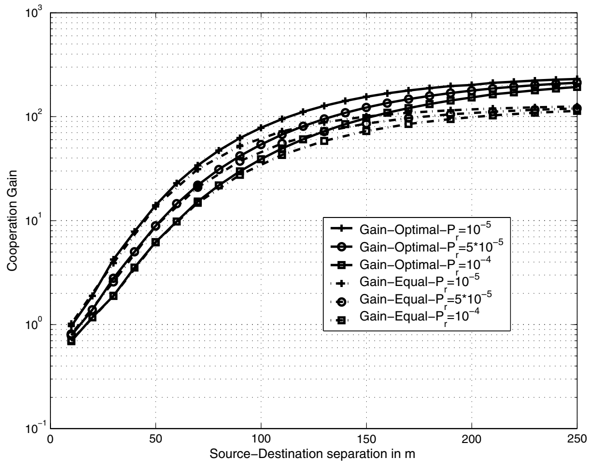

Fig. 4. Cooperation gain versus the source-destination distance for different values of received power consumption .

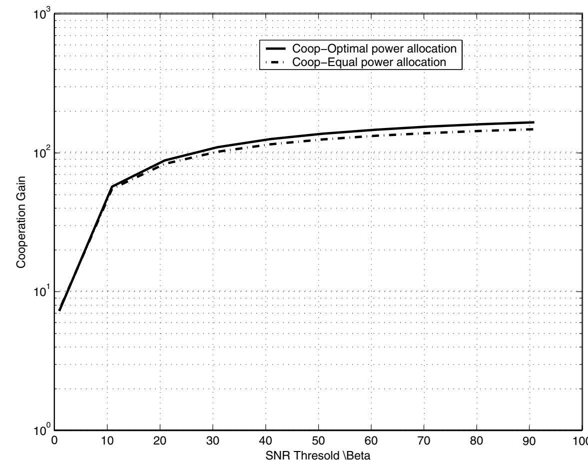

Fig. 5. Cooperation gain versus the SNR threshold β.

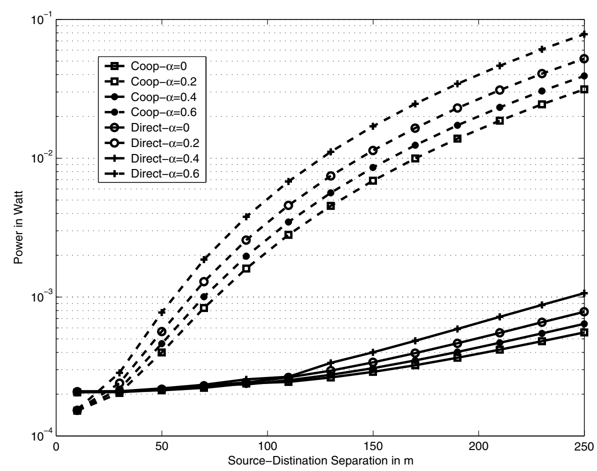

Fig. 6. Optimal power consumption for both cooperation and direct transmission scenarios for different values of α.

equal power allocation scenario the problem becomes symmetric in the source-relay and relay-destination distances. For the optimal power allocation scenario depicted in Fig. 9, the problem is no more symmetric because different power allocation is allowed at the source and destination. 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.

V. 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. We formulated a constrained optimization problem to minimize the total consumed power under a given QoS requirement. It is shown that for short distance separations and more specifically below a certain threshold between the source and the destination, 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.

Also, choosing the optimal relay location for cooperation plays an important role above a certain threshold and the best relay location depends on the power allocation scheme, whether optimal or equal. In summary, caution must be taken before applying coopera-

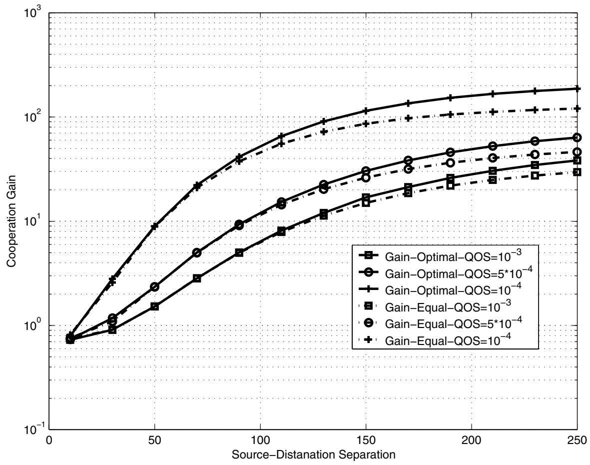

Fig. 7. Cooperation gain versus the source-destination distance for different values of QOS.

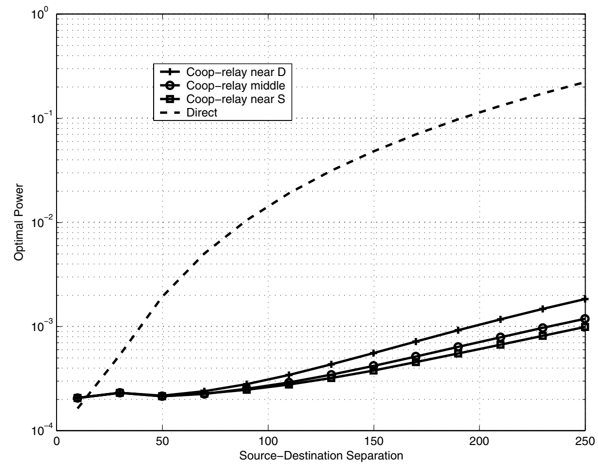

Fig. 9. Optimal Consumed Power versus distance for different relay locations for optimal power allocation at source and relay.

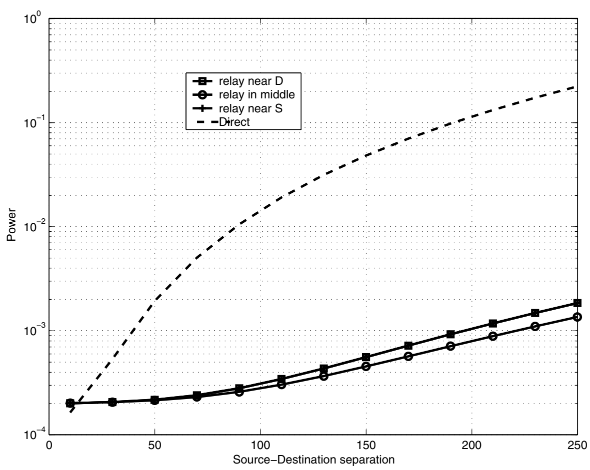

Fig. 8. Optimal Consumed Power versus distance for different relay locations for equal power allocation at source and relay.

tive communications to sensor networks, in particular whether we should apply cooperation or not, whether equal power allocation is good enough, and how to choose a partner or a relay for cooperation.

REFERENCES

[1] G. J. Foschini and M. Gans, "On the limits of wireless communication in a fading environment when using multiple antennas," *Wireless Personal Communication*, vol. 6, pp. 311-335, Mar. 1998.

[2] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Trans. Inform. Theory*, vol. 50, pp.3062-3080, Dec. 2004.

[3] J. N. Laneman and G. W. Wornell, "Distributed space-time coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Trans. Inform. Theory*, vol. 49, pp.2415-2525, Oct. 2003.

[4] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity-Part I: system description," *IEEE Trans. Comm.*, vol. 51, pp.1927-1938, Nov. 2003.

[5] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity-Part II: implementation aspects and performance analysis," *IEEE Trans. Comm.*, vol. 51, pp.1939-1948, Nov. 2003.

[6] W. Su, A. K. Sadek, and K. J. R. Liu, "SER performance analysis and optimum power allocation for decode-and-forward cooperation protocol in wireless networks," in *Proc. of IEEE Wireless Communications and Networking Conference (WCNC'05)*, vol. 2, pp. 984 - 989, New Orleans, LA, March 13-17, 2005.

[7] A. K. Sadek, W. Su, and K. J. R. Liu, "A class of cooperative communication protocols for multi-node wireless networks", in *Proc. IEEE International Workshop on Signal Processing Advances in Wireless Communications SPAWC*, pp. 560 - 564, New York, June 2005.

[8] G. Kramer, M. Gastpar, and P. Gupta, "Cooperative strategies and capacity theorems for relay networks," submitted to *IEEE Trans. Inform. Theory*, version May 7, 2004.

[9] G. Scutari and S. Barbarossa,"Distributed space-time coding for regenerative relay networks," *IEEE Trans. on Wireless Communications.*, vol. 4, issue 5, Sept. 2005, pp. 2387 - 2399

[10] Huining Hu, Halim Yanikomeroglu, David D. Falconer, and Shalini Periyalwar, "Range extension without capacity penalty in cellular networks with digital fixed relays", *IEEE GGlobecom'04*, December 2004, Dallas, Texas, USA.