Performance of a Partner Selection Algorithm in IEEE 802.15.4 Based Wireless Sensor Networks

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***Abstract*— Selection of an appropriate relaying partner can be used to increase the network lifetime of a wireless sensor network. In this paper, the effectiveness of cooperative relaying in an IEEE 802.15.4 compatible wireless sensor network is investigated. The worst link first coding gain-based partner selection algorithm is applied together with a transmit power level that fulfilled a given outage criterion. Error rates are also evaluated. It is proven through simulations that cooperation can provide a significant energy reduction at a similar performance in terms of outage and error rate when compared to no cooperation. We have shown that this reduced energy increases the lifetime for the network by an order of 10^2 to 10^3 which is significant in practical wireless sensor networks where sensor nodes have limited energy supply.**

***Index Terms*— Cooperative communication, cooperative relaying, wireless sensor networks, IEEE 802.15.4**

I. Introduction

Wireless sensor networks (WSN) have found immense and diverse applications ranging from environment and health monitoring to smart buildings [1]. One of the major challenges faced in WSN is the constraint of resources, especially energy and hence, increasing network lifetime by reducing power consumption to a minimum is the most important design goal [1]. Cooperative diversity can be utilized in optimizing the overall energy consumption of the network [2].

Castiglione et al. [3] have proposed a partner selection algorithm for indoor-to-outdoor cooperative networks that increases the lifetime of the network by decreasing the energy consumption of the nodes using cooperative amplify and forward relaying. The worst link first (WLF) selection algorithm for relays is based on the coding gains (CG) of the links that exhibit Rician block fading. Sufficient transmit power is utilized by all nodes to meet the performance criterion in terms of outage probability. The algorithm in [3] demonstrated a substantial lifetime gain in the order of 2 to 3 magnitudes.

Most of the extensive available work on cooperation protocols does not consider any specific standard. Since IEEE 802.15.4 [4] is supported by most of the current sensor node hardware, we are interested in the application and performance of the WLF partner selection algorithm within its constraints. Our work is based on [3] with the following major contributions:

- The partner selection algorithm is modified to be applied in an IEEE 802.15.4 compliant environment.
- Lifetime gains have been re-evaluated in a standard compatible real-world environment.
- Error performance is evaluated for different scenarios to get pragmatic performance metrics for WSN.

II. System Model

We consider a scenario with multiple resource-constraint wireless sensor nodes that periodically transfer data to an access point (AP) using IEEE 802.15.4 compliant time division multiple access (TDMA) scheduling. Apart from periodic data transmissions, we assume the nodes can also measure link quality in terms of coding gain that specifies the asymptotic outage behavior of the channel [5]. The coding gain gives a simple expression for the probability that the received SNR at the receiver side falls below a defined threshold. For the SNR threshold γ_{th}, noise variance σ^2, transmit power ρ_i and coding gain $c_{i,j}$, the outage probability for node i communicating with node j is asymptotically given by [3]

$$P_{\text{out}} \approx \frac{\gamma_{\text{th}}\sigma^2}{c_{i,j}\rho_i} \tag{1}$$

We assume the channel in industrial scenarios can be modeled by a Rician distribution because the channel gain is made up of a deterministic component caused by reflections from static objects and temporal fading caused by moving scatterers in the environment [3]. An expression for its outage probability has been derived in [6]. If the Rician K-Factor and pathloss $L_{i,j}$ between nodes i and j are expressed in decibels, the coding gain $c_{i,j}$ of the link is [3],

$$c_{i,j} = \frac{e^{\theta(K_{i,j})}}{\theta(L_{i,j})[1+\theta(K_{i,j})]}, \tag{2}$$

where $\theta(\cdot) = 10^{(\cdot)/10}$.

The nodes use received signal strength indicator (RSSI) values of the signals overheard from other nodes and the beacon frame from the AP to estimate the CG by first estimating the channel parameters or by directly using an estimator as proposed by [3]. If a node observes a link to another node with a CG value better than its own link to the AP by a certain threshold τ, that node can be chosen as a possible partner. The nodes pass on this information to the AP which decides upon partner allocation based on this information using the WLF algorithm as follows: In case the number of nodes is odd, the node with the best link quality is left unpaired and is excluded from further pairing. The pairing process starts with the node with worst link quality. The node with the best link quality within the possible partner list is assigned as a partner to that node. These nodes are excluded from further pairing. The process repeats till either all nodes are paired or unpaired nodes are left with no possible partners. These allocation decisions and the required transmitter power values are then conveyed to all the nodes. The AP also performs the usual management functions like the provision of beacons and allocation of time slots.

III. IEEE 802.15.4 Simulator

The IEEE 802.15.4 low-rate wireless personal area networks standard [4] is a popular industrial wireless communication standard encompassing the physical (PHY) and medium access control (MAC) layers for different modulation schemes. A popular mode of IEEE 802.15.4 for the 2.4 GHz industrial, scientific and medical (ISM) band uses offset quadrature phase-shift keying (OQPSK) with half-sine pulse shaping with a data-rate of 250 kbps.

We developed a MATLAB-based simulator for 2.4 GHz OQPSK PHY and MAC features that are required for communication between nodes. The PHY payload in the PHY protocol data unit (PPDU) is randomly generated and all the other fields are calculated in accordance with the specifications provided in the standard [4]. Error performance is evaluated for additive white Gaussian noise, Rayleigh and Rician channels and found in accordance with already reported results, e.g. in [7].

IV. Results

The simulation setup is based on a 20 m x 20 m indoor environment with randomly distributed sensor nodes communicating with an outside AP 20 m away from the wall. The number of nodes is varied from 3 to 9. For each out of 10^3 random placements of nodes, Rician K-factor and pathloss are generated using the bivariate model given by [3] that is based on experimental measurements done at Stanford University [8] and WINNER-II channel models [9]. The combined K-factor and pathloss for the indoor to outdoor channels are, however, computed using simulations and are then used to calculate the CG. The same value for the noise power is taken for all links. For each scenario, 1000 frames are transmitted by each node using the IEEE 802.15.4 PHY and the number of errors is recorded. [3] used TDMA scheduling with each time slot divided in two parts for node's own data and relayed data for the partner node. To allow the same amount of data to be transmitted as without relaying demanded higher data rates, which in turn required the nodes to be able to transmit data using variable data rates with or without cooperation. With the available PHY options with the 2.4 GHz ISM band [4] other than UWB, this is not possible. So for our simulations, separate time slots are used by the nodes for transmitting their own data and the relayed data of their partners, thus reducing the overall throughput by a factor of 2 in case of relaying. This also affects the transmit power calculations and the subsequent lifetime gain. In order to investigate the effect of partner selection algorithm only, we assume that the nodes accurately determine the CG of the links from the RSSI values. Moreover, we assume that this information is reliably transmitted to the AP and the allocation decisions from the AP are also reliably received by the nodes. The SNR threshold for outage was initially varied from 0.01 to 10 but as it did not affect the improvement in lifetime, all the subsequent simulations are based on $\gamma_{\mathrm{th}} = 1$.

A. Lifetime Gain

The performance of the algorithm is shown in the form of lifetime gain that is expressed as $\mathbb{E}[E^{\max}(\mathrm{coop})]/\mathbb{E}[E^{\max}(\mathrm{no\_coop})]$ where $\mathbb{E}(\cdot)$ represents the expectation operation, i.e. the ratio between the average maximum energy for any node in a network with and without cooperation. The energy consumption model of [3] is used where only the energy required for transmission is considered assuming that it represents the major portion of the total energy consumption.

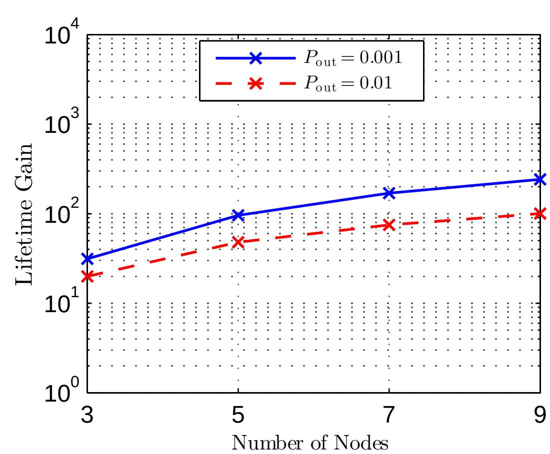

Fig. 1. Lifetime gains for different outage probabilities as a function of number of nodes in the network

Fig. 1 presents the lifetime gain for $P_{\mathrm{out}} = 0.01$ and 0.001 as a function of number of nodes in a network. Odd number of nodes are considered to allow for at least one unpaired node in the network. It can be observed that cooperation results in a significant improvement in the lifetime of the network. The gain increases with an increasing number of nodes available in the network. This is due to the fact that the assignment of good relay node to nodes with bad links can be done in a better way. The more variations in channel parameters we have in the network, the more advantage we can get using cooperation. Hence, a smaller outage probability value also results in a higher lifetime gain.

B. *Error Probabilities*

The number of errors in the frames received at the AP are measured for $P_{\text{out}} = 0.001$ and $\gamma_{\text{th}} = 1$. An error detected by the cyclic redundancy check of the received MAC frame is considered as a frame error. If the frame is in error, the number of errors at bit, symbol and chip levels are also determined. Frame error rates (FER) and symbol error rates (SER) from sensor nodes to the AP for the same scenarios are shown in Figs. 2 and 3 respectively.

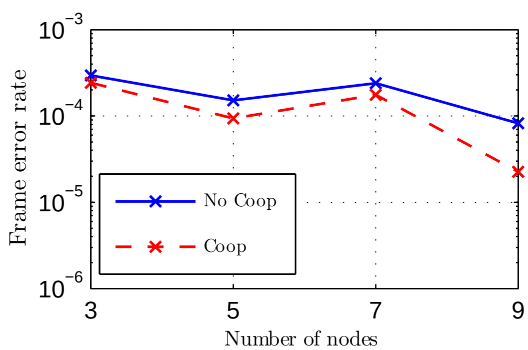

Fig. 2. FER from sensor nodes to the AP as a function of number of nodes with and without cooperation

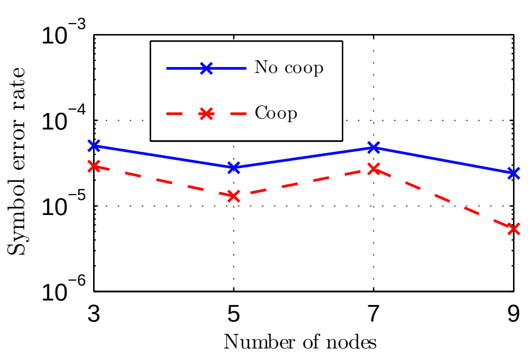

Fig. 3. SER from sensor nodes to the AP as a function of number of nodes with and without cooperation

From Figs. 2 and 3, it can be observed that the error rates, approximately, stay the same with and without cooperation, although according to Fig. 1, because of the reduced transmit power, the nodes spend much less energy when they are cooperating. One should note that the partner selection algorithm adapts the transmit power such that the target outage probability is met. Thus it does not affect the error probabilities but improves the nodes' lifetimes.

V. Conclusions

We have proven the applicability and effectiveness of the CG-based WLF partner selection algorithm for AF relaying in IEEE 802.15.4 based wireless sensor networks. It is shown that the algorithm provides improvement in the lifetime of the network. For 5 cooperating nodes with an outage probability of 0.001, the gain is about 100 and it increases as the number of cooperating nodes are increased, reaching about 250 for 9 nodes. The lifetime gain values are smaller than those reported in [3] because of the smaller environment size used for these simulations that subsequently result in less variation in channel parameters. The use of same data rates with and without cooperation results in decreasing the effective throughput of the system within the IEEE 802.15.4 standard. However, in wireless sensor applications, where data rate is not critical and nodes only require periodic transmission of data with long sleep intervals in-between, the advantage in lifetime improvement is a significant contribution.

Acknowledgment

This work was supported by the Telecommunications Research Center Vienna (FTW). FTW is supported by the Austrian Government and the City of Vienna within the competence center program COMET.

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