Sequential Random Selection Relaying for Energy Efficient Wireless Sensor Networks

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Abstract—In a wireless sensor network with relaying capability, intermediate relay nodes are with limited energy budget. To maximize lifetime of relay nodes, selective relay strategies, requiring full channel state information (CSI), are used to utilize the best relaying channel. Pilot overhead on relay nodes lifetime is reduced by assuming pilot transmission from destination instead of relay nodes. This is only valid if channel reciprocity is assumed. It is evident that channel reciprocity is not valid for low cost simple transceivers, such as sensor node transceivers. In this paper a novel sequential random (SR) selective cooperative relay strategy is proposed in amplify and forward (AF) relay networks for applications with non reciprocal links. The outage probability of SR strategy is derived and its average lifetime, average number of pilot signals per transmitted message, and average transmit energy per message are simulated. SR strategy uses less number of pilots than selective cooperative relay strategies (S-CRSs). A dynamic transmit power threshold is adopted for the proposed SR strategy to improve its performances. In contrast to S-CRSs, in which each relay knows its CSI to the destination before every transmission, SR acquires CSI on the need-to-know basis and significantly outperforms the lifetime of S-CRSs for large number of relays and relatively good channel conditions. The proposed SR selects relay nodes in a distributed manner which makes it suitable for heterogeneous ad-hoc sensor networks in which some relays have processing capabilities and less restricted energy supply, i.e. these relays can act as the intermediate destinations.

I. INTRODUCTION

Modern applications of wireless sensor networks mandate the use of large number of low cost sensor nodes capable of wireless transmission. These nodes are characterized by their low transmit power, low receiver sensitivity, and limited total energy (battery operated). Due to these characteristics, wireless relaying in these networks is an essential mechanism for covering large areas. Moreover, energy conservation (especially at the relay nodes with limited energy budget) is invaluable. In order to conserve energy at relay nodes, opportunistic selective cooperative relay strategies (S-CRSs), which utilizes the best available relay channel, are proposed in the literature [1], [3]. Single relay selection strategies or S-CRSs in [1] yield better lifetime than multiple relay selection strategies [4] while they can achieve full order diversity [2]. A simple and efficient distributed method for relay selection [3] is used in [1] assuming that the relay-destination links are reciprocal. The destination transmits one broadcast pilot signal which enables each relay to estimate the relay-destination gain about its own link. However, the reciprocity theorem can be assumed for the Radio Frequency (RF) channel between the antennas but not necessarily in the baseband due to circuitry limitations. To mitigate the effects of channel non-reciprocity in the baseband several methods are proposed in [5]–[7].

In [5] an external reference antenna is used at each node to calibrate the non reciprocity factor for each node. This method, namely absolute calibration, is not practical in some wireless relay network such as wireless sensor networks (WSN), i.e. in many applications of WSN the nodes (relays) are placed in the remote or sever environment and they are not accessible. In addition, in many application where large number of nodes are used the absolute calibration method may not be feasible.

Ensuring the reciprocity of the electronic circuitry through a specially crafted transceiver is studied in [6]. The requirement of calibration is lifted at the expense of design complexity. However, this method may not be practical in many WSN applications where inexpensive sensors with low complex circuitry in large number are used.

Therefore, in TDD the classical feedback method should be used for S-CRSs in [1] to ensure that each relay can obtain the CSI about its own link to the destination. The pilot signal from each relay enables the destination to compute and to feed the CSI about each relay-destination link back to the corresponding relay [13]. In the four S-CRSs studied in [1], before a message can be transmitted, each relay should acquire CSI from the destination. All relays consume resources (channel and energy) to send pilot signals and to receive the CSI regardless of the message transmission. Whether we use the distributed relay selection of [1] or a centralized node (such as the destination) to select a transmitting relay, all the relays use energy and RF resources to send pilot signals to the destination to obtain the CSI computation.

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In S-CRSs, the knowledge of local CSI for each relay allows the network to select the one which has relatively more favorable link conditions compared to the other relays. We simulate the average number of CSI acquisition per received message for such network and we investigate the effects of these pilot signals on the lifetime of the network. The simulation results motivate us to propose a new single relay selection strategy, namely SR strategy, which utilizes the channel and energy more efficiently.

In contrast to S-CRSs, in which relays are chosen based on local CSI and residual energy information (REI), in the SR strategy one relay is randomly selected to acquire CSI and to forward the message, if it can satisfy the system requirements. In SR strategy, the number, $N_{\text{Pilots/msg}}$, of pilots per received message is less than that of S-CRSs. Although the randomly selected transmitting relay may not have better channel conditions than other relays in SR strategy, the network compromises between the lower energy expenditure as a result of low CSI at all relays.

In addition, we adopt the dynamic transmit power threshold scheme studied in [10] [11] with the proposed SR strategy to simulate the average network lifetime and the average number, $N_{\text{Pilots/msg}}$, of pilots per received message. In Sections II, III, IV, and V, we will discuss the system model, the sequential random strategy, the simulation results, and the conclusion, respectively.

II. SYSTEM MODEL

Consider $N$ cooperative relay paths, each containing a single relay (node) which can forward a message to the destination using enough power to achieve the desired SNR at the destination while satisfying the system outage probability requirement, $\eta$. The destination keeps track of the Residual Energy (RE) of relays to calculate the system outage probability, $P_{\text{outage}}$. A Message is transmitted to the destination in two phases: the source broadcasts the signal (the relays and the destination) to forward the message, if it can satisfy the system outage probability, $P_{\text{outage}}$, due to lack of CSI at all relays.

The Maximal Ratio Combining (MRC) receiver at the destination receives any message over two phases as follows:

• Phase I: Receives the source broadcast signal intended for the relays.
• Phase II: Receives the signal forwarded by one of the relays.

The sum of the SNR achieved from the destination in Phase I and the $k$th relay in Phase II must satisfy the threshold SNR, $\gamma_{th}$, at the destination for a successful transmission. If the source-destination link is interrupted, one relay should satisfy $\gamma_{th}$ on its own.

![Fig. 1: System Model](image)

A. Channel and Noise

The channel gains are assumed to be independent, circularly symmetric complex Gaussian random variable with unit variances and zero means, i.e. $CN(0,1)$. We denote the channel gain from the source to the $k$th relay by $h_{Sk}$ and gain from the $k$th relay to the destination by $h_{kD}$. The channel gain from the source to the destination is denoted by $h_{SD}$, as shown in Fig. 1. Additive white Gaussian noise (AWGN) with unit variance is present at the relays and the destination.

The signals received at the $k$th relay and destination in Phases I and II are [1]:

$$r_k[I] = \sqrt{P_s}h_{Sk}m + w_k ,$$

$$y[I] = \sqrt{P_s}h_{SD}m + w_D[I] ,$$

and

$$y[II] = G_k r_k[I] h_{kD} + w_D[II],$$

where [I] and [II] denote the signals in Phases I and II. In (1) and (2), $m$ is the unit energy signal corresponding to the source messages, $r_k[I]$ and $y[I]$ are the signals received at the $k$th relay and destination in Phase I, and $y[II]$ is the received signal at the destination in Phase II. The noise at the $k$th relay in Phase I is denoted by $w_k$. And the noise at the destination in Phases I and II are denoted by $w_D[I]$ and $w_D[II]$, respectively. $P_s$ and $P_k$ denote the transmit power of the source and the $k$th relay, respectively. The gain at the $k$th relay, $G_k$, in Phase II is $\sqrt{P_s|h_{Sk}|^2+1}$.

B. Equivalent SNR and $P_{\text{outage}}$

The equivalent SNR, $\gamma_{eq}$, at the output of the destination MRC receiver is the sum of the SNR of the source-destination link, $\gamma_{SD}$, in Phase I and the SNR at the destination from a path passing through the $k$th AF relay [8] in Phase II, denoted by $\gamma_{SkD}$:

$$\gamma_{SD} = \frac{P_s|h_{SD}|^2}{N_0},$$

and

$$\gamma_{SkD} = \frac{P_s|h_{Sk}|^2 P_k|h_{kD}|^2}{N_0}.$$

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where the noise variance, denoted by \( N_0 \), will be assumed to be equal to 1 in our study. Thus,

\[
\gamma_{eq} = \gamma_{SD} + \gamma_{SkD}.
\]  (6)

Assuming each randomly chosen relay can obtain \( \gamma_{SD} \) and the CSI and REI about its own links and batteries, it can compute minimum required transmit power, \( P_k \), to satisfy \( \gamma_{eq} \geq \gamma_{th} \) using (6). A system outage occurs if \( \gamma_{eq} < \gamma_{th} \), i.e. the direct source-destination link does not satisfy \( \gamma_{th} \) in Phase I and none of the relays can satisfy \( \gamma_{th} - \gamma_{SD} \) in Phase II. The transmit power at the relays are restricted by the physical restriction on the maximum power, \( P_{max} \), a relay can transmit and the remainder energy of the \( k \)th relay, \( E_{0k} \), such that \( 0 < P_k \leq \min \{ P_{max}, E_{0k} \} \). Assuming that each message is transmitted in one unit time, we can compare \( P_{max} \) and \( E_{0k} \).

The probability that the source-destination path is in outage in Phase I is [8]:

\[
P_{out}(P_k|\gamma_{SD}) = 1 - \exp\left( \frac{\gamma_{th}}{P_k\sigma_{SD}^2} \right),
\]  (7)

where the source-destination link gain variance is denoted by \( \sigma_{SD}^2 \). We denote the maximum allowable transmission power of the \( k \)th relay by \( P'_k \), i.e. \( P'_k = \min \{ P_{max}, E_{0k} \} \). The outage probability of a single path consisting of an AF relay as a function of \( P'_k \) is [1]:

\[
P_{out}(P'_k|\gamma_{SD}) = 1 - e^{-\left( \frac{2\gamma_{th}-\gamma_{SD}}{P'_k\sigma_{Sk}^2} + \frac{\gamma_{th}-\gamma_{SD}}{P'_k\sigma_{kD}^2} \right)} \sqrt{3}K_1(\sqrt{3}).
\]  (8)

where \( K_1(.) \) is the modified Bessel function of the second kind of order 1 and \( \beta = \frac{4(\gamma_{th} + \gamma_{SD})}{P_k\sigma_{Sk}^2 + P'_k\sigma_{kD}^2} \). The variance of the channel gain from the source to \( k \)th relay and from the \( k \)th relay to the destination are denoted by \( \sigma_{Sk}^2 \) and \( \sigma_{kD}^2 \), respectively.

We can derive the system outage probability, \( P_{outage} \), as:

\[
P_{outage} = \prod_{k=1}^{N} P_{out}(P'_k|\gamma_{SD}) = \prod_{k=1}^{N} P'_k|\gamma_{SD} < \gamma_{th} = P'_k|\gamma_{SD} < \gamma_{th} \geq \gamma_{th} - \gamma_{SD}.
\]  (9)

where the product term is the probability that all of \( N \) paths are in outage. The dynamic transmit power control aims to maximize the number of successfully transmitted messages under the constraints that \( \gamma_{eq} \geq \gamma_{th} \) and \( P_{outage} < \eta \).

The details for the transmit power control, denoted by \( P_{soft} \), are described in [10] and [11]. As a result of applying \( P_{soft} \), new transmit power restriction will be added to the relays, i.e. \( 0 < P_k \leq \min \{ E_{0k} \text{ unit time}, P_{max}, P_{soft} \} \).

III. SEQUENTIAL RANDOM (SR) STRATEGY

The SR strategy aims to reduce the number CSI acquisition and consequently, to improve the energy consumption and channel utilization compared to S-CRSs. In Phase I, the source will broadcast a pilot signal and the relays acquire CSI of source-relay links. Then, the source broadcasts the message and the relays and the destination receive the message. In Phase II, the destination broadcasts the value of \( \gamma_{th} - \gamma_{SD} \) which must be satisfied by a randomly selected relay. A timer with a random value at each relay gets activated upon receiving \( \gamma_{th} - \gamma_{SD} \) or a clear-To-Send signal (CTS) from the destination. We assume all the relays can communicate with the source and the destination or they will not participate in the relay selection process. The first randomly expired relay will send a pilot signal to the destination and the destination computes the CSI about the relay-selection link and feeds it back to the relay while all other relays which have sensed the channel as busy refrain from transmitting and (may) sleep for a duration of ‘idle time’. The probability of collision of the pilot signals is beyond the scope of our study, and can be derived in the same manner as those of the message signals in [3]. Given that the selected relay receives reliable CSI signal, it computes \( P_k \) required to satisfy \( \gamma_{th} \) from Equations (5) and (6). If \( P_k \) also satisfies \( 0 < P_k \leq \min \{ E_{0k} \text{ unit time}, P_{max}, P_{soft} \} \), then the relay can forward the message to the destination. If the destination does not receive the message from the relay during the idle time, it assumes the selected relay is unable to satisfy \( \gamma_{th} - \gamma_{SD} \). The relays resume sensing the channel after the idle time has expired and the destination begins broadcasting \( \gamma_{th} - \gamma_{SD} \) and reactivating timers of each relay until one relay is able to satisfy \( \gamma_{th} - \gamma_{SD} \). The relays which have not satisfied the system requirements previously, will be disabled for one message transmission time (Phase I + II) and will not participate in the selection process. If none of the remaining relays can satisfy the required SNR, the system is in outage. The destination uses the REI of the relays and (8) to determine whether the network is inoperable or not, i.e. the network is considered in-operable if \( P_{outage} > \eta \).

<table>
<thead>
<tr>
<th>Phase I</th>
<th>Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source TX a Pilot</td>
<td>Source TX a Pilot</td>
</tr>
<tr>
<td>Source TX a Message</td>
<td>Source TX a Message</td>
</tr>
<tr>
<td>Destination TX CTS</td>
<td>Destination TX Clear-to-Send CTS</td>
</tr>
<tr>
<td>Pilot Signals from N relays</td>
<td>Destination Feedbacks N</td>
</tr>
<tr>
<td>TX to Destination Pilot</td>
<td>Another Random Relay TX a Pilot</td>
</tr>
<tr>
<td>Destination Feedbacks the CSI</td>
<td>Destination Feedbacks the CSI</td>
</tr>
<tr>
<td>One selected Relay TX a Message</td>
<td>...</td>
</tr>
</tbody>
</table>

Fig. 2: MTP of S-CRSs Medium Access

Fig. 3: SR Medium Access

In S-CRSs, each relay transmits a pilot signal in one of \( N \) sequential time slots to avoid interference with other pilots from other relays. Then, the destination computes and feeds the CSI back to each relay in the same manner. However, in SR strategy CSI is computed on a need-to-know basis and each relay transmits a pilot signal and receives its corresponding CSI signal from the destination in a sequential manner. Therefore, it is reasonable to compare the time that one CSI is acquired in SR and S-CRSs, because each CSI acquisition requires a pilots signal from relay to destination and one feedback in the opposite direction. However, channel
usage in SR is more favorable because CSI is computed on a need-to-know basis. The access to the medium during the CSI acquisition and message transmission in Minimum Transmission Power (MTP) of S-CRSs and SR are shown in Figs. 2 and 3, respectively.

The idle time can be adjusted to ensure short waiting time after a relay cannot satisfying the system requirements. When relays resume listening to the channel after each idle time, if the relays receive a pilot from the source, they drop the current message and they assume that the previous message has been received at the destination successfully while they were asleep (or in idle). A special scenario of our system model is when the source-destination link does not exist. The performance of our proposed method can be compared to the previously studied performances of the same system model. We will denote this scenario by Case I in the following Sections where we must assume \( \gamma_{SD} = 0 \) and \( P[\gamma_{SD} < \gamma_{th}] = 1 \) in Equations (6) and (9).

A. Number of Used Pilot Signals at the Relays

In the study of selective relay strategies in [1] [10] [11], each relay acquires CSI about its own link to the destination at the beginning of Phase II. Whether a message is transmitted or not, \( N \) CSI are acquired in the S-CRS networks. In SR \( N_{\text{Pilots/msg}} \) is less than \( N \) and at its worst case equals to that of S-CRSs, equal to \( N \), i.e. none of the sequential random selected relay have satisfied the system requirements and hence, it is reasonable to assume that the time that it takes to transmit a message in SR is shorter than S-CRSs. The strategy described for SR is shown in Fig. 4.

B. Pilot Signal Energy Cost

![Soft Flow Chart](image)

Fig. 4: SR + \( P_{\text{soft}} \) Flow Chart

In the study of network lifetime, the energy consumed by pilot signals play a crucial role. The pilot signals are similar to the message signals with less number of symbols (training symbols) than the message signals. The required number of symbols in the pilot signal for an accurate CSI estimation is studied in [9]. Hence, the amount of energy consumption of pilot signals can be considered as a fraction of the message signals.

We denote the average energy consumption of the pilot signals by \( \overline{E}_{\text{Pilot}} \) and the average energy consumption of the message signals by \( \overline{E}_{\text{msg}} \), i.e. at the beginning of each Phase II, \( \overline{E}_{\text{Pilot}} \) is deducted from the relay batteries which have used pilot signals and \( \overline{E}_{\text{msg}} \) is deducted from the relay which has transmitted a message.

IV. SIMULATION RESULTS

We show the average network lifetime, \( \overline{N}_{\text{Pilots/msg}} \), and \( \overline{E}_{\text{msg}} \) of the proposed SR strategy using computer simulations. We compare the simulation results with those of Minimum Transmission Power (MTP) studied in [1]. The values of the parameters in the simulations are similar to those in [1] [10] and [11] for fair comparisons. In our simulations, the source power and threshold SNR are chosen to be \( P_s = 12 \) dBm and \( \gamma_{th} = 8 \) dB, respectively. The relay channel gain and receiver noise are assumed to have unit variances. The initial energy level at the relay, system outage probability threshold, and physical power limit at the relays are chosen to be \( E_0 = 500 \) mJouls, \( \eta = 10\% \), and \( P_{\text{max}} = 80 \) mW, respectively. The \( \eta \) in [1] is considered as a good indication of the low residual energy level at the relays. We assume that the relays are located at equal distances from the source and destination and source-destination path suffers more attenuation, i.e. \( \sigma^2_{SE} = \frac{1}{4} \). The results are averaged over 10000 lifetimes in a Monte Carlo simulations. The values of these parameters are...
summarized in Table I.

<table>
<thead>
<tr>
<th>$\eta$</th>
<th>$E_0$ (mJ)</th>
<th>$P_s$ (dBm)</th>
<th>$P_{max}$ (mW)</th>
<th>$\gamma_{th}$ (dB)</th>
<th>$\sigma^2_{Sk}$</th>
<th>$\sigma^2_{SD}$</th>
<th>$\sigma^2_{D}$</th>
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<tbody>
<tr>
<td>10%</td>
<td>500</td>
<td>12</td>
<td>80</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
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</table>

TABLE I: Values of the Parameters in the Simulations

The results of the simulations in Fig. 5 show that $N_{Pilots/msg}$ in SR strategy is less than $N_{Pilots/msg}$ in MTP for any number of relays. SR uses less number of pilot signals than MTP because SR uses pilot signals on a need-to-know basis. However, the network in SR compromises between the energy saving due to low $N_{Pilots/msg}$ and the energy loss due to lack of CSI at all relays. The average lifetime and $E_{msg}$ for the SR and MTP for the general system model and Case I are shown in Fig. 6. The simulation results illustrate that when $E_{Pilot}$ is not considered, the average lifetime of the SR network with the dynamic transmit power control performs relatively close to MTP.

The impact of $E_{Pilot}$ on the network lifetime is shown in Fig. 8 where we assume $E_{Pilot}/E_{msg} = 1\%$. The results show that if a pilot signal consumes as low as 1% of the energy which a message signal consumes, the network lifetime of the proposed SR strategy can outperform that of MTP for large $N$ ($N > 10$). This confirms that SR with $P_{soft}$ can save energy due to less $N_{Pilots/msg}$ to offsets energy gain $E_{msg}$ that can be achieved as a result of CSI acquisition at each relay.

In addition, the average lifetime in SR and MTP for several energy consumption level of pilots ($E_{Pilot}/E_{msg} = 0 - 10\%$) are shown in Fig. 9. The result shows that the effect of pilot energy consumption is more significant on the lifetime of the MTP than that of SR. Furthermore, high $E_{Pilot}$ allows the average lifetime of SR to offset that of MTP at lower values of $N$.

Furthermore, the effects of the channel variance between the relays and the destination on the lifetime performance of the SR as well as MTP are shown in Fig. 10. The two cases are compared with previously simulated conditions:
The results show that when the channel condition between the relays and destination are bad, the SR strategy works less efficiently by using more pilot signals and consuming much higher $E_{msg}$ than the NCH. On the other hand, when the channels between the relays and destination are good, SR performs more efficiently because it can satisfy the system requirements with less $E_{msg}$.

V. CONCLUSION

A sequential random strategy was proposed in which the resources such as battery energy and channel usage were utilized more efficiently than S-CRSs in non-reciprocal channels applications such as ad hoc WSN. In the proposed SR strategy, relays acquire CSI on the need-to-know basis in contrast to S-CRSs, where each relay acquires CSI about its own channel to the destination before each message transmission. The simulation results show that the average number of required pilots per message in SR are less than half of those in MTP of S-CRSs.

Moreover, the results from the simulations show that average energy per transmitted messages and consequently, the average lifetime performances are better in S-CRSs because more number of CSI are available before transmitting a message. However, when the energy of CSI acquisition, namely pilot signals, is considered in the simulations the average lifetime of SR outperforms S-CRS for large $N$.

The low number of CSI acquisition in SR motivates us to further study the random batch processing, in which a batch of relays out of the total number of relays in the system are randomly chosen to acquire CSI. SR with random batch processing can mitigate the effects of bad channel condition between the relays and destination.

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