ENERGY ALLOCATION STRATEGIES FOR LLR-BASED SELECTION RELAYING IN COOPERATIVE TRANSMISSION

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ABSTRACT
Selection relaying (SR) achieves the powerful benefits of multi-antenna systems without the need for physical arrays. It is theoretically shown that when the relay measures log-likelihood ratio (LLR) instead of signal-to-noise ratio (SNR) to decide whether or not to forward the recovered symbols to the destination, the performance of SR with equal energy allocation is drastically improved. In this paper, we propose two energy allocation strategies based on long-term fading statistics without increasing implementation complexity as well as causing the loss of spectral efficiency to complete the framework for LLR-based SR and further enhance its performance.

1. INTRODUCTION
The spatial diversity owing to the feasibility of deploying multiple antennas at both transmitter and receiver is an efficient solution to mitigate the fading in wireless communications. However, when wireless mobiles may not be able to support multiple antennas due to size and power limitations or other constraints in wireless networks (especially, ad-hoc or sensor networks), this diversity technique is not exploited. Moreover, mobile stations (MSs) typically operate on battery, which means their consumed energy is extremely constrained. Hence how to minimize the average transmission energy is very important.

Appropriate energy allocation for all MSs is necessary to adapt channel fluctuations so as to improve communications performance. Optimum energy allocation strategies based on instantaneous fading statistics lead to some disadvantages [1]. First, they cause the loss of spectral efficiency and complexity increase because when MSs are mobile, the requirement of accurate channel state information (CSI) at all respective transmitters obtained through feedback channels may mean frequent update and an extra computation burden, which is certainly undesirable. Second, CSI can not be perfectly estimated at the receivers as well as feedback to the transmitters without any error. Noisy CSI induces inaccurate energy allocation which affects adversely the system performance. Therefore, energy allocation based on long-term fading statistics is preferred [2].

Selection relaying (SR) is one of the simple cooperative communications protocols where the relay must make an independent decision on whether or not to decode and forward source information [3]. Different performance criterions for making decision at the relay were mentioned. In [4] we proposed log-likelihood ratio (LLR) in place of signal-to-noise ratio (SNR) and verified that LLR-based SR outperforms SNR-based SR in case of equal energy allocation. In this paper, we propose two energy allocation strategies based on long-term fading statistics without increasing implementation complexity as well as causing the loss of spectral efficiency to complete the framework for LLR-based SR and further enhance its performance. Numerical results demonstrate that these strategies provide a significant energy saving for LLR-based SR over the conventional SNR-based SR and direct transmission under any relay position subject to total energy constraint.

The rest of this paper is organized as follows. Section 2 summarizes the main results in [4]. Then two energy allocation strategies are presented in Section 3. Numerical results are demonstrated in Section 4 and finally, the paper is concluded in Section 5.

2. LLR-BASED SELECTION RELAYING
Consider cooperative communications in a dual-hop wireless network where information is transmitted from a source S to a destination D with the assistance of a relay R as shown in Fig. 1.

All MSs equipped with single-antenna tran
receivers and sharing the same frequency band are under investigation. In addition, each MS does not transmit and is only for channel access. Assuming that channels between terminals experience independent slow and frequency-flat Rayleigh fading, i.e., they are constant during a N-symbol block but change independently to the next. Without loss of generality, we only illustrate the analysis for the first symbol of each block. Because of slow fading, accurate channel estimation is possible at receivers [5]. Thus, we will assume perfect CSI at all the respective receivers for coherent detection but only long-term fading statistics (particularly, the second-order moments) is known at the transmitters for energy allocation. Estimating the second-order moments at the transmitters can be easily performed by each MS. As a result, the implementation complexity due to energy allocation is negligible. Since the channel parameters vary with a frequency corresponding to the coherence time of the wireless propagation, the energies should be updated at least with the same time scale, which is of the order of hundreds of ms (according to the MS mobility).

To capture the effect of path-loss on BER performance, we use the model where the variance of $\alpha_i$ is given by $\lambda_i=(dSD/dij)^{\eta}$ with $\alpha_i$ and $dij$ being the path gain and the distance between transmitter $i$ and receiver $j$, respectively and $\eta$ being the path-loss exponent; i.e $\{S, R\}$ and $j \in \{R, D\}$ hereafter. For convenience of presentation, we utilize discrete-time complex equivalent base-band models to express all signals. In addition, we only consider binary phase shift keying (BPSK) modulation.

2.1. Selection Relaying description

Selection relaying consists of two phases. In the first phase, $S$ broadcasts a BPSK-modulated symbol $a$ and so, the signals received at $R$ and $D$ are given by

$$y_{ia} = a_{ia} \alpha_i \sqrt{E_i} a + n_{ia}$$

$$y_{ja} = a_{ja} \sqrt{E_j} a + n_{ja}$$

where $y_{ij}$ denotes a signal received at MS $j$ from MS $i$, $n_{ij}$ is a zero-mean unit-variance complex additive noise sample at MS $j$, $E_i$ is the average symbol energy (ASE) of MS $i$. Now $R$ processes the received signal according to the SR protocol [4]. That means it checks whether the received signals from both phases based on maximum ratio combining (MRC) and then detects the transmitted symbol $a$ as follows

$$\bar{a} = \text{sign}(\text{Re}(\sqrt{E_i} a_{ia} y_{ia} + \sqrt{E_j} a_{ja} y_{ja}))$$

In the rest of this section, we only summarize the main results in [4] to facilitate in addressing the proposed energy allocation strategies in Section 3.

For SNR-based SR, the condition to forward $a'$ in the second phase is

$$|\alpha|^2 \geq \frac{(\text{erfinv}(1-2P_e))^2}{E_i}$$

where $\text{erfinv}()$ is the inverse error function. For LLR-based SR, forwarding $a'$ in the second phase only takes place if

$$|\Lambda| \geq \ln \left( \frac{1}{P_{\eta}} - 1 \right) = \Lambda_0$$

where $\Lambda$ is the LLR of the received signal $y_{ia}$ at $R$ which is given by $\Lambda = 4y_{ja} \sqrt{E_i}$ and $\ln()$ denotes natural logarithm.

2.2. BER expressions

Let $\lambda_S = 1/(E_\lambda_{SD})$, $\lambda_R = 1/(E_\lambda_{DR})$, $\lambda_0 = 1/(E_\lambda_{SD})$, $\beta = E_{\beta} A_{SR}$ and denote $P_{c,E} E_{\beta}$ as the average bit error rate (BER) of SNR based SR and $P_{c,E}$ as that of LLR based SR. These BERs are given by

$$P_{c,E} = P_i \{ |\alpha|^2 < T_0 \} + P_i \{ |\alpha|^2 < T_0 \} + P_{\bar{a}} P_{c,E}$$

$$P_{c,E} = P_i \{ |\Lambda| < \Lambda_0 \} + P_i \{ |\Lambda| < \Lambda_0 \} + P_{\bar{a}} P_{c,E}$$

Note that $P_{c,E}$ is related to $T_0$ and $\Lambda_0$ in (6) and (7), respectively. Therefore, (8) and (9) are also functions of $P_{c,E}$. In addition, the optimum thresholds $P_{c,E}$ that minimizes BER conditioned on any pair $(E_S, E_R)$ for both SNR-based SR and LLR-based SR are of the same form, given by

$$P_{c,E} = \frac{P_i}{P_i - P_{\beta}}$$

3. ENERGY ALLOCATION STRATEGIES

For a fair comparison in terms of energy consumption between cooperative communications and direct transmission, it is essential that the total consumed energy of the cooperative system must be equal to that of corresponding direct transmission system. Therefore, we have $E_S + E_R = E$ where $E$ is total transmit energy of the system which is also the transmit energy of the source in case of direct transmission. In [4], the performance of SR with equal energy allocation $(E_S=E_R=0.5E)$ was presented. In this section, we propose two energy allocation strategies to further improve its performance.

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Let $E_S=\delta E$ where $0<\delta<1$ is energy sharing factor for cooperation. Then $E_R=(1-\delta)E$ and thus given a set of parameters $(E, \lambda_{SR}, \lambda_{SD}, \lambda_{RD})$, (8) and (9) are functions of $\delta$ and $P_{eT}$. Consequently, minimizing BER in (8) and (9) is equivalent to choosing jointly the appropriate values of $\delta$ and $P_{eT}$. In other words, optimum energy allocation for $S$ and $R$ in the sense of minimizing the BER is to solve the following optimum problem
\[
\text{Minimize } P_e \quad \text{subject to } 0<\delta<1\text{ and } P_{eT}>0 \quad (11)
\]
where $P_e=P_e(\lambda_{SR}, \delta)$ or $P_e=P_e(\lambda_{SD}, \delta)$.

3.1. Best-effort energy allocation strategy

The expression of $P_e$ in terms of parameters $\delta$ and $P_{eT}$ is too complicated to jointly optimize both $\delta$ and $P_{eT}$ for solving the optimum problem in (11). Therefore, we propose a best-BER searching strategy that separately optimizes the parameters $\delta$ and $P_{eT}$ as follows. First, find the optimum threshold $P_{eT,\text{opt}}$ conditioned on $\delta$ which is given by (10). Then substituting $P_{eT,\text{opt}}$ into (8) and (9), we obtain the BER expression $P_e$ that is only a single-variable function of $\delta$. Finally, compute $P_e$ for every possible value of $\delta$ and select the one that minimizes the BER. We consider $\delta$ corresponding to the minimum BER as a solution of (11). In the numerical results illustrated in Section 4, we limit the range of $\delta$ to [0.01, 0.99] with incremental step $\Delta\delta=0.01$ to avoid an exhaustive search. Thus, the found $\delta$ which offers the smallest BER is not the optimum $\delta$. We only call this value the best $\delta$ and denote it as $\delta^*$. Moreover, since $\delta^*$ is a constant with respect to a given set $(E, \lambda_{SR}, \lambda_{RD}, \lambda_{SD})$, the proposed energy allocation for $S$ and $R$ shows that it is extremely simple and causes no bandwidth loss. This comes from the fact that the transmission energies of $S$ and $R$ are only updated at least with the same time scale as the coherence time of the wireless propagation which is of the order of hundreds of ms (according to the MS mobility), and there is no requirement of instantaneous CSI $\alpha_i$ at the transmitters which is usually estimated at the receivers and sent through feedback channels.

3.2. Simple energy allocation strategy

This simple energy allocation strategy is based on the observation in [6] that when $R$ decodes successfully the signal from $S$, the MRC at $D$ is optimum in the sense of minimizing the BER if and only if the average energies that $D$ receives from $S$ and $R$ are the same. That means
\[
\mathbb{E}[\sqrt{E_sd}]=\mathbb{E}[\sqrt{E_rd}] \quad \text{or} \quad \lambda_{SR}E_s=\lambda_{SD}E_r \quad (12)
\]
where $\mathbb{E}(\cdot)$ is the expectation operator.

Combining (12) with the constraint $E_S+E_R=E$, we can allocate the energies for $S$ and $R$ as $E_S=E/(1+\lambda_{SD}/\lambda_{RD})$ and $E_R=E\lambda_{SD}/\lambda_{RD}$. In this case, $\delta$ is denoted as $\delta^*=1/(1+\lambda_{SD}/\lambda_{RD})$.

After selecting $E_S$ and $E_R$, the threshold $P_{eT}$ is calculated from (10).

It is obvious that this strategy is simpler than the best-effort energy allocation strategy because it doesn’t perform the exhaustive search for $\delta$ but it is only effective at high SNR at which $R$ can decode successfully, leading to the spatial diversity at $D$.

4. NUMERICAL RESULTS

We consider a network geometry where $R$ is located on the straight line between $S$ and $D$. The direct path length $S-D$ is normalized to be 1. We also denote $d$ as the distance between $S$ and $R$. In all presented results, the path-loss exponent $\eta=3$ is under investigation. Since the noise variances at $R$ and $D$ are assumed to be 1, the axis of all figures represents the total signal-to-noise ratio SNR that is defined as $E$ (the total transmitted energy). For notation convenience, we denote transmission schemes as shown in Table 1. Figures 2-4 compare BER performances of SR with different energy allocation strategies for some typical values of $d\in\{0.4, 0.6, 0.8\}$ and direct transmission. Based on $\delta^*=1/(1+\lambda_{SD}/\lambda_{RD})$, we calculate the corresponding values of $\delta^*$ (0.822, 0.94, 0.992) that are independent of SNR while the values of $\delta^*$ given in Table 2 increase with respect to SNR. It is observed that both $\delta^*$ and $\delta^*$ increase with $d$. This is reasonable because when $R$ is far away from $S$, the $S-R$ path loss is large. Therefore $S$ should transmit with higher energy to compensate for this path loss increase. Then $R$ can decode successfully, leading to spatial diversity at $D$. It is also seen that $\delta^*$ of SNR-based SR is always larger than that of LLR-based SR.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>DT</td>
<td>Direct transmission</td>
</tr>
<tr>
<td>C1</td>
<td>SNR-based SR with $\delta^*=0.5$ (equal energy allocation)</td>
</tr>
<tr>
<td>C2</td>
<td>SNR-based SR with $\delta^*$ (simple energy allocation)</td>
</tr>
<tr>
<td>C3</td>
<td>SNR-based SR with $\delta^*$ (best effort energy allocation)</td>
</tr>
<tr>
<td>P1</td>
<td>LLR-based SR with $\delta^*=0.5$ (equal energy allocation)</td>
</tr>
<tr>
<td>P2</td>
<td>LLR-based SR with $\delta^*$ (simple energy allocation)</td>
</tr>
<tr>
<td>P3</td>
<td>LLR-based SR with $\delta^*$ (best effort energy allocation)</td>
</tr>
</tbody>
</table>

Table 2. Values $\delta^*$ corresponding to each SNR

<table>
<thead>
<tr>
<th>$d=0.4$</th>
<th>$d=0.6$</th>
<th>$d=0.8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR(dB)</td>
<td>C3</td>
<td>P3</td>
</tr>
<tr>
<td>5</td>
<td>0.61</td>
<td>0.58</td>
</tr>
<tr>
<td>10</td>
<td>0.65</td>
<td>0.61</td>
</tr>
<tr>
<td>15</td>
<td>0.68</td>
<td>0.63</td>
</tr>
<tr>
<td>20</td>
<td>0.71</td>
<td>0.64</td>
</tr>
<tr>
<td>25</td>
<td>0.72</td>
<td>0.65</td>
</tr>
<tr>
<td>30</td>
<td>0.74</td>
<td>0.66</td>
</tr>
</tbody>
</table>
Figures 2-4 show that best-effort energy allocation strategy P3 (or C3) provides the best performance. Specifically, in comparison with equal energy allocation P1 (or C1) at target BER of $10^{-5}$, P3 (or C3) can save the energy of approximately 0.5, 1.5, and 2.5 dB (or 1, 2, and 3 dB) for $d=0.4$, 0.6 and 0.8 respectively. Additionally, P3 significantly outperforms direct transmission with energy gain of about 12.5 dB at target BER of $10^{-5}$ and any value of $d$. Due to the diversity order of P3 higher than that of DT, P3 keeps better than DT as SNR increases. Also in Figs. 2-4, we observe that simple energy allocation strategy P2 (or C2) performs better than P1 (or C1) and worse than P3 (or C3). At high values of SNR, it reaches the performance of P3 (or C3). This is consistent with an observation from the results in [6] that when the paths which are maximum-ratio combined are symmetric (i.e. $E_{sA_{SD}}=E_{rA_{SD}}$), the MRC achieves the best performance. However, P2 (or C2) can be inferior to P1 (or C1) at low values of SNR and a certain value of $d$. For example, in case of $d=0.4$, P2 is worse than P1 for SNR of less than 25 dB and C2 is inferior to C1 for SNR of less than 15 dB.

5. CONCLUSION

This paper proposes two energy allocation strategies based on long-term fading statistics to complete the framework for LLR-based selection relaying. These strategies represent the trade-off between the performance and computation burden. However, both provide a significant energy saving compared to direct transmission as well as the conventional SNR-based SR. Since LLR-based SR with the best-effort energy allocation strategy is extremely energy-efficient, it should be considered as a promising technical solution for ad hoc networking to satisfy the stringent energy constraint and extend the coverage area as well.

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6. REFERENCES