COMPARISON OF POWER CONTROL SCHEMES FOR RELAY SENSOR NETWORKS

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ABSTRACT

Three power control schemes for the space-time coded amplify-and-forward (AF) relaying scheme targeting at wireless sensor network applications are examined and compared. The opportunistic scheme performs the best by considering the signal-to-noise-ratio (SNR) of the received signal. However, if the power for the relay is limited, the performance of the opportunistic scheme degrades due to the loss of active relay nodes that have better channel conditions. Since the battery lifetime of nodes for wireless sensor networks is limited and the loss of relay nodes is critical to system performance, we propose an SNR-constrained power reduction scheme to prolong the relay lifetime for the opportunistic scheme. It is demonstrated by computer simulation that the opportunistic scheme with SNR-constrained power reduction is power efficient and the relay lifetime of dense relay networks can be significantly prolonged.

Index Terms— Power allocation, cooperative network, energy efficiency, network lifetime

1. INTRODUCTION

A wireless Sensor network (WSN) may consist of hundreds or thousands of low cost sensor nodes with limited energy. Typically, these nodes monitor the environment, collect data and communicate to the data sink by transversing a multihop data gathering tree. Similar to other wireless networks, communications in WSNs suffer from channel fading which results in packet loss and reduces the spectral efficiency. The cooperative diversity [1, 2] has been introduced recently in [3, 4] to deal with the fading effect and enhance power efficiency in WSNs. That is, a sensor node located between the transmit node and the receive node is chosen as a relay node that cooperates with the transmit node in packet forwarding. There are two forwarding strategies in a relay node: amplified-forward (AF) and decode-forward (DF)[2]. The multi-hop AF cooperative relay scheme was developed and analyzed in [3], where a significant gain in the network lifetime due to node cooperation was shown. Besides, the gain increases with the node density. For a given outage probability, the energy consumption of AF and DF cooperative relay schemes was compared with that of a direct transmission scheme in [4]. It was shown that cooperative relaying is more energy efficient when the distance between nodes is larger in a Rayleigh fading channel.

With the clustered data gathering scheme [9] in WSNs, sensor nodes are clustered. They first send data to their cluster head and, then, cluster heads send aggregated data to the sink along the multihop routing tree. In this work, we consider two adjacent cluster heads whose data transmission is aided by neighboring sensor nodes, which act as relay nodes to provide the spatial diversity gain and save the path loss between cluster heads. Distributed space-time block coding (DSTC) and power allocation schemes are adopted by these relays. It is worthwhile to point out that the optimal power allocation method for AF relay networks was studied in [6, 7] to maximize the information rate and the instantaneous capacity with the perfect channel status information (CSI). Here, instead of maximizing the achievable rate, we target at the saving of the aggregate transmit power since power consumption is a more critical issue in most WSN applications.

Three power control schemes for a space-time coded AF relay system are compared in this work. Their selection depends on the link quality of wireless channels. Our main focus is their impact on the power consumption of relay nodes. This is because that sensor nodes have a more stringent battery resource as compared with that of cluster heads in heterogeneous WSNs. The three power control schemes under our study are stated below.

- Scheme 1. The transmission power of a relay node is proportional to the SNR value of the single-relay path.
- Scheme 2. Relay nodes with their path SNR lower than a threshold are dropped and others transmit with the same power.
- Scheme 3. Only the best node is allowed to connect using all available power.

Scheme 3 is called the *opportunistic relaying* [8], which exploits the spatial diversity most effectively and maximize the averaged system SNR. However, in a sensor network with slowly varying link conditions, relay nodes with a better channel condition will suffer from energy depletion much earlier. To address this problem, we propose an SNR-constrained power reduction algorithm that reduces the transmit power when the system SNR meets a target value. The performance of the opportunistic scheme aided by SNR-constrained power reduction is analyzed in this work. It is shown by simulation that the relay lifetime can be prolonged significantly at the cost of a slightly increased error rate.

The rest of the paper is organized as follows. The system model is introduced in Sec. 2. Three power control schemes and the SNR-constrained power reduction are presented in Sec. 3. The performance comparisons of these schemes without the energy constraint and the lifetime performance with energy constraint are studied in Sec. 4.

2. CHANNEL MODELS

Consider a cooperative network with R relay nodes as shown in Fig. 1. At the first phase, the transmitter sends a block $\mathbf{s}$ of dimension $T \times 1$ with a unit norm to relay nodes. The received signal at the k^{th} relay nodes can be written as

$$\mathbf{r}_k = \sqrt{P_0 T} f_k \mathbf{s} + \mathbf{v}_k, \quad k = 1, 2, \ldots, R, \tag{1}$$

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where f_k is the channel coefficient between the k^{th} relay node and the transmitter, $\mathbf{v}_k$ is additive white Gaussian noise (AWGN) with variance normalized to unity, and P_0 is the transmit power of the transmitter. Coefficients $f_k, 1 \leq k \leq R$, are i.i.d. complex Gaussian distributed $N(0,1)$.

At the second phase, each relay node encodes the received signal by multiplying it with a space-time encoding matrix $\mathbf{A}_k$ which is generated at each relay node[5]. It is worthwhile to point out the the distributed space-time coding scheme [5] achieves full diversity order at high SNR regime if block length T is larger than the number of relays N. Consequently, the signal to be transmitted by the k^{th} node can be written as

$$\mathbf{t}_k = \sqrt{\frac{P_k}{P_0|f_k|^2+1}}\mathbf{A}_k\mathbf{r}_k, \tag{2}$$

where $\mathbf{A}_k$, $1 \leq k \leq R$, in (2) are unitary and isotropically random with zero mean, P_k is the transmit power assigned to the k^{th} relay node, and

$$\sum_{k=1}^{R} P_k = P_r. \tag{3}$$

The transmit power of each relay is controlled by the receiver using various power control strategies under the assumption that the feedback channel is reliable through channel coding. When received signals from all relay nodes are coherent at the symbol level, the signal at the receive node can be written as

$$\begin{aligned}\mathbf{x} &= \sum_{k=1}^{R}\sqrt{\frac{P_0P_kT}{P_0|f_k|^2+1}}f_kg_k\mathbf{A}_k\mathbf{s} \\ &+ \sum_{k=1}^{R}\sqrt{\frac{P_k}{P_0|f_k|^2+1}}g_k\mathbf{A}_k\mathbf{v}_k + \mathbf{w},\end{aligned} \tag{4}$$

where g_k is the channel coefficient between the k^{th} relay node and the receive node and $\mathbf{w}$ is AWGN at the receiver. Assume that g_k and $\mathbf{w}$ have the same distribution as f_k and $\mathbf{v}_k$, respectively. The second term in the right-hand-side of (4) is the propagating noise from relay nodes, which is not negligible.

Assume that the received has knowledge of f_k, g_k and $\mathbf{A}_k$, the transmitted message can be decoded by maximum likelihood (ML) estimation,

$$\widehat{\mathbf{s}} = \arg\min_{\mathbf{s}_i} \|\mathbf{x} - \sum_{k=1}^{R}\sqrt{\frac{P_0P_kT}{P_0|f_k|^2+1}}f_kg_k\mathbf{A}_k\mathbf{s}_i\|^2. \tag{5}$$

3. POWER CONTROL SCHEMES

3.1. Three Basic Schemes

The SNR of the whole relay network averaged over all random coding matrices is given by

$$SNR = \frac{\sum_{k=1}^{R}\frac{P_0P_k}{P_0|f_k|^2+1}|f_kg_k|^2}{1+\sum_{k=1}^{R}\frac{P_k|g_k|^2}{P_0|f_k|^2+1}} = \sum_{k=1}^{R}\alpha_k\rho_k, \tag{6}$$

where ρ_k is the SNR value that all relay power P_r is allocated to the k^{th} relay node. That is,

$$\rho_k \equiv \frac{P_0P_r|f_kg_k|^2}{1+P_0|f_k|^2+P_r|g_k|^2}, \quad k = 1,2,\cdots,R. \tag{7}$$

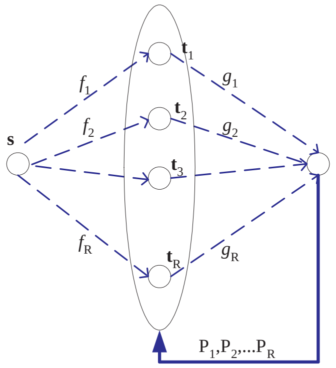

Fig. 1. The system model of a wireless relay channel.

The weight in (6) is related to power allocation $\{P_k\}$ via

$$\alpha_k \sim \frac{P_k}{P_0|f_k|^2+1}(1+P_0|f_k|^2+P_r|g_k|^2), \tag{8}$$

subject to $\sum_{k=1}^{R}\alpha_k = 1$.

In this work, we would like to compare the following three power control schemes by taking the path SNR value, ρ_k, into account in different ways.

- Scheme 1: assignment in proportion with path SNR
  The transmitted power assigned to each relay node is proportional to ρ_k in (7).
- Scheme 2: assignment by dropping paths of low path SNR
  We drop paths whose path SNR values are lower than a threshold, and assign all active nodes with equal power. The diversity gain of employing the LD codes in this scheme depends on the number of active nodes.
- Scheme 3: opportunistic assignment
  All power is assigned to the single relay node that has the largest path SNR.

Besides, we use the equal power scheme (*i.e.* $P_k = P_r/R$), as the performance benchmark. From the linearity between system SNR and path SNR, we can conclude that the system SNR in equation (6) attains its maximum when opportunistic assignment is applied. Actually, the equal power scheme and the opportunistic scheme are two extreme cases of Scheme 2 by choosing the lowest and the highest threshold values, respectively.

If the battery energy of each relays is limited, the number of active relay nodes decreases with time and it influences the cooperative diversity gain. Therefore, it is important to manage the power consumption of relay nodes effectively. If the channel condition varies slowly in a wireless sensor network, the node with the largest path SNR will be the only relay node for a long while in the opportunistic scheme. Consequently, it suffers from power depletion faster than other nodes. Due to the decreased number of active relay nodes, the diversity gain of the opportunistic scheme decreases and the error rate increases with time. On the other hand, all relay nodes share the power usage equally at all time in the equal power scheme, all links last for a longer period at the price of having a lower SNR value at the receive end.

3.2. Power Saving Strategy for Relay Nodes

To obtain a good balance between the diversity gain and fairness of battery usage, we propose a power saving strategy that minimizes the aggregate transmitted power of relay nodes subject to a target SNR constraint. Let γ be the target system SNR and κ the power reduction ratio. When the system SNR exceeds γ, we can adjust the transmit power of relay nodes to be

$$P_k^{(s)} = \kappa P_k, \tag{9}$$

where

$$\kappa = \frac{\gamma}{\sum_{k=1}^{R} \frac{P_k|g_k|^2}{P_0|f_k|^2+1}(P_0|f_k|^2-\gamma)}. \tag{10}$$

The value of κ is obtained by substituting P_k in (6) with $P_k^{(s)}$ in (9). When the denominator of (10) is negative, it means that the propagated error at relays is amplified such that system SNR fails to achieve the target value γ no matter how large the relay power is. When the target SNR γ is achieved, $0 \leq \kappa \leq 1$. We see from (10) that a large value of the channel strength between relays and the receiver, indicated by $|g_k|^2$, is helpful to decrease factor κ. However, when the channel strength between the transmitter and relays increases, the value of $(P_0|f_k|^2-\gamma)/(P_0|f_k|^2+1)$ will be saturated at 1. Therefore, the benefit of power saving for a large value of $|f_k|^2$ is limited and the reason is that the forwarding power is normalized at the relay nodes.

The choice of γ depends on the desired error probability. For example, if the signal is modulated by QPSK and the number of relay nodes is large, then the bit error rate of the received symbols is roughly proportional to $Q(\sqrt{\gamma})$ [10].

4. PERFORMANCE COMPARISONS

4.1. Without Battery Energy Constraint

In this section, we compare the performance of various power control schemes without battery energy constraint in relay nodes. When the total transmit power (*i.e.* $P_0 + P_r$) is fixed, it is optimal for the equal power scheme by setting $P_0 = P_r$ if g_k and f_k are i.i.d. [5]. To fairly compare it with three power control schemes described in Sec. 3.1, we also choose $P_0 = P_r = 15$dB in our simulations. In Fig. 2, we show the BER performance versus the total transmit power for a relay system with $R = T = 6$. Source symbols are modulated by QPSK and the threshold of the second scheme is set to the averaged path SNR over all relay nodes, *i.e.*, nodes with the path SNR below the averaged value are dropped. We see that the three power control schemes outperforms the equal power scheme by 3dB, 4dB and 8dB, respectively. When applying the opportunistic power control scheme (Scheme 3), it is not necessary to encode retransmit signals with LD codes since only one node relays signal at a time. Therefore, the opportunistic power control scheme always provides the best choice if the instantaneous channel status is known and the lifetime energy of relay nodes is not of concern.

4.2. With Battery Energy Constraint

In this section, we consider the constraint of limited power on relay nodes and study their effect on the system. We compare the averaged transmit and relay lifetime of each scheme. Since the opportunistic scheme has severe unbalanced power usage among relay nodes (especially in a slowly fading environment), we are more interested in the effect of the SNR-constrained power saving strategy on this scheme. If the target SNR γ is achieved, the transmit power of the best relay node after power saving is

$$P_{\text{opp},\gamma} = \min_{k:P_0|f_k|^2>\gamma} \frac{\gamma}{|g_k|^2}\frac{P_0|f_k|^2+1}{P_0|f_k|^2-\gamma}. \tag{11}$$

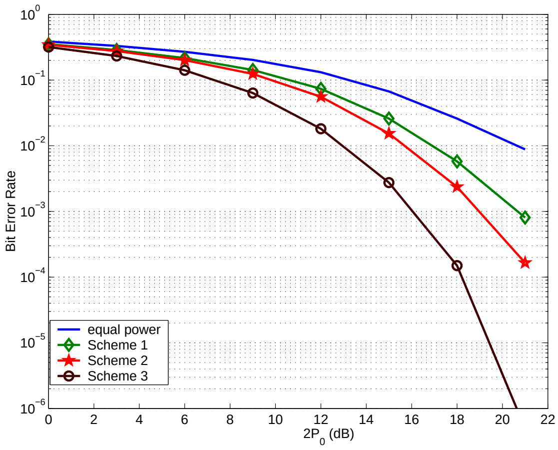

Fig. 2. Comparison of the BER performance as a function of the total transmit power.

We see from (11) that a larger value of the relay-receiver channel gain $|g_k|$ is more helpful in reducing the power consumption, since the amplification caused by the transmitter-relay channel gain $|f_k|$ is normalized before retransmission at relay nodes. The distribution function of the transmit power of the opportunistic scheme with target SNR γ is

$$f_{\text{opp},\gamma}(v) = R\,(1-F_{P,\gamma}(v))^{R-1} f_{\text{P},\gamma}(v), \tag{12}$$

where $F_{P,\gamma}$ is the distribution function of the transmit power for a single relay node to achieve target SNR γ and of the following form:

$$F_{\text{P},\gamma}(v) = e^{-\frac{\gamma}{P_0}-\frac{\gamma}{v}}\sqrt{\frac{4\gamma(1+\gamma)}{P_0 v}}K_1(\sqrt{\frac{4\gamma(1+\gamma)}{P_0 v}})). \tag{13}$$

where $K_\nu(\cdot)$ is the modified Bessel function of the second kind and order ν. The averaged transmit power after power saving with target SNR γ becomes

$$\overline{P_{\text{opp},\gamma}} = \int_0^{P_0} u f_{\text{opp},\gamma}(u)du + P_0\int_{P_0}^{\infty} f_{\text{opp},\gamma}(u)du. \tag{14}$$

We define the relay lifetime to be the duration that all relay nodes are still active. After applying the power saving strategy to the opportunistic scheme, the averaged transmit power and the averaged relay lifetime versus the number of relay nodes, R, are shown in Fig. 3 and Fig. 4, respectively. It is assumed in the simulation that the channel suffers from slowly fading with $f_dT_b = 5$, where T_b is the duration of relay nodes being active with energy consumption P_0. Without the power saving strategy, the total transmit power is fixed at 15dB as shown in Fig. 3. With the power saving strategy, the average transmit power becomes smaller for a larger value in the relay node number (R) and/or a smaller target SNR value (γ). As shown in Fig. 4, the relay lifetime is significantly prolonged especially for a smaller target SNR value and the performance degradation from γ=12dB to γ=9dB on the BER performance is acceptable as shown in Fig. 5.

In Fig. 5, we compare long term BER performance for the equal power scheme, the three power control schemes, and the opportunistic schemes with power saving. The number of relay nodes is 6 and the assumption of the channel statistics in the simulation is the same as Fig.3. After the death of the first relay node, the performance

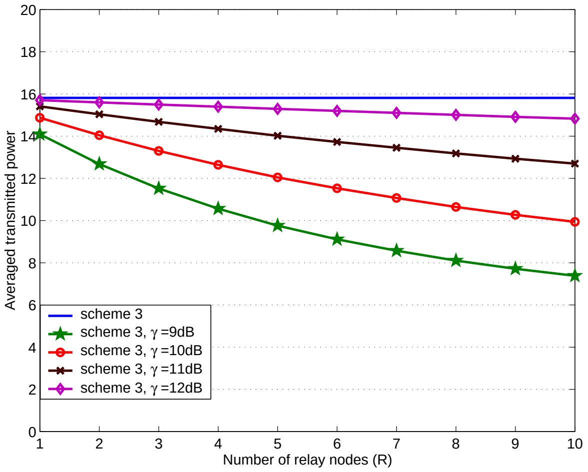

Fig. 3. Comparison of the averaged transmit power of the opportunistic scheme with power saving as a function of the relay node number.

of the opportunistic scheme begins to degrade gradually due to decrease in diversity. At the 300th time step, relay nodes with the equal power scheme suffer power outage simultaneously. From the beginning up to this point, we see that all power control schemes have better BER performance than the equal power scheme. For the opportunistic scheme with power saving and target SNR equal to 12 dB, the time of the death of the first relay nodes is slightly extended. By setting the target SNR at 9dB, the long-term performance clearly outperforms other power control schemes in terms of lifetime and BER. The tradeoff between network lifetime and BER degradation is observed here and the BER degradation for power saying with target SNR at 9dB is acceptable.

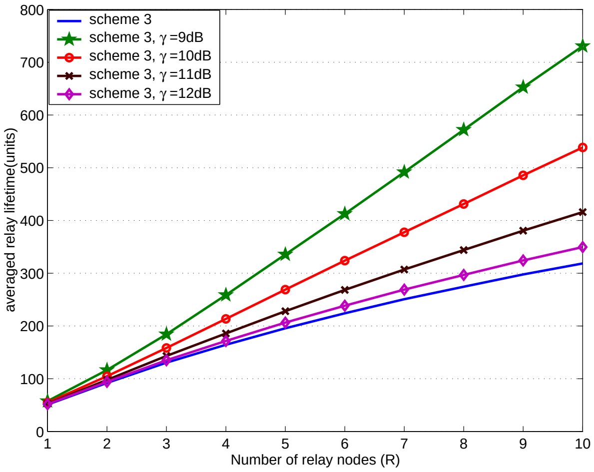

Fig. 4. The averaged relay lifetime of the opportunistic scheme with power saving as a function of the relay node number.

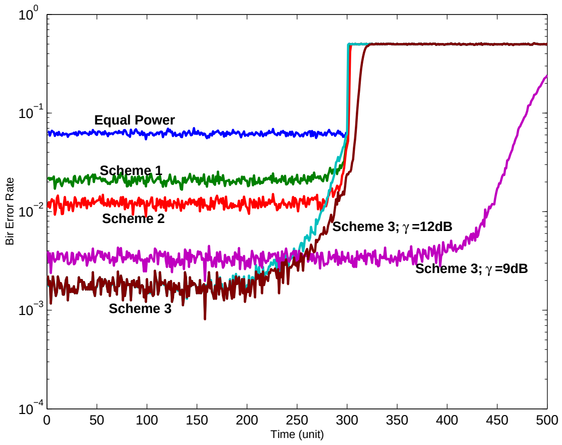

Fig. 5. Long-term BER performance for different power control schemes.

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