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A Relay Selection and Power Allocation Scheme for Cooperative Wireless Sensor Networks

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Abstract

This paper investigates optimal relay selection and power allocation under an aggregate power constraint for cooperative wireless sensor networks assisted by amplify-and-forward relay nodes. By considering both transmission power and circuit power consumptions, the received signal-to-noise ratio (SNR) at the destination node is calculated, based on which, a relay selection and power allocation scheme is developed. The core idea is to adaptively adjust the selected relays and their transmission power to maximize the received SNR according to the channel state information. The proposed scheme is derived by recasting the optimization problem into a three-layered problem — determining the number of relays to be activated, selecting the active relays, and performing power allocation among the selected relays. Monte Carlo simulation results demonstrate that the proposed scheme provides a higher received SNR and a lower bit error rate as compared to the average power allocation scheme.

Keywords: Wireless sensor networks, cooperative communications, relay selection, power allocation, beamforming

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1. Introduction

Wireless sensor networks (WSNs) can provide an efficient sensing and computing solution for various applications ranging from environment monitoring to outer space exploration. Wireless sensor nodes are equipped with a radio transceiver and a set of transducers for data acquisition, transmission and processing. Since sensor nodes are usually powered by batteries which are difficult to change or recharge [1], the pursuit of better performance under given energy consumption is a critical issue in the design of WSNs.

Cooperative communication, as a popular technique for providing reliable transmission and high throughput in networks with single antenna nodes [2]-[5], has been widely used in WSNs. Various relay selection (RS) and power allocation (PA) schemes have been studied in the cooperative communication scenario [6]-[12]. Some of these schemes have considered individual power constraint, for example, the power allocation strategy for networks with perfect channel state information in [6] and that for networks with statistical channel information in [7]. Some of them assume aggregate power constraint, for example, the space-time coded cooperation with two relays in [10].

However, most of the earlier works on individual or aggregate power constrained communication have considered the transmission power only. This is reasonable in traditional wireless networks where a large amount of transmission power is required due to the large transmission distance and thus the power consumption on circuits is negligible. In a WSN, however, the dense distribution of sensor nodes makes the transmission power much smaller than that of a traditional cooperative network and hence the circuit power consumption cannot be ignored. Moreover, the circuit power consumed by the relays depends on their transmission power. Therefore, relay selection and power allocation with consideration of the circuit power consumption are more challenging than that without considering circuit power consumption, especially for cooperative networks under aggregate power constraint.

In fact, some optimization strategies, considering both transmission power and circuit power consumption, have been proposed for WSNs [13]-[16]. In [13] and [14], the best modulation and transmission strategy were analyzed to minimize the total energy consumption required to send a given number of bits and it was also confirmed that in some short-range communications, Single-Input Single-Output (SISO) systems may beat Multiple-Input Multiple-Output (MIMO) systems. In [15], a cooperative communication architecture with feedback was proposed to minimize the energy consumption per bit. Moreover, Shuguang Cui and Andrea J. Goldsmith have proved that having more relay nodes may lead to poorer performance due to the extra circuit power consumed by extra relays [14],[16]. However, to the best of our knowledge, no existing work on RS and PA which takes circuit power consumption into account has been found for cooperative WSNs.

In this paper, we propose a RS and PA scheme for a cooperative WSN with both transmission power and circuit power consumptions being considered. The scheme aims to maximize the received signal-to-noise ratio (SNR), which means more information bits will be correctly transmitted under certain aggregate power constraint, thus making the network more energy efficient. We derive the RS and PA scheme by recasting the optimization problem into a three-layered problem, namely, determination of the number of active relays, active relay selection, and power allocation of active relays. In our scheme, not only the transmission power of the relays but also the relays themselves are adaptively adjusted according to the channel state information. Simulation results showing the higher received SNR and lower bit error rate (BER) of the proposed scheme are provided.

The remainder of this paper is organized as follows. Section II describes the system model of a WSN using beamforming technique [6] at the relays. The received SNR is calculated in Section III, based on which we derive a RS and PA scheme. Simulation results are given in Section IV to demonstrate the advantage of the proposed scheme. Finally, Section V provides the conclusion.

Throughout the paper, the following notations are adopted: $|\cdot|$ denotes the module of a complex number. $\lceil \cdot \rceil$ is the ceiling function. $\langle \cdot,\cdot \rangle$ denotes the inner product and $\|.\|$ is the 2-norm.

2. System Model

Consider a wireless network consisting of two end-users, called the source node S and the destination node D, and M relay nodes R_i, $i = 1,\ldots,M$, as shown in Fig.1. Each node is equipped with a single antenna working in half-duplex mode. Assume that there is no direct link from the source to the destination due to the poor quality of the channel between them.

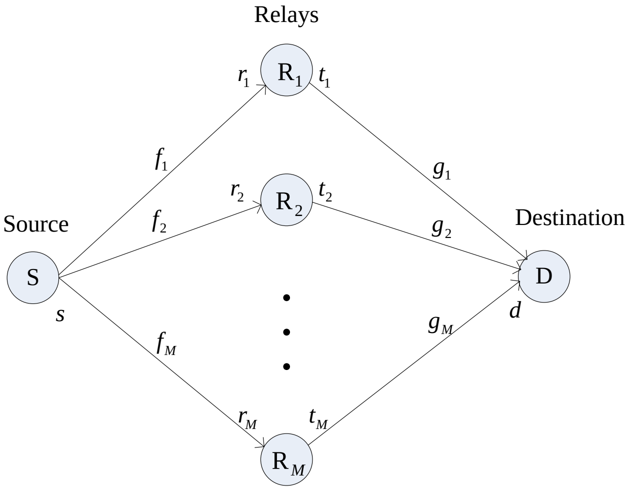

Fig. 1. A cooperative wireless sensor network

Denote the channel between S and R_i as f_i and the channel between R_i and D as g_i.

Suppose each link has a flat Rayleigh fading and the channels are independent of each other. We also assume that R_i knows its own channel while D knows all channels. A relay node is called an active relay if it is selected to cooperate.

A two-step amplify-and-forward (AF) protocol [2] is used in this network. During the first step, the source S broadcasts signal $\sqrt{P_\mathrm{s}}s$ to all relays where the information symbol s is selected randomly from a codebook and is normalized as $\mathrm{E}\left(|s|^2\right)=1$, and P_s is the transmission power used at S. Relay R_i receives

$$r_i = f_i\sqrt{P_\mathrm{s}}s+v_i \tag{1}$$

where v_i is the white Gaussian noise at R_i with zero mean and unit variance.

In the second step, by using an AF protocol and beamforming technique, R_i sends the following signal

$$t_i = \sqrt{\frac{P_{\mathrm{t}i}}{1+|f_i|^2 P_\mathrm{s}}}e^{j\theta_i}r_i \tag{2}$$

to the destination, where $P_{\mathrm{t}i}$ is the transmission power of R_i and is set to zero if R_i is not activated. The signals from relays are added up at the destination D:

$$\begin{aligned} d &= \sum_{i=1}^{M} g_i t_i + w \\ &= \sum_{i=1}^{M}\frac{f_i g_i e^{j\theta_i}\sqrt{P_\mathrm{s}P_{\mathrm{t}i}}}{\sqrt{1+|f_i|^2 P_\mathrm{s}}}s+\sum_{i=1}^{R}\frac{g_i e^{j\theta_i}\sqrt{P_{\mathrm{t}i}}}{\sqrt{1+|f_i|^2 P_\mathrm{s}}}v_i+w \end{aligned} \tag{3}$$

where w is the noise at D and also assumed to be $\mathcal{CN}\left(0,1\right)$. v_i and w are independent.

It has been proved that the optimal choice of the angles is $\theta_i=-\left(\arg f_i+\arg g_i\right)$ [6]. That means matched filters should be used at the relays to compensate for the phases of their channels. Thus,

$$d = \sum_{i=1}^{M}\frac{|f_i g_i|\sqrt{P_\mathrm{s}P_{\mathrm{t}i}}}{\sqrt{1+|f_i|^2 P_\mathrm{s}}}s+\sum_{i=1}^{M}\frac{|g_i|\sqrt{P_{\mathrm{t}i}}}{\sqrt{1+|f_i|^2 P_\mathrm{s}}}e^{-j\arg f_i}v_i+w \tag{4}$$

This is a general model for cooperative network using beamforming technique with no power constraint. However, in this paper, we aim to derive a RS and PA scheme under an aggregate power constraint with consideration of circuit power consumption. Thus, the model in (4) should be modified.

In order to consider the circuit power consumption, all signal processing blocks at the transmitter and receiver of each relay should be included. However, to avoid over-complicated modeling, some blocks are intentionally omitted, e.g., source coding, pulse shaping, digital modulation and AD/DA conversion. Thus, the constituent modules of the transmitter and that of the receiver are shown in **Fig. 2** and **Fig. 3**, respectively.

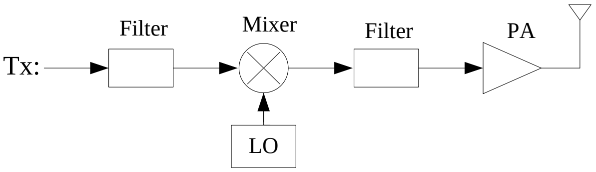

Fig. 2. Transmitter block diagram

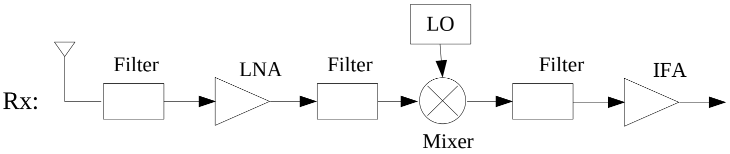

Fig. 3. Receiver block diagram

The circuit power consumption at R_i, denoted as $P_{\mathrm{c}i}$, consists of the mixer power consumption P_{mix}, the frequency synthesizer power consumption P_{syn}, the low noise amplifier (LNA) power consumption P_{LNA}, the active filters power consumption P_{fil}, the intermediate frequency amplifier (IFA) power consumption P_{IFA} and the power amplifier power consumption $P_{\mathrm{amp},\,i} = \mu P_{\mathrm{t}i}$, where $\mu = \frac{\xi}{\eta} - 1$ with η being the drain efficiency of the RF power amplifier and ξ being the peak to average ratio (PAR), which is dependent on the modulation scheme and the associated constellation size. Therefore, the total power consumed by R_i can be written as $P_{\mathrm{t}i} + P_{\mathrm{c}i} = (1+\mu)P_{\mathrm{t}i} + P_{0i}$ where P_{0i} denotes the power consumption of all other circuit blocks except the power amplifier. Set $P_0 = 2P_{\mathrm{mix}} + 2P_{\mathrm{syn}} + P_{\mathrm{LNA}} + P_{\mathrm{fil}} + P_{\mathrm{IFA}}$, then we have $P_{0i} = P_0$ if R_i is activated and $P_{0i} = 0$ if it is not.

The aggregate power constraint can be expressed as

$$\begin{aligned} P &= P_{\mathrm{s}} + \sum_{i=1}^{M} \left(P_{\mathrm{t}i} + P_{\mathrm{c}i}\right) \\ &= P_{\mathrm{s}} + \sum_{i=1}^{M} (1+\mu) P_{\mathrm{t}i} + \sum_{i=1}^{M} P_{0i} \end{aligned} \tag{5}$$

Accordingly, the aggregate transmission power of all the relays can be written as

$$\sum_{i=1}^{M} P_{\mathrm{t}i} = \frac{P - P_{\mathrm{s}} - \sum_{i=1}^{M} P_{0i}}{1+\mu} \tag{6}$$

For the sake of convenience, we introduce a power control variable α_i into the model and let $\frac{\alpha_i^{\,2}}{\sum_{k=1}^{M}\alpha_k^{\,2}}$ be the power control coefficient of R_i, i.e., $P_{\mathrm{t}i} = \frac{\alpha_i^{\,2}}{\sum_{k=1}^{M}\alpha_k^{\,2}} \sum_{l=1}^{M} P_{\mathrm{t}l}$. By defining $\varepsilon(\alpha_i) = \begin{cases} 1 & \alpha_i \neq 0 \\ 0 & \alpha_i = 0 \end{cases}$ and $\beta_M^{\,2} = \sum_{i=1}^{M}\alpha_i^{\,2}$, we have $P_{0i} = \varepsilon(\alpha_i) P_0$, $n = \sum_{i=1}^{M} \varepsilon(\alpha_i)$, and

$$P_{\mathrm{t}i} = \alpha_i^{\,2}\left(\frac{P_1 - nP_2}{\beta_M^{\,2}}\right) \tag{7}$$

where $P_1 = \frac{P - P_{\mathrm{s}}}{1+\mu}$, $P_2 = \frac{P_0}{1+\mu}$. Apparently, n is the number of active relays and $n \le M$.

In order to guarantee that there is power left for relays to transmit, $\sum_{i=1}^{M} P_{\mathrm{t}i} > 0$ is needed, which means $n < \frac{P_1}{P_2}$. Let $N = \left\lceil \frac{P_1}{P_2} - 1 \right\rceil$, then $N \ge n$ is the largest number of relays that can be activated under aggregate power P.

Combining equations (4) and (7), the received signal at D is given by

$$d = \sum_{i=1}^{M} |f_i g_i| \frac{\alpha_i \sqrt{P_{\mathrm{s}}(P_1 - nP_2)}}{\beta_M \sqrt{1+|f_i|^2 P_{\mathrm{s}}}} s + \sum_{i=1}^{M} |g_i| \frac{\alpha_i \sqrt{P_1 - nP_2}}{\beta_M \sqrt{1+|f_i|^2 P_{\mathrm{s}}}} e^{-j \arg f_i} v_i + w \tag{8}$$

By Shannon's information capacity theorem, the instantaneous capacity of the network is governed by $W \log_2(1+\mathrm{SNR})$. Since the base-2 logarithm is an increasing function, the maximization of the received SNR is equivalent to the maximization of the capacity. It is also equivalent to error rate minimization.

3. Relay Selection and Power Allocation

In Section II, the network model of a cooperative WSN with consideration of circuit power consumption has been established. For selective-relay scenario with an aggregate power constraint, relay selection and power allocation are closely related. Here, we propose an optimal RS and PA scheme, i.e., determine the best value of α_i, which is the main contribution in this paper.

3.1 Optimal RS and PA Scheme

From (8), the received SNR can be calculated as

$$\begin{aligned}\mathrm{SNR} &= \frac{P_s\left(\sum_{i=1}^{M}\left|f_i g_i\right|\frac{\alpha_i\sqrt{P_1-nP_2}}{\beta_M\sqrt{1+\left|f_i\right|^2 P_\mathrm{s}}}\right)^2}{1+\sum_{i=1}^{M}\left|g_i\right|^2\frac{\alpha_i^{\,2}\left(P_1-nP_2\right)}{\beta_M^{\,2}\left(1+\left|f_i\right|^2 P_\mathrm{s}\right)}} \\ &= \frac{\left(\sum_{i=1}^{M}\left|f_i g_i\right|\frac{\alpha_i\sqrt{P_\mathrm{s}\left(P_1-nP_2\right)}}{\sqrt{1+\left|f_i\right|^2 P_\mathrm{s}}}\right)^2}{\sum_{i=1}^{M}\alpha_i^{\,2}\left(1+\frac{\left|g_i\right|^2\left(P_1-nP_2\right)}{1+\left|f_i\right|^2 P_\mathrm{s}}\right)}\end{aligned} \tag{9}$$

By defining $b_{i,n}=\frac{\left|f_i g_i\right|\sqrt{P_\mathrm{s}\left(P_1-nP_2\right)}}{\sqrt{1+\left|f_i\right|^2 P_\mathrm{s}}}$ and $c_{i,n}=1+\frac{\left|g_i\right|^2\left(P_1-nP_2\right)}{1+\left|f_i\right|^2 P_\mathrm{s}}$, equation (9) can be simplified to $\mathrm{SNR}=\left(\sum_{i=1}^{M}\alpha_i b_{i,n}\right)^2 \Big/ \sum_{i=1}^{M}\alpha_i^{\,2}c_{i,n}$, which can be more conveniently rewritten as

$$\mathrm{SNR}=\left\langle\frac{\boldsymbol{\gamma}}{\left\|\boldsymbol{\gamma}\right\|},\boldsymbol{\rho}\right\rangle^2 \tag{10}$$

where $\boldsymbol{\rho}=\left(\frac{b_{1,n}}{\sqrt{c_{1,n}}},\ldots,\frac{b_{M,n}}{\sqrt{c_{M,n}}}\right)$ and $\boldsymbol{\gamma}=\left(\alpha_1\sqrt{c_{1,n}},\ldots,\alpha_M\sqrt{c_{M,n}}\right)$. The SNR optimization problem can now be expressed as

$$\max_{\alpha_i}\left\langle\frac{\boldsymbol{\gamma}}{\left\|\boldsymbol{\gamma}\right\|},\boldsymbol{\rho}\right\rangle^2 \ \text{ s.t. } \sum_{i=1}^{M}\varepsilon\left(\alpha_i\right)\le N \tag{11}$$

To maximize an inner product of two vectors, we normally set the angle between the two vectors to 0°. However, this does not work for the above optimization problem. Denoting the angle between $\boldsymbol{\gamma}$ and $\boldsymbol{\rho}$ by φ, we have $\mathrm{SNR}=\left\|\boldsymbol{\rho}\right\|^2\cos^2\varphi$. Note that $\left\|\boldsymbol{\rho}\right\|^2$ is a function of n, so both $\|\boldsymbol{\rho}\|^2$ and $\cos^2\varphi$ are functions of $\{\alpha_i\}_{i=1}^M$. If $\cos^2\varphi = 1$, $\boldsymbol{\gamma}$ and $\boldsymbol{\rho}$ should be in the same or opposite direction, which means there is no zero-value element in $\boldsymbol{\gamma}$ since the elements in $\boldsymbol{\rho}$ are all non-zero, i.e., $n = M$. However, $n = M$ may not yield the maximal $\|\boldsymbol{\rho}\|^2$, not even to mention that the aggregate power may not allow all relays to be activated. Thus, we divide the problem in (11) into several sub-problems, and solve it by an alternative method.

Suppose the number of relays to be selected is n, namely, there are n non-zero elements in $\boldsymbol{\gamma}$. Then the above optimization problem can be seen as, for a given value of n, selecting the best n relays, allocating power properly among them to obtain the maximal received SNR, and determining the best value of n through comparing the maximal received SNRs. Therefore, instead of optimizing SNR over all α_i, we first determine the value of non-zero α_i, then their indices and finally the number of them. This being said, the optimization problem in (11) can be recast as

$$\begin{aligned}&\max_{n}\max_{\{k_1,\cdots,k_n\}}\max_{\alpha_{k_i}}\left\langle \frac{\boldsymbol{\gamma}'}{\|\boldsymbol{\gamma}'\|}, \boldsymbol{\rho}'\right\rangle^2\\ &\text{s.t. } \alpha_{k_i} \neq 0, \{k_1,\cdots,k_n\} \subseteq \{1,\cdots,M\}, n \le N\end{aligned} \tag{12}$$

where $\boldsymbol{\gamma}' = \left(\alpha_{k_1}\sqrt{c_{k_1,n}},\ldots,\alpha_{k_n}\sqrt{c_{k_n,n}}\right)$ is a vector consisting of all the non-zero elements of $\boldsymbol{\gamma}$ and $\boldsymbol{\rho}' = \left(\frac{b_{k_1,n}}{\sqrt{c_{k_1,n}}},\ldots,\frac{b_{k_n,n}}{\sqrt{c_{k_n,n}}}\right)$.

Recalling that $n \le M$, we have $n \le \min(M,N)$. So the optimization problem in (11) has been decomposed into $\min(M,N)$ sub-problems. We now work on the nth sub-problem of (12):

$$\begin{aligned}&\max_{\{k_1,\cdots,k_n\}}\max_{\alpha_{k_i}}\left\langle \frac{\boldsymbol{\gamma}'}{\|\boldsymbol{\gamma}'\|}, \boldsymbol{\rho}'\right\rangle^2\\ &\text{s.t. } \alpha_{k_i} \neq 0, \{k_1,\cdots,k_n\} \subseteq \{1,\cdots,M\}\end{aligned} \tag{13}$$

Theorem 1: The solution of the inner optimization problem $\max_{\alpha_{k_i}\neq 0}\left\langle \frac{\boldsymbol{\gamma}'}{\|\boldsymbol{\gamma}'\|}, \boldsymbol{\rho}'\right\rangle^2$, denoted as $\alpha_{k_i}{}^*$, is given by $\alpha_{k_i}{}^* = \frac{\mathrm{K} b_{k_i,n}}{c_{k_i,n}}$, where K is an arbitrary non-zero constant.

Proof: Denote the angle between $\boldsymbol{\gamma}'$ and $\boldsymbol{\rho}'$ as φ'. Then we have $\left\langle \frac{\boldsymbol{\gamma}'}{\|\boldsymbol{\gamma}'\|}, \boldsymbol{\rho}' \right\rangle^2 = \|\boldsymbol{\rho}'\|^2 \cos^2 \varphi'$. Obviously, the maximal value is attained iff $\boldsymbol{\gamma}'$ and $\boldsymbol{\rho}'$ are in the same or opposite direction, i.e., $\varphi' = 0^\circ \text{ or } 180^\circ$. This indicates that $\frac{\alpha_{k_i}\sqrt{c_{k_i,n}}}{b_{k_i,n}\big/\sqrt{c_{k_i,n}}}$ should be a non-zero constant (denoted by K). Thus, we have the optimal PA solution $\alpha_{k_i}{}^* = \frac{\mathrm{K} b_{k_i,n}}{c_{k_i,n}}$ where K can take any non-zero value since it does not affect the power control coefficient $\alpha_i{}^2 \Big/ \sum_{k=1}^{M} \alpha_k{}^2$.

Using the obtained results, one can derive that the outer optimization problem of the n th sub-problem is $\max_{\{k_1,k_2,\cdots,k_n\}} \|\boldsymbol{\rho}'\|^2$. This is a relay selection problem which can obviously be solved by the exhaustive method. But there are $\binom{M}{n}$ combinations of relays, which requires a large amount of computation. By looking into the structure of $\|\boldsymbol{\rho}'\|^2$, we may find a way to reduce the computation.

Note that

$$\|\boldsymbol{\rho}'\|^2 = \sum_{i=1}^{n} \frac{\left|f_{k_i}\right|^2 P_s \left|g_{k_i}\right|^2 \left(P_1 - nP_2\right)}{1+\left|f_{k_i}\right|^2 P_s + \left|g_{k_i}\right|^2 \left(P_1 - nP_2\right)} \tag{14}$$

The maximal received SNR, by using $\mathrm{R}_{k_1}, \mathrm{R}_{k_2}, \cdots, \mathrm{R}_{k_n}$ as active relays and the above PA scheme, is simply the sum of each relay's contribution. Hence, we can order the relays according to their contributions.

By defining $\rho_{i^{(n)}} = \frac{b_{i,n}}{\sqrt{c_{i,n}}}$, we have $\rho^2_{i^{(n)}}$ as the SNR contribution of R_i using the above PA scheme if it is one of the n active relays. Arrange $\rho_{i^{(n)}}$ in non-increasing order as $\rho_{\tau_1^{(n)}} \ge \rho_{\tau_2^{(n)}} \ge \cdots \ge \rho_{\tau_M^{(n)}}$, then $\left(\tau_1^{(n)}, \tau_2^{(n)}, \ldots, \tau_M^{(n)}\right)$ is a permutation of $(1, 2, \ldots, M)$. Apparently, the n best relays are $\mathrm{R}_{\tau_1^{(n)}}, \mathrm{R}_{\tau_2^{(n)}}, \ldots, \mathrm{R}_{\tau_n^{(n)}}$, i.e., $\{k_1, k_2, \cdots, k_n\}^* = \left\{\tau_1^{(n)}, \tau_2^{(n)}, \cdots, \tau_n^{(n)}\right\}$.

Define $\mathrm{A}_n = \left\{\tau_1^{(n)}, \tau_2^{(n)}, \cdots, \tau_n^{(n)}\right\}$ and $\boldsymbol{\rho}_{\mathrm{A}_n} = \left(\rho_{\tau_1^{(n)}}, \rho_{\tau_2^{(n)}}, \cdots, \rho_{\tau_n^{(n)}}\right)$. $\left\|\boldsymbol{\rho}_{\mathrm{A}_n}\right\|^2$ is the maximal received SNR that can be attained by using n relays. Now that we have solved the n th sub-problem, what is left is to optimize $\left\|\boldsymbol{\rho}_{\mathrm{A}_n}\right\|^2$, i.e., $n^* = \arg\max_n \left\|\boldsymbol{\rho}_{\mathrm{A}_n}\right\|^2$, s.t. $n \le N$. Since

$\left\|\boldsymbol{\rho}_{\mathrm{A}_n}\right\|^2$ is a function of both n and A_n (which cannot be expressed by n in a closed form), it is impossible to derive n^* analytically. Thus, we can determine n^* by comparing $\left\|\boldsymbol{\rho}_{\mathrm{A}_1}\right\|^2$, $\left\|\boldsymbol{\rho}_{\mathrm{A}_2}\right\|^2$, ..., $\left\|\boldsymbol{\rho}_{\mathrm{A}_{\min(M,N)}}\right\|^2$.

The proposed RS and PA scheme is described in the following table.

```
Algorithm
1. Set $n = 1$.
2. Calculate $\rho_{i^{(n)}}$, $i = 1, \ldots, M$, and arrange them in non-increasing order as
   $\rho_{\tau_1^{(n)}} \geq \rho_{\tau_2^{(n)}} \geq \cdots \geq \rho_{\tau_M^{(n)}}$.
3. Let the indices of the best relays be $\mathrm{A}_n = \left\{\tau_1^{(n)}, \tau_2^{(n)}, \cdots, \tau_n^{(n)}\right\}$, and calculate $\left\|\boldsymbol{\rho}_{\mathrm{A}_n}\right\|^2$.
4. Set $n = n + 1$. If $n \leq \min(M, N)$, go back to step 2. Otherwise, terminate the iteration.
5. Compare $\left\|\boldsymbol{\rho}_{\mathrm{A}_1}\right\|^2$, $\left\|\boldsymbol{\rho}_{\mathrm{A}_2}\right\|^2$, ..., $\left\|\boldsymbol{\rho}_{\mathrm{A}_{\min(M,N)}}\right\|^2$ and choose the best value $n^*$ that corresponds
   to the maximum $\left\|\boldsymbol{\rho}_{\mathrm{A}_{n*}}\right\|^2$.
6. Select relays with indices in $\mathrm{A}_{n*}$ and allocate power to these relays according to
   $\alpha_i^* = \frac{\mathrm{K}b_{i,n*}}{c_{i,n*}}$.
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The above algorithm gives the optimal solution as

$$\alpha_i^* = \begin{cases} \dfrac{\mathrm{K}b_{i,n*}}{c_{i,n*}} & i \in \mathrm{A}_{n*} \\ 0 & i \notin \mathrm{A}_{n*} \end{cases} \tag{15}$$

The power control coefficient of R_i is given by $\left(\alpha_i^*\right)^2 \Big/ \sum_{k=1}^{M}\left(\alpha_k^*\right)^2$. The destination can calculate $c = \sum_{k=1}^{M}\left(\alpha_k^*\right)^2$ and A_{n^*}, and broadcast them to every relay. After receiving that, relay R_i can find out whether it should cooperate and calculate the transmission power by using its own channel state information.

3.2 Discussion

It is to be noted that in obtaining the received SNR in (14) we have actually performed a maximal-ratio-combining (MRC) [17] through power allocation.

It is also to be noted that there are $\sum_{n=1}^{\min(M,N)}\binom{M}{n}$ combinations of relays to be considered if an exhaustive method is used in relay selection. However, the scheme proposed above, due to the decomposition of the received SNR and the ordering of each relay’s maximal contribution, drops the number of combinations to $\min(M,N)$ and hence reduces the computational complexity greatly.

Another thing to be noted is that, to apply the solution in (15) requires the destination to estimate the channels and each relay to know its own channel state information. Hence, this scheme should be implemented to cooperative networks where training sequences and feedback are allowed.

4. Simulation Results

In this section, we verify the proposed RS and PA scheme by computer simulation. The simulation experiments are conducted using MATLAB R2010a. In our simulations, the source signal is a binary sequence following the discrete uniform distribution and it is then modulated by 4QAM. All the channels are generated as i.i.d. normalized Rayleigh fading channels obeying $\mathcal{CN}(0,1)$. The noises are also generated as i.i.d. complex Gaussian distribution following $\mathcal{CN}(0,1)$. The source uses 20 percent of the aggregate power. The power consumption of each circuit block is given in the following table [13]:

Table 1. Circuit power parameters

P_{mix}	P_{syn}	P_{LNA}	P_{fil}	P_{IFA}	η
30.3mW	50mW	20mW	5mW	3mW	0.35

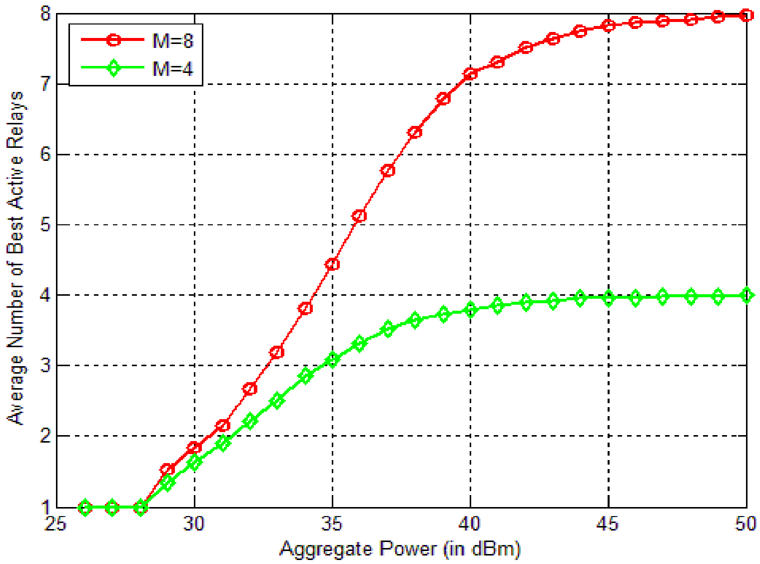

Fig.4. Average number of best active relays

As the optimal number of active relays cannot be obtained in closed form, we show the relationship between the optimal number and the aggregate power through Monte Carlo simulation. **Fig.4** shows the simulation results on the average number of best active relays of two networks with 8 and 4 relays, respectively. As described above, the channels were generated following $\mathcal{CN}(0,1)$, the number of best relays was derived for every realization of f_i and g_i by using the algorithm in subsection 3.1, and all results were averaged over 10,000 independent realizations of the channels. From **Fig.4**, we can see that the number grows with the aggregate power and tends to the number of relays available. This is reasonable because the proportion of extra circuit power consumption in the aggregate power gradually reduces when the aggregate power increases and the benefit due to using more relays can make up for the disadvantage brought by extra consumption. When the aggregate power is large enough, all relays in the network should be activated. For a network with 4 relays, this happens when the aggregate power is higher than 47dBm and this value changes to 50dBm for a network with 8 relays, exactly twice of the former value.

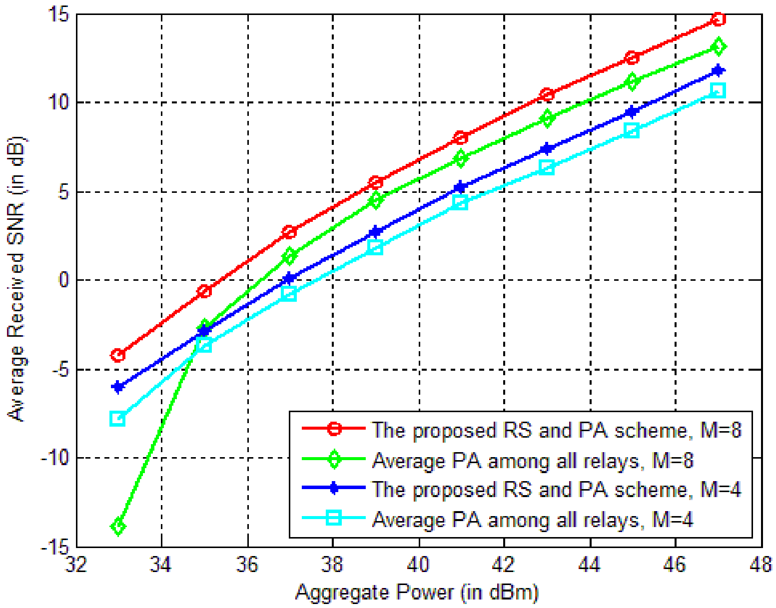

Fig.5. Average received SNR versus aggregate power

Fig.5 provides the comparison of the proposed scheme with average power allocation among all relays in terms of the received SNR. The advantage of the proposed scheme is obvious and is especially high when the aggregate power is small. For example, the proposed scheme has 10dB improvement, i.e., 10 times the received SNR of average power allocation, when $M=8$ and $P=33\text{dBm}$. This attributes to the over-large circuit power consumption which leaves no much power for relays to transmit when all relays are activated. We can also see from **Fig.4** that the number of best active relays is about 3 in this case. Thus, in our scheme, the extra circuit power consumed by the other 5 relays is used on the 3 activated ones to achieve higher received SNR. Besides, by comparing the two curves of average power allocation scheme, we can see that using 4 relays achieves higher received SNR than using 8 relays when $P < 35\text{dBm}$ which would not be possible if the circuit power consumption is negelected.

Moreover, we can estimate the power saving and the network lifetime prolonging from **Fig.4**. Suppose that the aggregate power needed in our scheme and in the average power allocation scheme are P_o and P_a (in mW), respectively, to guarantee a certain received SNR (say 10dB) when $M = 8$. From the two curves of $M = 8$, we can see that about $10\log_{10} P_a - 10\log_{10} P_o \approx 43.8 - 42.6 = 1.2$ dBm can be saved, which means $P_a / P_o \approx 1.32$. So the average power allocation scheme needs to use about 32% more power than the proposed scheme to achieve the same received SNR and therefore a network using the proposed scheme has about 32% more lifetime.

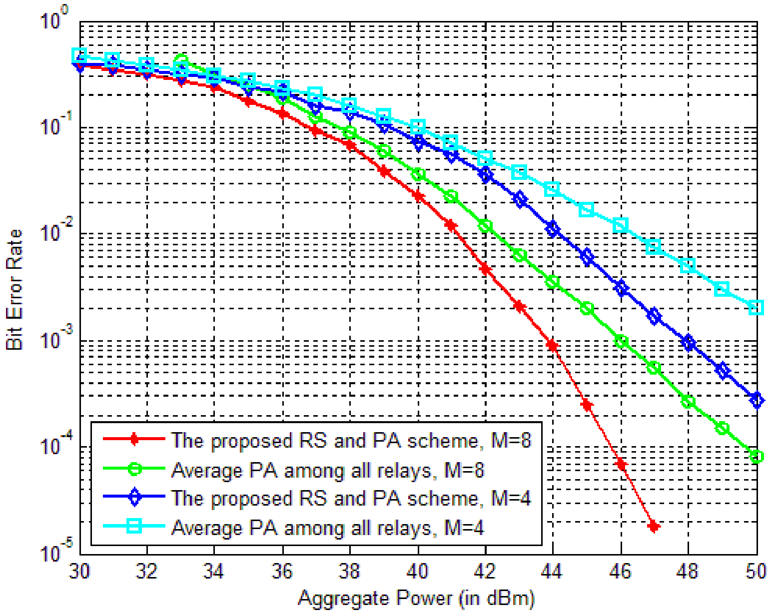

Fig.6. Bit error rate versus aggregate power

Fig.6 shows the BER curves of our scheme and of the average power allocation scheme in WSNs with 8 relays and 4 relays, respectively. It can be seen that the proposed scheme outperforms the average power allocation scheme in both cases. Thus, by using the proposed scheme, more information bits can be correctly transmitted which also indicates the effectivemess of our scheme.

5. Conclusion

In this paper, we have proposed a RS and PA scheme for a cooperative WSN with consideration of circuit power consumption. Our new scheme selects active relays and allocate their transmission power according to the channel state information to maximize the received SNR. The power allocation among active relays has been given in a closed form. The relay selection has been simplified to relay ordering by using the result of power allocation. This ordering reduces the computational complexity greatly due to the reduction in the number of relay combinations to be chosen. The simulation results have demonstrated that the new scheme provides a higher received SNR and a lower BER as compared to the simple average power allocation scheme.

As our scheme is only for two-hop cooperative networks with single-antena nodes while a practical WSN might be a multi-hop one or/and the nodes may be equipped with multiple antennas, a new RS and PA scheme for a more general network model shall be further investigated.

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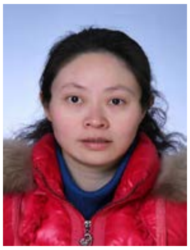

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