Lifetime Maximization for Amplify-and-Forward Cooperative Networks

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Abstract— **Power allocation strategies are devised to maximize the network lifetime of amplify-and-forward (AF) cooperative networks in this work. We consider the scenario where one source and multiple partners cooperate to transmit messages to the destination, where the power emitted by sensors is subject to the SNR requirement at the destination. First, the power allocation strategy that demands the minimum instantaneous aggregate transmit power of all cooperating partners is described and analyzed. The optimal solution results in a form of selective relaying; namely, the sensor with the best channel condition is selected for transmission. However, this instantaneous power minimization strategy does not necessarily maximize the lifetime of battery-limited systems. Then, we propose three AF cooperative schemes to exploit the channel state information (CSI), the residual battery energy and the QoS requirement. It is shown that the network lifetime can be extended considerably by taking all these three factors into account.**

I. INTRODUCTION

The multiple-input multiple-output (MIMO) techniques have been proposed to exploit spatial and temporal diversities to combat fading in a wireless environment [1]. However, due to the decreasing size and cost of mobile devices, it becomes difficult to place multiple antennas on a single terminal. This is especially true in sensor networks where terminals are low cost, low power and extremely small in size. The use of cooperation among simple and constrained users for wireless message transmission becomes an attractive alternative.

Cooperation communications [2], [3] allow users to cooperate in relaying each other's messages to the destination. Although each user may be equipped with only one antenna, their relays form a distributed antenna array to achieve the diversity gain of a MIMO system. Several cooperation strategies with different relaying techniques have been studied in the literature [3], *e.g.*, amplify-and-forward (AF), decode-and-forward (DF), selective relaying (SR) *etc.* Distributed space-time codes (DSTC) [4], [5] have also been used to improve the bandwidth efficiency of cooperative transmissions.

In resource-constrained wireless systems such as sensor networks, it is often desirable to exploit the knowledge of the channel state information (CSI) and perform optimal power allocation for cooperative relays to minimize the energy consumption or prolong the network lifetime. Several power allocation strategies were proposed based on different cooperation strategies and network topologies [6]. However, most of the existing works focus on minimizing the transmission power to meet the QoS constraint at the destination without considering the residual battery energy at each node. Without balanced energy consumption among nodes, some parts of the network may run out of battery and rapidly become nonfunctional while other parts may still have a large amount of remaining energy.

In this work, we propose power allocation strategies that take both the CSI and the residual energy information (REI) into account to prolong the network lifetime while meeting the QoS requirement of the destination. In particular, we focus on the AF cooperation scheme in an environment with one source transmitting to the destination through multiple relays that form a distributed antenna array employing the DSTC [4]. In this cooperation system, we first derive the optimal power allocation strategy that minimizes the total relay power subject to the SNR requirement at the destination. The optimal solution is in the form of *selective relaying* (SR) where only the relay with the best channel condition is chosen to transmit. Actually, this method is proven to achieve full diversity and it is optimal for several different optimizing criteria, *e.g.* [6]–[8]. Furthermore, it only demands local CSI at each relay, and can be conducted in a distributed manner [9].

In sensor networks where the replacement of batteries is prohibitive, the problem of lifetime maximization has become increasingly important and has been extensively studied in this context [10]. In the sensor network literature, the network lifetime is mostly defined as the duration of time for which all sensors are active. This may not be a suitable definition since the operability of the system is not governed by the life/death of a single sensor. In cooperative communications, we measure the operability of the network as the ability of users to achieve the end-to-end outage probability at the destination. In this case, the death of a user due to energy depletion will cause a loss in diversity and robustness but may still maintain the desired QoS. Based on selective relaying, we propose three strategies to maximize network lifetime and show that the strategies considering both the CSI and the REI achieve better performance than that using the CSI only in this work.

II. SYSTEM MODEL

Consider a network where $N+1$ nodes cooperate in transmitting messages to the destination. At any time instance, we have one user act as the source and the remaining N users

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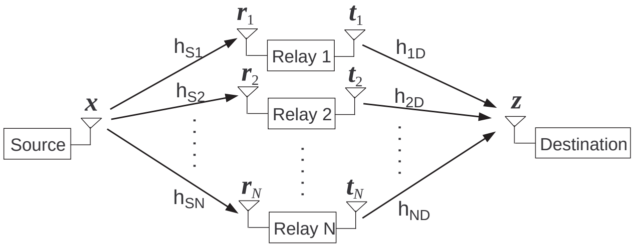

Fig. 1. A system model of the proposed cooperative relay network.

serve as cooperative partners that relay the source message to the destination as shown in Fig. 1. In this work, we consider the case where the source is fixed throughout the whole transmission process.

The cooperation takes on two phases of transmission. In the first phase, the source sends message $\mathbf{x}$ of dimension $T \times 1$ with zero-mean and covariance matrix $E\{\mathbf{x}^\dagger \mathbf{x}\} = \mathbf{I}_T$ to relay nodes, where $\mathbf{I}_T$ is a $T \times T$ identity matrix. The signal received at the k-th relay is

$$\mathbf{r}_k = \sqrt{P_S} h_{Sk} \mathbf{x} + \mathbf{v}_k, \quad k = 1, 2, \ldots, N, \tag{1}$$

where h_{Sk} is the channel coefficient from the source to the k-th relay, $\mathbf{v}_k$ is the additive white Gaussian noise (AWGN) at the k-th relay with $E\{\mathbf{v}_k \mathbf{v}_j^\dagger\} = \mathbf{I}_T \cdot \delta_{kj}$ [1], and P_S is the transmit power of the source. Channel coefficients, h_{Sk}, $1 \leq k \leq N$, are assumed to be independent and circularly symmetric complex Gaussian random variables with $\mathcal{CN}(0, \sigma_{Sk}^2)$.

In the second phase, each relay transmits an amplified version of the received signal to the destination using the DSTC proposed in [4]. Specifically, the signal transmitted by the k-th node is expressed as

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

where P_k is the transmit power of the k-th relay and $\mathbf{A}_k$ is the $T \times T$ space-time encoding matrix that is chosen randomly at relay k. Let $\mathbf{A}_k$, for $k = 1, \cdots, N$, be unitary and *i.i.d.* isotropically random with zero mean [4]. It was shown that, for $T > N$, the DSTC achieves full diversity at high SNR. Then, the signal received at the destination becomes

$$\mathbf{z} = \sum_{k=1}^{N} h_{kD} \mathbf{t}_k + \mathbf{w}, \tag{3}$$

where h_{kD} is the channel coefficient from the k-th relay to the destination and $\mathbf{w}$ is the AWGN at the destination with $E\{\mathbf{w}\mathbf{w}^\dagger\} = \mathbf{I}$. Again, h_{kD} is assumed to be *i.i.d.* circularly symmetric with distribution $\mathcal{CN}(0, \sigma_{kD}^2)$.

The maximum likelihood (ML) detection scheme is performed at the destination with full knowledge of the CSI, *i.e.,* h_{Sk} and h_{kD} for all k, and the ST coding matrices $\mathbf{A}_k$. The SNR at the destination averaged over random choices of coding matrices is given by

$$SNR = \frac{\sum_{k=1}^{N} \frac{P_S P_k}{P_S |h_{Sk}|^2 + 1} |h_{Sk} h_{kD}|^2}{1 + \sum_{k=1}^{N} \frac{P_k |h_{kD}|^2}{P_S |h_{Sk}|^2 + 1}}. \tag{4}$$

Note that we are not concerned with the combining of signals transmitted from the source at the destination but focus on the power allocation over relays in this work.

III. Optimal Power Allocation for Aggregate Power Minimization

We first derive the optimal power allocation scheme over relays that minimizes the instantaneous aggregate transmit power subject to the average SNR requirement at the destination. Given the knowledge of channel coefficients, the optimal power allocation problem can be formulated as

$$\begin{aligned} \min \quad & \sum_{k=1}^{N} P_k \\ \text{subject to} \quad & \text{(i) } SNR \geq \gamma \text{ and (ii) } P_k \geq 0, \ \forall k. \end{aligned} \tag{5}$$

where γ is the target SNR at the destination. In fact, constraint (i) can be expressed in linear form as

$$\sum_{k=1}^{N} P_k \left[|h_{kD}|^2 \left(1 - \frac{\gamma + 1}{P_S |h_{Sk}|^2 + 1} \right) \right] \geq \gamma. \tag{6}$$

Please note that, when $P_S |h_{Sk}|^2 < \gamma$, the contribution of relay k to the summation in (6) is negative and thereby should be allocated with no power, *i.e.,* $P_k = 0$. This is intuitively true since the relays that do not receive the source message reliably should not be allowed to transmit. Specifically, the power is allocated over the subset of relays $\mathcal{R}_D = \{k : P_S |h_{Sk}|^2 \geq \gamma\}$. When the set $\mathcal{R}_D$ is empty, the target SNR at the destination is not achievable and an outage is recorded. The optimal power allocation strategy is shown in the proposition below, where the proof follows from results in linear programming [11].

Proposition 1: For $\mathcal{R}_D$ nonempty, the optimal power allocation of (5) is

$$P_k = \begin{cases} \frac{\gamma}{|h_{kD}|^2} \frac{P_S |h_{Sk}|^2 + 1}{P_S |h_{Sk}|^2 - \gamma}, & k = k^*; \\ 0, & \text{otherwise}, \end{cases} \tag{7}$$

$$\text{where} \quad k^* = \arg \min_{k \in \mathcal{R}_D} \frac{\gamma}{|h_{kD}|^2} \frac{P_S |h_{Sk}|^2 + 1}{P_S |h_{Sk}|^2 - \gamma}. \tag{8}$$

We choose the weight for all $k \in \mathcal{R}_D$ as

$$w_k \triangleq \frac{\gamma}{|h_{kD}|^2} \frac{P_S |h_{Sk}|^2 + 1}{P_S |h_{Sk}|^2 - \gamma},$$

which is the transmit power needed for the k-th relay to achieve γ alone. Proposition 1 shows that the optimal power allocation scheme in an AF-DSTC cooperative network is the selective relaying strategy, where the relay with the best composite channel is chosen to transmit. This implies that no STC is required, which significantly reduces the complexity

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[1] δ_{kj} is the Kronecker delta and † is the conjugate transpose.

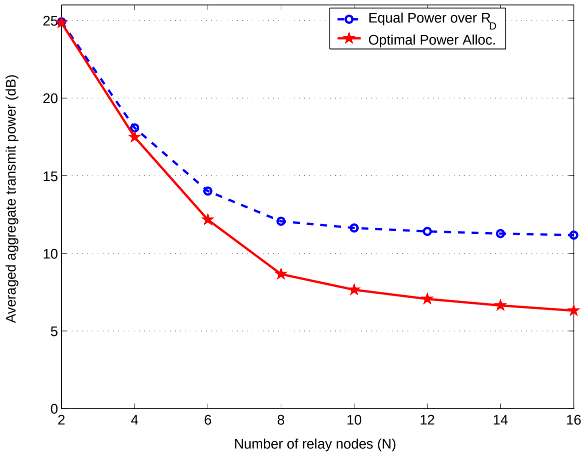

Fig. 2. The average transmit power versus the number of relay nodes.

of the system. The numerical studies in [13] show that the selective relaying scheme achieves a better lifetime than those employing more than one relay. More importantly, the selective relaying scheme achieves full diversity gains [3] and requires only the local CSI for the computation of weights $\{w_k, \forall k\}$ at each relay. In fact, (8) can be achieved in a distributed manner through the methods given in [9].

We show in Fig. 2 the average total transmit power required to achieve the target SNR, γ, as the number of relays increases. In this experiment, we choose $P_S = 12$dB, $\gamma = 8$dB, and $\sigma^2_{Sk} = \sigma^2_{kD} = 1$ for all k. Here, the unit of power is set to the transmit power required to achieve $SNR = 0$dB at the receiver when the channel gain is one. We compare the performance between the optimal power allocation and the case with an equal power distribution among users in $\mathcal{R}_D$. Since the diversity increases with N, the total power for both cases decreases as N increases. In fact, the gain achieved by power allocation also increases with N since a larger degree of freedom is available for power distribution. A gain of approximately 5dB is observed for 16 relays.

IV. POWER ALLOCATION STRATEGIES FOR NETWORK LIFETIME MAXIMIZATION

One important goal of power allocation in wireless networks is to prolong the lifetime of the battery-powered devices. In cooperative networks, users transmit messages cooperatively to achieve the QoS requirement at the destination with each user operating under individual battery constraints. The network lifetime is no longer maximized with the optimal power allocation strategy described in Sec. III. Most previous work on this subject defines the network lifetime as the time when one or several users are depleted with energy [10]. However, this definition does not accurately characterize the duration in which the network operates properly in a cooperative system. In the context of our interest, the network is said to be "dead" if the target SNR at the destination cannot be achieved with a certain probability. Based on the selective relaying strategy proposed in the last section, we will discuss relay selection methods to maximize the duration for which the outage probability is kept under a certain level.

We use $e_k[m]$ to denote the residual energy of relay k after the m-th message is transmitted. When relay k is chosen by the selection method, the outage will occur if the SNR at the relay is lower than γ, *i.e.*, $k \notin \mathcal{R}_D$, or if the remaining energy is not sufficient to reach the SNR at the destination. [2] The outage probability of the k-th relay at time m can be written as

$$\begin{aligned} P_{out}(e_k[m]) &= \Pr\{k \notin \mathcal{R}_D\} + \Pr\{w_k > e_k[m], k \in \mathcal{R}_D\} \\ &= \Pr\left(\frac{P_S e_k[m] |h_{Sk} h_{kD}|^2}{1 + P_S |h_{Sk}|^2 + e_k[m] |h_{kD}|^2} < \gamma \right). \quad (9) \end{aligned}$$

If $|h_{Sk}|^2$ and $|h_{kD}|^2$, for all k, are *i.i.d.* exponentially distributed with mean σ^2_{Sk} and σ^2_{kD}, respectively, it can be shown that

$$P_{out}(e_k[m]) = 1 - \exp\left\{ -\frac{\gamma}{P_S \sigma^2_{Sk}} - \frac{\gamma}{e_k[m] \sigma^2_{kD}} \right\} \delta_k K_1(\delta_k), \quad (10)$$

where $K_1(\cdot)$ is the modified Bessel function of the second kind of order one and

$$\delta_k = \sqrt{\frac{4\gamma(\gamma+1)}{P_S e_k[m] \sigma^2_{Sk} \sigma^2_{kD}}}.$$

The outage probability of the network at time m is then given by

$$P_{out}(\mathbf{e}[m]) = \prod_{k=1}^{N} P_{out}(e_k[m]).$$

Let $\mathbf{e}[m] = [e_1[m], \cdots, e_N[m]]$, where $\mathbf{e}[0]$ is the initial energy at relays. The *network lifetime* is defined mathematically as

$$\mathcal{L} = \min_m \{ m : P_{out}(\mathbf{e}[m]) > \eta \}.$$

With the strong law of large numbers, the average network lifetime can be derived as [10]

$$E\{\mathcal{L}\} = \frac{\sum_{k=1}^{N} e_k[0] - \mathcal{E}_w}{\mathcal{E}_r}, \quad (11)$$

where $\mathcal{E}_w$ is the total residual energy at all relays when the network dies (*i.e.*, the wasted energy) and $\mathcal{E}_r$ is the average energy consumed by relays in each transmission. Both $\mathcal{E}_w$ and $\mathcal{E}_r$ must be minimized so as to maximize the network lifetime. However, they are closely coupled through the relay selection method. Specifically, the power allocation strategy proposed in (7) minimizes the term $\mathcal{E}_r$. However, this may result in an unbalanced battery energy consumption at different relays and, thus, increases the value of $\mathcal{E}_w$. In fact, as users gradually die, the network loses its diversity and the transmit power required to achieve the target SNR increases gradually that in turn causes remaining users to die faster. Thus, to extend the network lifetime, one must minimize the transmit power while keeping as many users alive as possible.

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[2] The case with the peak power constraint at relays is considered in [11].

In the following, we propose three relay selection methods exploiting both the CSI information (in form of $\{w_k, \forall k\}$) and the REI information (in form of $\{e_k, \forall k\}$) to maximize the average lifetime as defined in (11). These methods will be compared with the minimum power solution derived in Section III. However, only nodes with sufficient residual energy are selected in this case. We use $\mathcal{S}_D = \mathcal{R}_D \cap \{k : e_k \geq w_k\}$ to denote the set of eligible relays. When $\mathcal{S}$ is empty, no relay is selected and an outage is declared.

The four power allocation strategies under our consideration are given below.

(I) **The minimal transmit power strategy**

Choose the node with the minimal transmit power:

$$k^* = \arg\min_{k\in\mathcal{S}_D} w_k.$$

This is the one discussed in Sec. III.

(II) **The maximal residual energy strategy**

Choose the node with the largest residual energy after relaying the current message [10], *i.e.,*

$$k^*_{res} = \arg\max_{k\in\mathcal{S}_D} e_k - w_k.$$

The goal is to prevent fast energy depletion of some relay nodes to maintain the diversity. Therefore, it emphasizes the balance of energy consumption among relays.

(III) **The maximal energy efficiency index strategy**

The energy efficiency index is defined as the ratio between e_k and w_k, *i.e.,* $\rho_k = \frac{e_k}{w_k}$, at the k-th relay [12]. The strategy selects node k^* with the maximal energy efficiency index, *i.e.,*

$$k^*_{eff} = \arg\max_{k\in\mathcal{S}_\mathcal{D}} \frac{e_k}{w_k}.$$

In words, the node whose transmit power occupies the least portion of its current residual energy is chosen.

(IV) **The minimal outage probability strategy**

To reduce the increasing rate of the outage probability, we choose the relay that has the minimum outage probability after the current message is transmitted, *i.e.,*

$$\begin{aligned} k^*_{outage} &= \arg\min_{k\in\mathcal{S}_D} P_{out}(\mathbf{e} - w_k\mathbf{1}_k) \\ &= \arg\min_{k\in\mathcal{S}_D} \frac{P_{out}(\mathbf{e} - w_k\mathbf{1}_k)}{P_{out}(\mathbf{e})} \\ &= \arg\min_{k\in\mathcal{S}_D} \frac{P_{out}(e_k - w_k)}{P_{out}(e_k)}, \qquad (12) \end{aligned}$$

where $\mathbf{1}_k$ is an $N \times 1$ vector with the k-th element equal to 1 and zero everywhere else.

Since the above four selection strategies demand only the local REI and CSI information at each relay, they can be implemented in a distributed manner as discussed in [9].

Even though strategies (II) and (III) use both CSI and REI in selecting relay nodes, the latter actually achieves better performance in terms of network lifetime maximization. This can be proved below. As shown in (11) for $\sum_k e_k[0] \gg \mathcal{E}_w$, maximizing the average lifetime is equal to maximizing the ratio between the residual energy and the transmit power. When the two strategies select different relays, *i.e.,* $k^*_{res} \neq k^*_{eff}$, we have

$$\begin{aligned} e_{k^*_{res}} - w_{k^*_{res}} &> e_{k^*_{eff}} - w_{k^*_{eff}}, \\ e_{k^*_{res}}/w_{k^*_{res}} &< e_{k^*_{eff}}/w_{k^*_{eff}}. \end{aligned}$$

Thus, we have $w_{k^*_{eff}} < w_{k^*_{res}}$. When the node selection disagrees, we should favor the one with the lower transmit power.

Strategy (IV) attempts to minimize the outage probability based on the local information. When e_k is sufficiently large, the value of δ_k is very small and the Bessel function in (10) can be approximated by $K_1(\delta_k) \approx \delta_k^{-1}$. In this case, strategy (IV) reduces to

$$k^*_{outage} = \arg\max_{k\in\mathcal{S}_D} (e_k - w_k)\frac{e_k}{w_k}, \qquad (13)$$

which is a combination of (II) and (III).

V. NUMERICAL SIMULATION AND DISCUSSION

We compare the average network lifetime of the four relay strategies discussed in the last section for two test scenarios. In the experiments, we set the transmit power of the source $P_S = 12$dB and the target SNR at $\gamma = 8$ dB. The threshold for the outage probability is $\eta = 0.1$. The channel coefficients h_{Sk} and h_{kD} are *i.i.d.* complex Gaussian distributed with unit variance and varying independently with time.

Experiment I: For a network of $N = 6$ relays, we show in Fig. 3 the average network lifetime of different power allocation schemes with respect to the initial energy at each node. The initial battery energy of relays is assumed to be equal, *i.e.* $e_k[0] = E_0$ for all k. Specifically, we take E_0 to be an integer multiple of P_S ranging from $250P_S$ to $450P_S$. We see from (11) that the average network lifetime is a linear function of the total initial energy and the slopes are determined by the average transmit power of the corresponding strategies. As shown in the figure, strategies (I), (III) and (IV) have a similar slope since they have a similar average transmit power. Since the initial energy selected in this experiment is much larger than the wasted energy, the optimal strategy can be approximated with strategy (III) that considers the ratio of the residual energy and the transmit power. Also, the strategy in (13) closely approximates strategy (IV), in which the outage probability is used as the selection criterion. Although the network lifetime is defined in terms of the outage probability, strategy (IV) only performs the step-by-step optimization, which does not yield the globally optimal solution, which explains the loss in Fig. 3.

Experiment 2: We compare the lifetime performance of four strategies with different numbers of relays and a limited total battery energy at relays in Fig. 4. The total initial relay battery-energy is $60P_S$, which is equally distributed among all relays. In this case, the wasted energy in (11) cannot be neglected, especially when the number of relays increases so that the energy at each node becomes small. However, the

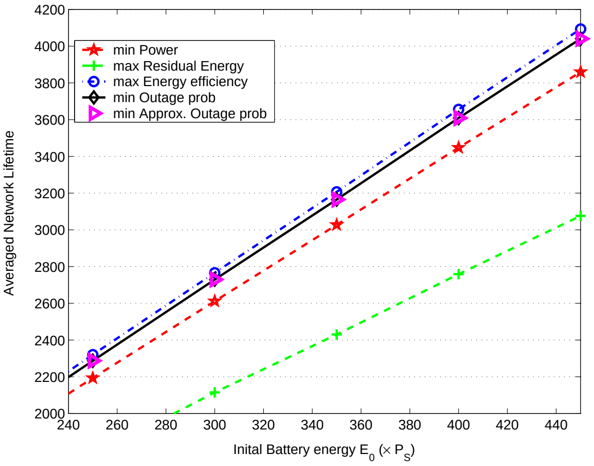

Fig. 3. The average network lifetime versus the initial energy of each relay for Test Case no. 1.

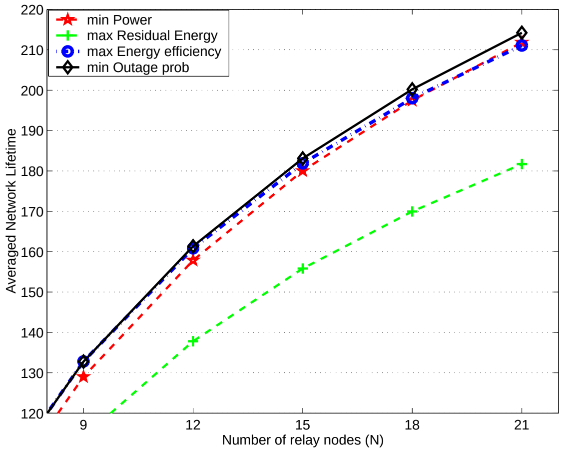

Fig. 4. The average network lifetime versus the number of relays for Test Case no. 2

network lifetime still increases with the number of relays due to the increased spatial diversity gain. Since the wasted energy cannot be neglected, the strategy based on the energy efficiency index no longer gives the longest average lifetime. Specifically, for a small N value, strategy (III) performs as well as that minimizes the outage probability, which is the best in this scenario. However, it gradually degrades when the number of relays increases. As N increases, it is gradually close to the minimum transmit power strategy. Strategy (IV) achieves the best performance when the initial energy is comparable to the wasted energy. In this case, only a few steps are taken before the network dies so that the step-by-step maximization can be used to approximate the global solution.

Overall, selective strategy (III) that chooses the node with largest energy efficiency index e_k/w_k appears to be a good one since it offers good lifetime performance in both test cases.

VI. CONCLUSION AND FUTURE WORK

Power allocation strategies to maximize the network lifetime of amplify-and-forward (AF) cooperative networks were examined in this work. The optimal power allocation strategy for the ST-encoded AF relaying scheme with multiple relays was first derived. To achieve the SNR requirement at the destination, the minimum energy solution that chooses only the relay with the best composite channel to transmit gives the best solution. This implies that no DSTC is needed when the CSI is known at the relays since only one single relay is used at any time instance. Furthermore, three additional selective relaying strategies that incorporate REI and CSI in the selection process were proposed and studied. It was shown that the network lifetime of cooperative networks is no longer maximized by the minimum power solution. It was shown that, with sufficient battery energy, the strategy maximizing the energy efficiency index gives the longest average lifetime. On the other hand, when the initial battery energy is comparable with the wasted energy, the strategy that minimizes the outage probability gives better performance. More extensive performance comparison of proposed power allocation strategies under different network conditions and energy distribution settings is under our current study. The lifetime maximization with consideration of energy consumption due to signal reception, CSI acquisition *etc*, and its applications to multi-hop networks are subjects of our future research.

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