Lifetime Maximization for Amplify-and-Forward Cooperative Networks

Wan-Jen Huang, *Student Member, IEEE,* Y.-W. Peter Hong, *Member, IEEE,* and C.-C. Jay Kuo, *Fellow, IEEE*

Abstract—**Joint relay-selection and power-allocation strategies are devised to prolong the lifetime of amplify-and-forward (AF) cooperative networks. Lifetime is defined as the time duration within which the desired signal-to-noise ratio (SNR) at the destination is met with a certain probability. Based on selective relaying, we propose three strategies that take into account the local channel state information (CSI) and the local residual energy information (REI) at each relay to prolong the network lifetime. With a finite number of power levels, the energy dissipation process can be modeled as a finite-state Markov chain and the optimal lifetime maximization strategy can be derived using dynamic programming. We demonstrate that the network lifetime can be extended considerably by exploiting both CSI and REI via numerical simulation. The performance of the proposed strategies that utilize only local CSI and REI is shown to be comparable to that of the optimal strategy that demands global CSI and REI.**

Index Terms—**Cooperative communications, lifetime maximization, selective relaying, energy efficiency, power allocation.**

I. INTRODUCTION

COOPERATIVE networks [1]–[3] refer to communication systems where users cooperate by relaying each others' messages to the destination. Many cooperation strategies have been proposed with different relaying techniques [2], such as amplify-and-forward (AF) and decode-and-forward (DF). At each time, one user serves as the source while others form a distributed antenna array that simultaneously retransmits messages to enhance the detection at the destination. Multiple-input multiple-output (MIMO) techniques, such as beamforming [4], space-time coding [5] and antenna selection [6], [7] have been examined to exploit the diversity and the multiplexing gains. The AF selective relaying, also referred to as opportunistic relaying, is shown to achieve full diversity at high SNR regimes in [6] and can be carried out in a distributed manner [7] since it requires only local CSI at the relays.

Due to the spatial diversity gain, user cooperation reduces the total energy required to meet the quality-of-service (QoS) requirement at the destination. Several power allocation strategies [8] have been proposed to minimize the average transmission power for different cooperation schemes, system objectives and network topologies. However, minimizing the average power consumption in cooperative networks does not necessarily maximize the network lifetime since the lifetime depends not only on the average power consumption but the residual energy information (REI) of the users as well. Without balanced energy usage, some users may run out of battery-energy more rapidly than others, and the network may become non-functional even when some users have a large amount of battery-energy remaining.

Based on selective relaying, we examine four joint relay-selection and power-allocation strategies, namely, the minimum transmission power (MTP) strategy, the maximum residual energy (MRE) strategy, the maximal energy-efficiency index (MEI) strategy, and the minimum outage probability (MOP) strategy, to prolong network lifetime. Here, lifetime is defined as the time duration during which the SNR requirement at the destination is met with a certain probability, *i.e.,* the time during which the outage probability constraint is met. Lifetime maximization methods have been studied extensively in sensor networks, *e.g.* [9]–[13], but most works along these lines define the network lifetime as the time duration during which all users or a particular number of users remain active. This definition does not fully characterize the operability of cooperative systems since the energy depletion of a single node (or a certain number of nodes) only decreases the diversity available in the system while QoS may still be achieved cooperatively with the remaining relays. The MRE and MEI strategies studied in this work was proposed and analyzed in [13] for data gathering applications in sensor networks. In our work, we adopt the MRE and MEI strategies for relay selection in AF cooperative networks. Due to the differences in the nature of the AF transmission and the definition of network lifetime, we show that the MRE no longer performs well in the cooperative system, which is in contrast to that shown in [13]. Moreover, based on our definition of lifetime, we propose the MOP strategy, where a relay is selected to minimize the outage probability after each transmission. This is equivalent to performing step-by-step maximization on the network lifetime. We show that the MOP outperforms all schemes, but the MEI is able to achieve comparable performances with MOP when the initial energy is large [c.f. Section V].

Furthermore, with a finite number of power levels, the evolution of users' residual energies can be modeled as a finite state Markov chain, where each state records the REI of all users [11]. In this case, the average network lifetime is equivalent to the average time to absorption in the Markov chain, where the absorption states correspond to non-operable REI values, *i.e.,* values that cannot meet the outage constraint. Moreover, with global knowledge of CSI and REI, the optimal

Manuscript received December 15, 2006; revised September 11, 2007 and February 17, 2008; accepted February 20, 2008. The associate editor coordinating the review of this paper and approving it for publication was R. Fantacci. This work is supported in part by the National Science Council of Taiwan, R.O.C., under the grants NSC-95-2221-E-007-043-MY3, NSC-96-2628-E-007-012-MY2 and NSC-96-2219-E-007-012.

W.-J. Huang and C.-C. Jay Kuo are with the Ming-Hsieh Department of Electrical Engineering, University of Southern California, Los Angeles, CA 90089-2564, USA (e-mail: wanjenhu@usc.edu, cckuo@sipi.usc.edu).

Y.-W. Peter Hong is with the Institute of Communications Engineering, National Tsing Hua University, Hsinchu, Taiwan (e-mail: ywhong@ee.nthu.edu.tw).

Digital Object Identifier 10.1109/TWC.2008.061075.

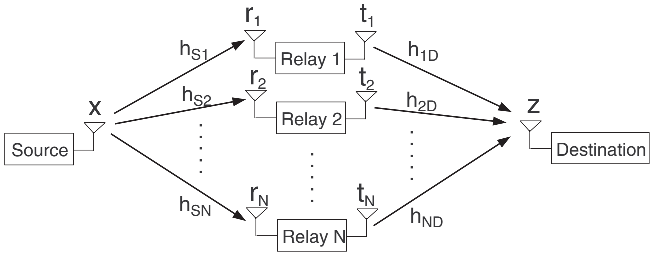

Fig. 1. A system model of the proposed cooperative relay network.

lifetime maximization strategy can be obtained by dynamic programming [11]. We show that, compared with the optimal strategy that requires global CSI and REI, the performance loss of the strategies that demand only local CSI and REI (*e.g.* MOP and MEI) is negligible.

II. System Model

Consider a network with $N+1$ users cooperating to transmit a common message to the destination. In this system, one user acts as the source and the other N users serve as cooperative partners that relay the messages from the source to the destination, as shown in Fig. 1.

Cooperative transmission from the source to the destination is achieved in two phases. In the first phase, the source sends data symbol x to the relay nodes, where x has zero-mean and unit-variance. The signal received at the k-th relay is

$$r_k = \sqrt{P_S} h_{Sk} x + v_k, \quad k = 1, 2, \ldots, N, \tag{1}$$

where h_{Sk} is the channel coefficient from the source to the k-th relay, v_k is the additive white Gaussian noise (AWGN) at the k-th relay with $E\{v_k v_j^*\} = \delta_{kj}$ [1], and P_S is the transmission power of the source. Assume that h_{Sk} is circularly symmetric complex Gaussian with zero mean and variance σ_{Sk}^2, *i.e.,* $\mathcal{C}N(0, \sigma_{Sk}^2)$, and is independent for all k.

In the second phase, we adopt the selective relaying method where only one of N relays is selected to transmit, as proposed in [6], [7]. When relay k is selected to transmit, it will send an amplified version of the received message, *i.e.,*

$$t_k = \sqrt{\frac{P_k}{P_S |h_{Sk}|^2 + 1}} r_k,$$

where P_k is the transmit power of the k-th relay. Suppose that users are limited to L discrete power levels, *i.e.,* $P_k \in \{\varepsilon_i, 1 \leq i \leq L\}$ where $0 < \varepsilon_1 < \varepsilon_2 < \cdots < \varepsilon_L = P_{max}$. The signal received at the destination in the second phase is given by

$$z = \sqrt{\frac{P_S P_k}{P_S |h_{Sk}|^2 + 1}} h_{Sk} h_{kD} x + \sqrt{\frac{P_k}{P_S |h_{Sk}|^2 + 1}} h_{kD} v_k + v_D, \tag{2}$$

where $h_{kD} \sim \mathcal{CN}(0, \sigma_{kD}^2)$ is the channel coefficient from the k-th relay to the destination and v_D is AWGN with unit variance. Assume that h_{kD} is independent for all k. The signal to noise ratio (SNR) observed at the destination is given by

$$SNR = \frac{P_S P_k |h_{Sk} h_{kD}|^2}{1 + P_S |h_{Sk}|^2 + P_k |h_{kD}|^2}. \tag{3}$$

Our goal is to study joint relay-selection and power-allocation strategies to prolong network lifetime. Most previous works [9]–[13] view the network lifetime as the time duration in which all users (or a certain number of users) in the network remain active. Instead, we define the network lifetime as the duration in which the SNR requirement at the destination is achieved with a certain probability.

Let $e_k[m]$ be the residual energy of relay k at the beginning of the m-th time slot. It is assumed that each transmission lasts for one time unit and the transmission power is equal to the amount of energy consumed during the transmission interval. The maximum power that relay k can transmit in the m-th time interval is denoted by $\lfloor e_k \rfloor = \max\{\varepsilon_i : \varepsilon_i \leq e_k, i = 1, 2, \cdots, L\}$. The outage of relay k occurs when the maximum achievable SNR at the destination is lower than the target value γ. The outage probability of the k-th relay in the m-th time slot is given by

$$P_{out}(\lfloor e_k[m] \rfloor) = \Pr\left(\frac{P_S \lfloor e_k[m] \rfloor |h_{Sk} h_{kD}|^2}{1 + P_S |h_{Sk}|^2 + \lfloor e_k[m] \rfloor |h_{kD}|^2} < \gamma \right), \tag{4}$$

which is a function of the residual energy $e_k[m]$. It was shown in [14] that

$$P_{out}(\lfloor e_k[m] \rfloor) = 1 - \left[e^{-\left(\frac{\gamma}{P_S \sigma_{Sk}^2} + \frac{\gamma}{\lfloor e_k[m] \rfloor \sigma_{kD}^2}\right)} \sqrt{\frac{4\gamma(\gamma+1)}{P_S \lfloor e_k[m] \rfloor \sigma_{Sk}^2 \sigma_{kD}^2}} K_1\left(\sqrt{\frac{4\gamma(\gamma+1)}{P_S \lfloor e_k[m] \rfloor \sigma_{Sk}^2 \sigma_{kD}^2}} \right) \right], \tag{5}$$

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

Let $\mathbf{e}[m] = [e_1[m], \cdots, e_N[m]]$, and let $\mathbf{e}[1]$ be the initial energy distribution at the relays. Notice that, with selective relaying, only one of the relays is selected to forward the source's message in each time slot. For any reasonable relay selection strategy and for any given channel state, a relay may be selected only if it belongs to the set of relays that is able to achieve the target SNR with its residual energy. Therefore, system outage occurs if and only if the set of relays that satisfies this condition is empty, *i.e.,* no relay is able to achieve the target SNR. Given the residual energy at the beginning of the m-th time slot, *i.e.,* $\mathbf{e}[m]$, the system outage probability is computed as

$$P_{out}(\lfloor \mathbf{e}[m] \rfloor) = \prod_{k=1}^{N} P_{out}(\lfloor e_k[m] \rfloor). \tag{6}$$

Notice that, given the residual energy values, the probability that a system outage occurs is independent of the relay selection strategy. Lifetime is then defined as follows.

Definition : *The network lifetime is defined as*

$$\mathcal{L}(\mathbf{e}[1]) = \max_{m} \{ m : P_{out}(\lfloor \mathbf{e}[m] \rfloor) \leq \eta \}$$

where threshold η is the maximum tolerable outage probability.

---

[1] δ_{kj} is the Kronecker delta function where $\delta_{kj} = 1$ if $k = j$ and $\delta_{kj} = 0$ if $k \neq j$.

More specifically, lifetime is defined as the maximum m after which an outage would occur with probability greater than η. Since the system outage probability in (6) depends only on the residual energy at each node, the lifetime for any given strategy is then determined by the average number of transmissions that it takes before the system enters one of the energy states that causes the system outage probability to exceed the required value.

III. JOINT RELAY-SELECTION AND POWER-ALLOCATION FOR LIFETIME MAXIMIZATION

In this section, we propose several joint relay-selection and power-allocation strategies for lifetime maximization in cooperative networks. Note that, with the maximum power constraint P_{max}, a selected relay must satisfy the condition that $\frac{P_S P_{max}|h_{Sk}h_{kD}|^2}{1+P_S|h_{Sk}|^2+P_{max}|h_{kD}|^2} \geq \gamma$. Let

$$\mathcal{R}_S = \{k : \frac{P_S P_{max}|h_{Sk}h_{kD}|^2}{1+P_S|h_{Sk}|^2+P_{max}|h_{kD}|^2} \geq \gamma\}$$

be the set of such relays. If all relays experience a deep fade at the same time such that $\mathcal{R}_S$ becomes empty, none of the relays will be selected and an outage will be automatically declared. As long as the system outage probability (as defined in (6)) is below the given threshold η, the network is still considered to be active.

Let w_k be the minimum transmission power level needed for the k-th relay to achieve the target SNR, *i.e.,* γ, at the destination. For $k \in \mathcal{R}_S$, we have

$$w_k = \min\{\varepsilon_i : \frac{P_S \varepsilon_i |h_{Sk}h_{kD}|^2}{1+P_S|h_{Sk}|^2+\varepsilon_i|h_{kD}|^2} \geq \gamma\}.$$

Without considering the residual battery energy at the relays, the best strategy is to choose the relay node that demands the least transmission power to meet the target SNR, *i.e.,* the node with minimal w_k. However, in cooperative networks, minimizing the instantaneous transmission power does not necessarily lead to maximum lifetime. In fact, the residual energy distribution is also an important factor in this problem.

As shown in [10], the average network lifetime can be computed as

$$\mathbf{E}[\mathcal{L}(\mathbf{e}[1])] = \frac{\sum_{k=1}^{N} e_k[1] - \mathcal{E}_w}{\mathcal{E}_r}, \tag{7}$$

where $\mathcal{E}_w$ is the average sum of residual energy at all relays when the network becomes non-operable, and $\mathcal{E}_r$ is the average sum of energy consumed by all relays during each transmission. To maximize the network lifetime, relay selection must minimize the average energy consumption as well as the wasted energy, which are closely coupled. Since the minimum average transmission power decreases with the number of relays due to increased spatial diversity, it is desirable to maintain the maximum number of active relays to minimize the rate of energy consumption.

Here, we study three joint relay selection and power allocation strategies that exploit local instantaneous CSI and REI, *i.e.,* $w_k[m]$ and $e_k[m]$ for relay k, to maximize the average lifetime in (7). In these schemes, only nodes that belong to the set $\mathcal{R}_E = \mathcal{R}_S \cap \{k : w_k[m] \leq e_k[m]\}$ are eligible to relay the m-th message. When $\mathcal{R}_E$ is empty, no relay is selected and an outage occurs. As long as the outage probability of the network satisfies the QoS requirement, the network remains active even though the current transmission fails. Since these methods demand only the instantaneous information, index m is omitted in the following discussion.

The three methods along with the minimum power solution are described below.

(I) **The minimum transmission power strategy (MTP):** Choose the relay that requires the minimum transmission power, *i.e.,*

$$k^*_{MTP} = \arg\min_{k\in\mathcal{R}_E} w_k.$$

(II) **The maximum residual energy strategy (MRE) [10]:** Choose the relay with the largest residual energy after retransmitting the current message, *i.e.,*

$$k^*_{MRE} = \arg\max_{k\in\mathcal{R}_E} e_k - w_k.$$

The goal is to maintain the maximum diversity gain by preventing any node from depleting its energy earlier than others. This method balances the energy consumption across relays.

(III) **The maximum energy-efficiency index strategy (MEI) [12]:** Choose the relay with the maximal energy efficiency index e_k/w_k, *i.e.,*

$$k^*_{MEI} = \arg\max_{k\in\mathcal{R}_E} \frac{e_k}{w_k}.$$

That is, we choose the relay that consumes the least portion of its residual energy.

(IV) **The minimum outage probability strategy (MOP) [15], [16]:** Choose the relay that has the minimum outage probability after the current message is transmitted (even if it is allowed to expend all its residual energy for transmission), *i.e.,*

$$\begin{aligned} k^*_{MOP} &= \arg\min_{k\in\mathcal{R}_E} P_{out}(\mathbf{e}-w_k\mathbf{1}_k) \\ &= \arg\min_{k\in\mathcal{R}_E} \frac{P_{out}(\mathbf{e}-w_k\mathbf{1}_k)}{P_{out}(\mathbf{e})} \\ &= \arg\min_{k\in\mathcal{R}_E} \frac{P_{out}(e_k-w_k)}{P_{out}(e_k)}, \end{aligned} \tag{8}$$

where $\mathbf{1}_k$ is an $N \times 1$ vector with the k-th element equal to 1 and 0 elsewhere. The MOP selects a relay that minimizes the outage probability after each transmission. Since the network lifetime is defined by the outage probability, it is equivalent to performing step-by-step maximization of network lifetime.

With a finite number of power levels, there is a non-zero probability that the optimal selection criterion is achieved by more than one relay. In this case, a relay is selected among this optimal set to transmit with equal probability. It is reasonable to assume that each relay is aware of its residual energy and the transmission power required to achieve target SNR at the destination. Since these strategies depend only on local REI and CSI at each relay, they can be implemented in a distributed manner by employing the so-called *opportunistic carrier sensing* method proposed in [7], [13]. Although both MRE and MEI meet well our intuition in preserving battery

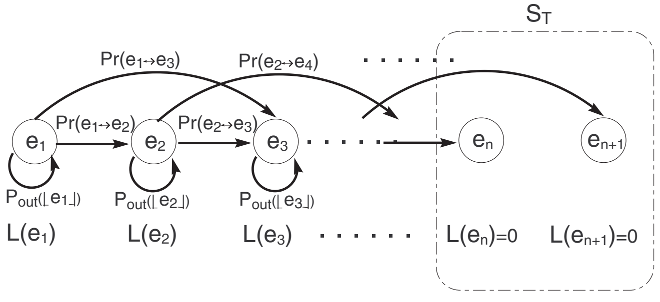

Fig. 2. The state transition diagram of an energy-consuming process.

energy, the latter actually achieves better performance. This is because, when $\sum_k e_k[1] \gg \mathcal{E}_w$, maximizing the average lifetime is approximately equivalent to minimizing the average transmission power. In fact, when the relays selected under the MRE and the MEI strategies differ, the relay selected by MEI always demands lower transmit power. To show this, let us assume that the two strategies select different relays, *i.e.*, $k^*_{MRE} \neq k^*_{MEI}$. By definition of the two strategies, the following inequalities must hold, *i.e.*, $e_{k^*_{MRE}} - w_{k^*_{MRE}} > e_{k^*_{MEI}} - w_{k^*_{MEI}}$ and $e_{k^*_{MRE}}/w_{k^*_{MRE}} < e_{k^*_{MEI}}/w_{k^*_{MEI}}$. It follows that $w_{k^*_{MEI}} < w_{k^*_{MRE}}$. Therefore, MEI is expected to have longer network lifetime than MRE when the initial energy is large. The asymptotic optimality of MEI have been studied in [13] for sensor network applications. The performance of these methods are evaluated in Sec. V by computer simulation.

IV. MARKOV ANALYSIS AND LIFETIME MAXIMIZATION VIA DYNAMIC PROGRAMMING

A. *Performance Analysis of the Proposed Strategies*

With a finite number of power levels, the set containing all possible values of residual energy $\mathbf{e}[m]$ will be finite. Moreover, since the energy consumed during each transmission depends only on the current REI and CSI, which is assumed to be *i.i.d.* in time, the evolution of the residual energy levels $\{\mathbf{e}[m]\}_{m=1}^{\infty}$ can be modeled as a finite-state Markov chain, as shown in Fig. 2, and the network lifetime can be derived by computing the average time to absorption to the non-operable energy states as detailed in the following.

The state space, $\mathcal{S}$, of the Markov chain is the set of all possible residual energy levels, *i.e.*, $\mathcal{S} = \{\mathbf{e} : e_k = e_k[1] - \sum_{l=1}^{L} \upsilon_l \varepsilon_l \geq 0, \forall \upsilon_l \in N \cup \{0\}, \forall k\}$, where $e_k[1]$ is the initial battery energy of the k-th relay. A state transition occurs after each transmission, with transition probabilities that depend on the current energy state and the joint relay-selection and power-allocation strategy. The set of non-operable energy states is defined as $\mathcal{S}_T = \{\mathbf{e} \in \mathcal{S} : P_{out}(\lfloor \mathbf{e} \rfloor) > \eta\}$.

Let $\mathbf{E}[\mathcal{L}(\mathbf{e})]$ be the average residual lifetime given that the current energy state is $\mathbf{e}$. By definition, we have $\mathbf{E}[\mathcal{L}(\mathbf{e})] = 0$ for $\mathbf{e} \in \mathcal{S}_T$. For a state $\mathbf{e} \notin \mathcal{S}_T$, the average residual lifetime is equal to the average number of transitions that occurs before entering a state in $\mathcal{S}_T$. Note that, when an outage occurs, no energy is consumed and a self-transition takes place for states $\mathbf{e} \notin \mathcal{S}_T$. When a transition occurs from $\mathbf{e} \notin \mathcal{S}_T$ to $\mathbf{e}'$, a unit time passes and the average residual lifetime becomes $\mathbf{E}[\mathcal{L}(\mathbf{e}')]$. The average residual lifetime of energy state $\mathbf{e} \notin \mathcal{S}_T$ is given by

$$\mathbf{E}[\mathcal{L}(\mathbf{e})] = \sum_{\mathbf{e}'} \Pr\{\mathbf{e} \to \mathbf{e}'\}(1 + \mathbf{E}[\mathcal{L}(\mathbf{e}')]), \tag{9}$$

where $\Pr\{\mathbf{e} \to \mathbf{e}'\}$ is the transition probability from $\mathbf{e}$ to $\mathbf{e}'$. Since the probability of self-transition at state $\mathbf{e}$ is equal to outage probability $P_{out}(\lfloor \mathbf{e} \rfloor)$, it follows from (9) that

$$\mathbf{E}[\mathcal{L}(\mathbf{e})] = \frac{1}{1 - P_{out}(\lfloor \mathbf{e} \rfloor)} \left(1 + \sum_{\mathbf{e}' \neq \mathbf{e}} \Pr\{\mathbf{e} \to \mathbf{e}'\} \mathbf{E}[\mathcal{L}(\mathbf{e}')]\right). \tag{10}$$

The average lifetime of a network with initial energy $\mathbf{e}[1]$ is $\mathbf{E}[\mathcal{L}(\mathbf{e}[1])]$, which can be evaluated recursively from the terminating states. The computational complexity of the recursive algorithm is $\mathcal{O}(N|\mathcal{S} \backslash \mathcal{S}_T|)$ since there are N possible transitions from each state. When the initial energy is the same for all users, *i.e.*, $e_k[1] = E_0$ for all k, and the energy levels are uniformly spaced, *i.e.*, $\varepsilon_i = i \times \frac{P_{max}}{L}$, the number of states is approximately equal to $\lfloor LE_0/P_{max} \rfloor^N$. Hence, the computational complexity is exponential to the number of relays. It is worthwhile to notice that, when the relay channels are *i.i.d.*, $\mathbf{E}[\mathcal{L}(\mathbf{e})]$ is invariant to the ordering of residual energies in the state vector $\mathbf{e}$. This property can be utilized to reduce the computational complexity when evaluating (10).

B. *Optimal Selection Strategy with Global CSI*

For a given set of power levels and initial battery energy, the optimal network lifetime can be computed using dynamic programming techniques [11]. Specifically, we construct a path for each state that goes through the maximum average number of transitions before entering a terminating state. The maximum average network lifetime is obtained by Bellman's equation as

$$\mathbf{E}[\mathcal{L}_{optimal}(\mathbf{e})] = \frac{1}{1 - P_{out}(\lfloor \mathbf{e} \rfloor)} \times \left(1 + \sum_{\{\mathbf{u} : \exists k, \mathrm{s}.t. 0 < u_k \leq e_k\}} \Pr\{\mathbf{w} = \mathbf{u}\} \cdot \max_{k \in \mathcal{R}_E} \mathbf{E}[\mathcal{L}_{optimal}(\mathbf{e} - u_k \mathbf{1}_k)]\right), \tag{11}$$

where $\mathbf{u} = (u_1, \cdots, u_N)$ is a set of discrete transmission powers with $u_k \in \{0, \varepsilon_1, \cdots, \varepsilon_L\}$. For a given set of power levels, the optimal network lifetime $\mathbf{E}[\mathcal{L}_{optimal}(\mathbf{e}[1])]$ is obtained backwards from terminating states. With global knowledge of REI and CSI at all relays, the strategy that maximizes the average network lifetime is given by

$$k^*_{optimal} = \arg \max_{k \in \mathcal{R}_E} \mathbf{E}[\mathcal{L}_{optimal}(\mathbf{e} - w_k \mathbf{1}_k)]. \tag{12}$$

Although this strategy maximizes the average network lifetime, it is difficult to implement in practice since it requires global CSI and REI, and that $\mathbf{E}[\mathcal{L}_{optimal}(\mathbf{e})]$ must be computed in advance. The computational complexity may be in the order of $\mathcal{O}(NL^N|\mathcal{S} \backslash \mathcal{S}_T|)$, as discussed in [11]. The performance of this strategy serves primarily as an upper bound to other schemes.

V. SIMULATION RESULTS

We compare the average network lifetime of the joint relay-selection and power-allocation strategies by computer simulation in this section. In the simulations, the transmit power of the source and the target SNR are chosen to be $P_S = 12$dB and $\gamma = 8$ dB, respectively. The threshold for the outage probability is $\eta = 0.1$. Channel coefficients h_{Sk} and h_{kD} are *i.i.d.* $\mathcal{CN}(0,1)$ and varies independently in each transmission.

First, we compare the average lifetime achieved by MTP, MRE, MEI and MOP along with the optimal strategy in (11) for a network with 3 relays. Suppose that the initial energy $e_k[1] = E_0$ for all k. In Fig. 3, we show the average lifetime in terms of initial energy E_0 for the case with continuous power levels, *i.e.,* $L = \infty$ (dash-dot), and the case with $L = 10$ (solid) and $L = 5$ (dashed) number of discrete power levels. We set $P_{max} = 82.25$ and the discrete power levels $\varepsilon_i = i \times \frac{P_{max}}{L}$. The average network lifetime for the discrete case is obtained via the Markov analysis described in Sec. IV and the continuous case (*i.e.,* $L = \infty$) is obtained with Monte-Carlo simulations over 25000 realizations. From (7), we know that the average network lifetime is a linear function of the total initial energy and the rate of increase with respect to the initial energy is determined by the average transmission power. As shown in Fig. 3, MEI and MOP have a faster increase in lifetime than MTP and MRE. This shows that, although MTP minimizes the energy consumption of each transmission, the MEI and MOP demands less average transmission power than MTP because a balanced usage of battery energy at the relays results in higher spatial diversity. Although MRE has a much lower amount of wasted energy, it does not perform as well as MEI and MOP since it tends to choose a node with higher transmission power. In the discrete case, we see that the MEI and MOP have comparable lifetime performance compared with the optimal strategy. Due to the quantization effect, discrete power allocation loses by approximately 22% and 39% for $L = 10$ and $L = 5$, respectively.

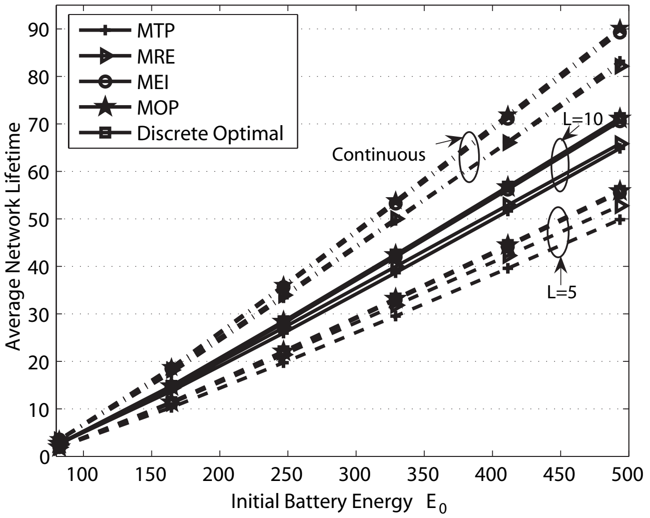

Fig. 3. The average lifetime of MTP, MRE, MEI and MOP strategies and the maximal lifetime derived in (11) for a 3-relay network with continuous transmit power (dash-dot) and discrete transmit power with $L = 5$(dash) and $L = 10$(solid).

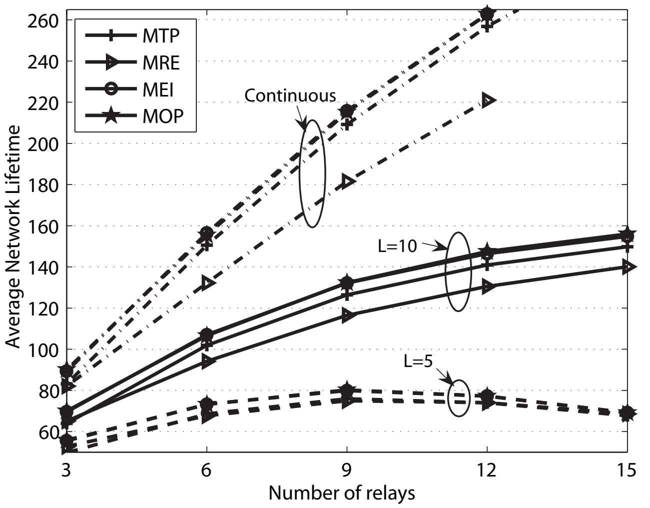

Fig. 4. The average lifetime versus the number of relays (N) for a cooperative network given fixed sum of the initial energy at relays, *i.e.,* $NE_0 = 18P_{max}$.

In Fig. 4, we compare the average lifetime of the four strategies for a cooperative network with different number of relays N. The sum of initial battery energy at all relays is fixed $NE_0 = 18P_{max}$, which is equally distributed among all relays. In Fig. 4, all curves are obtained with Monte Carlo simulations averaged over 20000 runs. As the number of relays increases, the average transmission power decreases because of spatial diversity. When N is small, the network lifetime increases with N although the initial energy at each relay is reduced. When N is sufficiently large such that the initial energy E_0 becomes comparable to the average transmission power, the network lifetime begins to decrease with N. This is shown in Fig. 4 for $L = 5$. However, this is observed for other cases as well at larger values of N. Although MRE performs slightly better than MTP when $N = 3$ (as shown in Fig. 3 for $L = 5$ and 10), the performance degrades rapidly as N increases. This is in contrast to that observed in [13], where lifetime is defined as the time duration during which a certain number of sensors remain active. Indeed, in MRE, the relay with the maximum residual energy is chosen and, thus, reduces the probability that a relay dies out after each transmission. Therefore, MRE outperforms MTP in [13]. However, by defining the network lifetime with the outage probability constraint, having a certain number of relays become inactive does not necessarily cause the system outage probability to exceed the required value. In fact, as shown in our simulations, minimizing the transmit power may be more beneficial than balancing the residual energy at each node. Furthermore, we can see that the MOP performs better than the other strategies in all cases (*i.e.,* for different number of relays or initial energies). Similar performance has been observed for the case with non-identical channel statistics. Interested users are referred to [16] for further detail.

In Fig. 5, we compare the average outage probability of the four strategies with respect to the number of time slots. We consider a network with $N = 12$, continuous transmission power (*i.e.,* $L = \infty$), and small initial energy at relays,

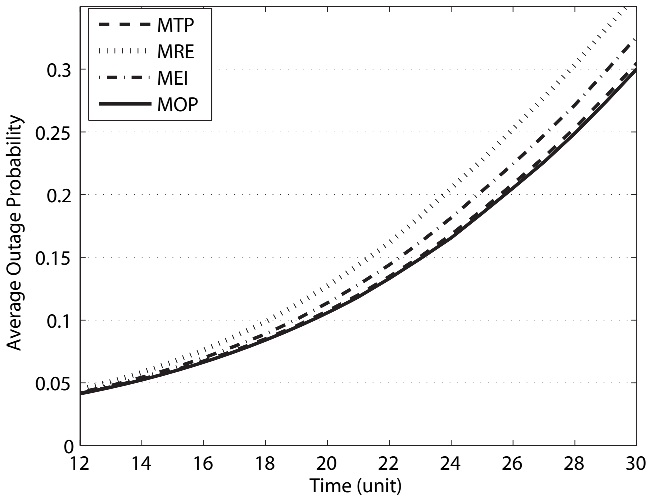

Fig. 5. The average outage probability versus time for a 12-relay cooperative network with small initial energy and $L = \infty$.

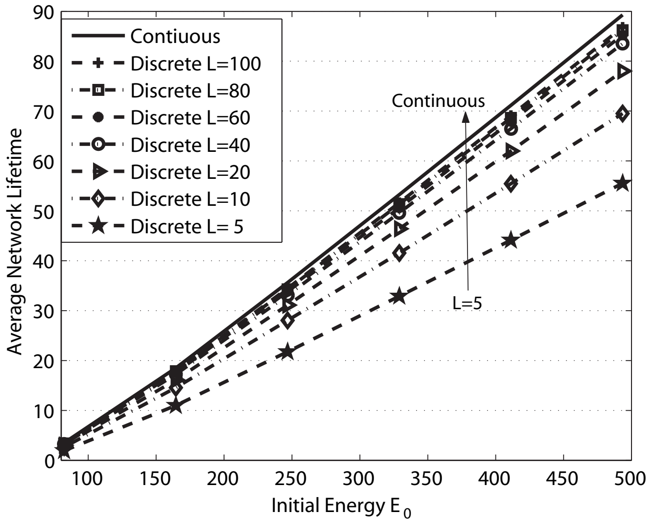

Fig. 6. Lifetime achieved with strategy MEI for different L for a three-relay cooperative network.

namely, $E_0 = 0.5P_{max}$. In this case, we show that the MTP outperforms both the MRE and the MEI strategies, which is to say that one should choose the relay that consumes the least transmission power when the residual energy at each relay is small. The MOP also outperforms MTP in this case. Finally, using the energy efficiency index as the selection criterion, we compare in Fig. 6 the lifetime of the continuous-power case and cases of discrete power levels with $L = 5, 10, 20, 40, 60, 80, 100$ for a network with 3 relays. The results are obtained with Monte Carlo simulations over 25000 realizations. As shown in Fig. 6, the loss of discrete power levels decreases rapidly as L increases from 5 to 40. A loss of roughly 7.5% is still observed for $L = 40$. However, increasing the power level after this point does not provide significant improvement. Thus, with a suitable number of power levels, the design of a good selection strategy is actually more important than increasing the power levels with complex hardware.

VI. CONCLUSION

Based on selective relaying, three lifetime maximization strategies that take into consideration both CSI and REI, *i.e.,* strategies MRE, MEI and MOP, were proposed and compared in this work. For the system with a discrete power level, the average network lifetime of the proposed strategies were derived using Markov chain analysis and the optimal strategy was obtained via dynamic programming. The MEI and MOP were shown to achieve near optimal performance with significantly lower complexity.

REFERENCES

[1] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity–part I: system description," and "User cooperation diversity–part II: implementation aspects and performance analysis," *IEEE Trans. Commun.*, vol. 51, no. 11, Nov. 2003.

[2] J. Laneman, D. Tse, and G. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inform. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[3] A. Scaglione and Y.-W. Hong, "Opportunistic large arrays: cooperative transmission in wireless multi-hop ad hoc networks for the reach back channel," *IEEE Trans. Signal Processing*, vol. 51, no. 8, pp. 2082–2092, Aug. 2003.

[4] M. Abdallah and H. C. Papadopoulos, "Beamforming algorithms for decode-and-forward relaying in wireless networks," in *Proc. the Conference on Information Sciences and Systems (CISS) 2005.*

[5] J. Laneman and G. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Trans. Inform. Theory*, vol. 49, no. 10, pp. 2415–2425, Oct. 2003.

[6] Y. Zhao, R. Adve, and T. Lim, "Improving amplify-and-forward relay networks: optimal power allocation versus selection," in *Proc. IEEE International Symposium on Information Theory (ISIT) 2006.*

[7] A. Bletsas, A. Khisti, D. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Select. Areas Commun.*, vol. 24, no. 3, pp. 659–672, Mar. 2006.

[8] Y.-W. Hong, W.-J. Huang, F.-H. Chiu, and C.-C. J. Kuo, "Cooperative communications in resource-constrained wireless networks," in *IEEE Signal Processing Mag.*, vol. 24, no. 3, pp. 47–57, May 2007.

[9] J.-H. Chang and L. Tassiulas, "Routing for maximum system lifetime in wireless ad-hoc networks,“ in *Proc. 37th Annual Allerton Conf. on Communication, Control, and Computing*, vol. 1, pp. 22–31, Sept. 1999.

[10] Y. Chen and Q. Zhao, "Maximizing the lifetime of sensor network using local information on channel state and residual energy," in *Proc. Conference on Information Science and Systems (CISS) 2005.*

[11] Y. Chen, Q. Zhao, V. Krishnamurthy, and D. Djonin, "Transmission scheduling for optimizing sensor network lifetime: a stochastic shortest path approach," *IEEE Trans. Signal Processing*, vol. 55, no. 5, pp. 2294–2309, May 2007.

[12] Q. Zhao, L. Tong, and Y. Chen, "Energy-aware data-centric MAC for application-specific sensor networks," in *Proc. IEEE Workshop on Statistical Signal Processing*, July 2005.

[13] Y. Chen and Q. Zhao, "An integreated approach to energy-aware medium access for wireless sensor network," *IEEE Trans. Signal Processing*, vol. 55, no. 7, pp. 3429–3444, July 2007.

[14] V. Emamian, P. Anghel, and M. Kaveh, "Multi-user spatial diversity in a shadow-fading environment," in *Proc. IEEE Vehi. Tech. Conf.*(VTC), Fall 2002.

[15] W.-J. Huang, Y.-W. Hong, and C.-C. Jay Kuo, "Lifetime maximization for amplify-and-forward cooperative networks," in *Proc. IEEE Wireless Communications and Networking Conference(WCNC) 2007.*

[16] W.-J. Huang, Y.-W. Hong, and C.-C. Jay Kuo, "Discrete power allocation for lifetime maximization in cooperative networks," in *Proc. IEEE Vehicular Technology Conference*(VTC), Fall 2007.