Discrete Power Allocation for Lifetime Maximization in Cooperative Networks

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***Abstract*— Discrete power allocation strategies for amplify-and-forward cooperative networks are proposed based on selective relaying methods. The goal of power allocation is to maximize the network lifetime, which is defined as the duration of time for which the outage probability at the destination can be maintained above a certain level. The discrete power levels enable a low cost implementation and a close integration with high speed digital circuits. We propose three power allocation strategies that take into consideration both the channel state information (CSI) and the residual energy information (REI) at each node. By modeling the residual energy of each node as the states of a Markov Chain, we are able to derive the network lifetime analytically by computing the expected number of transitions to the absorbing states, *i.e.,* the energy states for which the outage probability is no longer achievable. The performance of the three strategies are compared through numerical simulations and a significant improvement in network lifetime is shown, when compared with the case considering only the local CSI.**

I. Introduction

Cooperative communications has been proposed in [1]–[4] to achieve spatial diversity gains in the wireless network without requiring multiple antennas at each user. This method allows the users in a network to cooperate in relaying each other's messages to the destination. The cooperative relays form a distributed antenna array for the source to provide multiple diversity paths towards the destination. The concept of cooperative communications is particularly important in energy-constrained wireless systems, such as that of sensor networks, since the cooperation among users allow us to efficiently distribute the traffic load based on the channel quality of each user and, thus, reduce the total energy consumption. In fact, many power allocation strategies have been proposed based on different cooperation strategies [4], such as amplify-and-forward or decode-and-forward [2].

Due to the simplicity and ease of implementation, we study, in this paper, the case of selective relaying with amplify-and-forward (AF) operations at each node. Interestingly, it has been shown in [5] that selective relaying is optimal in terms of minimizing the total instantaneous transmission power in the AF cooperative network with distributed space-time codes [6]. In other words, the optimal power control policy in this case should allocate power only to the node with the best channel. The selective relaying scheme, also referred to as opportunistic relaying, is also known to achieve full diversity [7]. Since the implementation of selective relaying demands only local channel state information (CSI) at relays, it can be conducted in a distributed manner with the method described in [8].

The underlying goal of power allocation is to extend the duration for which the network remain functional, *i.e.,* the network lifetime. However, minimizing the transmission power based only on the CSI, as done in most cases [4], does not necessarily maximize the network lifetime, especially in cooperative networks. In fact, several lifetime maximization strategies have been proposed [5], [9]–[11] that take into consideration both the CSI and the residual energy information (REI) of each user. Most of these work define the network lifetime as the duration for which all nodes remain active [9], [10]. In other words, the network is dead if at least one node is depleted with battery energy. In cooperative networks, the task is achieved with the cooperation among multiple users and the death of any particular node does not govern the operability of the system. Thus, we consider the network lifetime as the duration for which the outage probability is maintained above a certain level at the destination [5]. This depends on the cooperative effort of multiple users and cannot be measured with the life-and-death of any particular user.

To integrate these strategies in low cost and high speed digital circuits, we analyze the achievable network lifetime when only a finite set of power levels are available at each user and the maximal transmit power is constrained by the linear operating range of the power amplifier. Similar to [5], three power allocation strategies are proposed and analyzed by considering both the CSI and the REI. In contrast to [5] where no constraints are given to the adjustable power levels, we analyze the network lifetime where only finite power levels are used at each node. The problem is formulated as a discrete time Markov Chain and the optimal power allocation strategy is obtained by solving the well-known stochastic shortest-path problem [10] using dynamic programming. We show that the selection strategies that consider both CSI and REI extend the network lifetime considerably, which is especially true when the number of power levels is small.

II. System Model

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

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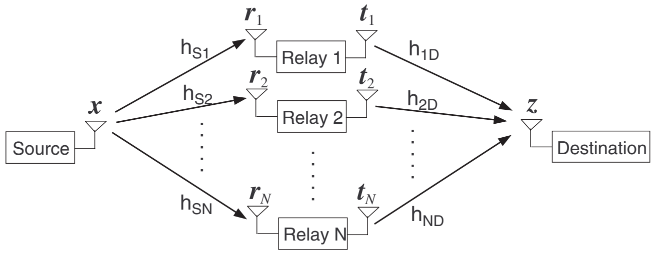

Fig. 1. The system model.

N users serve as cooperative partners that relay the message to the destination as shown in Fig. 1. 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 signal x with variance $\mathbf{E}|x|^2 = 1$ to the relay nodes. The received signal at the i-th relay is

$$r_i = \sqrt{P_S} h_{Si} x + v_i, \quad i = 1, 2, \ldots, N, \tag{1}$$

where h_{Si} is the channel coefficient from the source to the i-th relay node, v_i is *i.i.d.* additive white Gaussian noise (AWGN) at the i-th relay with unit variance, and P_S is the transmit power of the source. The channel coefficients h_{Si}, $1 \leq i \leq N$, are independent complex and circularly symmetric Gaussian random variables; namely, $h_{Si} \sim \mathcal{C}N(0, \sigma_{Si}^2)$.

Let us consider the selective cooperation method using AF schemes at the relays [5]. If the k-th relay node is selected, it forwards the signal with power P_k in the second phase. The signal received at the destination is

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

where $h_{kD} \sim \mathcal{C}N(0, \sigma_{kD}^2)$ is the channel coefficient from relay k to the destination and w is AWGN with unit variance. Let $\{h_{Si}, \forall i\}$ and $\{h_{jD}, \forall j\}$ be independent random variables. Assume the amplitude of local channel gains are known at each relay, *i.e.,* $|h_{Sk}|$ and $|h_{kD}|$ are known at the k-th relay, and the global CSI is known at the destination.

If the power allocated to the selected relay node is continuous, the transmit power for the selected relay to achieve a target SNR γ is found to be [5]

$$P_{k,c} = \begin{cases} \frac{\gamma}{|h_{kD}|^2} \frac{P_S |h_{Sk}|^2 + 1}{P_S |h_{Sk}|^2 - \gamma}, & P_S |h_{Sk}|^2 \geq \gamma; \\ 0, & P_S |h_{Sk}|^2 < \gamma. \end{cases} \tag{2}$$

Note that when the S-k link is extremely noisy, to the point where $P_S |h_{Sk}|^2 < \gamma$, no power is allocated to the k-th relay since the re-transmitted signal cannot achieve the target SNR at the destination.

Let us consider a maximum power level $\varepsilon_{\max}$ at the relays. The maximum power level must achieve an outage probability at the destination that is sufficiently lower than the system requirement. Without loss of generality, assume that each transmission lasts for one time unit and the transmission power is equal to the amount of energy consumed during the interval. Let e_k be the residual battery energy at sensor k and let $\mathbf{e} = (e_1, e_2, \cdots, e_N)$. We say that a relay, say relay k, is not able to transmit successfully if the allocated transmit power is zero or exceeds the remaining energy e_k or the maximal power constraint $\varepsilon_{\max}$, *i.e.,* when $P_{k,c} > \min(e_k, \varepsilon_{\max})$. If no user is able to relay the message at a particular time, a network outage is recorded. The probability of outage is given by

$$\begin{aligned} P_{out,c}(\mathbf{e}) &= \prod_{k=1}^{N} P_{out,c}(e_k) \\ &= \prod_{k=1}^{N} Pr\{P_{k,c} = 0\} + Pr\{P_{k,c} > \min(e_k, \varepsilon_{\max})\} \\ &= \prod_{k=1}^{N} 1 - F_k\left(\min(e_k, \varepsilon_{\max})\right), \end{aligned} \tag{3}$$

where

$$F_k(u) = e^{-\left(\frac{\gamma}{P_S \sigma_{Sk}^2} + \frac{\gamma}{u \sigma_{kD}^2}\right)} \sqrt{\frac{4\gamma(\gamma+1)}{P_S u \sigma_{Sk}^2 \sigma_{kD}^2}} K_1\left(\sqrt{\frac{4\gamma(\gamma+1)}{P_S u \sigma_{Sk}^2 \sigma_{kD}^2}}\right). \tag{4}$$

is the distribution function of $P_{k,c}$ and $K_1(\cdot)$ is the modified Bessel function of the second kind of order one.

III. Discrete Power Allocation Strategies

For most low-cost wireless devices, the signal can only be transmitted at finite power levels due to hardware limitation. Consider a discrete power allocation with L power levels $0 < \varepsilon_1 < \varepsilon_2 < \cdots < \varepsilon_L \leq \varepsilon_{\max}$. If the k-th relay is selected, the minimal power level to achieve the target SNR γ is

$$P_{k,d} = \begin{cases} \varepsilon_i, & P_{k,c} \in (\varepsilon_{i-1}, \varepsilon_i], \forall 1 \leq i \leq L, \\ 0, & \text{otherwise}, \end{cases} \tag{5}$$

where ε_0 is zero and $\varepsilon_L = \varepsilon_{\max}$. The discrete power allocation given in (5) is equivalent to the quantization of the continuous allocated power. We note that the discrete power allocation consumes more energy in each transmissions due to the quantization effect. The outage probability of selective relaying with discrete transmit power is given by,

$$P_{out,d}(\mathbf{e}) = \prod_{k=1}^{N} 1 - F_k(\lfloor e_k \rfloor), \tag{6}$$

where $\lfloor e_k \rfloor$ is the maximal transmit power of k-th relay under the residual energy constraint, *i.e.,* $\lfloor e_k \rfloor = \max\{\varepsilon_i : \varepsilon_i \leq e_k, i = 1, 2, \cdots, L\}$.

Suppose that the outage probability η is desired at the destination. In order to achieve η when the residual energy is sufficient, we must have ε_L that satisfies

$$\prod_{k=1}^{N} 1 - F_k(\varepsilon_L) < \eta. \tag{7}$$

We say that the network is dead if the residual energy $\mathbf{e}$ results in $P_{out,d}(\mathbf{e}) > \eta$. The *network lifetime* is defined as the number of cooperative transmissions for which the outage probability is maintained above the value η.

To maximize the network lifetime, the selection of a relay node needs to minimize the averaged transmit power and balance the use of battery energy at different relays. Therefore, both the CSI and the REI must be taken into consideration when designing the power allocation strategies. In this work, we compare the lifetime of the power allocation strategies over a finite set of power levels based on the concept of selective relaying. Specifically, define the set of eligible relays as $\mathcal{R}_E = \{k : e_k \geq P_{k,d} > 0\}$. A relay is included in the set $\mathcal{R}_E$ if the source-relay channel is sufficiently reliable and the relay has sufficient battery energy remaining to achieve the target SNR. The best relay node is selected from subset $\mathcal{R}_E$ using the following three selection strategies.

(I) **Minimal transmit power(MTP):** Choose the node with the minimal transmit power,

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

(II) **Maximal energy-efficiency index (MEI):** Define the energy efficiency index [11] of the k-th relay as the ratio of e_k to $P_{k,d}$ and select the relay with the maximal index, *i.e.,*

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

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

(III) **Minimal outage probability(MOP):** In this scheme, we select the node with the smallest outage probability after it is chosen to transmit. We apply the strategy to the case with the discrete power level by choosing

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

where $\mathbf{1}_k$ is an $N\times 1$ column vector whose k-th element is one and others are equal to zero and the maximal power constraint in equation (3) is assumed infinity to have a node selection at high residual energy.

When $\mathcal{R}_E$ is empty, no relay can achieve the target SNR with the discrete power levels. Therefore, the message will not be relayed and an outage is recorded. As long as the outage probability of the network satisfies the QoS requirement, the network remains active even when the instantaneous transmission fails. It is also possible that more than one relay can be chosen under a certain criterion since the allocated power is discrete. In this case, these relays will be selected at random with an equal probability. Interestingly, the three selection strategies demand only the local REI and CSI of respective relays and, therefore, can be implemented in a distributed manner by the contention-based method described in [8].

IV. Network Lifetime Analysis

Since the allocated power is discrete and the initial battery energy at the relays is finite, the set of all possible residual energy levels is discrete and finite. The evolution of the residual energy levels at all users can then be modeled as a finite-state Markov Chain and the network lifetime is, thus, derived through the analysis on the Markov Chain. In this section, we analyze the average network lifetime for the class of selective relaying strategies.

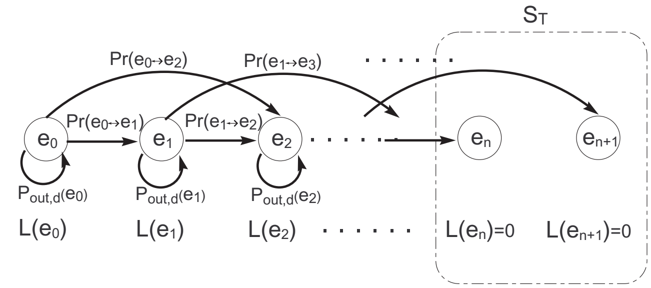

Fig. 2. The state transition diagram of an energy-consuming process.

The state space of the network, S, is defined as the set of all possible residual energy levels, *i.e.,*

$$\mathcal{S} = \{\mathbf{e} : e_k = E_{0,k} - \sum_{l=1}^{L} \upsilon_l \varepsilon_l \geq 0, \forall \upsilon_l \in \mathrm{N}, \forall k\}, \quad (9)$$

where $E_{0,k}$ is the initial battery energy of the k-th relay. After every transmission, a transition occurs among the energy states depending on the selection strategy used and the power level of the selected relay. The network is dead when the transition enters the state for which the outage probability is not achievable. Define S_T as the set of terminating states in which the QoS requirement of the network cannot be met, *i.e.,*

$$\mathcal{S}_T = \{\mathbf{e} : P_{out,d}(\mathbf{e}) > \eta\}. \quad (10)$$

The energy-consuming process of the network is a Markov chain, which can be represented by a state transition diagram as shown in Fig. 2 that consists of all states and the transition probabilities among each state. When an outage event occurs, no energy is consumed and a self-transition takes place for any non-terminating state $\mathbf{e} \notin \mathcal{S}_T$.

Let $\mathcal{L}(\mathbf{e})$ be the average network lifetime given that it is in the state $\mathbf{e}$. For $\mathbf{e} \in \mathcal{S}_T$, we have $\mathcal{L}(\mathbf{e}) = 0$ since $\mathcal{S}_T$ are the terminating states. For a given state $\mathbf{e} \notin \mathcal{S}_T$, the average network lifetime is equal to the average number of transitions from state $\mathbf{e}$ to any state in $\mathcal{S}_T$. When a transition occurs from $\mathbf{e}$ to $\mathbf{e}'$, a unit of time will pass and the average lifetime remaining is $\mathcal{L}(\mathbf{e}')$, therefore, $\mathcal{L}(\mathbf{e})$ is given as

$$\mathcal{L}(\mathbf{e}) = \sum_{\mathbf{0}\leq\mathbf{e}'\leq\mathbf{e}} \Pr\{\mathbf{e}\to\mathbf{e}'\}(1 + \mathcal{L}(\mathbf{e}')), \quad (11)$$

where $\Pr\{\mathbf{e}\to\mathbf{e}'\}$ is the transition probability from state $\mathbf{e}$ to state $\mathbf{e}'$. Here, we define vectors $\mathbf{u} \geq \mathbf{v}$ if $u_k \geq v_k, \forall k$, and define $\mathbf{u} > \mathbf{v}$ if $\mathbf{u} \geq \mathbf{v}$ and $\max_k\{u_k - v_k\} > 0$. Note that the self-transition of a state, say state $\mathbf{e}$, occurs with probability $P_{out,d}(\mathbf{e})$. The average network lifetime in (11) can be expressed as

$$\mathcal{L}(\mathbf{e}) = \frac{1}{1-P_{out,d}(\mathbf{e})}\left(1+\sum_{\mathbf{0}\le\mathbf{e}'<\mathbf{e}}\Pr(\mathbf{e}\to\mathbf{e}')\mathcal{L}(\mathbf{e}')\right). \tag{12}$$

Based on (12), the average lifetime of a network with its initial battery energy of relays $\mathbf{e}_0$ can be calculated recursively starting from the terminating state.

Since only one relay is selected at a time, the number of valid transitions of each state is at most L. For $\mathbf{e} > \mathbf{e}' \geq \mathbf{0}$, the transition probability of state $\mathbf{e}$ to $\mathbf{e}'$ is non-zero only if

$$\mathbf{e}-\mathbf{e}' = \varepsilon_j \mathbf{1}_k, \quad \forall 1 \le k \le N, 1 \le j \le L.$$

The probability of a valid transition is determined by the selection strategy and the probability mass function (PMF) of the discrete power levels. The transition probability for the strategies proposed in Section III are given as follows.

For MTP strategy, the k-th relay node is selected to transmit with power ε_j only if the transmit power levels required at the other eligible relays are no less than ε_j. If more than one eligible relay require the same minimal power ε_j, those nodes are selected randomly with an equal probability. For a valid transition from $\mathbf{e}$ to $\mathbf{e}'$ and $\mathbf{e}-\mathbf{e}' = \varepsilon_j\mathbf{1}_k$, the transition probability is

$$\Pr{}^{(I)}(\mathbf{e}\to\mathbf{e}') = \Pr(P_{k,d}=\varepsilon_j)\left[\prod_{m\neq k}\Pr(P_{m,d}>\varepsilon_j \text{ or } m\notin\mathcal{R}_E)\right.$$
$$\left.+\frac{1}{2}\sum_{\substack{n\neq k:\\ e_n\ge\varepsilon_j}}\Pr(P_{n,d}=\varepsilon_j)\prod_{m\neq k,n}\Pr(P_{m,d}>\varepsilon_j \text{ or } m\notin\mathcal{R}_E)+\cdots\right].$$

For MEI strategy, the k-th relay node is selected to transmit with power ε_j only if the energy efficiency indices of other eligible relays are not larger than e_k/ε_j. For a valid transition from $\mathbf{e}$ to $\mathbf{e}'$ and $\mathbf{e}-\mathbf{e}' = \varepsilon_j\mathbf{1}_k$, the transition probability is given by

$$\Pr{}^{(II)}(\mathbf{e}\to\mathbf{e}') = \Pr(P_{k,d}=\varepsilon_j)\left[\prod_{m\neq k}\Pr\left(\frac{e_m}{P_{m,d}}<\frac{e_k}{\varepsilon_j} \text{ or } P_{m,d}=0\right)\right.$$
$$\left.+\frac{1}{2}\sum_{n\neq k}\Pr\left(\frac{e_n}{P_{n,d}}=\frac{e_k}{\varepsilon_j}\right)\prod_{m\neq k,n}\Pr\left(\frac{e_m}{P_{m,d}}<\frac{e_k}{\varepsilon_j} \text{ or } P_{m,d}=0\right)+\cdots\right].$$

For MOP Strategy, the k-th relay node is selected to transmit with power ε_j only if the ratio of $P_{out,c}(e_m - P_{m,d})$ to $P_{out,c}(e_m)$ of any other eligible relay m is not less than $P_{out,c}(e_k-\varepsilon_j)/P_{out,c}(e_k)$. For a valid transition from $\mathbf{e}$ to $\mathbf{e}'$ and $\mathbf{e}-\mathbf{e}' = \varepsilon_j\mathbf{1}_k$, the transition probability is

$$\Pr{}^{(III)}(\mathbf{e}\to\mathbf{e}') = \Pr(P_{k,d}=\varepsilon_j)$$
$$\times\left[\prod_{m\neq k}\Pr\left(\frac{P_{out,c}(e_m-P_{m,d})}{P_{out}(e_m)}>\frac{P_{out,c}(e_k-\varepsilon_j)}{P_{out,c}(e_k)} \text{ or } m\notin\mathcal{R}_E\right)\right.$$
$$+\frac{1}{2}\sum_{n\neq k}\Pr\left(\frac{P_{out,c}(e_n-P_{n,d})}{P_{out,c}(e_n)}=\frac{P_{out,c}(e_k-\varepsilon_j)}{P_{out,c}(e_k)}\right)$$
$$\left.\times\prod_{m\neq k,n}\Pr\left(\frac{P_{out,c}(e_m-P_{m,d})}{P_{out,c}(e_m)}>\frac{P_{out,c}(e_k-\varepsilon_j)}{P_{out,c}(e_k)} \text{ or } m\notin\mathcal{R}_E\right)+\cdots\right].$$

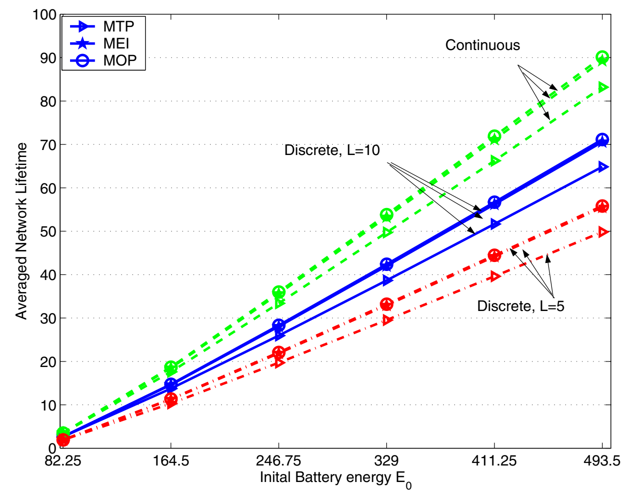

Fig. 3. Averaged network lifetime of MTP, MEI and MOP Strategies.

V. Numerical Simulations and Discussion

We compare the average lifetime of a cooperative network with three relays for different power allocation schemes. In the experiment, we set the transmit power of the source to $P_S = 12$dB and the value of target SNR is $\gamma = 8$ dB. The desired outage probability at the destination is set as $\eta = 0.1$. The channel coefficients h_{Sk} and h_{kD} are complex Gaussian distributed with unit variance and are *i.i.d.* over the sensor index k and over time.

In Fig. 3, we show the average lifetime of the three power allocation strategies, *i.e.,* MTP, MEI and MOP, for the case with continuous power levels (dashed line), the case of discrete power levels with $L = 10$ (solid) and with $L = 5$ (dash-dot). The power levels for the discrete case are set as $\varepsilon_i = i \times \frac{\varepsilon_{\max}}{L}$ with $\varepsilon_{\max} = 82.25$. The lines marked by triangles, stars and circles indicate the cases with MTP, MEI and MOP strategies, respectively. The average network lifetime for the discrete case is obtained from the recursive Markov Chain analysis described in Sec. IV while it is obtained through Monte-Carlo simulations for the case with continuous power levels. The average network lifetime increases linearly with the initial battery energy and the slopes of the lines are inversely proportional to the averaged transmit power according to the strong law of large numbers [5], [11]. As shown in Fig. 3, the discrete power allocation requires more transmit power and the average network lifetime increases by approximately 22% and 39% for the cases where $L = 10$ and $L = 5$, respectively, due to the quantization effect. Note that both the MEI and the MOP outperforms the MTP strategy, especially for the cases with discrete power allocation. Although MTP minimizes the energy consumed during each transmission, MEI and MOP consider a balanced use of the battery energy at the relays.

In Fig. 4, we compare lifetime for the MEI strategy of the continuous case and the cases of discrete power levels with $L = 5, 10, 20, 40, 60, 80, 100$. The parameters are the same as in the previous experiment but are obtained with Monte Carlo

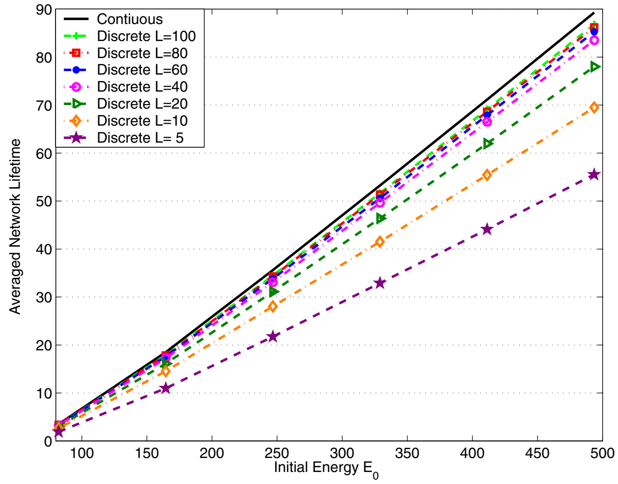

Fig. 4. Lifetime achieved with MEI strategy for different number of energy levels L.

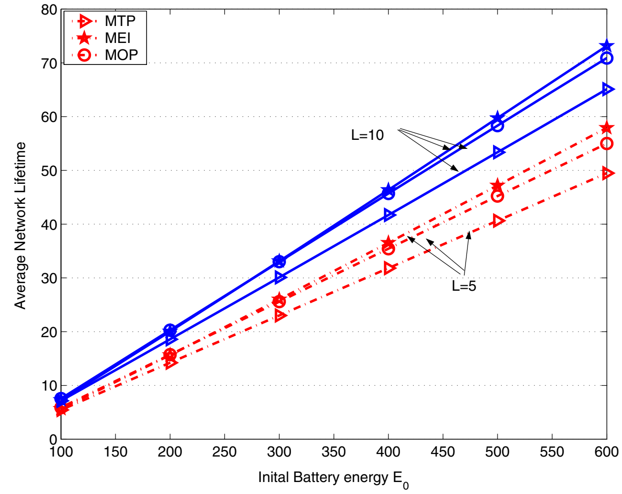

Fig. 5. Average lifetime of a network with non-identical channel statistics.

simulations. As shown in 4, the loss of using discrete power levels decreases rapidly as L increases when $L < 40$. Even though a loss of roughly 7.5% is still observed for $L = 40$, increasing the power level after this point does not provide a significant improvement over the lifetime. Therefore, with a reasonable number of power levels, the design of the selection strategy may be more important than increasing the power levels with complex hardware.

In Fig.5, we compare the average lifetime of a cooperative network where the three relays are at different distances to the destination. Specifically, let the source, the three relays and the destination be arranged in order on a line with equal distance, where the distance between source and destination d_{SD} is 2. The transmit power of the source is $P_S = 15$dB, and the value of target SNR and the desired outage probability are the same as Fig.3. The channel coefficients h_{Sk} and h_{kD} are independent complex Gaussian distributed with zero mean and variances d_{Sk}^{-2} and d_{kD}^{-2} respectively. In Fig. 5, we show the average lifetime of the three power allocation strategies for the case with discrete power levels with $L = 10$ (solid) and with $L = 5$ (dash-dot). Also, we set $\varepsilon_{\max} = 100$. When MTP is applied, the relay in the middle of the line is most likely to be chosen since it often achieves the target SNR with lower transmit power. In this case, the relay is more likely to run out of battery energy and, thus, reduces the network lifetime. On the other hand, the average lifetimes of MEI with L=5 and L=10 are respectively 12% and 16% longer than the lifetimes of MTP strategy. MOP does not perform the best since it minimizing outage probability step-by-step, which does not guarantee to minimize the outage performance globally. It shows that the MEI achieves the best balance between minimizing energy consumption and preserving residual energy when the channel statistics are not identical.

VI. Conclusion

Three selection relaying strategies under discrete power allocation were proposed to maximize the network lifetime. The averaged network lifetime for different selection strategies was analyzed and compared. The selection strategies that take both the CSI and the REI into account outperforms the strategy that considers the CSI alone.

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