Lifetime Maximization via Cooperative Nodes and Relay Deployment in Wireless Networks

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***Abstract*— Extending lifetime of battery-operated devices is a key design issue that allows uninterrupted information exchange among distributed nodes in wireless networks. Cooperative communications has recently emerged as a new communication paradigm that enables and leverages effective resource sharing among cooperative nodes. In this paper, a general framework for lifetime extension of battery-operated devices by exploiting cooperative diversity is proposed. The framework efficiently takes advantage of different locations and energy levels among distributed nodes. First, a lifetime maximization problem via cooperative nodes is considered and performance analysis for M-ary PSK modulation is provided. With an objective to maximize the minimum device lifetime under a constraint on bit-error-rate performance, the optimization problem determines which nodes should cooperate and how much power should be allocated for cooperation. Since the formulated problem is NP hard, a closed-form solution for a two-node network is derived to obtain some insights. Based on the two-node solution, a fast suboptimal algorithm is developed for multi-node scenarios. Moreover, the device lifetime is further improved by a deployment of cooperative relays in order to help forward information of the distributed nodes in the network. Optimum location and power allocation for each cooperative relay are determined with an aim to maximize the minimum device lifetime. A suboptimal algorithm is developed to solve the problem with multiple cooperative relays and cooperative nodes. Simulation results show that the minimum device lifetime of the network with cooperative nodes improves 2 times longer than the lifetime of the non-cooperative network. In addition, deploying a cooperative relay in a proper location leads up to 12 times longer lifetime than that of the non-cooperative network.**

***Index Terms*— Cooperative diversity, wireless networks, decode-and-forward protocol, lifetime maximization.**

I. INTRODUCTION

In many applications of wireless networks, extending lifetime of battery-operated devices is a key design issue that ensures uninterrupted information exchange and alleviates burden of replenishing batteries. Several approaches for lifetime extension of battery-limited devices have been proposed in the literature. In [1], a data routing algorithm was proposed with an aim to maximize the minimum lifetime among nodes in wireless sensor networks. Later, considerable research efforts have been devoted to maximize such minimum lifetime, which is also referred to as network lifetime. For example, upper bounds on lifetime of various wireless networks with energy-constrained nodes are derived in [2]-[4] and references therein. The problem of finding an energy-efficient tree for network lifetime maximization has been considered in [2], [5] for broadcasting scenario and in [6] for multicasting scenario. The works in [7]-[9] considered a problem of minimum-energy broadcasting, which is proved to be NP-complete. In [10], a technique for network lifetime maximization by employing accumulative broadcast strategy was considered. The proposed work relies on the assumption that nodes cooperatively accumulate energy of unreliable receptions over the relay channels. The work in [11] considered provisioning additional energy on existing nodes and deploying relays to extend the network lifetime.

Recently, cooperative diversity concept has been introduced as a promising alternative to combat fading in wireless relay channels. The basic idea of cooperative diversity is to allow distributed users in the network help relay information of each other so as to explore inherent spatial diversity which is available in the relay channels. Several cooperation protocols have been proposed, e.g. amplify-and-forward and decode-and-forward protocols [12], user cooperation protocol [13], [14], and coded cooperation protocol [15]. In [12]-[20], physical layer issues such as outage probability analysis and symbol error rate (SER) analysis for different cooperation systems were considered. The channel capacity of cooperative networks was investigated in [16], [17]. The outage probability of the coded cooperation protocol was analyzed in [18], while the exact SER analysis as well as optimum power allocation for the decode-and-forward protocol were provided in [19], [20]. Later, higher layer issues were considered in [21]-[22] to determine which nodes are appropriate for cooperation and how much power should be facilitated. The work in [23] considers a distributed relay selection scheme by which one relay out of multiple relays is selected for cooperation. The scheme requires limited network knowledge, and the relay selection strategy relies on instantaneous signal-to-noise ratio.

The research works in [12]-[23] have proved significant potential of using cooperative diversity in wireless networks. However, most of the existing works focus on improving physical layer performance or minimizing energy consumption. On the other hand, most of previous works on extending lifetime [1]-[11] concentrate on non-cooperative transmissions

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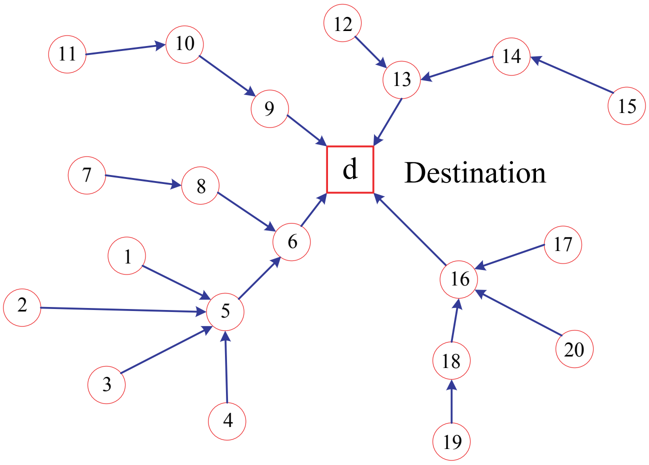

Fig. 1. An example of a wireless network with a destination (d) and N distributed nodes (N = 20).

in which received signals from a source and each relay are not combined to explore the cooperative diversity. Consider contemporary wireless networks which comprise heterogeneous devices such as mobile phones, laptop computers, personal digital assistants (PDAs), and etc. These devices have limited lifetime; nevertheless, some of them may have longer lifetimes due to their location or energy advantages. For instance, the devices in some ideal locations may have location advantage, while the other devices may have energy advantage if they are equipped with high initial energy. By introducing cooperation protocol among distributed nodes, a portion of energy from these devices can be allocated to help forward information of other energy depleting devices in the network. In this way, the lifetime of the energy depleting devices can be greatly improved, and hence, the minimum device lifetime of the network is increased.

In this paper, we propose to increase the device lifetime by exploiting the cooperative diversity and taking both location and energy advantages in wireless networks. The framework is based on the decode-and-forward (DF) cooperation protocol which is well suitable for wireless LAN or cellular settings; nevertheless, other cooperation protocols such as amplify-and-forward protocol can be used as well. We first describe a signal model for a non-cooperative network. Then, we present a signal model for a cooperative networks employing the DF protocol. After that, we formulate an optimization problem with an objective to maximize the minimum device lifetime under bit-error-rate (BER) constraint. The analysis based on M-ary phase shift keying (M-PSK) modulation is provided. We derive an analytical solution for a two-node cooperative network to obtain some insights on the formulated problem which is NP hard. Based on the two-node solution, we develop a fast suboptimal algorithm to reduce the complexity of the formulated problem. Furthermore, we propose to improve the device lifetime by deploying additional relays over a network with energy depleting nodes. We determine which locations to place the relays and how much power should these relays use for cooperation in order to maximize the device lifetime. To reduce complexity of the formulated problem, we also develop an efficient suboptimal algorithm which solves the problem using at most one relay per node. Simulation results are given to show the merit of the proposed work and support our theoretical analysis.

The rest of the paper is organized as follows. Section II outlines system models for a non-cooperative network and a cooperative network. In Section III, first we formulate an optimization problem to maximize the minimum device lifetime. Then, an analytical solution is provided for a two-node cooperative network. After that a suboptimal algorithm is developed for a multi-node scenario. In Section IV, we further improve the device lifetime by deploying relays in the network. Optimum relay locations and power allocations are determined based on the proposed algorithm. Simulation results and discussions are shown in Section V. Finally, Section VI concludes the paper.

II. System Models

Consider a wireless network with N randomly deployed nodes as shown in Figure 1. Each node knows its next node in a predetermined route by which its information can be delivered to the destination. The destination node can be a base station or an access point in wireless LANs, a piconet coordinator in wireless PANs, or a data gathering unit in wireless sensor networks. In this section, a system model of a non-cooperative network is described. Then, a system model of a cooperative network is considered.

A. Non-Cooperative Wireless Networks

In a non-cooperative wireless network, each source node only transmits its own information to the destination node through a predetermined route. Figure 1 shows an example of a wireless network with several randomly deployed nodes. Suppose there are N nodes in the network, and let x_j denotes a symbol to be transmitted from node j to its next node, defined as n_j, in its predetermined route. The symbol x_j can be the information of node j itself, or it can be the information of other nodes that node j routes through the destination. The received signal at n_j due to the transmitted information from node j can be expressed as

$$y_{jn_j} = \sqrt{P_j} h_{jn_j} x_j + w_{jn_j}, \tag{1}$$

where P_j is the transmit power of node j, h_{jn_j} is the fading coefficient from node j to n_j, and w_{jn_j} is an additive noise. The channel coefficient h_{jn_j} is modeled as a complex Gaussian random variable with zero mean and variance $\sigma^2_{jn_j}$, i.e., $\mathcal{CN}(0, \sigma^2_{jn_j})$, and w_{jn_j} is $\mathcal{CN}(0, N_0)$ distributed. The channel variance $\sigma^2_{jn_j}$ is modeled as

$$\sigma^2_{jn_j} = \eta D^{-\alpha}_{jn_j}, \tag{2}$$

where D_{jn_j} denotes distance between node j and n_j, α is the propagation loss factor, and η is a constant whose value depends on the propagation environment. Considering an uncoded system and using a BER formulation in [19], the average BER performance for a non-cooperative node with M-PSK modulation is upper bounded by

$$\text{BER}_j \le \frac{N_0}{4bP_j \sigma^2_{jn_j} \log_2 M}, \tag{3}$$

where $b = \sin^2(\pi/M)$.

Let the performance requirement of node j be $\text{BER}_j \leq \varepsilon$ in which ε represents the maximum allowable BER. We assume that ε is the same for every node. Accordingly, the optimum transmit power of a non-cooperative node is given by

$$P_j = \frac{N_0}{4b\varepsilon\sigma^2_{jn_j}\log_2 M}. \tag{4}$$

We denote E_j as an initial battery of node j, and denote P_s as an amount of processing power (i.e. power used for encoding information, collecting data, and etc.) at the source node. Let λ_{lj} ($l = 1, 2, \ldots, N$ and $l \neq j$) be the data rate that node l sends information to node j, and λ_j be a data rate that node j sends information to its next node n_j. Then, the total power that node j uses to send information to n_j is $\lambda_j P_s + \sum_{l=1}^{N} \lambda_{lj} P_j$, where $\lambda_j P_s$ is the total processing power at node j, $\lambda_j P_j$ represents the power that node j sends its own formation, and $\sum_{l=1, l\neq j}^{N} \lambda_{lj} P_j$ corresponds to the power that node j routes information of other nodes.

B. Cooperative Wireless Networks Employing DF Protocol

We consider a cooperative wireless network where all nodes can transmit information cooperatively. Each node can be a source node that transmits its information or it can be a relay node that helps forward information of other nodes. The cooperation strategy is based on the DF protocol which comprises two transmission phases. In Phase 1, the source node sends the information to its next node on the route. In Phase 2, the relay node decodes the information it receives from the source and helps forward the correctly decoded information. We assume that each signal transmission is constrained to half-duplex mode, the system is uncoded, and the source and the relay transmit signals through orthogonal channels by using existing TDMA, FDMA, or CDMA schemes.

For subsequent derivations, we define a power allocation matrix $\mathbf{P}$ as an $N \times N$ matrix with the following properties:

1) Each element $P_{ij} \geq 0$, for $i, j = 1, 2, \cdots, N$.
2) P_j represents a power that node j uses to transmit its own information to its next node n_j and the relays.
3) P_{ij} represents a power that node i helps forward information of node j (information of other nodes) to the next node n_j.

Assuming that all nodes have their information to be transmitted, then $P_j > 0$ for all j. Figure 2 (a) illustrates a cooperative network with $N = 4$ nodes. Each solid line represents a transmission link from a source node to its next node, and each dash line represents a link from a source to a relay. In addition, Figure 2 (b) shows a power allocation matrix $\mathbf{P}$ which corresponds to the cooperative network in Figure 2 (a). Each non-zero diagonal element of $\mathbf{P}$ represents a transmit power of a source node. In Figure 2 (a), node 1 helps relay information of node 2 and 3 to their intended destination. Therefore, P_{12} and P_{13} in the first row of $\mathbf{P}$ contains non-zero elements, they represent power that node 1 helps node 2 and node 3, respectively. Similarly, P_{41} is a non-zero element because node 4 helps forward information of node 1.

Suppose node j acts as a source (or a helped node) and node i acts as a relay (or a helping node). When node j sends information to n_j in Phase 1, the received signal at n_j is given

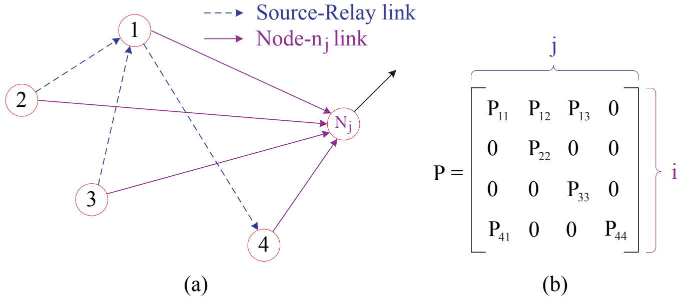

Fig. 2. Illustration of a cooperative wireless network: (a) a network with 4 nodes; (b) the corresponding power allocation matrix.

in (1). However, the received signal at the helping node i is given by

$$y_{ji} = \sqrt{P_j} h_{ji} x_j + w_{ji}, \tag{5}$$

where h_{ji} denotes a channel coefficient from node j to node i, and w_{ji} represents an additive noise. In Phase 2, the relay (node i in this case) forwards the information of node j to n_j only if the symbol is correctly decoded [19]. The received signal at n_j can be expressed as [19]

$$y_{in_j} = \sqrt{\tilde{P}_{ij}} h_{in_j} x_j + w_{in_j}, \tag{6}$$

where $\tilde{P}_{ij} = P_{ij}$ if the relay correctly decodes the symbol, and $\tilde{P}_{ij} = 0$ otherwise. In (6), h_{in_j} and w_{in_j} are modeled as $\mathcal{CN}(0, \sigma^2_{in_j})$ and $\mathcal{CN}(0, N_o)$, respectively. After that the destination (n_j in this case) combines the directly received signal from the source in Phase 1 and that from the relay in Phase 2 by the sue of the maximum ratio combining (MRC). Assuming that x_j has unit energy, then an instantaneous SNR at the MRC output of n_j is

$$\gamma_{n_j} = \frac{P_j |h_{jn_j}|^2 + \tilde{P}_{ij} |h_{in_j}|^2}{N_0}. \tag{7}$$

By taking into account the decoding result at the relay and averaging the conditional BER over the Rayleigh distributed random variables, the average BER in case of M-PSK modulation can be expressed as [19]

$$\begin{aligned} \text{BER}_j &= \frac{1}{\log_2 M} F\left(1 + \frac{bP_j\sigma^2_{jn_j}}{N_0 \sin^2\theta}\right) \cdot F\left(1 + \frac{bP_j\sigma^2_{ji}}{N_0 \sin^2\theta}\right) \\ &+ \frac{1}{\log_2 M} F\left(\left(1 + \frac{bP_j\sigma^2_{jn_j}}{N_0 \sin^2\theta}\right)\left(1 + \frac{bP_{ij}\sigma^2_{in_j}}{N_0 \sin^2\theta}\right)\right) \\ &\times \left[1 - F\left(1 + \frac{bP_j\sigma^2_{ji}}{N_0 \sin^2\theta}\right)\right], \end{aligned} \tag{8}$$

where $F(x(\theta)) = \frac{1}{\pi}\int_0^{(M-1)\pi/M} [x(\theta)]^{-1} d\theta$ and b is defined in (3). The first term on the right hand side of (8) corresponds to an incorrectly decoding at the relay whereas the second term corresponds to a correctly decoding at the relay. By assuming that all channel links are available, i.e., $\sigma^2_{jn_j} \neq 0$ and $\sigma^2_{ji} \neq 0$, the BER upper bound of (8) can be obtained by removing the negative term and all one's in (8), we have [19]

$$\text{BER}_j \leq \frac{N_0^2}{b^2 \log_2 M} \cdot \frac{A^2 P_{ij}\sigma^2_{in_j} + BP_j\sigma^2_{ji}}{P_j^2 P_{ij}\sigma^2_{jn_j}\sigma^2_{ji}\sigma^2_{in_j}}, \tag{9}$$

where $A \triangleq (M-1)/(2M) + \sin(2\pi/M)/(4\pi)$ and $B \triangleq 3(M-1)/(8M) + \sin(2\pi/M)/(4\pi) - \sin(4\pi/M)/(32\pi)$. We can see from (9) that cooperative transmission obtains a diversity order of two as indicated in the power of N_o. Hence, with cooperative diversity, the total power required at the source and the relay is less than that required for non-cooperative transmission in order to obtain the same BER performance. Therefore, by properly allocating the transmit power at the source (P_j) and the transmit power at the relay (P_{ij}), the lifetime of the source can be significantly increased whereas the lifetime of the relay is slightly decreased. Note that, for multi-hop relay networks, the signal model in [20] can also be applied to the proposed framework in a similar way. In addition, a practical way to perform symbol-by-symbol detection at the relay is to use a simple threshold test on the received signal as proposed in [12], [25], [26].

III. Lifetime Maximization by Cooperative Node Employment

In this section, we aim to maximize the minimum device lifetime among all cooperative nodes in the network. First, we formulate the lifetime maximization problem. Then, an analytical solution is provided for a network with two cooperative nodes. After that, based on the solution for the two-node network, a fast suboptimal algorithm is developed to solve a problem for a network with multiple cooperative nodes.

A. Problem Formulation

As shown in the previous section that the cooperative scheme requires less power to achieve the same performance as the non-cooperative scheme, and thus it can be used to improve the minimum device lifetime. Note that different nodes may have different remaining energy, and they may contribute to different performance improvement due to their different locations. So the nodes with energy or location advantages can help forward information of other energy depleting nodes. In what follows, we formulate an optimization problem to determine which node should be a helping node and how much power should be allocated in order to efficiently increase the minimum device lifetime.

Let us first determine the device lifetime in a non-cooperative network. From Section II-A, the non-cooperative device lifetime of node j is given by

$$T_j = \frac{\kappa\varepsilon\sigma_{jn_j}^2 E_j}{\left(\kappa\varepsilon\sigma_{jn_j}^2 \lambda_j P_s + N_0 \sum_{l=1}^N \lambda_{lj}\right)}, \tag{10}$$

where $\kappa \triangleq 4b\log_2 M$ and P_s represents a processing power. From (10), we can see that the lifetime of each node depends on its initial energy and its geographical location. Intuitively, the node whose energy is small and location is far away from its next node tends to have small device lifetime.

In case of a cooperative network, the overall transmit power of each node is a summation of the power that the node transmits its own information and the power that the node cooperatively helps forward information of other nodes. Let P_r be a processing power at each relay node, i.e., a power that the relay uses for decoding and forwarding information. From the power allocation matrix $\mathbf{P}$ in Section II-B, the overall transmit power of the cooperating node i is $P_i \sum_{l=1}^N \lambda_{li} + \sum_{j=1, j\neq i}^N P_{ij}(\sum_{l=1}^N \lambda_{lj})$, and the overall processing power of node i is $\lambda_i P_s + \sum_{j=1,j\neq i}^N P_r \mathrm{sgn}(P_{ij})(\sum_{l=1}^N \lambda_{lj})$ where $\mathrm{sgn}(P_{ij})$ represents the sign function that returns 1 if $P_{ij} > 0$, and 0 otherwise. Therefore, the lifetime of the cooperative node i can be written as

$$T_i(\mathbf{P}) = \frac{E_i}{\lambda_i P_s + P_i \sum_{l=1}^N \lambda_{li} + \Lambda(P_r, P_{ij}, \lambda_{lj})}, \tag{11}$$

where

$$\Lambda(P_r, P_{ij}, \lambda_{lj}) \triangleq \sum_{j=1,j\neq i}^N \left(P_r \mathrm{sgn}(P_{ij}) + P_{ij}\right)\left(\sum_{l=1}^N \lambda_{lj}\right),$$

and E_i is an initial energy of node i. Obviously, the lifetime of node i reduces if node i helps transmit information of other nodes. However, the more the power P_{ij} that node i helps forwarding information of node j, the longer the lifetime of node j. Therefore, it is crucial to properly design the power allocation matrix $\mathbf{P}$ such that the minimum device lifetime is maximized.

With an objective to maximize the minimum device lifetime under the BER constraint on each node, the optimization problem can be formulated as

$$\max_{\mathbf{P}} \min_i T_i(\mathbf{P}) \tag{12}$$

$$\text{s.t.} \begin{cases} \text{Performance: } \mathrm{BER}_i \leq \varepsilon,\ \forall i; \\ \text{Power: } 0 < P_i \leq P_{\max},\ \forall i; \\ \text{Power: } 0 \leq P_{ij} \leq P_{\max},\ \forall j \neq i, \end{cases}$$

where ε denotes a BER requirement. In (12), the first constraint is to satisfy the BER requirement as specified in (8), the second constraint guarantees that each node has information to be transmitted and the transmit power is no greater than $P_{\max}$, the third constraint ensures that all the allocated power is non-negative and no greater than $P_{\max}$. Due to its assignment and combinatorial nature, the formulated problem is NP hard [27]. Even though each source-destination route is already known, the proposed work needs to optimize the pairing between each source and its relay. This problem of choosing relay is an assignment problem.

B. Analytical Solution for a Two-Node Wireless Network

To get some insightful understanding on the formulated problem, we provide in this section a closed-form analytical solution at high SNR scenario for a network with two cooperative nodes ($N = 2$). Each node transmits its information directly to the destination d. In this two-node network, there are three possible transmission strategies, namely, 1) each node transmits non-cooperatively, 2) one node helps forward information of the other, and 3) both nodes help forward information of each other. In the sequel, we will maximize the minimum device lifetime for each strategy. Without loss of generality, we assume that a transmit power required for a non-cooperative transmission is less than $P_{\max}$.

1) Non-cooperative transmission among nodes: Based on the discussion in Section II-A, the optimum power allocation for non-cooperative case is $P_j = N_0/(\kappa\varepsilon\sigma_{jd}^2)$ for $j = 1, 2$, and $P_{ij} = 0$ for $i \neq j$. Using (10), the optimum device lifetime for this transmission strategy is given by

$$T^*_{non-coop} = \min\left[\frac{\kappa\varepsilon\sigma^2_{1d}E_1}{\lambda_{11}(\kappa\varepsilon\sigma^2_{1d}P_s+N_0)}, \frac{\kappa\varepsilon\sigma^2_{2d}E_2}{\lambda_{22}(\kappa\varepsilon\sigma^2_{2d}P_s+N_0)}\right]. \quad (13)$$

2) Cooperative transmission when one node helps the other node: Without loss of generality, we will provide a solution for a case that node i helps relay information of node j to the destination. In this case, the lifetimes of node i and node j are given by $T_i = E_i/(\lambda_i(P_s+P_i)+\lambda_j(P_r+P_{ij}))$ and $T_j = E_j/(\lambda_j(P_s+P_j))$, respectively. Hence, appropriately choosing P_i, P_{ij}, and P_j can improve the minimum device lifetime while maintaining a specified BER requirement.

In order for node i to satisfy the BER requirement ε, the optimum transmit power of node i is $P_i = N_0/(\kappa\varepsilon\sigma^2_{id})$. To determine P_j and P_{ij}, we first note that, according to the BER upper bound in (9), P_j and P_{ij} must satisfy

$$\frac{N_0^2A^2P_{ij}\sigma^2_{id}+N_0^2BP_j\sigma^2_{ji}}{b^2\log_2(M)P_j^2P_{ij}\sigma^2_{jd}\sigma^2_{ji}\sigma^2_i} = \varepsilon. \quad (14)$$

Then, we can express P_{ij} in term of P_j as

$$P_{ij} = \frac{P_j}{C_{ij}P_j^2 - D_{ij}} \triangleq f(P_j), \quad (15)$$

where $C_{ij} = (\varepsilon\sigma^2_{id}\sigma^2_{jd}b^2\log_2 M)/(BN_0^2)$ and $D_{ij} = (A^2\sigma^2_{id})/(B\sigma^2_{ji})$. With P_i and P_{ij}, we have

$$T_i = \frac{E_i}{\lambda_i(P_s+\frac{N_0}{\kappa\varepsilon\sigma^2_{id}})+\lambda_j(P_r+f(P_j))}, \quad (16)$$

which is a function of P_j. Therefore, the optimization problem (12) is simplified to

$$T^*_{i-helps-j} = \max_{P_j}\left[\min\left(\frac{E_i}{\lambda_i(P_s+\frac{N_0}{\kappa\varepsilon\sigma^2_{id}})+\lambda_j(P_r+f(P_j))}, \frac{E_j}{\lambda_j(P_s+P_j)}\right)\right]. \quad (17)$$

As an illustrated example, Figure 3 plots the lifetime T_i and T_j as functions of P_j for a specific set of parameters. For unconstraint optimization of (17), Figure 3 shows that the optimum power P_j in (17) is the one that results in $T_i = T_j$. Therefore, the optimum device lifetime in case that node i helps node j is

$$T^*_{i-helps-j} = \frac{E_i}{\lambda_i(P_s+\frac{N_0}{\kappa\varepsilon\sigma^2_{id}})+\lambda_j(P_r+f(P_j^*))} = \frac{E_j}{\lambda_j(P_s+P_j^*)}, \quad (18)$$

where P_j^* is the solution to $C_{ij}E_i\lambda_jP_j^3 + KC_{ij}P_j^2 - (D_{ij}\lambda_jE_i+\lambda_jE_j)P_j - \Upsilon D_{ij} = 0$ in which $\Upsilon = E_i\lambda_jP_s - E_j\lambda_iP_s - \lambda_jE_jP_r + (\lambda_iN_0E_j)/(\kappa\varepsilon\sigma^2_{id})$. Accordingly, we can find $P^*_{ij} = f(P^*_j)$ from (15).

If the resulting P^*_{ij} is not larger than $P_{\max}$, then (18) is the optimum device lifetime for this scenario. Otherwise, let $P^*_{ij} = P_{\max}$ and find P^*_j that satisfies the BER requirement (14). After some manipulations, we have

$$P_j^* = \frac{-Q_1+\sqrt{Q_1^2+Q_2Q_3P^2_{\max}}}{Q_2P_{\max}}, \quad (19)$$

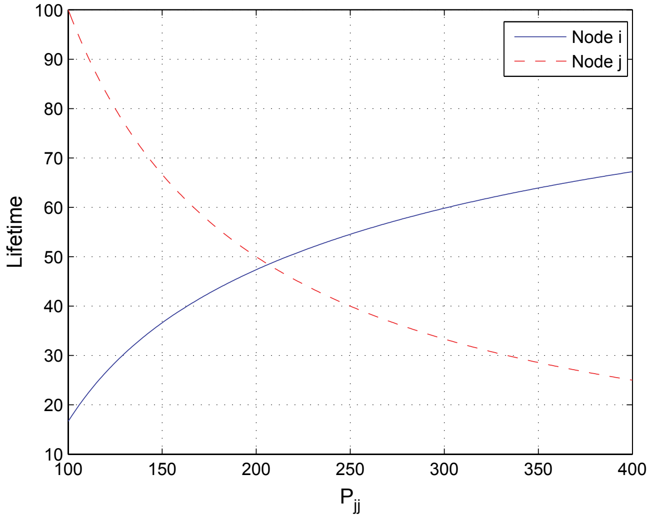

Fig. 3. Lifetimes of the two cooperative nodes as functions of the transmit power of the helped node (P_{22})

where $Q_1 = B\sigma^2_{ji}N_o^2/(b^2\log_2 M)$, $Q_2 = 2\varepsilon\sigma^2_{id}\sigma^2_{ji}\sigma^2_{jd}$, and $Q_3 = 2A^2\sigma^2_{id}N_o^2/(b^2\log_2 M)$. Therefore, the lifetime of node i and node j are $T_i^* = E_i/(\lambda_i(P_s+P_i)+\lambda_j(P_r+P_{\max}))$ and $T_j^* = E_j/(\lambda_j(P_s+P_j^*))$, respectively. Hence, the optimum device lifetime when $P^*_{ij} > P_{\max}$ is the minimum among T_i^* and T_j^*. As a result, the optimum device lifetime when node i helps node j can be summarized as follows:

$$T^*_{i-helps-j} = \begin{cases} \frac{E_j}{\lambda_j(P_s+P_j^*)}, & P^*_{ij} \le P_{\max}; \\ \min\{T_i^*, T_j^*\}, & T^*_{ij} > P_{\max}. \end{cases} \quad (20)$$

3) Cooperative transmission when both nodes help each other: Under this cooperation strategy, P_{ij} and T_i are given in (15) and (16), respectively. The optimum device lifetime in this case can be obtained by finding P_i^* and P_j^* that maximizes T_i (or T_j) under the condition: $T_i = T_j$, we have

$$T^*_{both\text{-}help} = \frac{E_i}{\lambda_i(P_s+P_i^*)+\lambda_j(P_r+\frac{P_j^*}{C_{ij}(P_j^*)^2-D_{ij}})} = \frac{E_j}{\lambda_j(P_s+P_j^*)+\lambda_i(P_r+\frac{P_i^*}{C_{ji}(P_i^*)^2-D_{ji}})}, \quad (21)$$

where P_i^* and P_j^* are the solutions to:

$$\arg\max_{P_i,P_j} \frac{E_i}{\lambda_{id}(P_s+P_i)+\lambda_{ji}(P_r+\frac{P_j}{C_{ij}P_j^2-D_{ij}})} \quad (22)$$

$$\text{s.t.} \begin{cases} \frac{[(\lambda_iP_s+\lambda_jP_r+\lambda_iP_i)(C_{ij}P_j^2-D_{ij})+\lambda_jP_j](C_{ji}P_i^2-D_{ji})}{[(\lambda_jP_s+\lambda_iP_r+\lambda_jP_j)(C_{ji}P_i^2-D_{ji})+\lambda_iP_i](C_{ij}P_j^2-D_{ij})} = \frac{E_i}{E_j}; \\ P_j > \sqrt{\frac{D_{ij}}{C_{ij}}}, \ \forall j \ne i, \end{cases}$$

in which, the first constraint ensures that $T_i = T_j$, and the second constraint guarantees that $P_{ij} = P_j/(C_{ij}P_j^2 - D_{ij}) > 0$.

If $P^*_{ij} \le P_{\max}$ and $P^*_{ji} \le P_{\max}$, then the solution to (21) is the optimum device lifetime for this transmission strategy. Otherwise, the optimization problem is separated into two subproblems. Firstly, we let $P^*_{ij} = P_{\max}$ and find P^*_j from (19). Then both T_i and T_j are functions of P_i. Therefore, the optimum device lifetime for this subproblem is to maximize

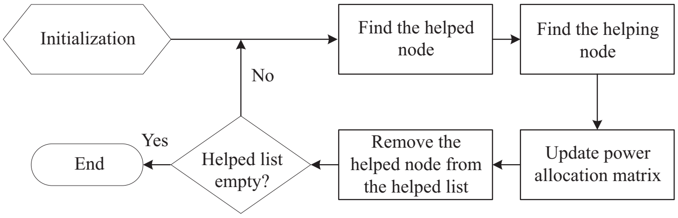

Fig. 4. A flowchart to illustrate the proposed suboptimal algorithm.

$\min\{T_i, T_j\}$ over P_i. Secondly, we let $P^*_{ji} = P_{\max}$ and find P^*_i from (19). In this case, T_i and T_j are functions of P_j. The optimum device lifetime for the second subproblem is to maximize $\min\{T_i, T_j\}$ over P_j. Finally, the optimum device lifetime when $P^*_{ij} > P_{\max}$ or $P^*_{ji} > P_{\max}$ is the maximum among these two solutions. Therefore, the optimum device lifetime when both nodes help each other can be summarized as follows:

$$T^*_{\textit{both-help}} = \begin{cases} \mathcal{T}_i, & P^*_{ij} \text{ and } P^*_{ji} \le P_{\max}, \\ \max\ (\mathcal{T}(ii), \mathcal{T}(jj)), & P^*_{ij} \text{ or } P^*_{ji} > P_{\max}, \end{cases} \tag{23}$$

where $\mathcal{T}_i \triangleq E_i/(\lambda_i(P_s + P^*_i) + \lambda_j(P_r + \frac{P^*_j}{C_{ij}(P^*_j)^2 - D_{ij}}))$,. In (23), we denote $\mathcal{T}(ii) \triangleq \max_{P_{ii}} \min\{T_i, T_j\}$, and $\mathcal{T}(jj) \triangleq \max_{P_{jj}} \min\{T_i, T_j\}$.

Finally the optimum device lifetime for the two-node cooperative network is

$$T^*_D = \max\left\{T^*_{non-coop}, T^*_{1-helps-2}, T^*_{2-helps-1}, T^*_{both-help}\right\}. \tag{24}$$

in which T^*_D is the maximum among lifetime of these four possible transmission strategies. Although the optimum solution can be obtained through full searching, it is computationally expensive for a large cooperative network. To reduce complexity of the problem, we propose in the subsequent subsection a suboptimal greedy algorithm to determine the power allocation and the corresponding device lifetime.

C. Suboptimal Algorithm for a Multi-Node Wireless Network

The basic idea of the greedy suboptimal algorithm is to find a node to be helped and a helping node step by step. In each step, the algorithm selects a node to be helped as the one with minimum lifetime and it has never been helped by others. Then, the algorithm chooses a helping node as the one that maximizes the minimum device lifetime after the helped node has been served. In this way, the minimum device lifetime can be increased step by step. The iteration stops when the device lifetime cannot be significantly improved or all cooperative nodes have been helped. A flowchart that summarizes the proposed algorithm is shown in Figure 4. Note that the proposed greedy suboptimal approach can be applied to any multi-node cooperation strategy.

In what follows, we first maximize the minimum device lifetime for a given pair of helped and helping nodes, and then we describe our proposed algorithm in details. For a given pair of helped and helping nodes, their transmit power and the corresponding lifetime can be determined in a similar way as those for the two-node network in the previous subsection. Specifically, consider a two-node cooperation strategy, then the optimum device lifetime when node i helps node j can be obtained by solving

$$T^*_{i-helps-j} = \max_{P_j}\Big[\min\Big(\frac{E_i}{\Psi_i + (P_r + f(P_j))\Sigma_{l=1}^N \lambda_{lj}}, \frac{E_j}{\Psi_j + P_j \Sigma_{l=1}^N \lambda_{lj}}\Big)\Big] \tag{25}$$

where

$$\Psi_i = \lambda_i P_s + P_i \Sigma_{l=1}^N \lambda_{li} + \Sigma_{k=1,\ k\neq i,j}^N\ (P_r \text{sgn}(P_{ik}) + P_{ik})(\Sigma_{l=1}^N \lambda_{lk}), \tag{26}$$

and

$$\Psi_j = \lambda_j P_s + \Sigma_{k=1,\ k\neq j}^N\ (P_r \text{sgn}(P_{jk}) + P_{jk})(\Sigma_{l=1}^N \lambda_{lk}), \tag{27}$$

in which Ψ_i and Ψ_j are constants that do not depend on P_j. Using the equality $T_i = T_j$ and after some manipulations, we can find that

$$T^*_{i-helps-j} = \frac{E_j}{\Psi_j + P^*_j \Sigma_{l=1}^N \lambda_{lj}}, \tag{28}$$

where P^*_j is the solution to

$$C_{ij} E_i \Sigma_{l=1}^N \lambda_{lj} P_j^3 + G C_{ij} P_j^2 - (D_{ij} E_i + E_j)(\Sigma_{l=1}^N \lambda_{lj}) P_j - G D_{ij} = 0, \tag{29}$$

in which $G \triangleq E_i \Psi_j - E_j \Psi_i - E_j P_r \Sigma_{l=1}^N \lambda_{lj}$. If the resulting $P^*_{ij} = f(P^*_j)$ is larger than $P_{\max}$ then the same calculation steps as in the previous subsection can be used to determine $T^*_{i-helps-j}$. This formulation is used to find the device lifetime at each step in the proposed algorithm.

Initially, the power allocation matrix $\mathbf{P}$ is assigned as a diagonal matrix with its diagonal component $P_j = N_0/(\kappa\varepsilon\sigma^2_{jd})$, i.e., the initial scheme is the non-cooperative transmission scheme. The corresponding lifetime of node j is $T_j = E_j/(\lambda_j P_s + P_j \Sigma_{l=1}^N \lambda_{lj})$. Construct a helped list which is a list of all possible nodes to be helped: $H_{list} = \{1, 2, \ldots, N\}$. First, the algorithm finds a helped node from the helped list by choosing the node who has minimum lifetime, i.e., the helped node $\hat{j}$ is given by

$$\hat{j} = \arg \min_{j \in H_{list}} T_j. \tag{30}$$

Second, the algorithm finds a node to help node $\hat{j}$ from all nodes i, $i = 1, 2, \ldots, N$ and $i \neq \hat{j}$. For each possible helping node i, the algorithm uses (25) to find power allocation for the helping node i and the helped node $\hat{j}$. Then, the algorithm determines $T^*_D(i)$ as the minimum lifetime among cooperative nodes after node i finishes helping node $\hat{j}$. The obtained $T^*_D(i)$ from all possible helping nodes are compared, and then the algorithm selects node $\hat{i} = \arg\max_i T^*_D(i)$ as the one who helps node $\hat{j}$. Next, the algorithm updates $\mathbf{P}$ and the helped list by removing node $\hat{j}$ from the helped list. Then, the algorithm goes back to the first step. The iteration continues until all nodes have been helped, i.e., the helped list is empty, or the device lifetime cannot be significantly increased. The resulting $\mathbf{P}$ is the optimum power allocation which gives answer to the questions: which node should help which node and how much power should be used for cooperation. The detailed algorithm is summarized in Table I.

TABLE I

SUBOPTIMAL ALGORITHM FOR MAXIMIZING THE MINIMUM DEVICE LIFETIME OF WIRELESS NETWORK WITH MULTIPLE COOPERATIVE NODES

Initialization: $P_j = N_0/(\kappa\varepsilon\sigma_{jd}^2)$, $T_j = E_j/\lambda_j(P_s + P_j)$, $T_D^* = \min T_j$, and $H_{list} = \{1, 2, \ldots, N\}$.
Iteration: 1) Select the helped node with the minimum lifetime from the helped list: $\hat{j} = \arg\min_{j \in H_{list}} T_j$, where $T_j = E_j/(\lambda_j P_s + P_j \sum_{l=1}^{N} \lambda_{lj})$. 2) Select the helping node from $\phi_{\hat{j}} = \{1, 2, \ldots, N\} - \{\hat{j}\}$. • For each $i \in \phi_{\hat{j}}$, solve (17) for T_i and $T_{\hat{j}}$, and then find the corresponding minimum device lifetime $T_D^*(i)$. • Select $\hat{i}$ that results in maximum of minimum device lifetime, $\hat{i} = \arg\max_{i \in \phi_{\hat{j}}} T_D^*(i)$, as the helping node. 3) Update power allocation matrix $\mathbf{P}$ and helped list H_{list}. Go to 1).
End If the helped list is empty: $H_{list} = \emptyset$, or the device lifetime cannot be significantly increased. return $\mathbf{P}$.

Note that the proposed algorithm is suboptimal. Eventhough the algorithm is based on a cooperation strategy with only one relay ($K = 1$), the proposed algorithm significantly improves the device lifetime and this will be confirmed by simulation results in Section V. In terms of complexity of the proposed algorithm, it only increases quadratically with the number of cooperative nodes. In addition, the minimum device lifetime can be further improved by a cooperation with more than one relay; nevertheless, such lifetime improvement trades off with higher complexity. Note also that all necessary computations can be performed offline. Once the algorithm is executed, each cooperative node follows the determined power allocation and cooperation strategy. Since the proposed algorithm allocates power based on the average channel realizations, the algorithm is updated only when the network topology considerably changes. Furthermore, additional overhead for the cooperation assignment is required only at the beginning of the transmission. In (25), It is obvious that the helped node and helping node should be close to each other. According to this observation, we can further reduce the complexity of the proposed algorithm by searching for a helping node among cooperative nodes that are in the vicinity of the helped node. In this way, only local information is needed to compute the power allocation matrix. Although this may leads to some performance degradations, we will show through computer simulations in Section V that such performance loss is insignificant.

IV. LIFETIME MAXIMIZATION BY COOPERATIVE RELAY DEPLOYMENT

In this section, we improve the device lifetime by exploiting cooperative diversity through a deployment of cooperative relays in an energy depleting network. Each of these relays does not have information to be transmitted; however, they help forward information of all energy depleting nodes. The relay deployment reduces the need of frequent battery changing for each node which in turn helps reduce maintenance cost. In addition, the relay deployment does not require any modification in the cooperative nodes. An additional implementation cost is installation cost of the relays. By using a proper number of cooperative relays and placing these relays in appropriate locations, the device lifetime can be greatly increased while the overall cost is minimized. In the sequel, we determine location of each cooperative relay in the network with an objective to maximize the minimum device lifetime.

We consider a wireless network with N randomly-located nodes, K cooperative relays, and a destination. The cooperative nodes are denoted as nodes $1, 2, \ldots, N$, and the cooperative relays are represented by $R_1, R_2, \ldots, R_K$. Since there is no cooperation among the cooperative nodes, the power allocation matrix $\mathbf{P}$ as defined in Section II-B is an $N \times N$ diagonal matrix whose diagonal element, P_j, represents a power that node j transmits information to its next node n_j. We assume that all cooperative nodes have information to be transmitted, i.e., $P_j > 0$ for all j. Hence, the lifetime of node j is given by

$$T_j(\mathbf{P}) = \frac{E_j}{\lambda_j P_s + P_j \Sigma_{l=1}^{N} \lambda_{lj}}. \tag{31}$$

In addition, we also define a $K \times N$ relay power allocation matrix $\hat{\mathbf{P}}$ whose the $(i,j)^{th}$ element, $\hat{P}_{ij}$, represents a power that the relay R_i helps the node j. We assume that each relay does not have its own information to transmit; it only helps transmit information of other cooperative nodes. By denoting E_{R_i} as an initial energy of a relay R_i, the lifetime of R_i is

$$T_{R_i}(\hat{\mathbf{P}}) = \frac{E_{R_i}}{\sum_{j=1}^{N} (P_r \text{sgn}(\hat{P}_{ij}) + \hat{P}_{ij})(\sum_{l=1}^{N} \lambda_{lj})}. \tag{32}$$

As an example, a wireless network with four cooperative nodes and two cooperative relays is depicted in Figure 5 (a). In the figure, the solid line represents a link from a node (source j or relay) to the next node n_j, and the dashed line represents a link from a source to a relay. Figure 5 (b) shows the power allocation matrix $\mathbf{P}$ and the relay power allocation matrix $\hat{\mathbf{P}}$ which correspond to the wireless network in Figure 5 (a). Since all four cooperative nodes transmit their information to n_j, then all diagonal elements of $\mathbf{P}$ are non-zeros. As shown in Figure 5 (a), solid lines with square ("□") and circle ("○") represent the case when relay R_1 helps transmit information of node 1 and node 2, respectively. Accordingly, $\hat{P}_{11}$ and $\hat{P}_{12}$ are non-zero elements in the first row of $\hat{P}$. Similarly, relay R_2 helps transmit information of node 3 and node 4 to the next node n_j; $\hat{P}_{23}$ and $\hat{P}_{24}$ are non-zero elements in the second row of $\hat{P}$.

Denote x_j and y_j as a location of node j on the x-axis and the y-axis, respectively. Then we represent a location of node j in a vector form as $\bar{\mathbf{D}}_j = [x_j \ y_j]^T$. Accordingly, the channel variance between node j and its next node n_j is given by $\sigma_{jn_j}^2 = \eta \|\bar{\mathbf{D}}_j - \bar{\mathbf{D}}_{n_j}\|^{-\alpha}$ where $\|\cdot\|$ denotes the Frobenius norm [28]. Locations of the cooperative relays are specified by a $2 \times K$ matrix $\mathbf{D}_R = [\bar{\mathbf{D}}_{R_1} \ \bar{\mathbf{D}}_{R_2} \ \cdots \ \bar{\mathbf{D}}_{R_K}]$ in which the i^{th} column indicates the location of relay R_i, i.e., $\bar{\mathbf{D}}_{R_i} = [x_{R_i} \ y_{R_i}]^T$ is the location vector of the relay R_i. Then, the channel variance between R_i and node n_j is $\sigma_{R_i,n_j}^2 = \eta \|\bar{\mathbf{D}}_{R_i} - \bar{\mathbf{D}}_{n_j}\|^{-\alpha}$, and the channel variance between node j and R_i is $\sigma_{j,R_i}^2 = \eta \|\bar{\mathbf{D}}_j - \bar{\mathbf{D}}_{R_i}\|^{-\alpha}$. If node j is helped by R_i, then the BER of node j has a similar form as

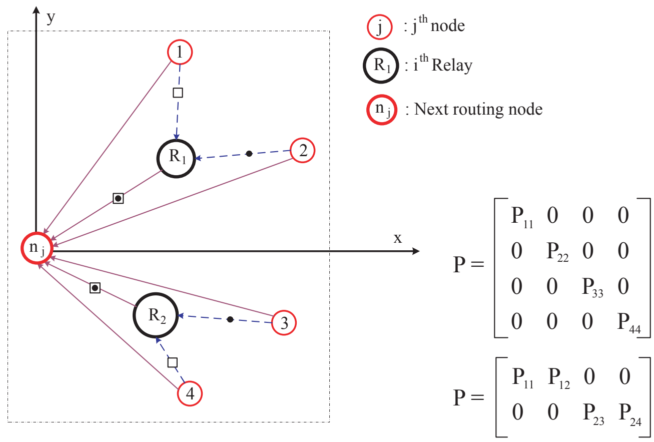

Fig. 5. Cooperative wireless network with relay deployment: (a) one cluster with 4 nodes, 2 relays, and 1 destination; (b) the corresponding power allocation matrices ($\mathbf{P}$) and ($\hat{\mathbf{P}}$) for the nodes and the relays, respectively.

(8) with P_{ij} and σ_{ji}^2 replaced by $\hat{P}_{ij}$ and σ_{j,R_i}^2, respectively. Our objective is to determine $\mathbf{D}_R$, $\mathbf{P}$, and $\hat{\mathbf{P}}$ such that the minimum device lifetime is maximized. We formulated the optimization problem as

$$\max_{\mathbf{D}_R,\mathbf{P},\hat{\mathbf{P}}} \min_{i,j} \{T_j(\mathbf{P}), T_{R_i}(\hat{\mathbf{P}})\} \tag{33}$$

$$\text{s.t.} \begin{cases} \text{Performance: BER}_j \leq \varepsilon, \ \forall j; \\ \text{Power: } 0 < P_i \leq P_{\max}, P_{ij} = 0 \ \forall i, j \neq i; \\ \text{Power: } 0 \leq \hat{P}_{ij} \leq P_{\max}, \ \forall i, j. \end{cases}$$

In (33), the first constraint is to satisfy the BER requirement. The second constraint guarantees that all nodes transmit their information with power no greater than $P_{\max}$ and there is no cooperation among nodes. The third constraint ensures that the power that each cooperative relay helps a node is non-negative and not greater than $P_{\max}$. Due to the assignment and combinatorial nature of the formulated problem, the problem in (33) is NP hard [27]. Since it is computationally expensive to obtain the optimum solution to (33), a fast suboptimal algorithm is proposed to solve the formulated problem.

The basic idea of the proposed algorithm is to add one cooperative relay at a time into the network. Each time the optimum location of the added relay is chosen as the one, among all possible locations, that maximizes the minimum device lifetime. The algorithm stops when the device lifetime improvement is insignificant after adding another cooperative relay or when the maximum number of relays is reached. In the sequel, we first describe the algorithm to determine the device lifetime in each step, and then we describe the proposed algorithm in details. To maximize the minimum device lifetime when the number of relays and their locations are given, use the step algorithm similar to the one described in Figure 4 in Section III-C. Initially, all nodes are sorted in ascending order according to their non-cooperative lifetimes, as specified in (10), and then register them in a helped list H_{list}. In each iteration, first, select the first node in the helped list as the one to be helped. Second, determine the minimum device lifetime after all of the cooperative relay R_i's ($i = 1, 2, \ldots, K$) finish helping the selected node, and then choose the relay $R_{\hat{i}}$ where $\hat{i}$ is the relay that maximizes the minimum device lifetime to help the selected node. Next, update the power allocation matrices $\mathbf{P}$ and $\hat{\mathbf{P}}$, and remove the selected node in the first step from the helped list. The iteration continues until all nodes have been helped and the helped list is empty or until the device lifetime improvement is insignificant.

TABLE II
SUBOPTIMAL ALGORITHM TO DETERMINE DEVICE LIFETIME WHEN RELAY LOCATIONS ARE FIXED

Initialization: $P_j = \frac{N_0}{\kappa\varepsilon\sigma_{jd}^2}$, $T_j = \frac{E_j}{\lambda_j(P_s+P_j)}$, $T_D^* = \min T_j$, Sort N nodes by their lifetimes in ascending order and list in H_{list}.
Iteration: 1) Select the first node in the H_{list} as the helped node. 2) Select the helping relay $R_{\hat{i}}$ from the set of K relays. • For each i, use the heuristic algorithm to maximize the minimum device lifetime, $T_D^*(i)$. • Select $R_{\hat{i}}$ that results in maximum of minimum device lifetime to help the node $\hat{j}$. 3) Update $P_{\hat{j}\hat{j}}$ in $\mathbf{P}$ and update $\hat{P}_{\hat{i}\hat{j}}$ in $\hat{\mathbf{P}}$. Set $\hat{P}_{i\hat{j}} = 0$ for all $i \neq \hat{i}$ and set $T_D^* = T_D(\hat{i})$. Remove node $\hat{j}$ from the helped list H_{list}. Go to 1).
End: If the helped list is empty: $H_{list} = \emptyset$, or the device lifetime cannot be significantly increased. Return $\mathbf{P}$, $\hat{\mathbf{P}}$, T_D^*.

TABLE III
ALGORITHM TO DETERMINE RELAY LOCATIONS

Initialization: $q = 0$
Iteration: 1) Increase number of relays: q = q+1 2) For each location $\mathbf{D}_l \in \Phi_D$. Set $\mathbf{D}_{R_q} = \mathbf{D}_l$. Find T_D^*, $\mathbf{P}$ and $\hat{\mathbf{P}}$ using the algorithm in Table II Denote the obtained results by $T_D^*(l)$, $\mathbf{P}(l)$ and $\hat{\mathbf{P}}(l)$ 3) Find the relay location R_q: $\mathbf{D}_{R_q} = \mathbf{D}_{l^*}$, where $l^* = \arg\max_l T_D^*(l)$ 4) Update $\mathbf{P}$, $\hat{\mathbf{P}}$, and T_D^*. Go to 1).
End: If the device lifetime improvement is insignificant, or $q = K_{\max}$. Return $\mathbf{P}$, $\hat{\mathbf{P}}$, T_D^*.

The algorithm to find an optimum location of each cooperative relay is described as follows. We denote $K_{\max}$ as the maximum number of cooperative relays and denote Φ_D as a set of all possible relay locations. Initially, the number of relays is set to zero. In each iteration, the number of relay is increased by one, and the optimum relay location $\hat{\mathbf{D}}$ is determined using one of the heuristic search methods (e.g., local search or simulated annealing) together with the algorithm in Table II. The location $\hat{\mathbf{D}}$ that results in the maximum of the minimum device lifetime is selected as the optimum relay location. Then, the device lifetime is updated. Finally, the algorithm goes back to the first step. The algorithm stops if the device lifetime improvement is insignificant or the number of relays reaches $K_{\max}$. The detailed algorithm is presented in Table III.

Note that the proposed algorithm allows at most one relay to help each node. Although the algorithm is suboptimal, simulation results in Section V shows that the proposed algorithm significantly improves the device lifetime. In addition,

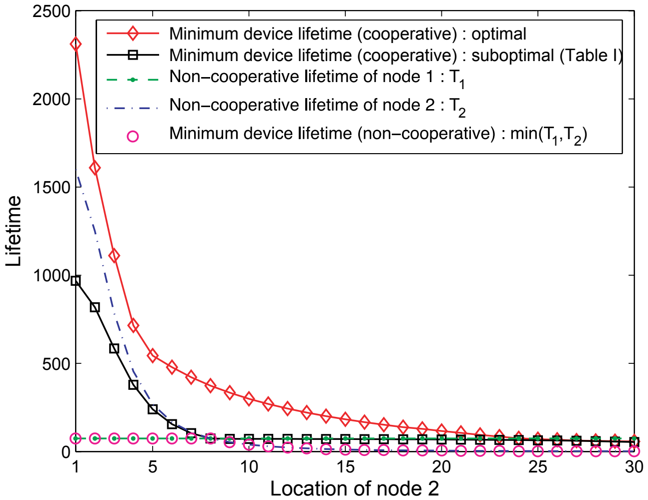

Fig. 6. Device lifetime in a two-node wireless network.

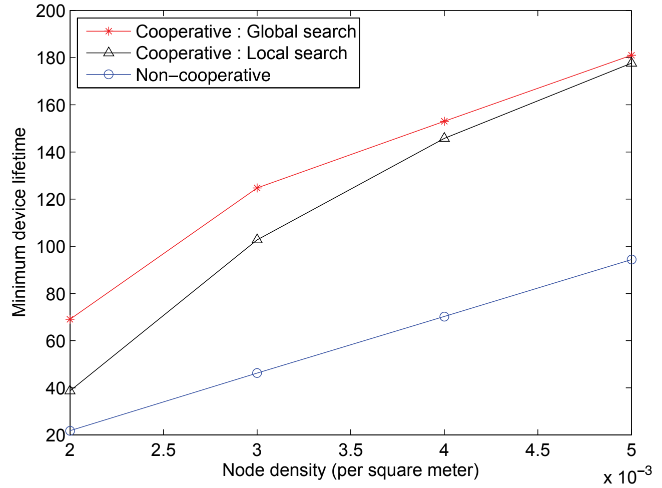

Fig. 7. Minimum device lifetime with different numbers of randomly-located nodes.

all of the required computations can be performed offline. In addition, the problems and algorithms in Section III and Section IV are closely related. Specifically, both sections aim to extend the device lifetime by exploiting cooperative diversity. In Section III, the cooperative diversity is exploited by cooperation among devices. In Section IV, however, cooperative relays are deployed, and the cooperative diversity is exploited by cooperation between each device and one of these additional cooperative relays. Therefore, the basic algorithm of finding $\mathbf{P}$ and $\hat{\mathbf{P}}$ in Section IV is similar to that in Section III. The search process of $\mathbf{P}$ and $\hat{\mathbf{P}}$ is done under the given locations of relays (i.e., for a fixed $\mathbf{D}$); the process is not affected by the method of finding $\mathbf{D}$.

V. Simulation Results and Discussions

In all simulations, BPSK modulation is used in the system, the propagation loss factor is $\alpha = 3$, $\eta = 1$, and $\varepsilon = 10^{-3}$ (unless stated otherwise). The processing power of each node (P_s) is set at 25% of transmit power of the node whose location is at (10m, 0) [29]. The processing power of each relay (P_r) is set at 50% of P_s. All nodes are equipped with equal initial energy of $E_j = 10^5$. The noise variance is set at $N_o = 10^{-2}$. The nodes are randomly distributed based on uniform distribution and the destination is located in the center of the area. Each node sends information to the destination via a route that is determined by the Dijkstra's algorithm.

In Figure 6, we consider a two-node wireless network where the destination is located at coordinate $(0, 0)$. Node 1 is fixed at coordinate (0, 8m). The location of node 2 varies from $(0, 1)$ to (0, 30m). We can see that the minimum device lifetime of the non-cooperative scheme is determined by the lifetime of the node who is located farther from the destination as shown by a curve with circle ("$\circ$"). Under cooperative transmission, the minimum device lifetime is significantly increased, especially when node 2 is located close to the destination. The reason is that node 2 requires small transmit power to reach the destination, after node 2 helps node 1, the transmit power of node 2 slightly increases, while the transmit power of node 1 greatly reduces due to the cooperative diversity. With the proposed suboptimal algorithm (Table I), the minimum device lifetime is improved to almost the same as the lifetime of the node who is closer to the destination (see a curve with rectangular "□"). By using the optimum power allocation obtained from Section III-B, the minimum device lifetime can be further increased (see a curve with diamond "◊") since both nodes take advantage of the cooperative diversity while using smaller amount of their transmit power.

Figure 7 depicts the minimum device lifetime according to density of cooperative nodes in a square area. The number of randomly-located nodes vary from 20 to 50 over an area of size $100m \times 100m$. In the simulation, we normalize the transmission rate to be the same for all network sizes. For local search, the helping node is chosen among the nodes whose distances from the source node are less than 20 meters. From the figure, we can see that the minimum device lifetime of the cooperative network is higher than that of the non-cooperative network for all network sizes. For example, the cooperative network improves the minimum device lifetime by 2 times longer than that of non-cooperative network when there are 50 nodes in the network. Note that the performance gain is calculated as $T_{coop}/T_{non-coop}$, where T_{coop} and $T_{non-coop}$ represent the lifetime of cooperative and non-cooperative networks, respectively. From Figure 7, the cooperative scheme with local search yields similar performance to the one with global search, especially when the node density is high. This confirms our expectation that the helping node is chosen as the one that is located close to the helped node. Note that the minimum device lifetimes for non-cooperative and cooperative networks increase with the number of nodes because the chance of being helped by a node with good location and high energy increases.

In Figure 8, we consider an improvement minimum device lifetime according to different BER requirements. We assume in the simulation that there are 30 randomly-located cooperative nodes in an area of size $100m \times 100m$. We can see from the figure that the minimum device lifetime is small at a BER requirement of 10^{-6} under both non-cooperative and cooperative networks. This is because each node requires large

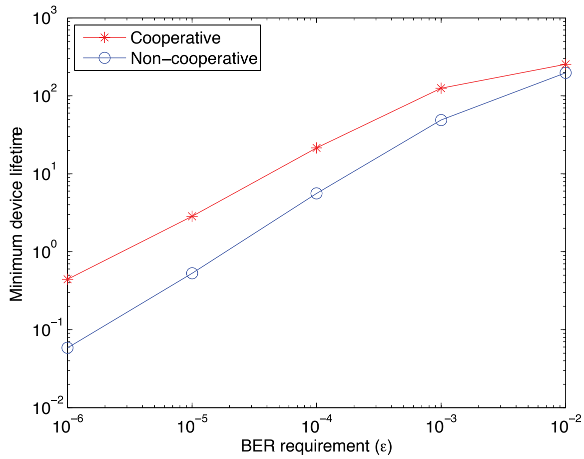

Fig. 8. Minimum device lifetime improvement according to different BER targets.

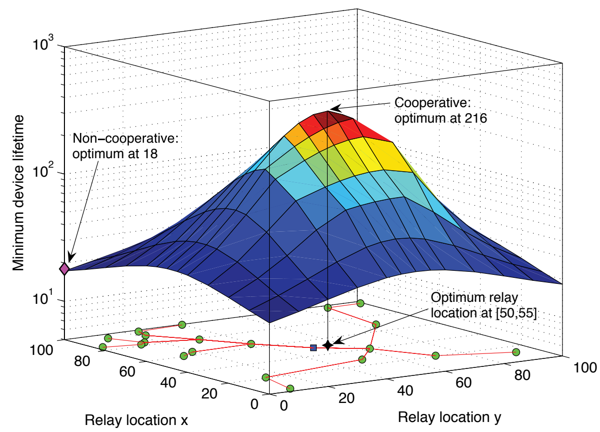

Fig. 9. Minimum device lifetime for a cooperative network with a cooperative relay.

transmit power to satisfy such small BER requirement. As the BER constraint increases, the minimum device lifetime also increases since the transmit power required to satisfy the BER constraint decreases. Note that the cooperative network achieves longer device lifetime than that for the non-cooperative network over the entire range of BER requirement. For example, the cooperative network achieves $125/49 = 2.6$ times longer lifetime than the non-cooperative network at a BER requirement of 10^{-3}. However, both cooperative and non-cooperative networks yield almost the same device lifetime at a BER constraint of 10^{-2}. The reason is that the transmit power required to satisfy the BER of 10^{-2} is much smaller than the processing power. The effect of processing power on the device lifetime dominates that of transmit power in this case.

Figure 9 shows the minimum device lifetime for different relay locations. We consider a case when there are 20 randomly-located nodes and a relay with initial energy of $E_{R_i} = 10^6$ in area of $100m \times 100m$. In the figure, a node with circle (" $\circ$ ") represents a randomly-located node, and a node with rectangular ("□") shows the location of the destination. In the simulation, we vary the relay location in a grid area of $100m \times 100m$. From the figure, the minimum device lifetime of the non-cooperative network is the same for all possible relay locations (as indicated by a point with "♢"). However, the minimum device lifetime of the cooperative network gradually increases when the relay moves closer to the destination. Specifically, the minimum device lifetime is the same as that of non-cooperative network when the relay is far away from the destination. But the minimum device lifetime further improves to $216/18 = 12$ times longer than that of the non-cooperative network when the relay is close to the center of the area. This is because the node that is nearest to the destination tends to drain out its battery first, and its lifetime can be greatly improved by placing the relay near the destination.

Figure 10 shows the minimum device lifetime according to the density of cooperative relays (i.e., the number of relays per square meter). We consider a cooperative network with 20 randomly-located nodes in an area of $100m \times 100m$. The initial energy of each relay is 10^5. The minimum device lifetime of the cooperative network with one randomly-added cooperative relay is about $28/11 = 2.55$ times longer than that of the non-cooperative network (as shown by a curve with circle " $\circ$ "). If the relay is placed at its optimum location, the minimum device lifetime (a curve with star " $*$ ") can be improved to $42/11 = 3.83$ times longer than that of non-cooperative network. Furthermore, when two to four relays are added into the network, the minimum device lifetime can be further increased under a case with optimally-placed relays as well as a case with randomly-placed relays. However, the minimum device lifetime is almost saturated when more than two relays are deployed in the network.

VI. Conclusions

We propose in this paper the lifetime maximization by cooperative-node employment and relay deployment in wireless networks. By introducing cooperation protocol among nodes, both energy advantage and location advantage can be explored such that the device lifetime is improved. First, decode-and-forward cooperation protocol is employed among nodes. We determine which nodes should cooperate and how much power should be allocated for cooperation. An optimization problem is formulated with an aim to maximize the minimum device lifetime under a BER constraint. An analytical solution for a two-node cooperative network is provided. In case of multiple-node scenario, it turns out that the formulated problem is NP hard. A suboptimal algorithm is developed to reduce the complexity of the formulated problem. By using the proposed suboptimal algorithm, simulation results show that the minimum device lifetime of the two-node cooperative network can be increased to almost the same as the lifetime of the node that is closer to the destination. In case of the multiple cooperative nodes, the minimum device lifetime of the cooperative network increases 2 times longer than that of the non-cooperative network. Furthermore, we propose to improve the device lifetime by adding cooperative relays into an energy depleting cooperative network. An optimization problem is formulated to determine the power allocation as well as the relay locations. By optimally placing a cooperative

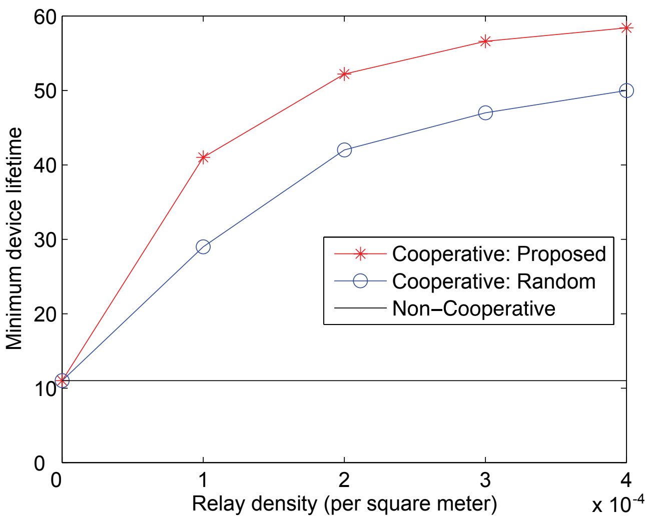

Fig. 10. Minimum device lifetime according to different numbers of deployed cooperative relays.

relay with energy 10 times higher than energy of the nodes, the device lifetime increases 12 times over that for the non-cooperative network. Furthermore, when energy of each cooperative relay is equal to energy of each cooperating node, the proposed algorithm shows that only a few cooperative relays are required in order to improve the device lifetime.

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