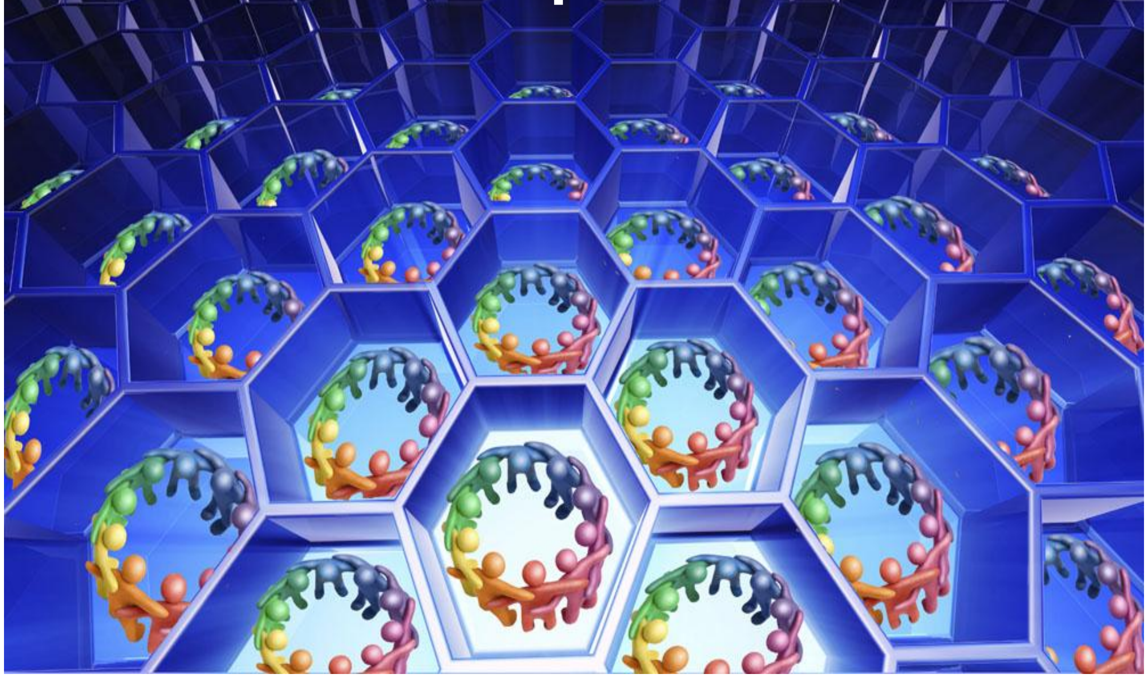
Cooperative Communications and Networking

Chapter 18

Network Lifetime Maximization via Cooperation



I. INTRODUCTION

- Extending the lifetime of battery-operated devices is a key design issue that ensures uninterrupted information exchange and alleviates burden of replenishing batteries.

  example: Sensor, ad-hoc networks

- The definition for network lifetime ???

✓ the time the first node dies (or a certain percentage)

✓ in term of quality of communication (packet delivery rate, the number of alive flows)

I. INTRODUCTION

- Contemporary wireless networks: mobile phones, laptop computers, PDAs, etc.
- Characteristics: limited lifetime, different lifetime, different location.
- 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.
- This chapter considerss a framework to increase the device lifetime by exploiting the cooperative diversity and by using both location and energy advantages in wireless networks.

I. INTRODUCTION

II. SYSTEM MODELS:

- A signal model for a non-cooperative network
- A signal model for a cooperative networks

III. LIFETIME MAXIMIZATION:

- Formulate an optimization problem with an objective to maximize the minimum device lifetime under bit-error-rate (BER) constraint
- Derive an analytical solution for a two-node cooperative network
- Develop a fast suboptimal algorithm to reduce the complexity of the formulated problem.

II. SYSTEM MODELS

- 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, or a data gathering unit in wireless sensor networks.
- Non-cooperative & cooperative system models

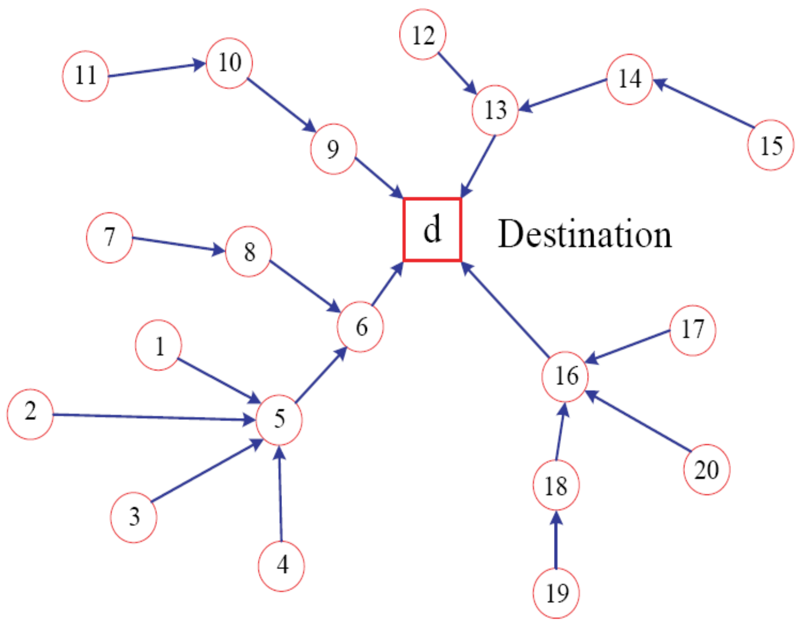


Fig. 1. An example of a wireless network with a destination (d) and N distributed nodes (N = 20).

II. SYSTEM MODELS

Non-Cooperative Model

• A non-cooperative wireless network

• N nodes in the network

• xj denotes a symbol to be transmitted from node j to its next node, defined as nj . The symbol xj can be the information of node j itself, or it can be the information of other nodes that node j routes through to the destination.

•The received signal at nj due to the transmitted information from node j can be expressed as

$$y_{jn_j} = \sqrt{P_j} h_{jn_j} x_j + w_{jn_j}, \quad (1)$$

$$\sigma^2_{jn_j} = \eta D^{-\alpha}_{jn_j}, \quad (2)$$

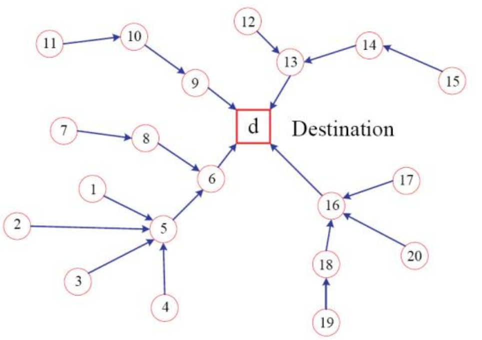


Fig. 1. An example of a wireless network with a destination (d) and N distributed nodes (N = 20).

II. SYSTEM MODELS

Non-Cooperative Model

- The average BER performance for a non-cooperative node with M-PSK modulation is upper bounded by

$$\mathrm{BER}_j \leq \frac{N_0}{4bP_j\sigma_{jn_j}^2 \log_2 M}, \qquad (3)$$

- Let the performance requirement of node j be BERj ≤ ε 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

$$P_j = \frac{N_0}{4b\varepsilon\sigma_{jn_j}^2 \log_2 M}. \qquad (4)$$

II. SYSTEM MODELS

Non-Cooperative Model

• Denote Ps as an amount of processing power (i.e. power used for encoding information, collecting data, and etc.) at the source node. Let λlj (l = 1, 2, . . .,N and l = j) be the data rate that node l sends information to node j, and λj be a data rate that node j sends information to its next node nj .

•the total power that node j uses to send information to nj is

$$\lambda_j P_s + \sum_{l=1}^{N} \lambda_{lj} P_j$$

II. SYSTEM MODELS

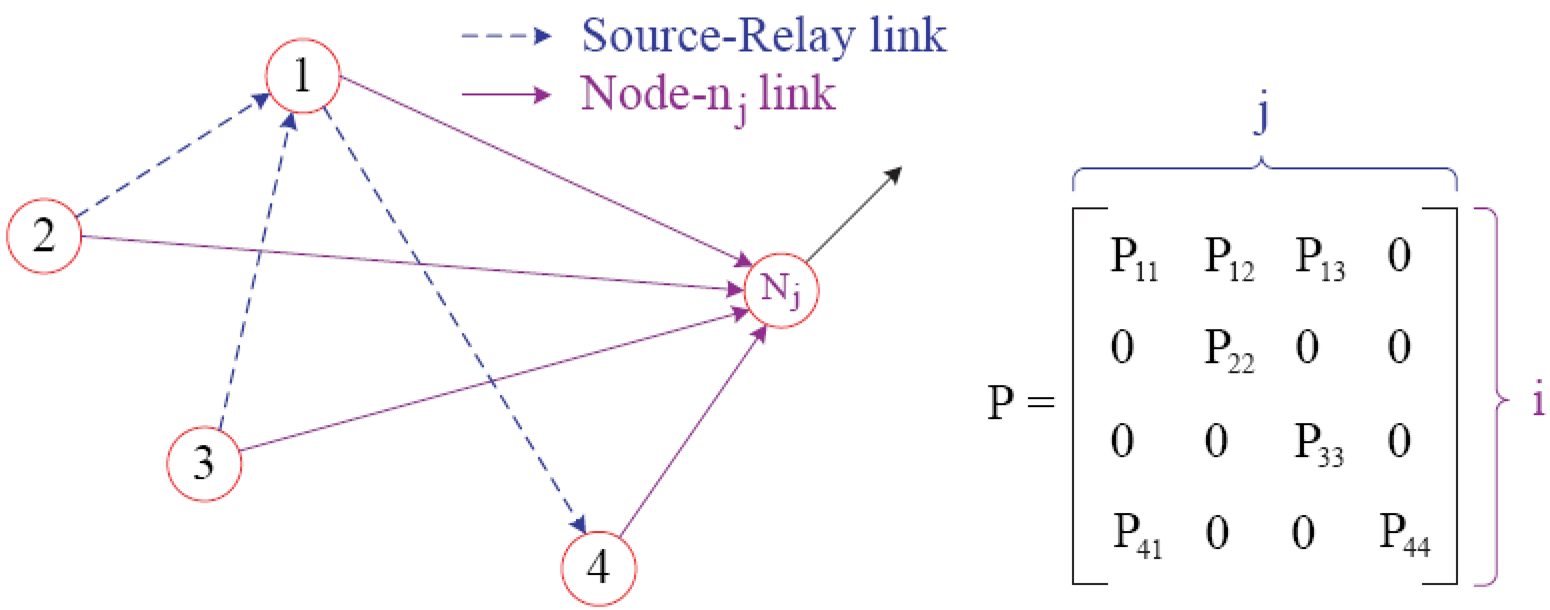
Cooperative Model

• **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 **decode-and-forward (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.

• Define a **power allocation matrix 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 .

II. SYSTEM MODELS

Cooperative Model



(a) (b)

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

II. SYSTEM MODELS

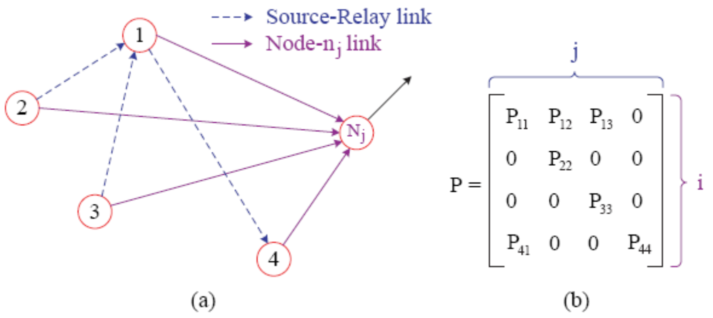
Cooperative Model

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

$$y_{ji} = \sqrt{P_j} h_{ji} x_j + w_{ji}, \qquad (5)$$

•In Phase 2, the relay (node i in this case) forwards the information of node j to nj only if the symbol is correctly decoded. The received signal at nj can be expressed as

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



II. SYSTEM MODELS

Cooperative Model

- The upper bound of BER is as

Cooperative system:

$$\mathrm{BER}_j \leq \frac{N_0^2}{b^2 \log_2 M} \cdot \frac{A^2 P_{ij} \sigma_{in_j}^2 + B P_j \sigma_{ji}^2}{P_j^2 P_{ij} \sigma_{jn_j}^2 \sigma_{ji}^2 \sigma_{in_j}^2}, \qquad (9)$$

$A \triangleq (M-1)/(2M) + \sin(2\pi/M)/(4\pi)$ and $B \triangleq 3(M-1)/(8M) + \sin(2\pi/M)/(4\pi) - \sin(4\pi/M)/(32\pi)$.

- Compare with the non-cooperative system

Non-cooperative system:

$$\mathrm{BER}_j \leq \frac{N_0}{4 b P_j \sigma_{jn_j}^2 \log_2 M}, \qquad (3)$$

III. LIFETIME MAXIMIZATION BY COOPERATIVE NODE EMPLOYMENT

• Maximize the minimum device lifetime among all cooperative nodes in the network.

A. Formulate the lifetime maximization problem.

B. An analytical solution is provided for a network with two cooperative nodes.

C. 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.

III. LIFETIME MAXIMIZATION BY COOPERATIVE NODE EMPLOYMENT

A. Problem formulation

- Determine the device lifetime in a non-cooperative network. The non-cooperative device lifetime of node j is given by

$$T_j \quad = E_j / (\lambda_j P_s + P_j \Sigma_{l=1}^{N} \lambda_{lj}).$$

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

$$\kappa \triangleq 4b \log_2 M$$

III. LIFETIME MAXIMIZATION BY COOPERATIVE NODE EMPLOYMENT

A. Problem formulation (cont.)

- The overall transmit power of the cooperating node i is

$$P_i \sum_{l=1}^{N} \lambda_{li} + \sum_{j=1, j\neq i}^{N} P_{ij} (\sum_{l=1}^{N} \lambda_{lj})$$

- The overall processing power of node i is

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

- The lifetime of the cooperative node *i can be written as*

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

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

III. LIFETIME MAXIMIZATION BY COOPERATIVE NODE EMPLOYMENT

A. Problem formulation (cont.)

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

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

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

III. LIFETIME MAXIMIZATION BY COOPERATIVE NODE EMPLOYMENT

B. Two nodes system

- A network with two cooperative nodes (*N = 2)*

  1) Each node transmits non-cooperatively
  2) one node helps forward information of the other
  3) both nodes help forward information of each other

- *Non-cooperative transmission among nodes:*

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

III. LIFETIME MAXIMIZATION BY COOPERATIVE NODE EMPLOYMENT

B. Two nodes system (cont.)

- *Cooperative transmission when one node helps the other node:*

$$T_i = E_i/(\lambda_i(P_s + P_i) + \lambda_j(P_r + P_{ij}))$$

$$T_j = E_j/(\lambda_j(P_s + P_j))$$

$$P_i = N_0/(\kappa\varepsilon\sigma_{id}^2). \quad \frac{N_0^2 A^2 P_{ij}\sigma_{id}^2 + N_0^2 B P_j \sigma_{ji}^2}{b^2 \log_2(M) P_j^2 P_{ij} \sigma_{jd}^2 \sigma_{ji}^2 \sigma_i^2} = \varepsilon.$$

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

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

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

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

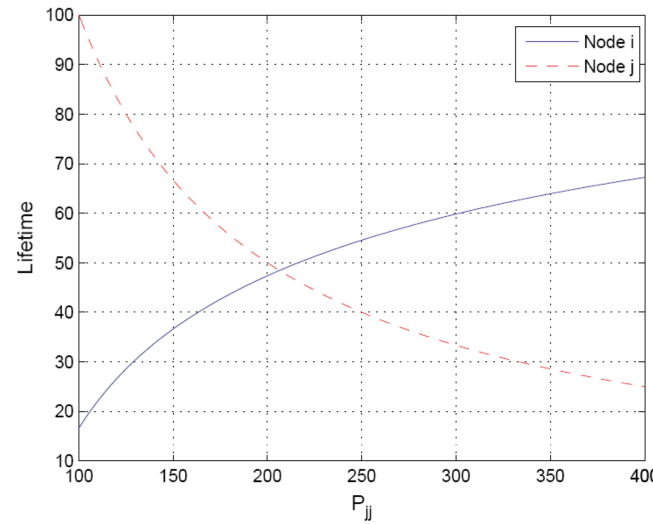


Fig. 3. Lifetimes of the two cooperative nodes as functions of the transmit power of the helped node (P_{22})

III. LIFETIME MAXIMIZATION BY COOPERATIVE NODE EMPLOYMENT

B. Two nodes system (cont.)

$$P_{ij}^* > P_{\max}$$

$$P_{ij}^* = P_{\max}$$

$$P_j^* = \frac{-Q_1 + \sqrt{Q_1^2 + Q_2 Q_3 P_{\max}^2}}{Q_2 P_{\max}}, \qquad (19)$$

$$T_i^* = E_i / (\lambda_i (P_s + P_i) + \lambda_j (P_r + P_{\max}))$$

$$T_j^* = E_j / (\lambda_j (P_s + P_j^*)),$$

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

III. LIFETIME MAXIMIZATION BY COOPERATIVE NODE EMPLOYMENT

B. Two nodes system (cont.)

- *Cooperative transmission when both nodes help each other:*

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

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

$$\text{s.t.} \begin{cases} \frac{\left[(\lambda_i P_s + \lambda_j P_r + \lambda_i P_i)(C_{ij}P_j^2 - D_{ij}) + \lambda_j P_j\right](C_{ji}P_i^2 - D_{ji})}{\left[(\lambda_j P_s + \lambda_i P_r + \lambda_j P_j)(C_{ji}P_i^2 - D_{ji}) + \lambda_i P_i\right](C_{ij}P_j^2 - D_{ij})} = \frac{E_i}{E_j}; \\ P_j > \sqrt{\frac{D_{ij}}{C_{ij}}}, \ \forall j \neq i, \end{cases}$$

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

$$\mathcal{T}_i \triangleq E_i/(\lambda_i(P_s + P_i^*) + \lambda_j(P_r + \frac{P_j^*}{C_{ij}(P_j^*)^2 - D_{ij}})),$$

$$\mathcal{T}(ii) \triangleq \max_{P_{ii}} \min\{T_i, T_j\}, \qquad \mathcal{T}(jj) \triangleq \max_{P_{jj}} \min\{T_i, T_j\}.$$

$$\boxed{T_D^* = \max\left\{T^*_{non-coop}, T^*_{1-helps-2}, T^*_{2-helps-1}, T^*_{both-help}\right\}. \quad (24)}$$

III. LIFETIME MAXIMIZATION BY COOPERATIVE NODE EMPLOYMENT

C. Suboptimal Algorithm

• For the optimization problem in the section A, it's computationally expensive for a large nodes in the network

• Suboptimal algorithm for multi-node wireless network
to reduce the complexity based on the two nodes solution in the section B.

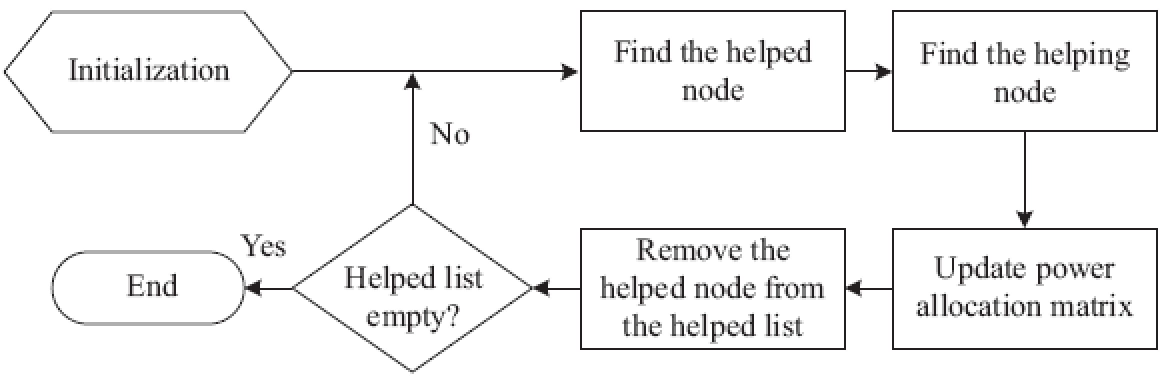


Fig. 4. A flowchart to illustrate the proposed suboptimal algorithm.

III. LIFETIME MAXIMIZATION BY COOPERATIVE NODE EMPLOYMENT

C. Suboptimal Algorithm (cont.)

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

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

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

$$T^*_{i-helps-j} = \frac{E_j}{\Psi_j + P_j^* \Sigma_{l=1}^{N} \lambda_{lj}}, \qquad (28)$$

III. LIFETIME MAXIMIZATION BY COOPERATIVE NODE EMPLOYMENT

C. Suboptimal Algorithm (cont.)

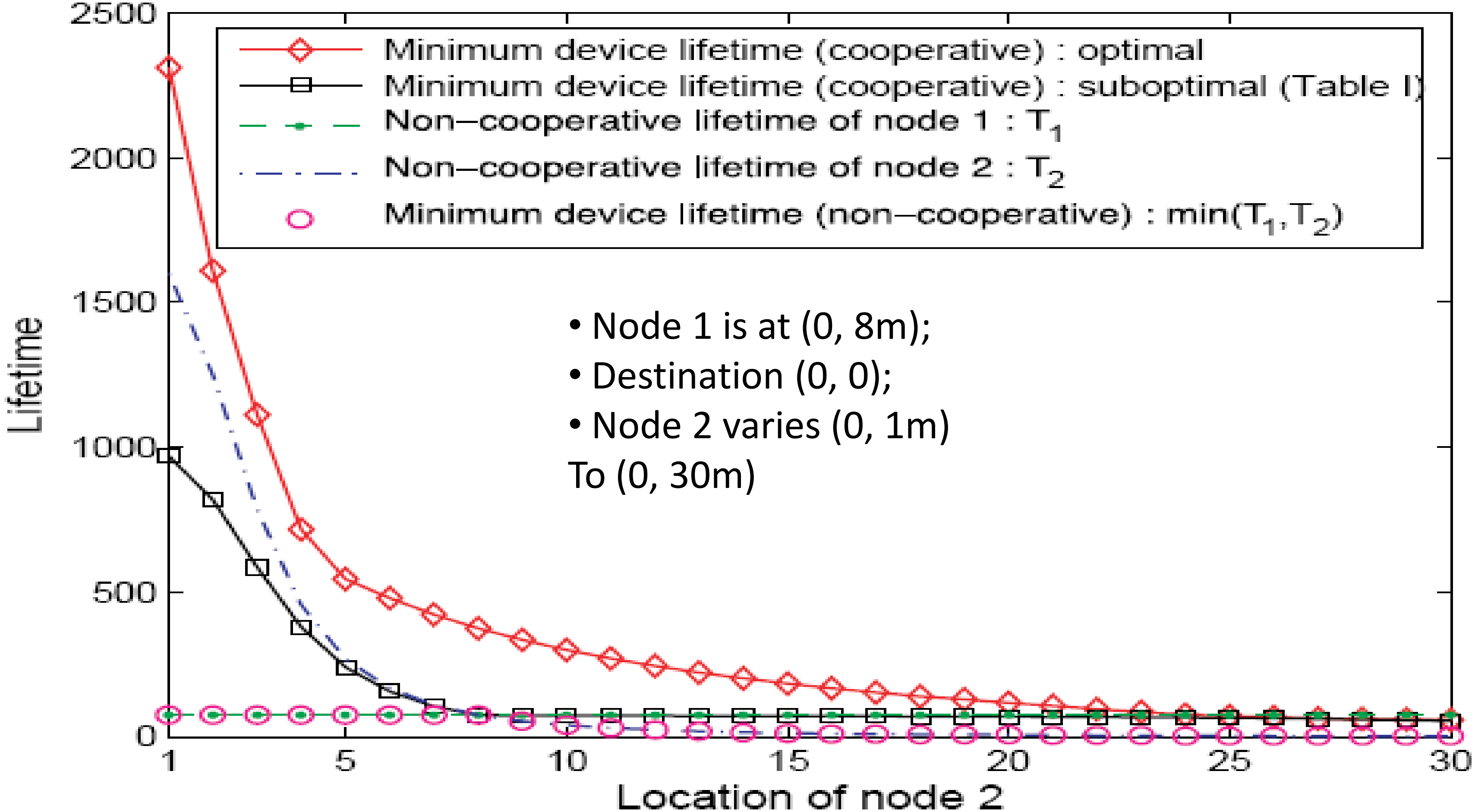
TABLE I

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 $\mathbf{P}$.

III. LIFETIME MAXIMIZATION BY COOPERATIVE NODE EMPLOYMENT

- Simulation results



- Node 1 is at (0, 8m);
- Destination (0, 0);
- Node 2 varies (0, 1m) To (0, 30m)

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

III. LIFETIME MAXIMIZATION BY COOPERATIVE NODE EMPLOYMENT

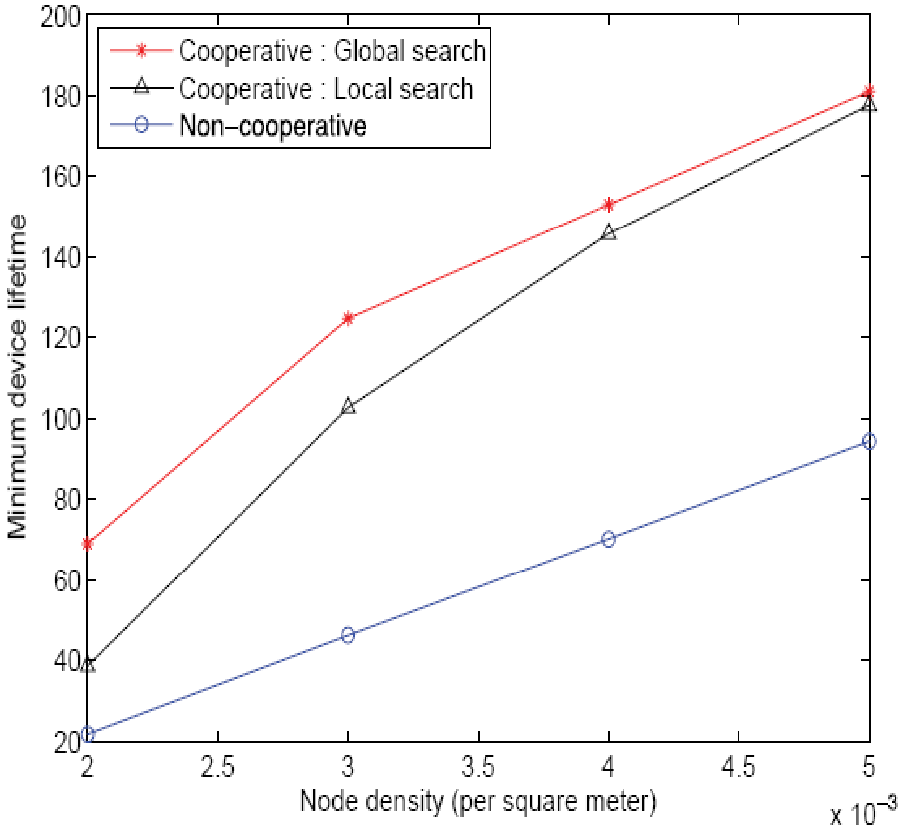


Fig. 7. Minimum device lifetime with different numbers of randomly-located nodes.

- The number of nodes varies from 20 to 50 over an area of size 100 m*100 m.
- Local search: the helping node is chosen among the nodes whose distances from the source node are less than 20 m.

III. LIFETIME MAXIMIZATION BY COOPERATIVE NODE EMPLOYMENT

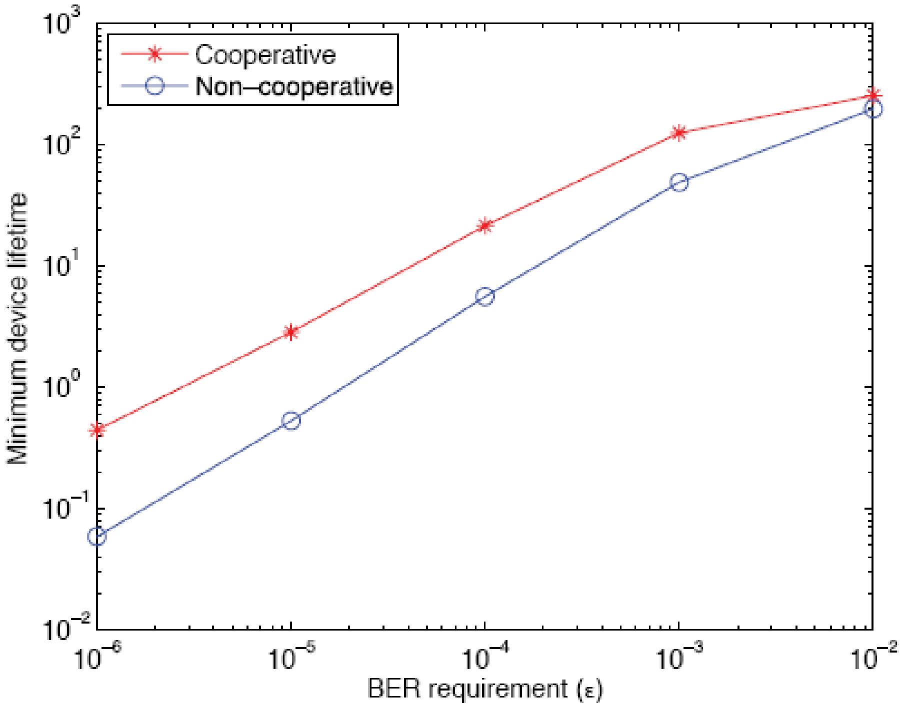


Fig. 8. Minimum device lifetime improvement according to different BER targets.

Conclusion

• Introduce the cooperative diversity , the cooperative scheme requires less power to achieve the same performance as the non-cooperative scheme.

• Using the power allocation matrix to maximize the minimum lifetime of the system.

• Based on the two nodes analytical solution, develop a fast suboptimal approach to reduce the complexity of the problem.