Distributed Lifetime Maximizing Cooperative Routing Algorithm in Wireless Ad Hoc Networks

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***Abstract*—In this paper, jointly combining advantages of cooperative communication at the physical layer and distributed routing schemes at the network layer, we propose a novel lifetime maximizing cooperative routing (LMCR) algorithm with decode-and-forward cooperative fashion to prolong the lifetime of wireless Ad-hoc networks. Optimal power allocation mechanism is analyzed for both cooperative and non-cooperative links with the constraint of average SER. Subsequently, link costs representing the weighted total consumed power are constructed to avoid the overuse of certain nodes with little energy. In addition, both the transmission energy and circuit energy are considered in energy consumption model. Finally, simulation results are provided to verify the efficiency of the proposed routing scheme.**

I. Introduction

Nowadays, energy-efficient communication has attracted a lot of attention because energy conservation is critical for extending the lifetime of wireless Ad-hoc networks. Energy efficient protocols can be approached at different communication layers. Indeed, cross-layer design is also an effective and practical way to address the complicated problems and realize the final objective of the network.

Recently, cooperative communication has been widely discussed as a promising technology to achieve spatial diversity in wireless networks. In [1], Laneman describes various protocols of cooperative communication, such as decode-and-forward (DF), and amplify-and-forward (AF). Symbol error rate (SER) performance and optimal power allocation for DF cooperative communications over Nakagami-m fading channels are investigated in [2]. Besides, with reference to [3], Su *et al.* derive the exact and upper bound expressions of average SER performance with M-PSK and M-QAM signals for DF and AF cooperative protocols over Rayleigh fading channels in [4].

Many energy efficient routing algorithms have been proposed. The minimum total energy routing (MTE) [5] algorithm selects the route that minimizes the total transmission energy along the route. Instead of trying to minimize the total consumed energy on the path, Jae-Hwan Chang *et al.* formulate the routing problem as a linear programming problem named flow augmentation (FA) algorithm [6], of which the objective is to maximize the network lifetime. In [7], cooperative communication scheme along the pre-selected shortest-path non-cooperative route is proposed to minimize the total energy consumption of the route. With the goal of minimizing the total power consumption while satisfying the end-to-end throughput constraint, a distributed cooperative routing scheme, named Minimum Power Cooperative Routing (MPCR), is proposed in [8]. Besides, in short-range applications such as sensor networks where the circuit energy consumption is comparable to or even dominates the transmission energy, different approaches need to be taken to minimize the total energy consumption [9]. In [9], the authors analyze the best modulation and transmission strategy to minimize the total energy consumption (including both the transmission energy and the circuit energy consumptions) required to send given data.

In this paper, we focus on the maximum lifetime routing with cooperative communication in wireless networks. The optimum route is defined as the route that can maximize the network lifetime while guaranteeing the point-to-point SER on each link. Both non-cooperative and cooperative link costs are formulated to avoid the inefficient use of some nodes with extremely low residual energy. Moreover, both the transmission energy and the circuit processing energy for short-range communications are included in energy consumption model. Combining DF cooperation fashion at the physical layer and distributed Bellman-Ford routing algorithm at the network layer, a new cooperative routing scheme, named lifetime maximizing cooperative routing (LMCR), is proposed. In this protocol, transmission power is optimally allocated between cooperative partners while meeting the SER requirement.

The rest of the paper is organized as follows. Section II describes the system model. In Section III, we derive the power allocation expressions and give the link cost for non-cooperative and cooperative modes. The distributed cooperative routing scheme is illustrated in section IV. The simulation results are presented in Section V. Finally, Section VI concludes the paper.

II. System Model

A. Network Model

We consider a multiple-node and multiple-edge system in Fig. 1. For a given source-destination pair (S, D), each route consists of multiple hops. The optimal path between (S, D) could be a combination of a series of non-cooperative and cooperative links. Therefore, we consider two types of link on the multi-hop route: non-cooperative link and cooperative

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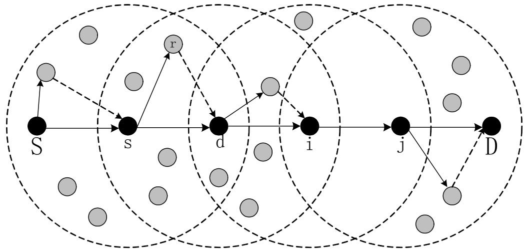

Fig. 1. The system model. (i, j) represents non-cooperative link and (s, r, d) represents cooperative link. The solid lines are direct transmission channels in the first time slot. The dashed line is relay transmission channel in the second time slot.

link. The non-cooperative link is represented by the link (i, j), where node i is the sender and node j is the receiver. It is assumed that there is no common node in the sense range of i and j. In addition, the cooperative link is represented by the link (s, r, d), where node s is the sender, node r is the relay, and node d is the receiver.

B. Approximation of Average SER

Channels between source-destination, source-relay and relay-destination are assumed to suffer independent non-identical Rayleigh flat fading, so the instantaneous SNR γ follows exponential distributed with parameter $\overline{\gamma}$, which is the expectation of γ [12]. The channel coefficients h_{sd}, h_{sr}, and h_{rd} are modeled as zero-mean, complex Gaussian random variables with variances σ_{sd}^2, σ_{sr}^2 and σ_{rd}^2, respectively. The noises are modeled as zero-mean, circularly symmetric complex Gaussian random variables with variance N_0.

DF cooperative protocol is adopted in our scheme. The communication is divided into two phases in order to support the cooperation. In the first phase, the source broadcasts signal to both the destination and the relay with power P_1. If the relay can decode the received symbol correctly, judging by Cyclic Redundancy Check (CRC), the relay forwards the decoded symbol with power P_2 to the destination in the second phase, otherwise the relay keeps silent. The instantaneous channel gains are assumed to be available at the receiver side, therefore, maximum ratio combining (MRC) technique can be adopted and coherent detection can be implemented.

For the non-cooperative mode, the average SER with M-PSK or M-QAM modulation is upper-bounded by [4]:

$$P_{sn} \leq \frac{AN_0}{bP_1\,\sigma_{sd}^2} \tag{1}$$

where P_1 is the transmission power of node i. For M-PSK, $A = \frac{M-1}{2M} + \frac{\sin\frac{2\pi}{M}}{4\pi}$, $b = b_{PSK} = \sin^2(\pi/M)$; For M-QAM, $A = \frac{M-1}{M} + \frac{2(\sqrt{M}-1)^2}{M\pi}$, $b = b_{QAM} = 3/(M-1)$. Besides, the SER of the cooperation systems with M-PSK or M-QAM modulation can be upper-bounded as

$$P_{sc} \leq \frac{N_0^2}{b^2}\cdot\frac{1}{P_1\,\sigma_{sd}^2}\left(\frac{A^2}{P_1\,\sigma_{sr}^2}+\frac{B}{P_2\,\sigma_{rd}^2}\right) \tag{2}$$

where in case of M-PSK, $B = \frac{3(M-1)}{8M} + \frac{\sin\frac{2\pi}{M}}{4\pi} - \frac{\sin\frac{4\pi}{M}}{32\pi}$; while for M-QAM, $B = \frac{3(M-1)}{2M} + \frac{4\left(\sqrt{M}-1\right)^2}{M\pi}$.

C. Approximation of Average PER

With reference to [13], the approximation of packet error rate (PER) can be formulated as

$$PER(\gamma) = \begin{cases} 1, & \text{if } 0 < \gamma < \gamma_p \\ \alpha\exp\left(-g\gamma\right), & \text{if } \gamma \geq \gamma_{\mathrm{p}} \end{cases} \tag{3}$$

where (α, g, γ_p) are found by least-squares fitting method and the switching threshold γ_p is set such that $\alpha\exp\left(-g\gamma_p\right) = 1$; For BPSK: $\alpha = 67.7328, g = 0.9819, \gamma_p = 6.3281$; For QPSK: $\alpha = 73.8279, g = 0.4945, \gamma_p = 9.3945$. Then, the average PER on the link can be derived by

$$\overline{PER} = \int_0^\infty PER\left(\gamma\right)\frac{e^{-\gamma/\overline{\gamma}}}{\overline{\gamma}}d\gamma = 1 - \frac{g\overline{\gamma}}{1+g\overline{\gamma}}\exp\left(-\frac{\gamma_p}{\overline{\gamma}}\right) \tag{4}$$

III. Power Allocation and Link Cost

Considering the goal of maximizing network lifetime via cooperative routing algorithm, new power allocation scheme is derived. Note that, in the FA routing algorithm, the path with minimum total transmission power weighted by the normalized residual energy is preferred. By weighting the energy metric with the normalized residual energy, the node with extremely low residual energy could be avoided. Based on the metric of weighted energy consumption and upper bound expressions of average SER, maximum lifetime power allocation problems for both cooperative and non-cooperative links are derived.

A. Non-cooperative Mode

Specially, using the upper bound of the average SER, the optimization problem for non-cooperative links can be formulated as:

$$\begin{aligned} &\min\left(\frac{E_s}{\underline{E}_s}\right)^x P_1 \\ &s.t. \quad P_{snu} = \frac{AN_0}{bP_1\,\sigma_{sd}^2} \leq \varepsilon_c \end{aligned} \tag{5}$$

The above optimization problem minimizes the weighted total transmission power while ensuring that average SER approximation is smaller than the maximum required SER denoted by ε_c. The residual energy at current time and the initial energy of node s, r, d are represented as $\underline{E}_s$, $\underline{E}_r$, $\underline{E}_d$ and E_s, E_r, E_d, respectively. x is the parameter that governs the effect of normalized residual energy, which is set as 5 in our scheme. Based on Eq. (5), as the average SER is a monotonically decreasing function of P_1, if the maximum allowed transmission power is $P_{\max}$, by setting $P_{snu} = \varepsilon_c$, we can get:

$$P_1 = \min\left\{\frac{AN_0}{b\,\varepsilon_c\sigma_{sd}^2}, P_{\max}\right\} \tag{6}$$

From expression (6), we can see that the initial energy and residual energy are not included in the power allocation process. Using maximum lifetime criterion, the transmission power can be allocated as P_1 for non-cooperative links.

In our scheme, we discuss the energy consumption model consisting of the transmission energy and the circuit processing energy. To simplify the formulation we assume two modes of operation for each node: active mode and sleep mode. Therefore, nodes s and d will be in active mode when link (s,d) is active, otherwise, they will be in sleep mode where all the circuits are turned off to save energy. Thus, the link cost of non-cooperative mode can be written as

$$LC_{LMCR-non}(s,d) = \left(\frac{E_s}{\underline{E}_s}\right)^x (P_1 + P_{to}) + \left(\frac{E_d}{\underline{E}_d}\right)^x P_{ro} \tag{7}$$

where the first term represents the weighted total power consumption of source node, and the second term represents the weighted power consumption of destination to receive packets. P_{to} is the total transmitter circuit power consumption of source node, and P_{ro} is the total receiver circuit power consumption of destination node.

B. Cooperative Mode

For the cooperative communication, we will determine the optimum transmission power P_1 at the source and P_2 at the relay. The optimization problem for cooperative links can be formulated as

$$\begin{aligned} &\min \left(\tfrac{E_s}{\underline{E}_s}\right)^x P_1 + \left(\tfrac{E_r}{\underline{E}_r}\right)^x P_2 \\ &s.t. \begin{cases} P_{scu} = \frac{N_0^2}{b^2} \cdot \frac{1}{P_1 \sigma_{sd}^2} \left(\frac{A^2}{P_1 \sigma_{sr}^2} + \frac{B}{P_2 \sigma_{rd}^2}\right) \le \varepsilon_c \\ 0 < P_1 \le P_{\max} \\ 0 < P_2 \le P_{\max} \end{cases} \end{aligned} \tag{8}$$

Using the Lagrange multiplier method, we have

$$\begin{aligned} L(P_1, P_2, \lambda) = &(\frac{E_s}{\underline{E}_s})^x P_1 + (\frac{E_r}{\underline{E}_r})^x P_2 \\ &+ \lambda(\frac{A^2 N_0^2}{b^2 P_1^2 \sigma_{sd}^2 \sigma_{sr}^2} + \frac{B N_0^2}{b^2 P_1 P_2 \sigma_{sd}^2 \sigma_{rd}^2} - \varepsilon_c) \end{aligned} \tag{9}$$

Taking the partial derivatives, if we set $P_1^2 = t$, the problem can be represented as

$$Wt^2 - 2Qt + U = 0 \tag{10}$$

Then $t = \frac{Q \pm \sqrt{Q^2 - 4WU}}{2W}$. Where $W = E\varepsilon_c^2$, $Q = 2GE\varepsilon_c + FH\varepsilon_c$, $U = EG^2 - FGH$, $E = (\frac{E_s}{\underline{E}_s})^x$, $F = (\frac{E_r}{\underline{E}_r})^x$, $G = \frac{A^2 N_0^2}{b^2 \sigma_{sd}^2 \sigma_{sr}^2}$, $H = \frac{B N_0^2}{b^2 \sigma_{sd}^2 \sigma_{rd}^2}$. Considering $t = \frac{Q + \sqrt{Q^2 - 4WU}}{2W}$, we get the final result: $P_1 = \sqrt{t} = \sqrt{\frac{Q + \sqrt{Q^2 - 4WU}}{2W}}$. Hence, the maximum lifetime power allocation can be derived as:

$$\begin{aligned} P_1 &= \min \left\{ \sqrt{\frac{Q + \sqrt{Q^2 - 4WU}}{2W}}, P_{\max} \right\} \\ P_2 &= \min \left\{ \frac{HP_1}{\varepsilon_c P_1^2 - G}, P_{\max} \right\} \end{aligned} \tag{11}$$

Taking both the transmission and circuit processing energy consumption into consideration, the link cost for cooperative mode can be given as:

$$\begin{aligned} &LC_{LMCR-coop}(s,r,d) \\ &= \left(\frac{E_s}{\underline{E}_s}\right)^x (P_1 + P_{to}) + \left(\frac{E_d}{\underline{E}_d}\right)^x [1 + (1 - P_{psr})] P_{ro} \\ &+ \left(\frac{E_r}{\underline{E}_r}\right)^x [P_{ro} + (1 - P_{psr})(P_2 + P_{to})] \end{aligned} \tag{12}$$

where P_{psr} is the average PER of the link (s,r). The average received SNR on link (s,r) can be denoted as $\overline{\gamma}_{sr} = \frac{P_1 \sigma_{sr}^2}{N_0}$. According to the detailed analysis in Section II. C and Eq. (4), the average PER can be be expressed as $P_{psr} = 1 - \frac{g P_1 \sigma_{sr}^2}{N_0 + g P_1 \sigma_{sr}^2} \exp\left(-\frac{N_0 \gamma_p}{P_1 \sigma_{sr}^2}\right)$. In Eq. (12), the three terms represent the weighted average power consumption of source, destination and relay nodes, respectively. Note that it is assumed that once the relay node is selected, other nodes in the sense range will enter into the sleep mode.

IV. The Proposed Routing Algorithm

Table I Lifetime Maximizing Cooperative Routing Algorithm

Step 1: Calculate the maximum lifetime path for the given source-desti -nation pair (S,D) with link costs according to Eq. (7) and (12).
Step 2: If none route can be found between the source-destination pair using the distributed Bellman-Ford algorithm, then stop. Otherwise, continue.
Step 3: Update the residual energy accordingly after a period. If there is not enough residual energy for a packet, then stop. Otherwise, repeat step 1.

Based on the metrics of non-cooperative and cooperative links analyzed in Section III, a new distributed cooperative routing algorithm is proposed to maximize the network lifetime with the constraint of link SER. Table I describes the lifetime maximizing cooperative routing (LMCR) algorithm in detail. It is assumed that each node broadcasts periodically HELLO packets to its neighbors to update the topology information. Through measuring the average strength of the HELLO packets, each node can evaluate the channel variance between itselef and its any neighbor. According to the derived link cost formulas for non-cooperative and cooperative link, the cost on each link is constructed. The optimal route can avoid the inefficient use of certain critical nodes with little residual energy, whose cost is computed by the summation of the link costs on the path. For a route $\omega \in \Omega$, denote ω_i as the ith hop of this route. The path can be formulated as $\min\limits_{\omega \in \Omega} \sum\limits_{\omega_i \in \omega} LC_{\omega_i}$,where Ω denotes the set of all possible routes. Thus, the minimization problem can be solved by applying the distributed Bellman-Ford shortest-path routing algorithm [11]. In this case, it can be approved the routing problem is $NP-complete$.

V. Simulation Results

In this section, the performance of network lifetime is compared between LMCR and other traditional routing schemes such as MTE and FA proposed in [5] and [6]. In addition,

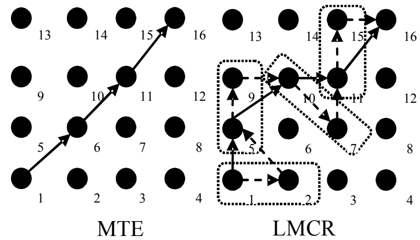

Fig. 2. An example showing the solution by MTE and LMCR in grid topology where node 1 is the source and node 16 is the destination.

concept of network lifetime defined as the time when the first sensor is depleted with energy or no sensor has enough energy for transmission during a data collection is adopted. We measure it in the total number of sent packets. The packet size is 1080 bits. Also, network size and average SER are changed to analyze the relation between performance improvement and different network factors. The detailed parameters used throughout the simulation are shown in Table II. In particular, networks with regular grid topology plotted in Fig. 2 and random topology are considered, respectively.

Table II Simulations Parameters

f_c	2.5GHz	E_{init}	1J
N_0	-40dBm	P_{to}	15mW
Data Rate R	10KB/s	P_{ro}	12mW

First, simulation is performed in the conventional grid networks with different number of nodes. The distance between adjacent nodes is set as 10m. Besides, source and destination nodes are randomly selected. Given a certain network topology, the SER is set as 10^{-4}, sense range is 18m, BPSK modulation is adopted. Fig. 3 shows the lifetime performances of different routing algorithms for different network sizes. It can be seen clearly that the proposed LMCR performs much better than MTE and FA, and FA outperforms the MTE scheme. With the decrease of the network size, the total traffic in the network decreases. It is easy to understand that the smaller number of nodes in the network, the less total energy will be consumed. Relatively the total lifetime is much shorter than the bigger network.

Second, the random network scenario with 36 nodes uniformly distributed in the $100m \times 100m$ area is considered. The sense range of each node is set as 25 meters. Fig. 4 shows the network lifetime over different link SER constraints. The quantities are averaged over 100 different topologies. Given a certain network topology, the traffic is generated between one pre-selected source-destination pair and the iteration time is 100. As shown, MTE has the worst performance, while the FA scheme performs much better than MTE when SER is above 10^{-5} . When the SER is low, in other words, the performance requirement is high, both MTE and FA schemes have the lifetime of zero. This is because when the SER is too low, the transmission energy is so high that the initial energy of the source can not even support the first transmission, thus, the lifetime is zero. Otherwise, when the SER is high, the required

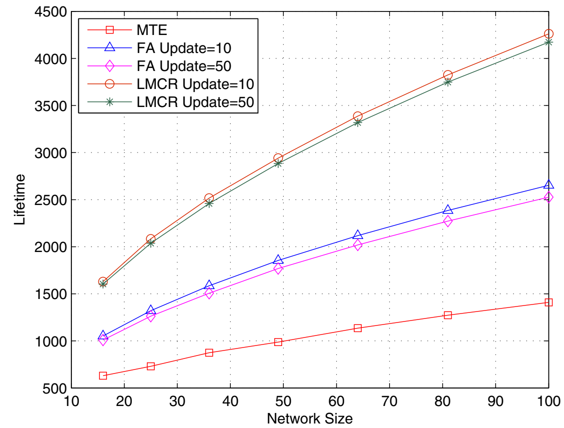

Fig. 3. Network lifetime versus network size for $\varepsilon_c = 10^{-4}$ in a 100×100 grid where "Update" represents the broadcast period of "HELLO" packets, which is measured by the number of sent packets.

transmission energy is low according to Eq. (6), so the network can load certain amounts of packets. Our scheme LMCR has much better performance compared with other two schemes when the SER is low, this is because, the required transmission energy according to Eq. (11) is very low, so the network can support over 260 times of transmissions. Besides, when the SER is as high as 10^{-3}, there is a cross point between LMCR and FA, this is because the transmission energy is at the same order, but LMCR will consume more circuit energy, so the performance deteriorates when SER is bigger than 10^{-3}. We also note that LMCR with QPSK modulation outperforms BPSK modulation when SER is bigger than 2.5×10^{-7}. Although the QPSK modulation needs more transmission energy than BPSK modulation when the SER is fixed, as with the M parameter increases, the minimum Euclidean distance of the constellation diagram is becoming shorter [10]. The transmission time is reduced while the transmission period of the fixed-length data packet is becoming shorter, which means more circuit energy will be saved. For QPSK modulation, the saved circuit energy is much more than the wasted transmission energy, therefore, QPSK outperforms BPSK significantly. But when the SER is lower than 2.5×10^{-7}, the performance of QPSK is worse than BPSK, this is because the saved circuit energy can not compensate for the wasted extra transmission energy compared with BPSK.

According to the above analysis, for the higher SER requirement, LMCR algorithm can significantly outperform other routing schemes. Besides, lifetime performance over different network environment with BPSK modulation under the same SER constraint is presented in Fig. 5. We can see that when the number of nodes is small, the lifetime is low for all these schemes. This is because the density of nodes is too low, which means that the adjacent nodes can not easily contact with each other in the sense range of 25m. Therefore, it is likely that the source can not reach the destination. In this case, the network can not work well, and it has the same meaning

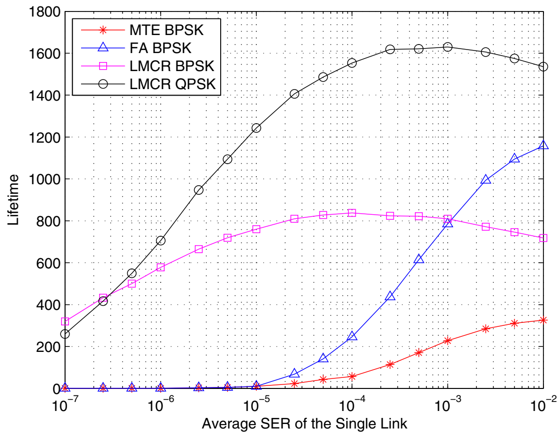

Fig. 4. Network lifetime versus average SER on the link

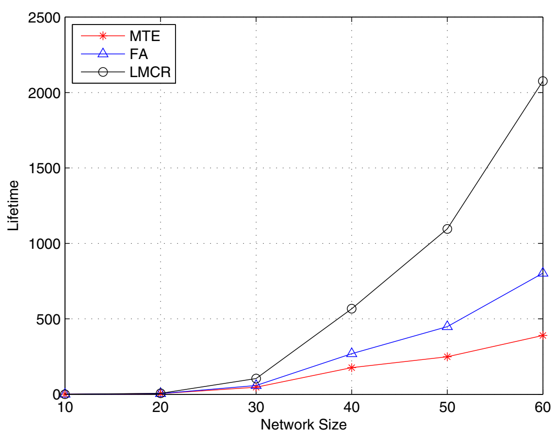

Fig. 5. Network lifetime versus network size for $\varepsilon_c = 10^{-4}$ in which nodes randomly placed in an $100m \times 100m$ area

as death. The density of nodes increases with the increase of node numbers, as the probability of successfully completing the communication process is high, accordingly the network lifetime is relatively long. It is also shown that our new scheme LMCR has a much better performance compared with MTE and FA schemes.

VI. Conclusion

In this paper, we have combined routing algorithm at network layer and cooperative DF protocol at physical layer to maximize the network lifetime. Optimal power allocation schemes which minimize the weighted transmission power while meeting the average SER requirement are derived. Besides, link costs representing the total power consumption including transmission and circuit power expenditure are constructed. Simulation results show that compared with MTE and FA schemes, the proposed LMCR algorithm can always achieve the best lifetime performance in different scenarios. It should be noted that the analysis does not take into consideration some important QoS parameters, such as the end-to-end SER and throughput on the path. In addition, the multiple-flow scenario and the best relay selection are not investigated. Future research directions will be focusing on formulating the power allocation and designing the routing algorithm guaranteeing the end-to-end constraints in both single-flow and multiple-flow networks.

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