Energy-Balanced Cooperative Routing in Multihop Wireless Ad Hoc Networks

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***Abstract*—Cooperative communication (CC) allows multiple nodes to simultaneously transmit the same packet to the receiver so that the combined signal at the receiver can be correctly decoded. Since the cooperative communication can reduce the transmission power and extend the transmission coverage, it has been considered in minimum energy routing protocols to reduce the total energy consumption. However, previous research on cooperative routing only focuses on minimizing the total energy consumption from the source node to the destination node, which may lead to the unbalanced energy distribution among nodes. In this paper, we aim to study the impact of cooperative routing on balancing the energy distribution among nodes. By introducing a new routing scheme which carefully selects cooperative relay nodes and assigns their transmission power, our cooperative routing method can balance the energy among neighboring nodes and maximize the remaining lifetime of the network. Simulation results demonstrate that the proposed cooperative routing algorithm significantly balances the energy distribution and prolongs the lifetime of the network.**

***Index Terms*—Energy balancing, cooperative routing, multihop wireless networks.**

I. INTRODUCTION

Multihop wireless ad hoc networks have various civilian or military applications and have drawn considerable attention in recent years. One of the major concerns in designing multihop ad hoc networks is energy consumption as wireless nodes are often powered by batteries only. Energy-aware routing protocols [1]–[4] have been well-studied. Most of these energy-aware routing protocols consider new energy-related metrics, such as a function of the energy required to communicate over a link [1], [2] or the nodes' remaining lifetime [3] or both [4], instead of classic route metric such as hop count or delay.

Recently, a new class of communication techniques, cooperative communication (CC) [5], has been introduced to allow single antenna devices to take the advantage of the multiple-input-multiple-output (MIMO) systems. This cooperative communication explores the broadcast nature of the wireless medium and the nodes that have received the transmitted signal can cooperatively help relaying data for other nodes. Recent works [6]–[10] have investigated the impacts of cooperative communications on the problem of minimum energy routing. Khandani *et al.* [6] first formulate the problem of finding the minimum energy cooperative route for a wireless network and develop a dynamic-programming-based algorithm as well as two polynomial-time heuristic algorithms. Li *et al.* [7] study the finding minimum energy cooperative route problem by assuming that the last L predecessor nodes along the path are allowed for cooperative transmission to the next hop. In [8], a cooperation-based routing algorithm (MPCR) is proposed to construct the minimum-power route using any number of the proposed cooperation-based building blocks which require the least possible transmission power. In [9], [10], the cooperative multi-hop routing under more complex fading model is studied for the purpose of energy savings. These methods only focus on minimizing the total energy consumption of routing the packet from the source node to the destination node. However, it is well known that consistently using the minimum cost path for routing may lead to uneven energy distribution among nodes, which could substantially reduce the network life-time.

Therefore, in this paper, we focus on studying the impact of cooperative communication on energy balancing among nodes. We introduce a new cooperative scheme to select cooperative relay nodes from one-hop neighbors around the current node and make smart decisions on their transmission power. It can be applied to any underlying energy-aware routing protocol, and only need local information to perform the optimization on cooperative communications. We formally prove that our cooperative routing method can indeed balance the energy consumption among nodes and prolong the network lifetime. Notice that Pandana *et al.* [4] also study how to maximize network lifetime by using cooperative routing. However, they limit the scope of cooperative relay within the nodes on the route and concentrate on minimizing the total energy consumption of all cooperative nodes. This limits the effectiveness of their method on energy balancing. In contrast, we allow all one-hop neighbors around the current node to participate the energy-balanced cooperative relay. In addition, under our cooperative communication model, one of their methods regresses to the minimum energy path based routing.

II. NETWORK MODELS AND ASSUMPTIONS

We first briefly introduce the network models and assumptions for our proposed cooperative routing. Consider a connected multihop wireless network with n nodes $v_1, v_2, \cdots, v_n$. Every node v_i can adjust its transmission power $P(v_i)$ which is limited by a maximum value P_{MAX}. If a sending node v_i wants to communicate with node v_j directly, the transmission power of node v_i must satisfy

$$P(v_i) \cdot (d(v_i, v_j))^{-\alpha} \geq \tau \quad (P(v_i) \leq P_{MAX}),$$

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Here, α is the path loss exponent (between 2 and 4), τ is the minimum average signal-to-noise ratio (SNR) for decoding received data successfully, and $d(v_i, v_j)$ is the distance between nodes v_i and v_j. Let $N(v_i)$ represent the set of direct neighbors of v_i under maximum transmission power, i.e., for any $v_j \in N(v_i)$, $(d(v_i, v_j))^{-\alpha} \cdot \tau \leq P_{MAX}$.

Our cooperative communication (CC) model is similar to those of [5], [9] but different from those of [4], [8]. CC model takes advantage of the physical layer design that combines partial signals containing the same information to obtain the complete information. Thus, a complete communication from v_i to v_j can be achieved by CC if v_i transits the same signal simultaneously with a set of helper nodes $H(v_i)$ and their transmission power satisfies

$$\sum_{v_k \in v_i \cup H(v_i)} P(v_k) \cdot (d(v_k, v_j))^{-\alpha} \geq \tau \quad (P(v_k) \leq P_{MAX}).$$

Carefully selecting the helper set and using CC can reduce the transmission power. More importantly, CC can also spread the energy consumption among multiple nodes which can benefit the energy balancing in the network. In this paper, we apply CC in the one-hop neighborhood along the energy efficient path to balance the energy in the network.

We assume that the initial battery level of each node v_i is $C^0(v_i)$ and the current battery level of v_i is $C^t(v_i)$. (For all definitions, when the time t is clear in context, it could be ignored.) When $C(v_i) = 0$, the node v_i is running out of its battery and dies. When node v_i transmits a packet using transmission power $P^t(v_i)$, its battery level reduces to $C^{t+1}(v_i) = C^t(v_i) - P^t(v_i)$. Here, for simplicity, we ignore the receiving energy cost and assume the unit size of packet.

In this paper, we assume that the underlying routing decision has been made by certain non-CC routing strategy (such as energy-efficient ad hoc routing protocols or shortest path based routing algorithms). We only focus on applying cooperative communication technique to improve the energy balancing along the selected path. For simplicity, we assume an all-to-all communication scenario, thus there are $n(n-1)$ routes in the network. Given a fixed routing strategy, let β_i be the number of routes passing via node v_i or using v_i as the source. Here, we do not consider the routes which end at v_i since such paths do not consume any energy of v_i. Let β_{ik} denote the number of routes that include the direct link $v_i v_k$. Obviously, for node v_i, $\sum_{k=1}^{|N(v_i)|} \beta_{ik} = \beta_i - (n-1)$, since there is $n-1$ paths end at v_i. Under the all-to-all communication scenario, the expected energy consumption of node v_i is

$$EP(v_i) = \sum_{v_k \in N(v_i)} P_{ik} \cdot \frac{\beta_{ik}}{n(n-1)}.$$

Here, $P_{ik} = (d(v_i, v_k))^{\alpha} \cdot \tau$ which is the energy consumption to support a direct link $v_i v_k$. Notice that $EP(v_i)$ is a fixed parameter if the underlying routing strategy and traffic demands are fixed. In addition, it can be adopted to any traffic pattern.

Since the total battery energy of v_i is $C^0(v_i)$, the expected number of routes that v_i can participate in is $\frac{C^0(v_i)}{EP(v_i)}$, i.e., the estimated lifetime of v_i. Then $\min_{v_i \in V}\{\frac{C^0(v_i)}{EP(v_i)}\}$ represents the estimated lifetime of the network. When node v_i's current energy is $C^t(v_i)$, the current remaining lifetime of v_i can be represented as $L^t(v_i) = \frac{C^t(v_i)}{EP(v_i)}$. For a node set S, its remaining lifetime is defined as $L(S) = \min_{v_i \in S} L(v_i)$.

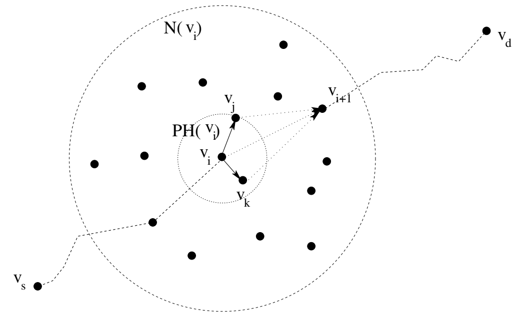


Fig. 1. Illustration of EBCR to pick the helper set $H(v_i)$ for current node v_i which will send the same packet simultaneously to next hop node v_{i+1}. The large circle represents neighborhood $N(v_i)$ of v_i and the small circle represents one of the potential cooperative helper sets $PH(v_i)$ of v_i.

III. Energy-Balanced Cooperative Routing (EBCR)

In this section, we first introduce how our proposed cooperative routing can balance the energy along a single path from its source v_s to its destination v_d, then we discuss how the proposed cooperative routing performs under multiple-flow routing and prove its optimality.

A. Balancing Energy Along Single Path

Our cooperative routing algorithm starts from a path generated by an underlying non-cooperative routing protocol. Assume the path is $\pi = v_0, v_1, v_2, \cdots, v_h$, where $v_s = v_0$ and $v_d = v_h$. Our goal is to perform CC for each hop $v_i v_{i+1}$ along the path to maximize v_i's remaining lifetime. See Fig. 1 for illustration. Here, we assume that each node exchanges the information of remaining energy, expected energy consumption, and position with all of its neighbors.

In order to apply CC, we need to pick the helper set for current node v_i which will send the same packet simultaneously to v_{i+1}. We first define a potential cooperative helper set $PH(v_i) \subset N(v_i)$. Obviously, in $PH(v_i)$, we only consider those neighbors of v_i closer to v_i than v_{i+1}; otherwise directly sending the packet to v_{i+1} is more energy efficient. Thus, $PH(v_i)$ could be any subset of $\{v_k | v_k \in N(v_i) \text{ and } d(v_i, v_k) < d(v_i, v_{i+1})\}$, as illustrated in Fig. 1.

Given a potential helper set $PH(v_i)$ with size k, we now introduce an algorithm to calculate the remaining lifetime of v_i and its helper set $H_k(v_i)$ under CC model. The basic idea of the algorithm is as follows. We first calculate the transmission power $P^h(v_i)$ needed to reach the farthest neighbor inside $PH(v_i)$, then use it to update the estimated remaining lifetime of v_i by $L^{t+1}(v_i) = \frac{C^t(v_i) - P^h(v_i)}{EP(v_i)}$. For other nodes v_j in $PH(v_i)$, let estimated remaining lifetime $L^{t+1}(v_j) = \frac{C^t(v_j)}{EP(v_j)}$. Then we sort all these $k+1$ nodes (define a set A) in the descending order by its remaining lifetime

$L^{t+1}(v_j)$. The sorted set is $\{v'_1, v'_2, \cdots, v'_{k+1}\}$. Our algorithm will greedily pick those nodes with larger remaining lifetime to be helpers of v_i, until their cumulated signal strength at v_{i+1} is larger than or equal to τ, i.e., $\sum_{j=1}^{w}(L^{t+1}(v'_j) - L^{t+1}(v'_{w+1}))EP(v'_j)(d(v'_j, v_{i+1}))^{-\alpha} \geq \tau$. If the cumulative power strength of the first w nodes in $PH(v_i)$ is enough to reach v_{i+1}, we will balance every helper's remaining lifetime after the transmission, i.e., the lifetime of all w nodes is the same at L_x. Thus,

$$\sum_{j=1}^{w}(L^{t+1}(v'_j) - L_x)EP(v'_j)(d(v'_j, v_{i+1}))^{-\alpha} = \tau.$$

Further,

$$L_x = \frac{\sum_{j=1}^{w} L^{t+1}(v'_j) \cdot EP(v'_j)(d(v'_j, v_{i+1}))^{-\alpha} - \tau}{\sum_{j=1}^{w} EP(v'_j)(d(v'_j, v_{i+1}))^{-\alpha}}.$$

If the energy consumption of v_i with CC $(L^{t+1}(v_i) - L_x)EP(v_i) + P^h(v_i)$ is less than the energy consumption of direct transmission $\tau \cdot (d(v_i, v_{i+1}))^{\alpha}$, we return L_x as the estimated lifetime and the first w nodes $\{v'_1, v'_2, \cdots, v'_w\}$ as the helper set $H_k(v_i)$. If $L_x < 0$ (together with all nodes in $H(v_i)$, the CC signal strength is still not enough to reach v_{i+1}) or $(L^{t+1}(v_i) - L_x)EP(v_i) + P^h(v_i) \geq \tau \cdot (d(v_i, v_{i+1}))^{\alpha}$, then CC with nodes in $PH(v_i)$ is not useful and v_i may need to directly send the packet to v_{i+1}. In that case, we return $L_k^{t+1}(v_i) = -\infty$ and $H_k(v_i) = \{v_i\}$. Algorithm 1 shows the detail. By running it, for a given $HP(v_i)$, we can decide which nodes have to involve into the cooperative routing.

Algorithm 1 Calculate Lifetime and Helper Set

Input: Potential helper set $PH(v_i)$ and its size $k = |PH(v_i)|$.
Output: Estimated lifetime $L_k^{t+1}(v_i)$ of v_i and its corresponding helper set $H_k(v_i)$.

Let $A = PH(v_i) \cup \{v_i\}$.
Calculate transmission energy of v_i need to reach the farthest helper: $P^h(v_i) = \max_{v_j \in A}(d(v_i, v_j))^{\alpha} \cdot \tau$.
Update the estimated remaining lifetime: $L^{t+1}(v_i) = \frac{C^t(v_i) - P^h(v_i)}{EP(v_i)}$ and $L^{t+1}(v_j) = \frac{C^t(v_j)}{EP(v_j)}$ for every other node $v_j \in A$.
Sort all elements in A in the descending order of its remaining lifetime $L^{t+1}(v_j)$. Assume that the sorted set is $\{v'_1, v'_2, \cdots, v'_{k+1}\}$.
$w = 1$.
while $w \leq k$ and $\sum_{j=1}^{w}(L^{t+1}(v'_j) - L^{t+1}(v'_{w+1}))EP(v'_j)(d(v'_j, v_{i+1}))^{-\alpha} < \tau$ **do**
    $w++$.
end while
Let $L_x = \frac{\sum_{j=1}^{w} L^{t+1}(v'_j) \cdot EP(v'_j)(d(v'_j, v_{i+1}))^{-\alpha} - \tau}{\sum_{j=1}^{w} EP(v'_j)(d(v'_j, v_{i+1}))^{-\alpha}}$
if $L_x \geq 0$ and $(L^{t+1}(v_i) - L_x)EP(v_i) + P^h(v_i) < \tau \cdot (d(v_i, v_{i+1}))^{\alpha}$ **then**
    return $L_k^{t+1}(v_i) = L_x$ and $H_k(v_i) = \{v'_1, v'_2, \cdots, v'_w\}$
else
    return $L_k^{t+1}(v_i) = -\infty$ and $H_k(v_i) = \{v_i\}$
end if

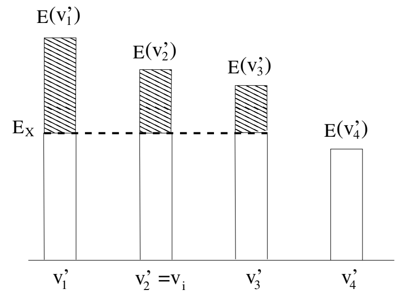


Fig. 2. Example for Algorithm 1.

Fig. 2 illustrates a simple example where there are 4 nodes inside $A = PH(v_i) \cup \{v_i\}$. Under CC model, the source v_i will first send the packet to other nodes in A. Then v_i will refresh its lifetime. The sorted remaining lifetime of the nodes in A is shown in the figure. The source v_i is assumed to have the second longest remaining lifetime, i.e. $v'_2 = v_i$. Based on Algorithm 1, we try to find first w nodes whose cumulated signal strength at v_{i+1} is strong enough as τ. In this example, $w = 3$. Then a target remaining lifetime L_x is calculated. As the output of Algorithm 1, v'_1 and v'_3 will help v'_2 (v_i) to perform CC transmission. After the transmission, the remaining lifetime of these three nodes is L_x.

Now we are ready to present our main algorithm (Algorithm 2) of the proposed energy-balanced cooperative routing (EBCR). Basically, it tries all possible initial setting of $PH(v_i)$ (m such settings) by running Algorithm 1 for each setting and picks the solution with the largest remaining lifetime as the final decision. If the best solution $L_{k*}^{t+1}(v_i) \geq 0$, we perform CC with its helper set $H_{k^*}(v_i)$, otherwise, send the packet directly to v_{i+1}. Notice that the proposed EBCR algorithm only use 1-hop neighbor information around node v_i and its time complexity is only $O(m^2)$ where $m \leq N(v_i)$. Thus, it is very efficient in term of computation cost.

Algorithm 2 Energy-Balanced Cooperative Routing (EBCR)

Sort all nodes $v_k \in N(v_i)$ in increasing order of $d(v_i, v_k)$. Assume that the ordered list is $v'_1, v'_2, \cdots, v'_{|N(v_i)|}$ and $v'_m = v_j$.
for $k = 1, 2, \cdots, m$ **do**
    Let $PH(v_i) = \{v'_1, v'_2, \cdots, v'_k\}$.
    Run Algorithm 1 which returns $L_k^{t+1}(v_i)$ and $H_k(v_i)$.
end for
Among m outputs, let $L_{k^*}^{t+1}(v_i)$ be the largest remaining lifetime of v_i and $H_{k^*}(v_i)$ be the corresponding helpers.
if $L_{k*}^{t+1}(v_i) \geq 0$ **then**
    Node v_i sends the packet to nodes in $H_{k^*}(v_i)$.
    Assign all nodes $v_j \in H_{k^*}(v_i)$ transmit the packet simultaneously to v_{i+1} using power $(L^t(v_j) - L_{k^*}^{t+1}(v_i))EP(v_j)$.
else
    v_i send packet to v_{i+1} directly.
end if

Next we formally prove that our proposed energy-balanced cooperative routing can improve the lifetime of the network.

Theorem 1: For a routing task between a pair of source and destination nodes, the proposed energy-balanced cooperative routing (EBCR) can improve the lifetime of the network.

Proof: Assume that $L(V)$ and $L'(V)$ are the lifetime of the network V with and without the proposed cooperative routing, respectively. In the network, there are three types of nodes: nodes in the original path π (denoted as R), nodes acting as helpers during CC (denoted as H), and nodes which do not participate in any packet forwarding process even under CC (denoted as U). So $V = R \cup H \cup U$. Assume that $L(S)$ and $L'(S)$ are the minimum lifetime of node set S with and without cooperative routing, respectively. Then we consider the minimum lifetime of these three types of nodes separately. First, the lifetime of U does not change, i.e., $L(U) = L'(U)$. Second, the lifetime of helpers H may be reduced by using CC ($L(H) \leq L'(H)$). However, since our cooperative routing guarantees that all helpers' lifetime is not less than the sender's lifetime after cooperative routing, $L(H) \geq L(R)$. Third, the lifetime of R must be extended by using CC, thus $L(R) \geq L'(R)$. Since $L(V) = \min\{L(R), L(H), L(U)\} = \min\{L(R), L(U)\}$ and $L'(V) = \min\{L'(R), L'(H), L'(U)\}$, we have $L(V) \geq L'(V)$. ■

B. Balancing Energy Along Multiple Routes

So far, we only consider to cooperatively route a single flow in the network. The proposed method can also handle multiple flows by serving them in turn. However, different serving orders may lead to different lifetime of the network. Fortunately, with any serving order our cooperative routing protocol can guarantee the improvement of network lifetime compared with the routing algorithms without using CC.

Theorem 2: For a routing task between k pairs of source and destination nodes, the proposed energy-balanced cooperative routing (EBCR) can improve the network lifetime.

Proof: Similarly, we define that $L(S)$ and $L'(S)$ are the minimum lifetime of node set S with and without cooperative routing, respectively. When $k = 1$, we already prove that $L(V) \geq L'(V)$ in Theorem 1. Now we consider that $k > 1$, i.e., there are k packet flows in the network. We want to prove that after all of these k packets $p_1, p_2, \cdots, p_k$ arrive to their final destinations, $L(V) \geq L'(V)$.

The proving technique is similar with the one used in Theorem 1. We now divide the all nodes V into $k+1$ disjoint node sets. With the cooperative routing, we divide V into node sets: $R_1, R_2, \cdots, R_k, U$. Here, R_i includes a subset of nodes participate in the cooperative routing of packet p_i and U is the set of nodes which do not participate any route. If a node v_k participates multiple flows, it only belongs to the set R_i in the last flow it participates (i.e., p_i is the last packet it transmits). Obviously, $V = R_1 \cup R_2 \cup \cdots \cup R_k \cup U$. Similarly, we can define $k+1$ node sets for the case without cooperative routing, and let them be $R'_1, R'_2, \cdots, R'_k$ and U'. $V = R'_1 \cup R'_2 \cup \cdots \cup R'_k \cup U'$.

First, $U \subset U'$ since some nodes in U' will be helpers in cooperative routing. Thus, $L(U) \geq L'(U')$. Assume that v_{min} is the node with least remaining lifetime in set R_j. It is either a node on the original route of packet p_j or a helper for a node on that route. If it is a node on the original route of packet p_j, the remaining lifetime of v_{min} must be larger than or equal to the lifetime of the same node in the set R'_j, because our algorithm can guarantee to extend the lifetime of node v_i at each step. Thus, $L(R_j) = L(v_{min}) \geq L'(v_{min}) \geq L(R'_j)$. If the node v_{min} is a helper of a node v_p on that route of packet p_j, there are three cases and we discuss them one by one.

Case 1: The last packet handled by v_p is p_j, i.e., $v_p \in R_j$. Based on our algorithm, $L(v_{min}) \geq L(v_p)$, since v_{min} is the helper of v_p. Notice that the remaining lifetime of v_p must also be larger than or equal to the lifetime of the same node in the set R'_j. Consequently, $L(R_j) = L(v_{min}) \geq L(v_p) \geq L'(v_p) \geq L'(R'_j)$.

Case 2: The last packet handled by v_p is not p_j but another packet p_s, and v_p is on the route of packet p_s. Thus, $v_p \in R_s$ and $v_p \in R'_s$. Recall that when v_p involves into p_j's forwarding, the remaining lifetime of v_{min} is already larger than or equal to the remaining life of v_p, thus $L(v_{min}) \geq L(v_p)$. And in the end, the remaining lifetime of v_p is also greater than or equal to the remaining life of the same node in R'_s at that time. Therefore, $L(R_j) = L(v_{min}) \geq L(v_p) \geq L'(v_p) \geq L'(R'_s)$.

Case 3: The last packet handled by v_p is not p_j but another packet p_s, and v_p is a helper for a node v_q on the route of packet p_s. Based on our cooperative routing algorithm, $L(v_p) \geq L(v_q)$ and $L(v_q) \geq L'(v_q)$. Hence, $L(R_j) = L(v_{min}) \geq L(v_p) \geq L(v_q) \geq L'(v_q) \geq L'(R'_s)$.

In summary, for any set R_i, we can always find a set R'_j such that $L(R_i) \geq L'(R'_j)$. Since $L(U) \geq L'(U')$, $L(V) = \min\{L(R_1), \cdots, L(R_k), L(U)\}$ and $L'(V) = \min\{L'(R'_1), \cdots, L'(R'_k), L'(U')\}$, we have $L(V) \geq L'(V)$. ■

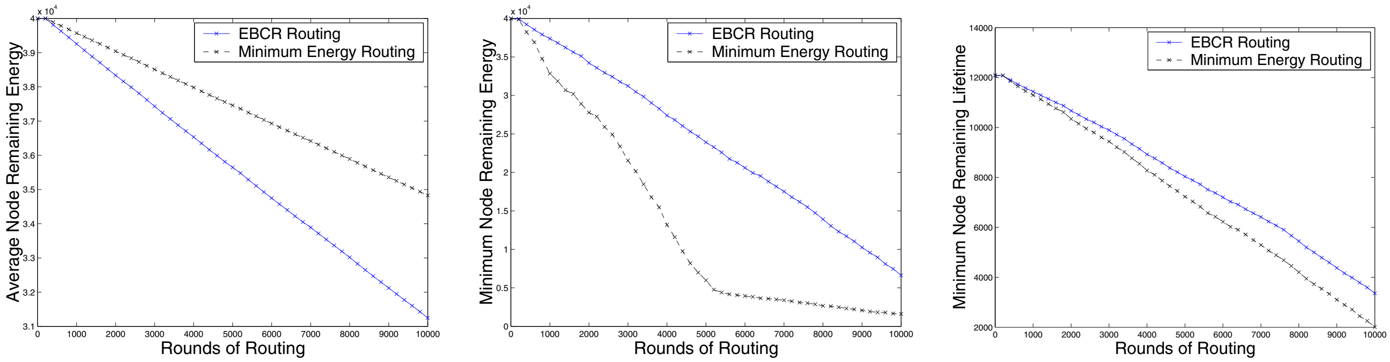
IV. Simulation

We evaluate our proposed EBCR protocol by comparing its performances with the classic minimum energy path based routing protocol. The underlying wireless networks and traffic demands (source-destination pairs) are randomly generated. For convenience, we set the path loss factor $\alpha = 2$ and the SNR threshold $\tau = 1$. In the simulations, we take two metrics as the performance measurement:

- **Node Remaining Energy:** current energy level of each node $C^t(v_i)$. We report the average or minimum node remaining energy of all the nodes in the network.
- **Node Remaining Lifetime:** current remaining lifetime $L^t(v_i) = \frac{C^t(v_i)}{EP(v_i)}$. We focus on the minimum node remaining lifetime among all nodes in the network, i.e., the remaining lifetime of the network $L^V = \min_{v_i \in V} L^t(v_i)$.

We repeat the experiment for multiple times and report the average values of these metrics.

For the first set of simulations, we randomly generate a network with 500 wireless nodes in an area of 100×100. The value of P_{MAX} is set to 400, so that the maximum transmission range of a direct link is 20. The initial energy level of each node $C^0(v_i)$ is set to $40,000$. For the expected



(a) Average Node Remaining Energy (b) Minimum Node Remaining Energy (c) Minimum Node Remaining Lifetime

Fig. 3. Simulation results over $10,000$ routes on a 500-node random network.

energy consumption of each node $EP(v_i)$, we use the traffic pattern of all-to-all communication and the underlying minimum energy path routing to calculate. Simulations are run in rounds. In each round, we randomly pick a pair of nodes as the source and the destination. The minimum energy routing protocol send the packet directly along the least energy path between the source and the destination, while our energy-balanced cooperative routing protocol uses the neighbors of the nodes on the least energy path to cooperatively forward the packet. We run $10,000$ rounds (routes) in total and record the node remaining energy and lifetime after each 200 rounds. Fig. 3(a) shows the average node remaining energy of the network at reach round. With more routing task completed, the average node remaining energy of the network reduces. Since the minimum energy routing protocol aims to minimize the total transmission energy, its average node remaining energy is better than that of our routing method. However, Fig. 3(b) indicates that the minimum node remaining energy of our routing method is much higher than that of the minimum energy routing protocol, especially after a certain rounds of routing. This shows that our energy-balanced routing can indeed lead to more even energy consumption among nodes. Additionally, Fig. 3(c) shows the minimum node remaining lifetime of both algorithms. Clearly, our routing algorithm can prolong the lifetime of the network significantly compared with the minimum energy routing protocol.

In the second set of simulations, we randomly generate 50 networks with 100 wireless nodes in the area of 100×100. P_{MAX} is still set to 400 but the initial energy level of each node is set to $18,000$ instead. The simulations are still run in rounds with randomly picked source-destination pairs. The total round number is 200. Table I summarizes the average performances (the node remaining energy (R-Energy) and lifetime (R-Lifetime) after the 200 rounds) among these 50 networks. From these results, the conclusion is consistent with the one in the first set of simulation. Even though our cooperative routing may cost more energy in total, it can indeed balance the remaining energy among nodes and prolong the lifetime of the network. This confirms the theoretical proofs we have in Section III.

TABLE I
SIMULATION RESULTS OVER 50 RANDOM NETWORKS WITH 100-NODES.

Routing Method	Avg R-Energy	Min R-Energy	Min R-Lifetime
Min energy routing	10372	4812.8	739.9
EBCR routing	10065	8361.5	791.8

V. CONCLUSION

In this paper, we study the impact of cooperative communication on energy balancing in multihop routing. We introduce a novel routing scheme (EBCR) to select cooperative relay nodes and their transmission power for each hop. It can be applied to any underlying energy-aware routing protocol with only local information. We formally prove that our cooperative routing method EBCR can indeed balance the energy among nodes and prolong the remaining lifetime of the network. Simulation results confirm the nice performance of our proposed method over the minimum energy routing.

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