Distributed Energy-Efficient Cooperative Routing in Wireless Networks

Ahmed S. Ibrahim, *Student Member, IEEE,* Zhu Han, *Member, IEEE,* and K. J. Ray Liu, *Fellow, IEEE*

***Abstract*—Recently, the merits of cooperative communication in the physical layer have been explored. However, the impact of cooperative communication on the design of the higher layers has not been well-understood yet. Cooperative routing in wireless networks has gained much interest due to its ability to exploit the broadcast nature of the wireless medium in designing power-efficient routing algorithms. Most of the existing cooperation-based routing algorithms are implemented by finding a shortest-path route first and then improving the route using cooperative communication. As such, these routing algorithms do not fully exploit the merits of cooperative communications, since the optimal cooperative route might not be similar to the shortest-path route. In this paper, we propose a cooperation-based routing algorithm, namely, the Minimum Power Cooperative Routing (MPCR) algorithm, which makes full use of the cooperative communications while constructing the minimum-power route. The MPCR algorithm constructs the minimum-power route, which guarantees certain throughput, as a cascade of the minimum-power single-relay building blocks from the source to the destination. Thus, any distributed shortest path algorithm can be utilized to find the optimal cooperative route with polynomial complexity. Using analysis, we show that the MPCR algorithm can achieve power saving of 65.61% in regular linear networks and 29.8% in regular grid networks compared to the existing cooperation-based routing algorithms, where the cooperative routes are constructed based on the shortest-path routes. From simulation results, MPCR algorithm can have 37.64% power saving in random networks compared to those cooperation-based routing algorithms.**

***Index Terms*—Cooperative diversity, distributed routing, power saving, QoS.**

I. Introduction

ENERGY saving is one of the main objectives of routing algorithms for different wireless networks such as mobile ad hoc networks [1] and sensor networks [2]. In [3], it was shown that in some wireless networks such as ad hoc networks, nodes spend most of their power in communication, either sending their own data or relaying other nodes' data. In addition to saving more energy, selected routes may guarantee certain Quality of Service (QoS). *QoS routing* is of great importance to some wireless applications (e.g. multimedia applications) [4]. Recently, there have been much interest in studying the interaction between the various network layers, which is known in the literature as *cross-layer* design [5]. In particular, the physical information about the wireless medium can be provided to the upper layers in order to provide efficient scheduling, routing, resource allocation, and flow control algorithms. For instance in Rayleigh networks, Haenggi *et al.* showed that for high end-to-end delivery probabilities and given certain delay constraint, long-hop schemes save more energy than that of the nearest-neighbor routing algorithm [6].

Recently, *cooperative communication* for wireless networks has gained much interest due to its ability to mitigate fading through achieving spatial diversity, while offering flexibility in addition to traditional Multiple-Input Multiple-Output (MIMO) communication. In cooperative communications, relays are assigned to help a sender in forwarding its information to its receiver. Thus, the receiver gets several replicas of the same information via independent channels. Various cooperative diversity protocols were proposed and analyzed in [7]-[11]. In [7], Laneman *et al.* described various techniques of cooperative communication, such as decode-and-forward, amplify-and-forward, selection relaying, and incremental relaying. In [8] and [9], relay-selection schemes for single- and multi-node decode-and-forward cooperative systems were proposed. In [10], the authors have provided symbol error rate performance analysis for the decode-and-forward multi-node scheme. Finally, a distributed relay-assignment algorithm for wireless communications has been proposed in [11].

The merits of the cooperative communications in the physical layer have been explored, however, the impact of the cooperative communications on the design of the higher layers has not been well-understood yet. Routing algorithms, which are based on the cooperative communications, are known in the literature as *cooperative routing* algorithms [12]. Designing cooperative routing algorithms is an interesting research area and can lead to significant power savings. The cooperative routing makes use of two facts: the Wireless Broadcast Advantage (WBA) in the broadcast mode and the Wireless Cooperative Advantage (WCA) in the cooperative mode. In the broadcast mode each node sends its data to more than one node, while in the cooperative mode many nodes send the same data to the same destination.

The cooperative routing problem has been recently considered in the literature [12]-[17]. In [12], the optimum route is found through a dynamic programming algorithm which is NP hard. Two heuristic algorithms (Cooperation Along the Minimum Energy Non-Cooperative Path (CAN-L) and Progressive Cooperation (PC-L)) are proposed in a centralized manner. In [13], two heuristic routing algorithms, namely, Cooperative routing along Truncated Non-Cooperative Route

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A. S. Ibrahim and K. J. R. Liu are with the Department of Electrical and Computer Engineering, University of Maryland, College Park, MD, 20742 USA (e-mail: {asalah, kjrliu}@umd.edu).

Z. Han is with the Department of Electrical and Computer Engineering, University of Houston, Houston, TX 77004 USA (e-mail: zhan2@mail.uh.edu).

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(CTNCR) and Source Node Expansion Routing (SNER) are proposed. These algorithms choose the minimum-power route while guaranteeing fixed transmission rate. In CTNCR, the shortest path is constructed first, then some of the nodes are truncated according to a specific power allocation. In SNER, the network is divided into two disjoint subsets: one that has the source initially and the other has the rest of the nodes. In each iteration one node that requires the least transmission power is added to the first set until the destination is reached. It is assumed that both the transmitter and receiver have perfect channel state information about the channel in a centralized manner.

In [14], Li *et al.* proposed the Cooperative Shortest Path (CSP) algorithm, which chooses the next node in the route that minimizes the power transmitted by the last L nodes added to the route. Sikora *et al.* presented in [15] an information-theoretic viewpoint of the cooperative routing in linear wireless network for both the power-limited and bandwidth-limited regimes. In addition, the authors in [15] analyzed the transmission power, required to achieve a desired end-to-end rate. In [16], Pandana *et al.* studied the impact of cooperative communication on maximizing the lifetime of wireless sensor networks. Finally, the authors in [17] proposed three cooperative routing algorithms, namely, relay-by-flooding, relay-assisted routing, and relay-enhanced routing. In the relay-by-flooding, the message is propagated by flooding and multiple hops. The relay-assisted routing uses cooperative nodes of an existing route and the relay-enhanced routing adds cooperative nodes to an existing route. Both of these routing schemes start with a route determined without cooperation.

Most of the existing cooperation-based routing algorithms are implemented by finding a shortest-path route first and then building the cooperative route based on the shortest-path one. Indeed, these routing algorithms do not fully exploit the merits of cooperative communications at the physical layer, since the optimal cooperative route might be completely different from the shortest-path route. In addition, most of these cooperation-based routing algorithms require a central node, which has global information about all the nodes in the network, in order to calculate the best route given a certain source-destination pair. Having such a central node may not be possible in some wireless networks. Particularly, in infrastructureless networks (e.g. ad hoc networks), routes should be constructed in a *distributed* manner, i.e., each node is responsible for choosing the next node towards the destination. These are our main motivations to propose a distributed cooperation-based routing algorithm that takes into consideration cooperative communications while constructing the minimum-power route.

In this paper, we consider the minimum-power routing problem with cooperation in wireless networks. The optimum route is defined as the route that requires the minimum transmission power while guaranteeing certain end-to-end throughput. First, we derive a cooperation-based link cost formula, which represents the minimum transmission power over a particular link, required to guarantee the desired QoS. The main contribution of this paper is the proposed cooperation-based routing algorithm, namely the Minimum Power Cooperative Routing (MPCR) algorithm, which can choose the minimum-power route while guaranteeing the desired QoS. For random network of 100 nodes, it will be shown that the MPCR algorithm can achieve power saving of 57.36% compared to the conventional shortest-path routing algorithms. Furthermore, it can achieve power saving of 37.64% with respect to the Cooperation Along the Shortest Non-Cooperative Path (CASNCP) algorithm, which finds the shortest-path route first then applies the cooperative communication upon the shortest-path route to reduce the transmission power. For regular linear network consisting of 100 nodes, we show in analysis that the power savings of the MPCR algorithm with respect to conventional shortest-path and CASNCP routing algorithms are 73.91% and 65.61%, respectively. For regular grid networks consisting of 100 nodes, we show that the power savings of the MPCR algorithm with respect to the shortest-path and CASNCP routing algorithms are 65.63% and 29.8%, respectively.

The rest of the paper is organized as follows. In the next section, we formulate the minimum-power routing problem and describe the network model. In Section III, we derive closed-form expressions for the minimum transmission power per hop. We propose two cooperation-based routing algorithms in Section IV, which are the MPCR and CASNCP routing algorithms. Then, we consider the regular linear and grid wireless networks and derive the analytical results for the power savings due to cooperation in these two networks. In Section V, we show the numerical results for the power savings of the proposed algorithm. Finally, Section VI concludes the paper.

II. Network Model and Transmission Modes

In this section, we describe the network model and formulate the minimum-power routing problem. Then, we present the direct transmission and cooperative transmission modes.

A. Network Model

We consider a graph $G(V, E)$ where V is the vertex set and E is the edge set. The number of nodes is $|V| = N$ nodes and the number of edges is $|E| = M$ edges. Given any source-destination pair (S, D), the goal is to find the $S - D$ route that minimizes the total transmission power, while satisfying a specific throughput. For a given source-destination pair, denote Ω as the set of all possible routes, where each route is defined as a set consisting of its hops. For a route $\omega \in \Omega$, denote ω_i as the i-th hop of this route. Thus, the problem can be formulated as

$$\min_{\omega \in \Omega} \sum_{\omega_i \in \omega} P_{\omega_i} \quad \text{s.t.} \quad \eta_\omega \geq \eta_o \ , \tag{1}$$

where P_{ω_i} denotes the transmission power over the i-th hop, η_ω is the end-to-end throughput, and η_o represents the desired value of the end-to-end throughput. Let η_{ω_i} denote the throughput of the i-th hop, which is defined as the number of successfully transmitted bits per second per hertz (b/s/Hz) of a given hop. Furthermore, the end-to-end throughput of a certain route ω is defined as the minimum of the throughput values of the hops constituting this route, i.e.,

$$\eta_\omega = \min_{\omega_i \in \omega} \eta_{\omega_i} \ . \tag{2}$$

It has been proven in [14] that the Minimum Energy Cooperative Path (MECP) routing problem, i.e., to find the

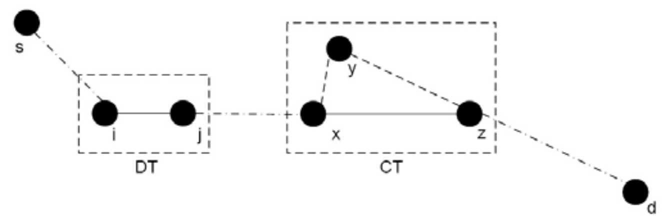


Fig. 1. Cooperative Transmission (CT) and Direct Transmission (DT) modes as building blocks for any route.

minimum-energy route using cooperative radio transmission, is *NP-complete*. This is due to the fact that the optimal path could be a combination of cooperative transmissions and point-to-point transmissions. Therefore, we consider two types of building blocks: direct transmission (DT) and cooperative transmission (CT) building blocks. In Fig. 1 the DT block is represented by the link (i, j), where node i is the sender and node j is the receiver. In addition, the CT block is represented by the links $(x, y), (x, z)$, and (y, z), where node x is the sender, node y is a relay, and node z is the receiver. The route can be considered as a cascade of any number of these two building blocks, and the total power of the route is the summation of the transmission powers along the route. Thus, the minimization problem in (1) can be solved by applying any distributed shortest-path routing algorithm such as the distributed Bellman-Ford algorithm [18].

B. Direct and Cooperative Transmission Modes

Let $h_{u,v}, d_{u,v}$, and $n_{u,v}$ represent the channel coefficient, length, and additive noise of the link (u, v), respectively. For the direct transmission between node i and node j, the received symbol can be modeled as

$$r^D_{i,j} = \sqrt{P^D \; d^{-\alpha}_{i,j}} \; h_{i,j} \; s + n_{i,j} \; , \tag{3}$$

where P^D is the transmission power in the direct transmission mode, α is the path loss exponent, and s is the transmitted symbol with unit power.

For the cooperative transmission, we consider a modified version of the decode-and-forward incremental relaying cooperative scheme, proposed in [7]. The transmission scheme for a sender x, a relay y, and a receiver z, can be described as follows. The sender sends its symbol in the current time slot. Due to the broadcast nature of the wireless medium, both the receiver and the relay receive noisy versions of the transmitted symbol. The received symbols at the receiver and the relay can be modeled as

$$r^C_{x,z} = \sqrt{P^C \; d^{-\alpha}_{x,z}} \; h_{x,z} \; s + n_{x,z} \tag{4}$$

and

$$r^C_{x,y} = \sqrt{P^C \; d^{-\alpha}_{x,y}} \; h_{x,y} \; s + n_{x,y} \; , \tag{5}$$

respectively, where P^C is the source transmission power in the cooperative transmission mode. Once the symbol is received, the receiver and the relay decode it. We assume that the relay and the receiver decide that the received symbol is correctly received if the received signal-to-noise ratio (SNR) is greater than a certain threshold, which depends on the transmitter and the receiver structures.

If the receiver decodes the symbol correctly, then it sends an acknowledgment (ACK) to the sender and the relay to confirm a correct reception. Otherwise, it sends a negative acknowledgment (NACK) that allows the relay, if it received the symbol correctly, to transmit this symbol to the receiver in the next time slot. This model represents a modified form of the Automatic Repeat Request (ARQ), where the relay retransmits the data instead of the sender, if necessary. The received symbol at the receiver can be written as

$$r^C_{y,z} = \sqrt{P^C \; d^{-\alpha}_{y,z}} \; h_{y,z} \; s + n_{y,z} \; . \tag{6}$$

In general, the relay can transmit with a power that is different from the sender power P^C. However, this complicates the problem of finding the minimum-power formula, as will be derived later. For simplicity, we consider that both the sender and the relay send their data employing the same power P^C.

In this paper, flat quasi-static fading channels are considered, hence, the channel coefficients are assumed to be constant during a complete frame, and may vary from a frame to another. We assume that all the channel terms are independent complex Gaussian random variables with zero mean and unit variance. Finally, the noise terms are modeled as zero-mean, complex Gaussian random variables with equal variance N_0. In this section, we have formulated the minimum-power routing problem and we have defined the two main transmission modes. In the next section, we derive the closed-from expressions for the transmission power in both direct and cooperative transmission modes required to achieve the desired throughput.

III. Link Analysis

In this section, we derive the required power for the direct and cooperative transmission modes in order to achieve certain throughput. Since the throughput is a continuous monotonously-increasing function of the transmission power, the optimization problem in (1) has the minimum when $\eta_\omega = \eta_o, \forall \omega \in \Omega$. Since the end-to-end throughput $\eta_\omega = \min_{\omega_i \in \omega} \eta_{\omega_i}$, then the optimum power allocation, which achieves a desired throughput η_o along the route ω, forces the throughput at all the hops η_{ω_i} to be equal to the desired one, i.e.,

$$\eta_{\omega_i} = \eta_o \; , \quad \forall \; \omega_i \in \omega \; . \tag{7}$$

This result can be explained as follows. Let $P^*_{\omega_1}, P^*_{\omega_2}, \cdots, P^*_{\omega_n}$ represent the required powers on a route consisting of n hops, where P^*_i results in $\eta_{\omega_i} = \eta_o$ for $i = 1, \cdots, n$. If we increase the power of the i-th block to $P_{\omega_i} > P^*_{\omega_i}$ then the resulting throughput of the i-th block increases, i.e. $\eta_{\omega_i} > \eta_o$, while the end-to-end throughput does not change as $\min_{\omega_i \in \omega} \eta_{\omega_i} = \eta_o$. Therefore, no need to increase the throughput of any hop over η_o, which is indicated in (7).

Since the throughput of a given link ω_i is defined as the number of successfully transmitted bits per second per hertz, thus it can be calculated as

$$\eta_{\omega_i} = p^S_{\omega_i} \times R_{\omega_i} \; , \tag{8}$$

where $p^S_{\omega_i}$ and R_{ω_i} denote the per-link probability of success and transmission rate, respectively. We assume that the desired throughput can be factorized as

$$\eta_o = p^S_o \times R_o \ , \tag{9}$$

where p^S_o and R_o denote the desired per-link probability of success and transmission rate, respectively. In the sequel, we calculate the required transmission power in order to achieve the desired per-link probability of success and transmission rate for both the direct and cooperative transmission modes.

For the direct transmission mode in (3), the mutual information between sender i and receiver j can be given by

$$I_{i,j} = \log\big(1 + \frac{P^D\ d_{i,j}^{-\alpha}\ |h_{i,j}|^2}{N_0}\big) \ , \tag{10}$$

where $\frac{P^D\ d_{i,j}^{-\alpha}\ |h_{i,j}|^2}{N_0}$ is the signal-to-noise ratio (SNR). Without loss of generality, we have assumed unit bandwidth in (10). The outage probability is defined as the probability that the mutual information is less than the required transmission rate R_o. Thus, the outage probability of the link (i,j) is calculated as

$$p^O_{i,j} = \Pr(I_{i,j} \leq\ R_o) \ . \tag{11}$$

By substituting (10) into (11), we get

$$p^O_{i,j} = \Pr(|h_{i,j}|^2 \leq\ \frac{(2^{R_o}-1)\ N_0\ d^{\alpha}_{i,j}}{P^D}) \ . \tag{12}$$

The channel coefficients between each two nodes $h_{i,j}$ are modeled as independent circular symmetric complex Gaussian random variables with zero-mean and unit variance. In other words, the fading model of any of the channels is Rayleigh fading model [19]. Hence, the channel gain $|h_{i,j}|^2$ is modeled as exponential random variable, i.e., $p(|h_{i,j}|^2) = \exp(-|h_{i,j}|^2)$ for $|h_{i,j}|^2\ \geqslant\ 0$ is the probability density function (PDF) of $|h_{i,j}|^2$. Thus, the outage probability in (12) is equal to

$$p^O_{i,j} = 1 - \exp\Big(-\frac{(2^{R_o}-1)\ N_0\ d^{\alpha}_{i,j}}{P^D}\Big) \ . \tag{13}$$

If an outage occurs, the data is considered lost. The probability of success is calculated as $p^S_{i,j} = 1 - p^O_{i,j}$. Thus using (13), to achieve the desired p^S_o and R_o for direct transmission mode, the required transmission power is

$$P^D(d_{i,j}) = \frac{(2^{R_o}-1)\ N_0\ d^{\alpha}_{i,j}}{-\log(p^S_o)} \ . \tag{14}$$

For the cooperative transmission mode, the total outage probability is given by

$$\begin{aligned} p^O_{x,y,z} &= \Pr(I_{x,z} \leq R^C)\cdot \Pr(I_{x,y} \leq R^C) \\ &+ \Pr(I_{x,z} \leq R^C)\cdot \big(1-\Pr(I_{x,y} \leq R^C)\big)\cdot \Pr(I_{y,z} \leq R^C) \ , \end{aligned} \tag{15}$$

where R^C denotes the transmission rate for each time slot. In (15), the first term corresponds to the event when both the sender-receiver and the sender-relay channels are in outage, and the second term corresponds to the event when both the sender-receiver and relay-receiver channels are in outage but the sender-relay is not. Consequently, the probability of success of the cooperative transmission mode can be calculated as

$$\begin{aligned} p^S &= \exp\big(-g\, d^{\alpha}_{x,z}\big) + \exp\big(-g\,(d^{\alpha}_{x,y} + d^{\alpha}_{y,z})\big) \\ &- \exp\big(-g\,(d^{\alpha}_{x,y} + d^{\alpha}_{y,z} + d^{\alpha}_{x,z})\big) \ , \end{aligned} \tag{16}$$

where

$$g = \frac{(2^{R^C}-1)\ N_0}{P^C} \ . \tag{17}$$

In (15) and (16), we assume that the receiver decodes the signals received from the relay either at the first time slot or at the second time slot, instead of combining the received signals together. In general, Maximum Ratio Combining (MRC) [20] at the receiver gives the optimum result. However, it requires the receiver to store an analog version of the received data from the sender, which requires huge storage capacity. The probability that the source transmits only, denoted by $\Pr(\phi)$, is calculated as

$$\begin{aligned} \Pr(\phi) &= 1 - \Pr(I_{x,z} \leq R^C) + \Pr(I_{x,z} \leq R^C)\Pr(I_{x,y} \leq R^C) \\ &= 1 - \exp\big(-g\ d^{\alpha}_{x,y}\big) + \exp\big(-g\ (d^{\alpha}_{x,y} + d^{\alpha}_{x,z})\big) \ , \end{aligned} \tag{18}$$

where the term $\big(1 - \Pr(I_{x,z}\ \leq\ R^C)\big)$ corresponds to the event when the sender-receiver channel is not in outage, while the other term corresponds to the event when both the sender-receiver and the sender-relay channels are in outage. The probability that the relay cooperates with the source is calculated as

$$\overline{\Pr(\phi)} = 1 - \Pr(\phi) \ . \tag{19}$$

Thus, the average transmission rate of the cooperative transmission mode can be calculated as

$$R = R^C\cdot\Pr(\phi) + \frac{R^C}{2}\cdot\overline{\Pr(\phi)}\ = \frac{R^C}{2}\ \big(1 + \Pr(\phi)\big) \ , \tag{20}$$

where R^C corresponds to the transmission rate if the sender is sending alone in one time slot and $R^C/2$ corresponds to the transmission rate if the relay cooperates with the sender in the consecutive time slot.

We set the probability of success in (16) as $p^S\ =\ p^S_o$ and the average transmission rate in (20) as $R\ =\ R_o$. By approximating the exponential functions in (16) as $\exp(-x) \approx 1 - x + x^2/2$, we obtain

$$g \approx \sqrt{\frac{1-p^S_o}{d_{eq}}} \ , \tag{21}$$

where $d_{eq}\ \triangleq\ d^{\alpha}_{x,z}(d^{\alpha}_{x,y} + d^{\alpha}_{y,z})$. Thus, R^C can be obtained using (20) as

$$\begin{aligned} R^C &= \frac{2\ R_o}{1 + \Pr(\phi)} \\ &\approx \frac{2\ R_o}{2 - \exp\big(-\sqrt{\frac{1-p^S_o}{d_{eq}}}\ d^{\alpha}_{x,y}\big) + \exp\big(-\sqrt{\frac{1-p^S_o}{d_{eq}}}\ (d^{\alpha}_{x,y} + d^{\alpha}_{x,z})\big)} \ , \end{aligned} \tag{22}$$

where we substituted (21) in (18). In addition, the required power per link can be calculated using (17) and (21) as

$$P^C \approx (2^{R^C}-1)\ N_0\ \sqrt{\frac{d_{eq}}{1-p^S_o}} \ . \tag{23}$$

Finally, the total transmission power of the cooperative transmission mode can be calculated as

$$\begin{aligned} P_{tot}^{C}(d_{x,z}, d_{x,y}, d_{y,z}) &= P^{C} \cdot \Pr(\phi) + 2\, P^{C} \cdot \overline{\Pr(\phi)} \\ &= P^{C}\big(2 - \Pr(\phi)\big) \ , \end{aligned} \tag{24}$$

where $\Pr(\phi)$ and P^C are given in (18) and (23), respectively. In this section, we have derived closed-from expressions for the transmission power in both the direct and the cooperative transmission modes required to achieve the desired throughput. In the next section, we describe our proposed cooperation-based routing algorithms.

IV. Cooperation-Based Routing Algorithms

In this section, we propose two cooperation-based routing algorithms, which require polynomial complexity to find the minimum-power route. Then, we discuss the impact of cooperative cooperation on the routing in specific regular wireless networks, which are the regular linear and grid networks. We assume that each node broadcasts periodically HELLO packet to its neighbors to update the topology information. In addition, we consider a simple Medium Access Control (MAC) protocol, which is the conventional Time Division Multiple Access (TDMA) scheme with equal time slots.

A. *Proposed Routing Algorithms*

First, we propose a cooperation-based routing algorithm, namely, the Minimum-Power Cooperative Routing (MPCR) algorithm. The MPCR algorithm takes into consideration the cooperative communications while constructing the minimum-power route. The derived power formulas for direct transmission and cooperative transmission are utilized to construct the minimum-power route. It can be distributively implemented by the Bellman-Ford shortest path algorithm [18]. In the conventional Bellman-Ford shortest path algorithm, each node $i \in \{1, \ldots, N\}$ executes the iteration $D_i = \min_{j \in N(i)} (d_{i,j}^{\alpha} + D_j)$, where $N(i)$ denotes the set of neighboring nodes of node i, $d_{i,j}^{\alpha}$ denotes the effective distance between node i and j, and D_j represents the latest estimate of the shortest path from node j to the destination [18] that is included in the HELLO packet.

The MPCR algorithm is implemented as follows. First, each node calculates the costs (required powers) of its outgoing links, and then applies the shortest-path Bellman-Ford algorithm using these newly calculated costs. The required transmission power between two nodes is the minimum power obtained by searching over all the possible nodes in the neighborhood to act as a relay. If there is no available relay in the neighborhood, a direct transmission mode is considered. Second, the distributed Bellman-Ford shortest-path routing algorithm is implemented at each node. Each node updates its cost toward the destination as

$$P_i = \min_{j \in N(i)} \left(P_{i,j} + P_j\right) \ , \tag{25}$$

where P_i denotes the required transmission power from node i to the destination and $P_{i,j}$ denotes the minimum transmission power between node i and node j. $P_{i,j}$ is equal to either P^D in (14) if direct transmission is considered or P_{tot}^C in (24) if cooperative transmission is considered employing one of the nodes in the neighborhood as a relay. Table I describes the MPCR algorithm in details. The worst-case computational complexity of calculating the costs at each node is $O(N^2)$ since it requires two nested loops, and each has a maximum length of $N-1$ to calculate all the possible cooperative transmission blocks.

TABLE I
MPCR Algorithm.

Step 1: Each node $x \in \{1, \ldots, N\}$ behaving as a sender calculates the cost of the its outgoing link (x, z), where $z \in N(x)$ is the receiver, as follows. For each other node $y \in N(x), y \neq z$, node x calculates the cost of the cooperative transmission in (24) employing node y as a relay.
Step 2: The cost of the (x, z)-th link is the minimum cost among all the costs obtained in *Step 1*.
Step 3: If the minimum cost corresponds to a certain relay $y*$, node x employs this relay to help the transmission over that hop. Otherwise, it uses the direct transmission over this hop.
Step 4: Distributed Bellman-Ford shortest-path algorithm is applied using the calculated cooperation-based link costs. Each node $i \in \{1, \ldots, N\}$ executes the iteration $P_i = \min_{j \in N(i)} (P_{i,j} + P_j)$, where $N(i)$ denotes the set of neighboring nodes of node i, P_j represents the latest estimate of the shortest path from node j to the destination, and $P_{i,j}$ is the minimum possible transmission power from node i to node j.

TABLE II
CASNCP Algorithm.

Step 1: Implement the Shortest Non-Cooperative Path (SNCP) algorithm using the distributed Bellman-Ford algorithm to choose the conventional shortest-path route ω_S as follows. Each node $i \in \{1, \ldots, N\}$ executes the iteration $D_i = \min_{j \in N(i)} (d_{i,j}^{\alpha} + D_j)$, where $N(i)$ denotes the set of neighboring nodes of node i and D_j represents the latest estimate of the shortest path from node j to the destination.
Step 2: For each three consecutive nodes on ω_S, either the cooperative transmission mode or the direct transmission mode is implemented. In the cooperative transmission mode, the first, second, and third nodes behave as the sender, relay, and receiver, respectively, i.e., the first node sends its data to the third node with the help of the second node as discussed in the cooperative transmission mode. In the direct transmission mode, the first node is the sender and the third node is the destination. The transmission mode that requires less power is chosen.

Second, we propose a cooperation-based routing algorithm, namely, Cooperation Along the Shortest Non-Cooperative Path (CASNCP) algorithm. The CASNCP algorithm is similar to the heuristic algorithms proposed by Khandani *et al.* in [12] and Yang *et al.* in [13] as it applies cooperative communications upon the shortest-path route. However, it is implemented in a different way using the proposed cooperation-based link cost formula. First, it chooses the shortest-path route. Second, for each three consecutive nodes in the route, it applies either the cooperative transmission mode; first node as the sender, second node as the relay, and third node as the receiver, or the direct transmission mode from the first to the third node. Table II describes the CASNCP algorithm.

We point out that in this paper, we restrict the cooperation

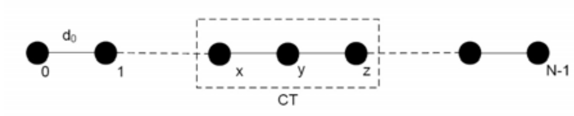


Fig. 2. Linear wireless network, d_0 denote the distance between each two adjacent nodes.

scheme between any two nodes to the single-relay case. First, the required power between each two nodes is calculated taken into consideration the possibility of having any other node as a relay in a single-relay cooperative communication model. Second, the optimum shortest-path algorithm is calculated based on these cooperation-based link costs. Based on that, the proposed MPCR algorithm calculates the optimum-route subject to the single-relay cooperation model. In other words, if we allow cooperation to happen using more than one relays, then the optimum path in this case can possibly require transmission power that is less than that required by the MPCR algorithm. However, this can cause significant increase in communication and computation burdens, and the performance increase might be sufficiently small. In other words, adding more relays might not be cost effective, and the proposed scheme is optimal in the sense of up to one relay case.

B. Performance Analysis: Regular Linear Networks

The regular linear network, shown in Fig. 2, is a one-dimensional chain of nodes placed at equal intervals d_0. Without taking into consideration the interference effect, nodes are placed at equal intervals to achieve the best performance in terms of the throughput and the energy consumption [15]. In order to illustrate the behavior of each routing algorithm, we consider the three consecutive nodes x, y, and z in Fig. 2, where node x needs to transmit its data to node z. The SNCP routing algorithm transmits the data directly from node x to node y then from node y to node z. Thus, the required power for the SNCP routing algorithm is

$$P_{SNCP}(x,z) = 2\ P^D(d_0)\ , \tag{26}$$

where $P^D(d_0)$ is the required transmission power over one hop and it is given by (14) with $d_{i,j} = d_0$. The CASNCP routing algorithm applies cooperative communication transmission on the shortest-path route as follows. Node x transmits the data directly to node z. If node z does not decode the data correctly, then node y retransmits the data if it has correctly decoded it during the first transmission. The transmission power for the CASNCP routing algorithm is given by

$$P_{CASNCP}(x,z) = P^C_{tot}(2\,d_0, d_0, d_0)\ , \tag{27}$$

where $P^C_{tot}(2\,d_0, d_0, d_0)$ represents the cooperative transmission power given in (24) with $d_{x,z} = 2\,d_0$, $d_{x,y} = d_0$, and $d_{y,z} = d_0$.

By applying the MPCR algorithm described above on this example, we find that the route is chosen on two consecutive phases as follows. First, node x transmits its data directly to node y utilizing direct transmission mode. Second, node y transmits its data to node z in a cooperative transmission mode utilizing node x as a relay. In other words, if node z does not receive the data correctly from node y, then node x will retransmit the data to node z. Thus, the total transmission power to transmit the data from node x to node z is

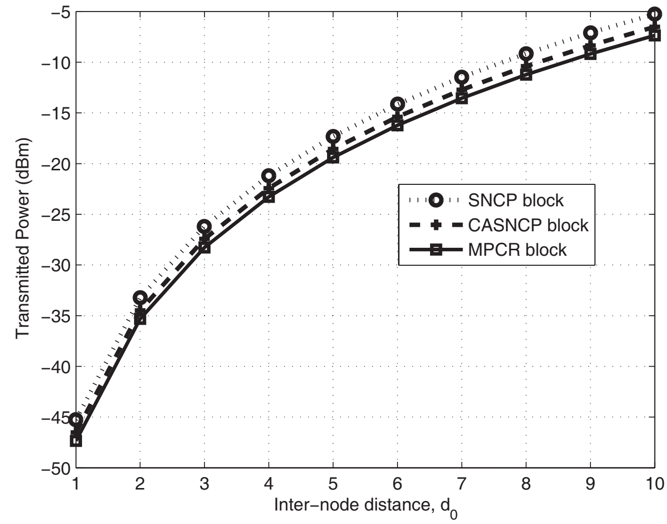


Fig. 3. Required transmission power per one block of three nodes versus the inter-node distance d_0 for $N_0 = -70$ dBm, $\alpha = 4$, $\eta_0 = 1.96$ b/s/Hz, and $R_0 = 2$ b/s/Hz in regular linear networks.

$$P_{MPCR}(x,z) = P^D(d_0) + P^C_{tot}(d_0, d_0, 2\,d_0)\ , \tag{28}$$

where $P^C_{tot}(d_0, d_0, 2\,d_0)$ is the required cooperative transmission power given in (24) with $d_{x,z} = d_0$, $d_{x,y} = d_0$, and $d_{y,z} = 2\,d_0$. Fig. 3 depicts the required transmission power per block (x, y, z) as a function of the distance d_0 at throughput $\eta_0 = 1.96$ b/s/Hz ,transmission rate $R_0 = 2$ b/s/Hz, noise variance $N_0 = -70$ dBm, and path loss exponent $\alpha = 4$. As shown, the MPCR algorithm requires the least transmission power compared to both the SNCP and CASNCP routing algorithm.

Based on this example, we explain the route chosen by each algorithm when the source is node 0 and the destination is node $N-1$. The SNCP routing algorithm constructs the shortest route as a sequence of all the nodes between the source and destination, i.e., $w_{SNCP} = \{(0,1),(1,2),\cdots,(N-2,N-1)\}$, where (i,j) denotes the direct transmission building block between sender i and receiver j. The CASNCP routing algorithm applies cooperative transmission mode on each three consecutive nodes in the SNCP route, i.e., $w_{CASNCP} = \{(0,1,2),(2,3,4),\cdots,(N-3,N-2,N-1)\}$, where (x,y,z) denotes a cooperative transmission building block with x, y, and z denoting the sender, relay, and receiver, respectively. Finally, the MPCR routing algorithm, applied on this linear network, chooses a different route, which is $w_{MPCR} = \{(0,1),(1,0,2),(2,1,3),\cdots,(N-2,N-3,N-1)\}$. In other words, each node sends its data to the adjacent node towards the destination utilizing its other adjacent node towards the source as a relay. In the following, we calculate the average required transmission power by each algorithm in a linear network.

For any routing scheme, the average end-to-end transmission power can be calculated as

$$P(\text{route}) = \sum_{l=1}^{N-1} P(\text{route}|l) \times \Pr(l) \ , \tag{29}$$

where $P(\text{route}|l)$ is the end-to-end transmission power when the destination is l hops away from the source and $\Pr(l)$ denotes the probability mass function (PMF) of having l hops between any source-destination pair. The PMF $\Pr(l)$ can be calculated as

$$\Pr(l) = \begin{cases} \frac{1}{N}, & \text{l=0} \\ \frac{2\,(N-l)}{N^2}, & \text{l=1,2,}\cdots\text{,N-1} \end{cases} . \tag{30}$$

In the sequel, we illustrate how (30) is derived. The probability of choosing a certain node is $\frac{1}{N}$. Thus, the probability of having the source and destination at certain locations is given by $\frac{1}{N} \times \frac{1}{N} = \frac{1}{N^2}$. At $l = 0$ hops there is N possible combinations of this event, where the source and destination are the same. Therefore, $\Pr(0) = \frac{N}{N^2} = \frac{1}{N}$. Considering one direction only (e.g., from left to right in Fig. 2), at $l = 1$ there is $N - 1$ distinct source-destination pairs: the first is the 0-to-1 pair and the last is the $(N - 1)$-to-N pair. By considering the other direction, the number of different source-destination pairs is $2 \times (N - 1)$. Therefore, the probability of having a source-destination pair with $l = 1$ hop in between is $\Pr(1) = \frac{2(N-1)}{N^2}$. In general, there is $2(N-l)$ different source-destination pairs with l hops in between, hence, the PMF of having source-destination pairs with l hops in between is given by (30).

For a route of l hops, the MPCR end-to-end transmission power can be calculated as

$$P_{MPCR}(\text{route}|l) = P^D(d_0) + P_{tot}^C(d_0, d_0, 2\,d_0) \times (l-1) \ , \tag{31}$$

where the term $P^D(d_0)$ accounts for the first transmission from the source to its adjacent node towards the destination and $P_{tot}^C(d_0, d_0, 2\,d_0)$ is the required cooperative transmission power over one hop, which is given in (24) with $d_{x,z} = d_0$, $d_{x,y} = d_0$, and $d_{y,z} = 2\ d_0$. The CASNCP end-to-end transmission power can be given as shown in (32). If l is even, there exist $\frac{l}{2}$ cooperative transmission blocks and each block requires a total power of $P_{tot}^C(2\,d_0, d_0, d_0)$. If l is odd, then a direct transmission mode is done over the last hop. Finally, the SNCP end-to-end transmission power is calculated as

$$P_{SNCP}(\text{route}|l) = P^D(d_0) \times l \ . \tag{33}$$

The average end-to-end transmission power for any routing scheme can be calculated by substituting the corresponding power formulas, which are (31), (32), and (33) for the MPCR, CASNCP, and SNCP, respectively in (29).

C. Performance Analysis: Regular Grid Networks

Fig. 4 shows a regular 4 x 4 grid topology and d_0 denotes the distance between each two nodes in the vertical or horizontal directions. To illustrate the routes selected by different routing schemes, we assume that the source is node 0 and the destination is node 7. The SNCP routing algorithm chooses one of the possible shortest routes. For instance, the chosen shortest-route is $w_{SNCP} = \{(0,1),(1,5),(5,6),(6,7)\}$,

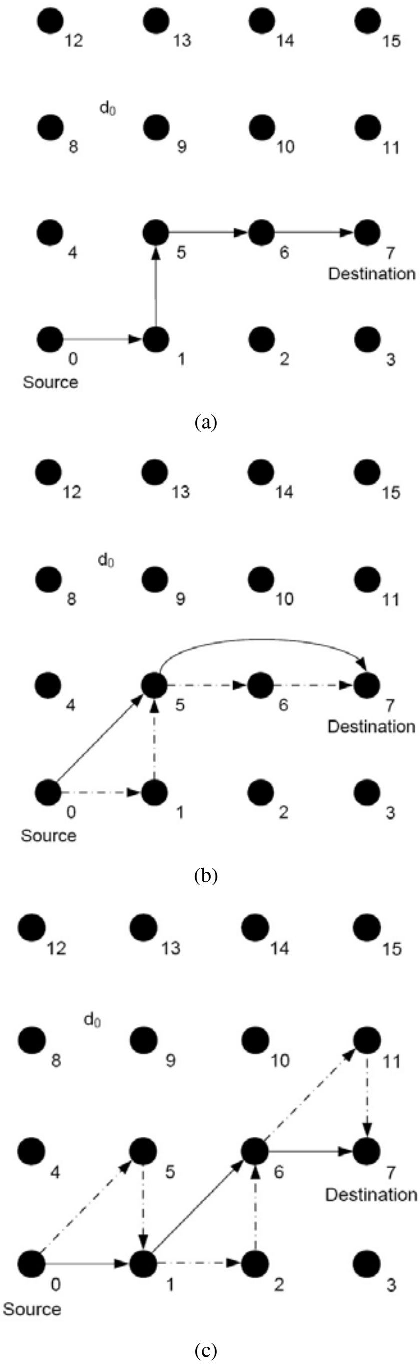


Fig. 4. Route chosen by the three routing algorithms in grid wireless network. (a) SNCP constructed route, (b) CASNCP constructed route, and (c) MPCR constructed route.

where (i, j) denotes the direct transmission mode from node i to node j. Fig. 4 (a) shows the route chosen by the SNCP routing algorithm, where the solid line between each two nodes indicates the direct transmission mode.

The CASNCP routing algorithm applies cooperation among each three consecutive nodes on the shortest-route, and the resulting route is $w_{CASNCP} = \{(0,1,5),(5,6,7)\}$, where (x, y, z) denotes the cooperative transmission mode between sender x, relay y, and destination z. Fig. 4 (b) shows the route chosen by the CASNCP algorithm. The solid lines indicate the sender-receiver transmissions and the dashed lines

$$P_{CASNCP}(\text{route}|l) = \begin{cases} P^C_{tot}(2\,d_0, d_0, d_0) \times \frac{l}{2} & \text{l is even} \\ P^C_{tot}(2\,d_0, d_0, d_0) \times \frac{l-1}{2} + P^D(d_0) & \text{l is odd} \end{cases} \tag{32}$$

indicate the sender-relay and relay-receiver transmissions. By applying the MPCR algorithm described in Section IV-A on this example, we find that MPCR chooses the route given by $w_{MPCR} = \{(0,5,1),\ (1,2,6), (6,11,7)\}$ as shown in Fig. 4 (c). If the MPCR is routing the data in the horizontal (vertical) direction only, MPCR considers the receiver to be the sender's nearest node towards the destination and the relay to be the node nearest to the receiver along the vertical (horizontal) direction. In this example, we can visually notice the difference between the routes chosen by the MPCR and CASNCP routing algorithms.

We define the power saving of scheme 2 with respect to scheme 1 as

$$\text{Power Saving} = \frac{P_{Scheme1} - P_{Scheme2}}{P_{Scheme1}}\ \% . \tag{34}$$

At throughput $\eta_o = 1.96$ b/s/Hz and path loss exponent $\alpha = 4$, the power saving ratios of the MPCR with respect to the SNCP and CASNCP in this example are 64.14% and 30.47%, respectively. Also, the power saving of the CASNCP with respect to the SNCP is 48.42%.

The average required transmission power by each algorithm can be calculated as

$$P(\text{route}) = \sum_{i=1}^{N-1}\sum_{j=0}^{i} P(route|\sqrt{i^2+j^2}) \times \Pr(\sqrt{i^2+j^2})\ , \tag{35}$$

where i and j denote the number of hops between the source and destination in the horizontal and vertical directions, respectively. In addition, $\sqrt{i^2+j^2}$ denotes the distance between the source and the destination. The PMF $\Pr(\sqrt{i^2+j^2})$, which depends on the number of hops between the source and destination as well as their relative locations, is given by (36). We explain (36) similar to (30) as follows. The probability of choosing a certain node to be the source or the destination is $\frac{1}{N^2}$. Thus, the probability of choosing any source-destination pair is given by $\frac{1}{N^2} \times \frac{1}{N^2} = \frac{1}{N^4}$. There are N^2 possible combinations, in which the source and the destination are the same. Hence at $i = j = 0$, $\Pr(0) = \frac{N^2}{N^4} = \frac{1}{N^2}$. In the following, we consider only the lower triangular part, i.e., $j \le i$. At $j = 0$, the grid network reduces to the linear case with $N - i$ possible source-destination pairs. For source-destination pair separated by $i = j$ hops in the horizontal and vertical directions, the number of possible source-destination pairs in one direction (e.g. left to right) is $(N-i)\times(N-j)$. This result is very similar to the one in (30) with considering the nodes on two dimensions instead of one dimension only in the linear case. At $i = j$ or $j = 0$, and considering the upper triangular part ($\times 2$) and reversing the source-destination pairs ($\times 2$), then the probability of having such source-destination pairs is $4\frac{(N-i)\,(N-j)}{N^4}$. For the third component in (36) i.e., at $j < i$, we additionally multiply this number by 2 to compensate the other combinations when i and j can be interchanged while giving the same distance of $\sqrt{i^2+j^2}$, which results in a total of 8.

The MPCR end-to-end transmission power can be calculated as

$$\begin{aligned} P_{MPCR}(\text{route}|\sqrt{i^2+j^2}) &= P^C_{tot}(\sqrt{2}\,d_0, d_0, d_0) \times j \\ &+ P^C_{tot}(d_0, \sqrt{2}\,d_0, d_0) \times |i-j|\ , \end{aligned} \tag{37}$$

where the first term represents the diagonal walk for j steps and the second term represents the horizontal $|i-j|$ steps. The CASNCP end-to-end transmission power is calculated by (38).

Finally, the SNCP end-to-end transmission power is given by

$$P_{SNCP}(\text{route}|\sqrt{i^2+j^2}) = P^D(d_0) \times (i+j)\ , \tag{39}$$

which represents a direct transmission over $i+j$ hops, each of length d_0. The average end-to-end transmission power for any routing scheme can be calculated by substituting the power formulas for the MPCR, CASNCP, and SNCP (given by (37), (38), and (39), respectively) in (35).

D. Comparisons

In the sequel, we assume the required throughput is $\eta_0 = 1.96$ b/s/Hz, the transmission rate is $R_0 = 2$ b/s/Hz, the noise variance is $N_0 = -70$ dBm, and the path loss exponent is $\alpha = 4$. In Fig. 5, we show the total required transmission power for the three routing algorithms as a function of the number of hops between the source and destination in regular networks. First, we consider a linear network of $N = 20$ nodes and the inter-node distance is $d_0 = 2$. Fig. 5 (a) depicts the average transmission power, required by the three routing algorithms, as a function of the number of hops between the source and the destination. As shown, the MPCR algorithm requires the least transmission power for any particular number of hops.

Second, we consider a 4×4 grid network, $N = 4$, and the inter-node distance is $d_0 = 2$. As described before, let i and j denote the number of hops between the source and the destination in the horizontal and vertical directions, respectively. In Fig. 5 (b), we show the required transmission power by the various routing algorithms as a function of the squared distance $(i^2 + j^2)$ between the source and the destination. Each point is identified using the notation (i, j), where $j \le i, 0 \le i \le 3$. This determines the relative positions of the source and destination. As shown, the MPCR algorithm requires the least transmission power for any source-destination pair. We note that in the diagonal case $i = j$, the MPCR and CASNCP algorithms require the same transmission power, as they both construct the same routes. In addition, the SNCP algorithm requires the same transmission power for different source-destination pairs, which have the same total number of hops $i + j$.

Fig. 6 depicts the end-to-end transmission power in linear and grid networks of the three different routing algorithms for throughput $\eta_0 = 1.96$ b/s/Hz ,transmission rate $R_0 = 2$

$$\Pr(\sqrt{i^2+j^2}) = \begin{cases} \frac{1}{N^2}, & \text{i=j=0;} \\ \frac{4\,(N-i)\,(N-j)}{N^4}, & \text{i=j or j=0;} \quad \text{for } j \le i \text{ and } 0 \le i \le (N-1) \\ \frac{8\,(N-i)\,(N-j)}{N^4}, & \text{otherwise} \end{cases} \tag{36}$$

$$P_{CASNCP}(\text{route}|\sqrt{i^2+j^2}) = \\ \begin{cases} P^C_{tot}(\sqrt{2}\,d_0, d_0, d_0) \times j + P^C_{tot}(2\,d_0, d_0, d_0) \times \frac{|i-j|}{2} & (|i-j|) \text{ is even;} \\ P^C_{tot}(\sqrt{2}\,d_0, d_0, d_0) \times j + P^C_{tot}(2\,d_0, d_0, d_0) \times \frac{|i-j-1|}{2} + P^D(d_0) & (|i-j|) \text{ is odd} \end{cases} \tag{38}$$

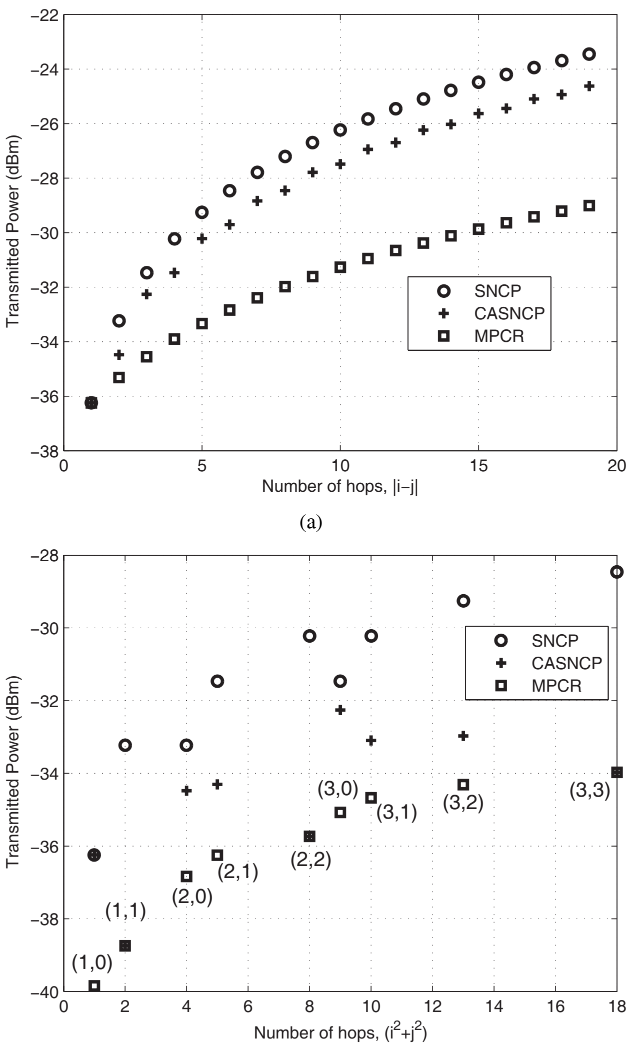


Fig. 5. Required transmission power per route versus the number of hops in regular (a) 20-node linear network, (b) 16-node grid network.

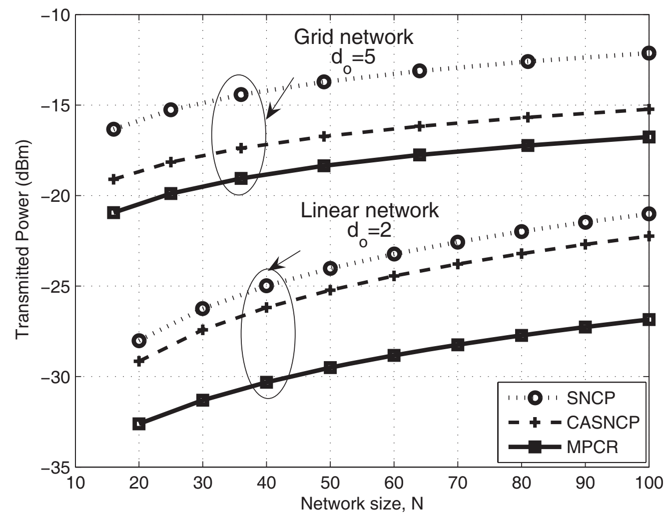


Fig. 6. Required transmission power per route versus the network size for $N_0 = -70$ dBm, $\alpha = 4$, $\eta_0 = 1.96$ b/s/Hz, and $R_0 = 2$ b/s/Hz in regular linear and grid networks.

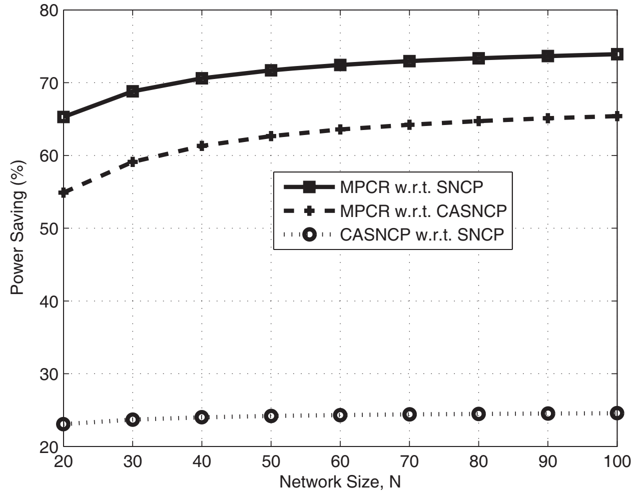
b/s/Hz, noise variance $N_0 = -70$ dBm, and path loss $\alpha = 4$. In both networks, the MPCR algorithm requires the minimum end-to-end transmission power compared to both CASNCP and SNCP routing algorithms.

For the linear network, Fig. 7 (a) depicts the power saving (34) versus the network size for the network setup defined above. It is shown that at $N = 100$ nodes, the power savings of the MPCR with respect to SNCP and CASNCP algorithms are 73.91% and 65.61%, respectively. On the other hand, applying cooperation over the shortest-path route results in power saving of 24.57% only, as illustrated in the the CASNCP with respect to the SNCP curve. Similarly, Fig. 7 (b) depicts the power savings for the grid network. At $N = 100$ nodes, the power savings of the MPCR with respect to SNCP and CASNCP algorithms are 65.63% and 29.8%, respectively. Applying cooperation over the shortest-path route results in power saving of 51.04%.

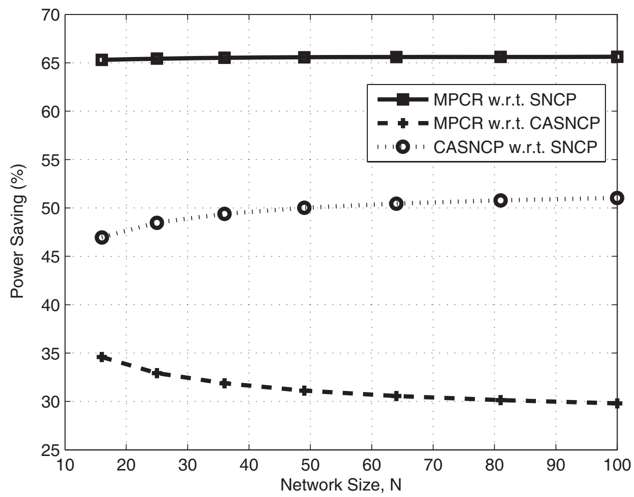
In this section, we have proposed two cooperation-based routing algorithms and applied them on regular networks. In the next section, we show the reduction in the end-to-end transmission power due to cooperation in random networks.

V. Numerical Results

In this section, we consider the random network case, in which nodes are deployed randomly in the network area. More precisely, we present computer simulations to illustrate the power savings of our proposed cooperation-based routing algorithms in random networks. We consider a 200m x 200m square, where N nodes are uniformly distributed. The additive white Gaussian noise has variance $N_0 = -70$ dBm and the path loss exponent is $\alpha = 4$. Given a certain network topology, we randomly choose a source-destination pair and apply the various routing algorithms, discussed in Section IV, to choose the corresponding route. For each algorithm, we calculate the



(a)



(b)

Fig. 7. Power saving due to cooperation versus the network size for $N_0 = -70$ dBm, $\alpha = 4$, $\eta_0 = 1.96$ b/s/Hz, and $R_0 = 2$ in regular (a) linear network, (b) grid network.

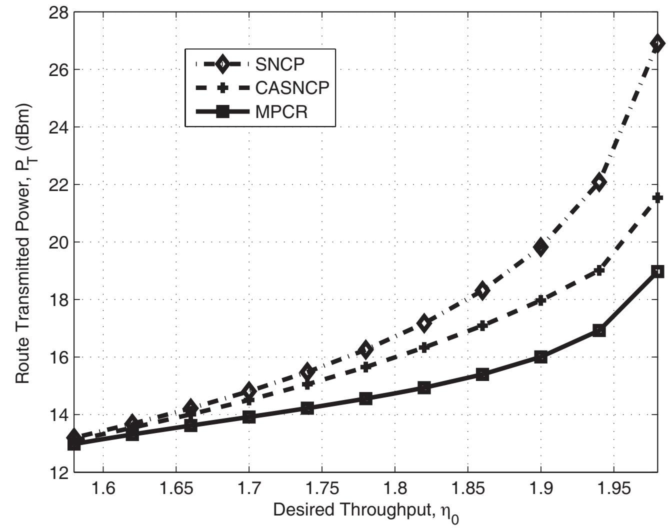


Fig. 8. Required transmission power per route versus the desired throughput for $N = 20$ nodes, $\alpha = 4$, $N_0 = -70$ dBm, and $R_0 = 2$ b/s/Hz in a 200m x 200m random network.

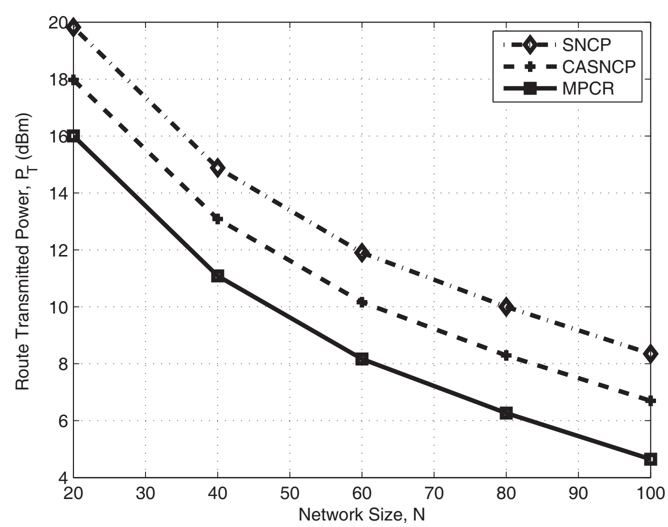


Fig. 9. Required transmission power per route versus the number of nodes for $\eta_o = 1.9$ b/s/Hz and α=4 in a 200m x 200m random network.

total transmission power per route. Finally, these quantities are averaged over 1000 different network topologies.

First, we illustrate the effect of varying the desired throughput on the required transmission power per route. Fig. 8 depicts the transmission power per route, required by the different routing algorithms. It is shown that the SNCP algorithm, which applies the Bellman-Ford shortest-path algorithm requires the most transmission power per route. Applying the cooperative communication mode on each three consecutive nodes in the SNCP route results in reduction in the required transmission power as shown in the CASNCP routing algorithm's curve. Moreover, the MPCR algorithm requires the least transmission power among the other routing algorithms.

One of the major results of this paper is that the MPCR algorithm requires less transmission power than the CASNCP algorithm. Intuitively, this result is because the MPCR applies the cooperation-based link cost formula to construct the minimum-power route. On the contrary, the CASNCP algorithm first constructs shortest-path route then it applies the cooperative communication protocol on the established route. Therefore, the CASNCP algorithm is limited to applying the cooperative-communication protocol on a certain number of nodes, while the MPCR algorithm can consider any node in the network to be in the CT blocks, which constitute the route. Thus, the MPCR algorithm reduces the required transmission power more than the CASNCP algorithm.

Fig. 9 depicts the required transmission power per route by the different routing algorithms for different number of nodes at $p_o^S = 0.95$ and $\eta_o = 1.9$ b/s/Hz. As shown, the required transmission power by any routing algorithm decreases with the number of nodes. Intuitively, the higher the number of nodes in a fixed area, the closer the nodes to each other, the lower the required transmission power between these nodes, which results in lower required end-to-end transmission power. We also calculate the power saving ratio as a measure of the improvement of the MPCR algorithm. At $N = 100$ nodes, $p_o^S = 0.95$, and $\eta_o = 1.9$ b/s/Hz, the power savings of MPCR algorithm with respect to the SNCP and CASNCP algorithms

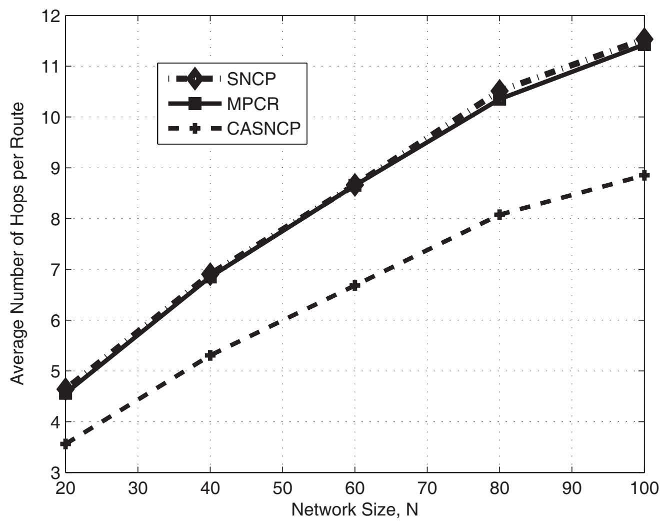


Fig. 10. Average number of hops per route versus the number of nodes for $\eta_o = 1.9$ b/s/Hz and α=4 in a 200m x 200m random network.

are 57.36% and 37.64%, respectively. In addition, the power saving of the CASNCP algorithm with respect to the SNCP algorithm is 31.62%.

In Fig. 10 the average number of hops in each route, constructed by the different routing algorithms, is shown versus the number of nodes in the network. For the cooperative transmission mode, the average number of hops is defined as

$$h^C = 1 \cdot \Pr(\phi) + 2 \cdot \overline{\Pr(\phi)} = 2 - \Pr(\phi) \ , \qquad (40)$$

and the average number of hops for the direct transmission mode is one. As shown, the routes constructed by either the CASNCP or the MPCR algorithms consist of number of hops that is less than the routes constructed by the SNCP algorithm. Moreover, the average number of hops increases with N as there are more available nodes in the network, which can be employed to reduce the transmission power. Although the MPCR scheme requires less power than the CASNCP routing algorithm, but it requires longer delay. Intuitively, this is because the minimum-power routes may involve more nodes. This shows the tradeoff between the required power and the delay in the routes chosen by the MPCR and CASNCP routing schemes.

VI. Conclusion

In this paper, we have investigated the impacts of the cooperative communications on the minimum-power routing problem in wireless networks. For a given source-destination pair, the optimum route requires the minimum end-to-end transmission power while guaranteeing certain throughput. We have proposed the MPCR algorithm, which applies the cooperative communication while constructing the route. The MPCR algorithm constructs the minimum-power route using any number of the proposed cooperation-based building blocks, which require the least possible transmission power. We have also presented the CASNCP algorithm, which is similar to most of the existing cooperative routing algorithms. The CASNCP algorithm first constructs the conventional shortest-path route then applies a cooperative-communication protocol upon the established route. We have shown that for random networks of $N = 100$ nodes, the power savings of the MPCR algorithm with respect to the conventional shortest-path and CASNCP routing algorithms are 57.36% and 37.64%, respectively. In addition, we have considered regular linear and grid networks, and we have derived the analytical results for the power savings due to cooperation in these cases. We have shown that in a regular linear network with $N = 100$ nodes, the power savings of the MPCR algorithm with respect to shortest-path and CASNCP routing algorithms are 73.91% and 65.61%, respectively. Similarly, the power savings of the MPCR algorithm with respect to shortest-path and CASNCP routing algorithms in a grid network of 100 nodes are 65.63% and 29.8%, respectively.

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Ahmed S. Ibrahim (S'04) received the B.S. (with highest honors) and M.S. degrees in electrical engineering from Cairo University, Cairo, Egypt, in 2002 and 2004, respectively, and he is currently pursuing his Ph.D. degree at the Electrical and Computer Engineering Department, University of Maryland, College Park. His research interests include cooperative communications and networking, cross-layer design of wireless networks, relay deployment and selection in wireless networks, and MIMO-OFDM systems.

Mr. Ibrahim is a recipient of the best speaker award of the Electrical and Computer Engineering Department seminar series at the University of Maryland in 2008. He was a nominee for the best student paper award of the IEEE Conference on Acoustics, Speech, and Signal Processing (ICASSP) in 2007. He is also a recipient of the Graduate School Fellowship from the University of Maryland in 2004 and 2005.

Zhu Han (S'01-M'04) received the B.S. degree in electronic engineering from Tsinghua University, in 1997, and the M.S. and Ph.D. degrees in electrical engineering from the University of Maryland, College Park, in 1999 and 2003, respectively.

From 2000 to 2002, he is an R&D Engineer of JDSU, Germantown, Maryland. From 2002 to 2003, he was a Graduate Research Assistant at the University of Maryland. From 2003 to 2006, he was a Research Associate at the University of Maryland. From 2006 to 2008, he was an assistant professor in Boise State University, Idaho. Currently, he is an Assistant Professor in Electrical and Computer Engineering Department at University of Houston, Texas. In June-August 2006, he was a visiting scholar in Princeton University. In May-August 2007, he was a visiting professor in Stanford University. In May-August 2008, he was a visiting professor in University of Oslo, Norway and Supelec, Paris, France. His research interests include wireless resource allocation and management, wireless communications and networking, game theory, wireless multimedia, and security.

Dr. Han is the MAC Symposium vice chair of IEEE Wireless Communications and Networking Conference, 2008. Dr. Han is the Guest Editor for Special Issue on Fairness of Radio Resource Management Techniques in Wireless Networks, EURASIP JOURNAL ON WIRELESS COMMUNICATIONS AND NETWORKING, and Special Issue on Game Theory, EURASIP JOURNAL ON ADVANCES IN SIGNAL PROCESSING. Dr. Han is a member of the Technical Programming Committee for the IEEE International Conference on Communications, the IEEE Vehicular Technology Conference, the IEEE Consumer Communications and Networking Conference, the IEEE Wireless Communications and Networking Conference, and the IEEE Globe Communication Conference.

K. J. Ray Liu (F'03) is Distinguished Scholar-Teacher of University of Maryland, College Park. He leads the Maryland Signals and Information Group conducting research encompassing broad aspects of information technology including communications and networking, information forensics and security, multimedia signal processing, biomedical imaging, and bioinformatics.

Dr. Liu is the recipient of numerous honors and awards including best paper awards from IEEE Signal Processing Society (twice), IEEE Vehicular Technology Society, and EURASIP; IEEE Signal Processing Society Distinguished Lecturer, EURASIP Meritorious Service Award, and National Science Foundation Young Investigator Award. He also received various teaching and research recognitions from University of Maryland including university-level Invention of the Year Award and both Outstanding Research Award and Poole and Kent Senior Faculty Teaching Award from A. James Clark School of Engineering Faculty.

Dr. Liu is Vice President - Publications and on the Board of Governor of IEEE Signal Processing Society. He was the Editor-in-Chief of IEEE SIGNAL PROCESSING MAGAZINE and the founding Editor-in-Chief of EURASIP JOURNAL ON APPLIED SIGNAL PROCESSING.

His recent books include *Cooperative Communications and Networking* (Cambridge University Press, 2008); RESOURCE ALLOCATION FOR WIRELESS NETWORKS: BASICS, TECHNIQUES, AND APPLICATIONS (Cambridge University Press, 2008); ULTRA-WIDEBAND COMMUNICATION SYSTEMS: THE MULTIBAND OFDM APPROACH (IEEE-Wiley, 2007); NETWORK-AWARE SECURITY FOR GROUP COMMUNICATIONS (Springer, 2007); MULTIMEDIA FINGERPRINTING FORENSICS FOR TRAITOR TRACING (Hindawi, 2005).