# On the Performance of Cooperative Routing in Wireless Networks

Mostafa Dehghan†, Majid Ghaderi†, and Dennis L. Goeckel‡

†Department of Computer Science, University of Calgary, Emails: {mdehghan, mghaderi}@ucalgary.ca

‡Department of Electrical and Computer Engineering, University of Massachusetts Amherst, Email: goeckel@ece.umass.edu

***Abstract*—This paper studies *energy* and *throughput* performance of cooperative routing in wireless networks that support cooperative beamforming at the physical layer. *Cooperative beamforming* is a form of cooperative communication in which multiple nodes each equipped with a single omnidirectional antenna coordinate their transmissions in such a way that the individual signals constructively combine at the intended receiver. It has been recently shown that *cooperative routing*, *i.e.*, joint optimization of network-layer routing and physical-layer cooperation, can achieve significant energy savings in wireless networks. Although energy efficiency of cooperative routing has been extensively studied in literature, its impact on network throughput is surprisingly overlooked. In this paper, we show that while cooperative routing can achieve considerable energy savings, it results in a sharp reduction in network throughput compared to non-cooperative routing. We then identify some potential causes of this problem and propose two solutions by exploring recent developments in multi-beam cooperative beamforming to increase parallelism in the network in order to improve throughput.**

## I. Introduction

Energy efficiency is a challenging problem in wireless networks, especially in ad hoc and sensor networks, where network nodes are typically battery powered. Among many techniques for reducing energy consumption, multi-antenna systems have been recently studied intensively. It has been shown that multi-antenna systems achieve considerable transmission energy savings compared to single-antenna systems by harvesting spatial diversity inherent in wireless networks. However, in some cases, the use of multiple antennas on a transmitter or receiver may be impractical (*e.g.*, due to small size of sensors) or too costly (*e.g.*, due to costly analog circuitry). Nevertheless, by allowing cooperation among spatially distributed single-antenna nodes, the so-called *cooperative beamforming (CB)* can achieve highly directional transmissions, resulting in significant power gains compared to independent signal transmissions [1]–[3].

Although there has been considerable research on energy efficient routing (*e.g.*, [4]), and cooperative beamforming (*e.g.*, [2]), in isolation, only recently a few works have addressed network layer routing and physical layer cooperation problems *jointly* [5]–[7]. This is surprising as CB is inherently a network solution; hence, it is essential to investigate routing and cooperation jointly [8]. One of the early works in this area is due to Khandani *et al.* [5], where the authors study energy efficient cooperative routing in a static wireless network. Specifically, they formulate the optimal energy cooperative routing, and design several heuristic algorithms to find energy efficient routes from a single source to a single destination. They show that optimal cooperative routing can achieve significant energy savings (*e.g.*, $39\%$ in a line topology and $56\%$ in a grid topology) compared to optimal non-cooperative routing. Extension of [5] to a multi-source multi-destination network is presented in [6], which also reports that significant energy savings can be achieved by cooperative routing. Distributed cooperative routing is studied in [7], where a limited form of cooperation is studied in which only two transmitters are allowed to cooperatively communicate with a single receiver. Analytical and simulation results in [7] confirm that significant energy savings can be achieved via cooperative routing.

None of these works, however, considers the impact of cooperation on the network *throughput*. Although cooperation results in significant energy savings, it can cause considerable *interference* in the network, negatively affecting throughput. In this work, we first study cooperative routing in regular line and grid network topologies to demonstrate the impact of cooperation on energy consumption and network throughput. Specifically, we show that network throughput is sharply reduced under the optimal cooperative routing. We argue that the physical-layer beamforming model considered in previous work [5]–[7] is perhaps too restrictive, inevitably reducing the network throughput. We refer to this model as *single-beam cooperative beamforming (SCB)* model. We then consider a generalization of cooperative routing based on the recent developments in *multi-beam cooperative beamforming (MCB)* in which multiple transmitters cooperatively beamform to multiple receivers *simultaneously* [3]. We argue that the optimal cooperative routing algorithm under this model is multi-hop in nature, where at each hop a decision has to be made about the *set* of transmitting and receiving nodes that form a cooperative link. This means that the receiving set is not necessarily a single node as in the SCB model, rather *multiple* nodes can be appropriately chosen by the routing algorithm to improve energy and throughput efficiency.

In this paper, we present some of our early results, hoping to motivate further research in this area that has the potential to significantly influence the design of future wireless networks. Our contributions can be summarized as follows:

1) We show that optimal cooperative routing under the SCB model severely affects network throughput, and discuss some causes of the problem. Specifically, we advocate for increasing *parallelism* at the physical layer by means of MCB.

This paper is based in part on work supported under National Science Foundation Grant CNS-0721861.

2) We formulate optimal power allocation under the MCB model in both single-flow and multi-flow networks, and provide approximate closed-form expressions for power allocation.
3) We present a discussion of open problems and future research directions toward having a comprehensive cooperative routing which is both energy and throughput efficient.

The rest of this paper is organized as follows. Section II describes our cooperative routing formulation. In Section III, we investigate energy and throughput of cooperative routing under the SCB model. Section IV presents our formulation of single-flow and multi-flow cooperative routing under the MCB model. Our concluding remarks as well as a discussion of future research directions are presented in Section V.

## II. Cooperative Routing

### A. Network Model

We consider a wireless network consisting of a set of nodes distributed randomly in an area, where each node has a single omnidirectional antenna. We assume that each node can adjust the magnitude and phase of its signal and that multiple nodes can coordinate their transmissions at the physical layer to form a CB link. In this section, we consider a general cooperative model in which a set of transmitting nodes denoted by $T = \{t_1, \ldots, t_m\}$, cooperatively communicate with a set of receiving nodes denoted by $R = \{r_1, \ldots, r_n\}$. In this model, every receiver has to successfully decode data at a target rate $\rho_0$, which is fixed across the receivers. A receiver can decode the received signal with *no error* if the received signal-to-noise-ratio (SNR) is above a minimum threshold $\mathrm{SNR}_{\min}$, otherwise, the signal can not be decoded. Based on the instantaneous capacity of a beamforming channel [9], we have $\rho_0 = \log_2(1 + \mathrm{SNR}_{\min})$, and, consequently $\mathrm{SNR}_{\min} = 2^{\rho_0} - 1$.

### B. Channel Model

The channel between each pair of transmitting and receiving nodes is a time-slotted wireless channel. Let $h_{ij}$ denote the complex channel gain between nodes $t_i$ and $r_j$, modeled as $h_{ij} = |h_{ij}| e^{\jmath\theta_{ij}}$, where $|h_{ij}|$ is the channel gain magnitude and $\theta_{ij}$ is the phase offset due to oscillator mismatch and propagation between $t_i$ and $r_j$. We assume that $|h_{ij}|^2$ is inversely proportional to $d_{ij}^{\alpha}$, where $d_{ij}$ is the distance between nodes $t_i$ and $r_j$ and $\alpha$ is the path-loss exponent (typically between 2 and 6). We further assume that channel parameters, namely, $h_{ij}$'s, are globally known at the transmitters. We denote the noise at node $r_j$ by $\eta_j[t]$, where $\eta_j[t]$ is assumed to be complex Gaussian with zero mean and variance $\mathrm{P}_\eta$. We assume that the noise processes are independent and identically distributed across nodes.

### C. Routing Model

A $K$-hop cooperative route $\ell$ is a sequence of $K$ cooperative links $\langle \ell_1, \ldots, \ell_K \rangle$, where link $\ell_k$ is formed between a set of transmitters $T_k$ and a set of receivers $R_k$ using CB at the physical layer. The sequence of links $\ell_k$ connects a source '$s$' to a destination '$d$' in a loop-free path. Our objective is to find a path that minimizes end-to-end transmission power to reach the destination subject to a constraint on the throughput of the path. Let $\mathcal{C}(T_k, R_k)$ denote the *cost* of link $\ell_k = (T_k, R_k)$, which is defined as the minimum transmission power to form the cooperative link $(T_k, R_k)$. The problem of energy efficient routing can then be formulated as follows

$$\begin{aligned} \min_{\ell} \quad & \sum_{(T_k, R_k) \in \ell} \mathcal{C}(T_k, R_k) \\ s.t. \quad & \rho(\ell) \geq \rho_0, \end{aligned} \tag{1}$$

where, $\rho(\ell)$ is the end-to-end throughput of path $\ell$, and $\rho_0$ is a target throughput. Since throughput is an increasing function of the transmission power, a necessary condition for minimizing power over a path $\ell$ is given by $\rho(T_k, R_k) = \rho_0$, for all $(T_k, R_k) \in \ell$, *i.e.*, all links should just achieve the minimum throughput $\rho_0$.

### D. Routing Algorithm

A cooperative route $\ell$ is essentially a sequence $\ell = \langle (T_1, R_1), \ldots, (T_K, R_K) \rangle$ of pairs of corresponding transmitting and receiving sets. Starting from the source node, the initial transmitting set, $T_1$, is simply $\{s\}$, and a route is found as soon as the receiving set contains the destination node '$d$'. We will show in Section III that the optimal transmitting set contains all the nodes that have received the data in previous steps. Therefore, the transmitting set evolves as follows

$$T_{k+1} = T_k \cup R_k, \qquad k = 1, \ldots, K-1\,. \tag{2}$$

Therefore, the route $\ell$ can be alternatively specified by the sequence $\ell = \langle R_1, \ldots, R_K \rangle$. Substituting in (1) yields the following formulation of the optimal cooperative routing

$$\min_{\ell = \langle R_1, \ldots, R_k \rangle \in G} \sum_{k=1}^{K} \mathcal{C}(T_{k-1} \cup R_{k-1}, R_k), \tag{3}$$

where, $G$ is a graph whose nodes are the subsets of the network nodes (all the subsets). A dynamic programming technique can be used to find the optimal cooperative route, which is essentially a shortest path in graph $G$.

## III. Single-Beam Cooperative Beamforming

In this section, we first describe the *single-beam cooperative beamforming (SCB)* model adopted in previous work [5]–[7], and then discuss the optimality and throughput of this model as a motivation for our discussion in the next section.

### A. Beamforming Model

In the SCB model, a set of transmitters $T = \{t_1, \ldots, t_m\}$ cooperatively beamform the *same* data to a single receiver $r_j$. Without loss of generality, we assume that the data is encoded in a signal $s[t]$ that has unit power, and that $t_i$ can arbitrarily adjust the phase and magnitude of its signal in the direction of $r_j$ by a complex weight factor $w_{ij} = |w_{ij}| e^{-\jmath\theta_{ij}}$. Using this model, the transmitted power by node $t_i$ is $|w_{ij}|^2$. Define

$\mathbf{w} = [w_{ij}]_{m\times 1}$ as the vector of beamforming weights $w_{ij}$ for $1 \leq i \leq m$. Let $\mathcal{W}$ denote the set of all feasible weight vectors $\mathbf{w}$. That is $\mathcal{W} = \{\mathbf{w} \,|\, \forall t_i \in T : |w_{ij}|^2 \leq \mathrm{P}_{\max}\}$, where, $\mathrm{P}_{\max}$ is the maximum transmission power of a transmitter.

The received signal at receiver $r_j$ can then be expressed as

$$y_j[t] = \mathbf{h}^H \mathbf{w} s[t] + \eta_j[t], \tag{4}$$

where, $h = [h_{ij}]_{m\times 1}$, for $1 \leq i \leq m$, is the channel gain vector between $T$ and $r_j$, and $\mathbf{A}^H$ denotes the conjugate transpose of a complex matrix $\mathbf{A}$. Using (4), the condition for successful decoding at the receiver $r_j$ is given by

$$\mathbf{h}^H \mathbf{w} \geq \sqrt{\mathrm{SNR}_{\min} \mathrm{P}_{\eta}}\,. \tag{5}$$

Therefore, the link cost $\mathcal{C}(T, r_j)$ for the cooperative link $(T, r_j)$ can be formulated as the following optimization problem:

$$\begin{aligned} \mathcal{C}(T, r_j) = \min_{\mathbf{w}\in\mathcal{W}} \; & \mathbf{w}^H \mathbf{w} \\ s.t. \quad & \mathbf{h}^H \mathbf{w} = \gamma, \end{aligned} \tag{6}$$

where, $\gamma = \sqrt{\mathrm{SNR}_{\min} \mathrm{P}_{\eta}}$. The reason for the equality constraint in (6) is that SNR is an increasing function of the transmission power. Thus, when the equality is satisfied, the minimum transmission power is achieved. The optimization problem (6) is a least-squares optimization, which has the following optimal solution:

$$\mathbf{w}^* = (\mathbf{h}\mathbf{h}^H)^{-1} \mathbf{h} \gamma\,. \tag{7}$$

Using (7), optimal link cost $\mathcal{C}(T, r_j)$ is now given by

$$\mathcal{C}(T, r_j) = \frac{\gamma^2}{\sum_{t_i \in T} |h_{ij}|^2} = \frac{1}{\sum_{t_i \in T} \frac{1}{\mathcal{C}(t_i, r_j)}}, \tag{8}$$

where, $\mathcal{C}(t_i, r_j) = \gamma^2 / |h_{ij}|^2$ is the link cost for a point-to-point communication between $t_i$ and $r_j$.

**Observation 1.** *Using* (8)*, it is clear that as the transmitting set becomes larger the link cost becomes smaller. Therefore, for optimal cooperative routing, the transmitting set in each step of the routing should contain all nodes that have received the data in previous steps.*

Fig. 1 shows the end-to-end energy cost for *optimal non-cooperative routing (NC-Routing)* and *optimal cooperative routing under the SCB model (SCB-Routing)*. The network is a regular grid and the nodes at lower left and upper right corners are chosen as the source and destination for routing. In the simulations, we set $\mathrm{P}_{\max} = 1$, $\alpha = 2$. We set $\mathrm{SNR}_{\min}$ in such a way that neighboring nodes can communicate successfully in a point-to-point model. It is observed that SCB-Routing achieves significant energy savings compared to NC-Routing even for relatively small networks.

### B. Cooperative Routing Throughput

Consider a regular line topology with $N + 1$ nodes with source node '$s$' being node 0 and destination node '$d$' being node $N$. It can be shown that in such a network SCB-Routing routing achieves $(1 - \frac{6}{\pi^2}) \approx 39\%$ energy savings compared to NC-Routing as $N \to \infty$ (see [5]).

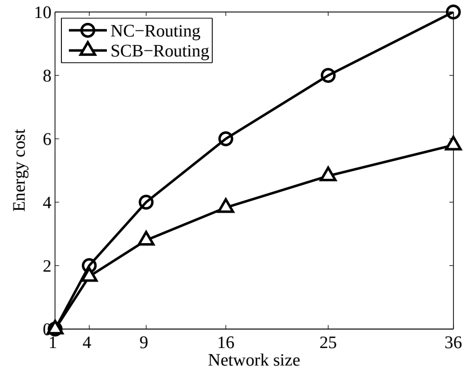

Fig. 1. End-to-end energy cost comparison.

Let us now consider the throughput achieved with and without cooperation. We consider *transport capacity* [10], and assume that a single packet can be transmitted in a time slot. Under NC-Routing, whenever node $j$ transmits a packet to node $j+1$, nodes $j+1$, $j+2$ and $j-1$, $j-2$ can not transmit. Therefore, the transport capacity of the network is $C_{\mathrm{NC}} = \frac{N}{4}$ hops per time slot for large $N$. According to Observation 1, in SCB-Routing, as the routing progresses, all nodes that have received the data participate in cooperative transmission to the next node along the line. For example, nodes $0, 1, \ldots, j-1$ cooperate with node $j$ to transmit the same packet to node $j + 1$. Therefore, the transport capacity of the network is $C_{\mathrm{CB}} = 1$ hop per time slot. Clearly, as $N \to \infty$, we have $C_{\mathrm{CB}}/C_{\mathrm{NC}} \to 0$.

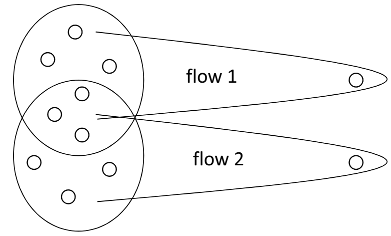

Fig. 2. Two flows with overlapping transmitting sets.

This problem persists even when there are multiple flows in the network. Recall that SCB-Routing has a progressive transmitting set which gets larger as the routing progresses. When there are multiple flows in the network, it is possible that some transmitting sets overlap (see Fig. 2). In this case, different flows should take turn under the SCB model, resulting in reduced throughput. In the MCB model, however, this problem can be alleviated by forming a *multi-beam* cooperative link. As will be discussed in the next section, in the particular example of Fig. 2, MCB requires only a single time slot to forward packets for flow 1 and flow 2, compared to 2 time slots required with SCB.

To further demonstrate the effect of cooperation on network throughput, we have simulated a $10 \times 10$ regular grid topology with a varying number of flows. For each flow, source and destination nodes are chosen randomly in such a way that the distance between every pair of source and destination nodes is at least 10 hops. Since all links have the same throughput in our model, we have computed the *mean number of scheduled links* in a time slot as the measure of throughput. Fig. 3

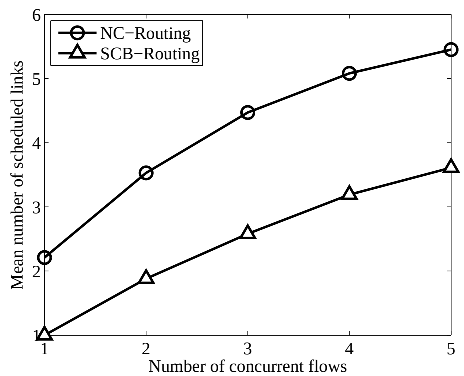


Fig. 3. Multi-flow throughput comparison.

presents the mean number of scheduled links for different number of flows. It is observed that the network throughput drops significantly as the result of cooperation. As the distance between source/destination nodes increases and the network becomes more congested (*i.e.*, more flows in the network), we expect to see even further drop in the throughput of SCB-Routing.

## IV. Multi-Beam Cooperative Beamforming

In this section, we develop a *multi-beam cooperative beamforming (MCB)* model for single-flow and multi-flow networks. We then formulate link cost as a minimization problem and derive approximate closed-form expressions for the cost of a MCB link.

### A. Single-Flow Formulation

Recall that in the SCB model, a set of transmitting nodes cooperatively beamform to a single receiver. With MCB, transmitting nodes $T = \{t_1, \dots, t_m\}$ form $n$ simultaneous beams toward receivers $R = \{r_1, \dots, r_n\}$. Following [3], to form a MCB link between $T$ and $R$, every transmitter $t_i \in T$ beamforms in the direction of each receiver $r_j \in R$, independently. Without loss of generality, we assume that the information is encoded in a signal $s[t]$ that has unit power, and that $t_i$ can arbitrarily adjust the phase and magnitude of its signal in the direction of $r_j$ by complex scaling factor $w_{ij}$. Thus, the signal transmitted by $t_i$ is given by $x_i[t] = \sum_{r_j \in R} w_{ij} s[t]$. Using this model, the transmitted power by node $t_i$ is then given by $\sum_{r_j \in R} |w_{ij}|^2$. Let $h_{ij}$ and $w_{ij}$ denote the complex channel gain and beamforming weight between $t_i \in T$ and $r_j \in R$. Define complex matrices $\mathbf{w} = [w_{ij}]_{m \times n}$ and $\mathbf{h} = [h_{ij}]_{m \times n}$. Let $\mathcal{W}$ denote the set of all feasible weight matrices $\mathbf{w}$. That is $\mathcal{W} = \{\mathbf{w} \,|\, \forall t_i \in T : \sum_{r_j \in R} |w_{ij}|^2 \leq \mathrm{P}_{\max}\}$.

The received signal at $r_j$ is then given by

$$y_j[t] = \mathbf{h_j}^H \mathbf{w_j}\, s[t] + \sum_{\substack{r_k \\ k \neq j}} \mathbf{h_j}^H \mathbf{w_k}\, s[t] + \eta_j[t], \tag{9}$$

where, $\mathbf{A_j}$ denotes the $j$-th column of matrix $\mathbf{A}$. The link cost $\mathcal{C}(T, R)$ is now given by the following optimization problem:

$$\begin{aligned} &\mathcal{C}(T,R) = \min_{\mathbf{w} \in \mathcal{W}} \sum_{r_j} \mathbf{w_j}^H \mathbf{w_j} \\ &s.t. \quad \Big| \mathbf{h_j}^H \mathbf{w_j}\, s[t] + \sum_{\substack{r_k \\ k \neq j}} \mathbf{h_j}^H \mathbf{w_k}\, s[t] \Big| = \gamma, \quad \forall r_j \in R \ . \end{aligned} \tag{10}$$

In general, this optimization problem does not have a closed-form solution [11]. Nevertheless, it can be solved numerically to find the optimal power allocation. In this section, we derive an approximate solution for this problem based on the *nulling* heuristic proposed in [3]. The idea is to completely null the inter-beam interference by having the interference caused by beam $j$ at other receivers to be zero. Thus, we have

$$\mathbf{h_k}^H \mathbf{w_j} = 0, \quad \forall r_k \neq r_j \ . \tag{11}$$

Moreover, we enforce complete phase synchronization in the direction of the intended receiver. That is

$$\mathbf{h_j}^H \mathbf{w_j} = \gamma \ . \tag{12}$$

These two conditions should be independently satisfied at every receiver $r_j$. Therefore, the optimization problem (10) can be decomposed into $n$ independent subproblems, one for each receiver, as follows:

$$\begin{aligned} &\min_{\mathbf{w_j}} \mathbf{w_j}^H \mathbf{w_j} \\ &s.t. \quad \mathbf{h}^H \mathbf{w_j} = \boldsymbol{\gamma_j}, \end{aligned} \tag{13}$$

where, $\boldsymbol{\gamma_j} = [\gamma_k]_{n \times 1}$, so that $\gamma_j = \gamma$ and $\gamma_k = 0$ for $k \neq j$. Optimization problem (13) is a least-squares optimization problem, which has the following optimal solution:

$$\mathbf{w_j^*} = (\mathbf{h}\mathbf{h}^H)^{-1} \mathbf{h} \boldsymbol{\gamma_j} \ . \tag{14}$$

### B. Multi-Flow Formulation

We assume that there are $n$ active unicast flows in the network and focus on a typical time slot $t$. Let $T_j$ and $r_j$, respectively, denote the transmitting set and receiving node for flow $j$ in this time slot. Define $T$ as the union of all transmitting sets in the network, that is $T = T_1 \cup \dots \cup T_n$. Also, define $R$ as the set of all receiving nodes in this time slot, that is $R = \{r_1, \dots, r_n\}$. Define matrix $\mathbf{e} = [e_{ij}]_{m \times n}$, where $e_{ij} = 1$ if $t_i \in T_j$, and $e_{ij} = 0$ otherwise.

To form multiple simultaneous beams toward the $n$ receivers, every transmitter $t_i$ transmits a *linear combination* of its packets using beamforming weights $w_{ij}$. Thus, the transmitted signal by $t_i$, denoted by $x_i[t]$, is expressed as

$$x_i[t] = \sum_{r_j \in R} w_{ij} e_{ij} s_j[t], \tag{15}$$

where, $s_j[t]$ is the signal corresponding to the packet destined to $r_j$. Consequently, the received signal at $r_j$ is given by

$$y_j[t] = \mathbf{h_j}^H (\mathbf{e_j} \cdot \mathbf{w_j}) s_j[t] + \sum_{\substack{r_k \\ k \neq j}} \mathbf{h_j}^H (\mathbf{e_k} \cdot \mathbf{w_k}) s_k[t] + \eta_j[t], \tag{16}$$

where, $\mathbf{A} \cdot \mathbf{B}$ denotes the Hadamard product of matrices $\mathbf{A}$ and $\mathbf{B}$. The link cost $\mathcal{C}(T, R)$ is now expressed as the following optimization problem:

$$\begin{aligned} &\mathcal{C}(T,R) = \min_{\mathbf{w} \in \mathcal{W}} \sum_{r_j} \mathbf{w_j}^H \mathbf{w_j} \\ &s.t. \quad \frac{|\mathbf{e_j} \cdot \mathbf{w_j}|^2}{\Big| \sum_{\forall r_k \neq r_j} \mathbf{h_j}^H (\mathbf{e_j} \cdot \mathbf{w_k}) \Big|^2 + \mathrm{P}_\eta} = \mathrm{SNR}_{\min}, \quad \forall r_j \in R \end{aligned} \tag{17}$$

This optimization problem can be solved numerically to find the optimal power allocation. However, similar to the single-flow case, we develop an approximate solution based on the complete nulling heuristic. Thus, the following constraints should be satisfied

$$\mathbf{h_k}^H(\mathbf{e_j}\cdot\mathbf{w_j}) = 0, \quad \forall r_k \neq r_j \tag{18}$$
$$\mathbf{h_j}^H(\mathbf{e_j}\cdot\mathbf{w_j}) = \gamma\,. \tag{19}$$

Similar to the single-flow case, after decomposing (17) into $n$ independent subproblems, the optimal beamforming weight vector in the direction of $r_j$ is given by:

$$\mathbf{w}^*_\mathbf{j} = (\mathbf{A}(j)\mathbf{A}(j)^H)^{-1}\mathbf{A}(j)\boldsymbol{\gamma_j}, \tag{20}$$

where, matrix $\mathbf{A}(j)$ is defined as $\mathbf{A}(j) = \mathbf{e_j}\cdot\mathbf{h}$.

## V. Concluding Remarks

In this paper, we studied energy and throughput performance of cooperative routing in wireless networks that support cooperative beamforming (CB) at the physical layer. We showed that while cooperative routing achieves significant energy savings, it results in a sharp reduction in network throughput. We then investigated the cause of this problem, and explored multi-beam cooperative beamforming (MCB) in order to develop energy and throughput efficient cooperative routing algorithms for wireless networks.

We should emphasize that this work is only a first attempt at designing energy-throughput efficient cooperative routing algorithms that take advantage of MCB at the physical layer. Several issues remain to be addressed toward having a comprehensive cooperative routing algorithm:

- **Routing Complexity and Heuristic Algorithms:** A dynamic programming technique can be used to find the optimal cooperative route formulated in (3). This is essentially a shortest path problem over graph $G$ whose nodes are subsets of the network nodes. For a network with $N$ nodes, there are $O(2^N)$ nodes in the routing graph $G$, hence, applying a standard shortest path algorithm (such as the Dijkstra's algorithm) to find the optimal cooperative route has exponential computational complexity. To reduce the complexity of the routing, one approach is to limit the search space for transmitting and receiving sets, for example, only to the nodes along the shortest non-cooperative path.
- **Distributed Implementation and Protocol Design:** By limiting the transmitting and receiving sets to neighboring nodes, a distributed routing algorithm can be designed. However, any implementation of the algorithm requires a protocol to form the transmitting and receiving clusters and determine the power allocation in a distributed manner. In particular, we did not discuss in this paper how to decide the power allocation in a distributed manner once the transmitting and receiving sets are chosen. A simple heuristic power allocation algorithm is to allocate power *equally* in the direction of each receiver. When transmitters and receivers are limited to neighboring nodes, this heuristic might provide a good approximation as channel gains are approximately similar in this case.
- **Multi-Flow Networks and Scheduling:** In this paper, we briefly eluded to cooperative routing in multi-flow networks, and developed models for joint power allocation across overlapping flows. However, we neither discussed joint routing and cooperation across different flows, nor did we discuss MAC-layer scheduling under the MCB model. Specifically, due to beamforming, the nature of interference is different from the interference caused by omnidirectional wireless broadcasts, and hence the scheduling problem requires special treatment [12].
- **Capacity Scaling:** Capacity scaling of wireless networks has been subject to extensive research in the past few years (for example, see [10], [13]). The latest result indicate that the capacity of a wireless network is inherently limited by physics laws regardless of the complexity of the communication schemes implemented in the network [14]. Specifically, the capacity of a wireless network with $N$ nodes randomly distributed in a unit disk area scales as $O(\sqrt{N})$ as $N \to \infty$. Although, advanced communication schemes, *e.g.*, cooperative beamforming, do not change the scaling behavior, it is of great interest to understand how they impact the capacity of the networks that have small number of nodes, and how they might change the exact scaling (*i.e.*, the constants hidden in $O(\sqrt{N})$) of large networks.

## References


[1] R. Mudumbai, D. R. B. III, U. Madhow, and H. V. Poor, "Distributed transmit beamforming: Challenges and recent progress," *IEEE Commun. Mag.*, vol. 47, no. 2, pp. 102–110, Feb. 2009.

[2] H. Ochiai, P. Mitran, H. V. Poor, and V. Tarokh, "Collaborative beamforming for distributed wireless ad hoc sensor networks," *IEEE Trans. Signal Process.*, vol. 53, no. 11, pp. 4110–4124, Nov. 2005.

[3] L. Dong, A. P. Petropula, and H. V. Poor, "Weighted cross-layer cooperative beamforming for wireless networks," *IEEE Trans. Signal Process.*, vol. 57, no. 8, pp. 3240–3252, Aug. 2009.

[4] J. Zhu, C. Qiao, and X. Wang, "A comprehensive minimum energy routing scheme for wireless ad hoc networks," in *Proc. IEEE Infocom*, Hong Kong, China, Mar. 2004, pp. 1437–1445.

[5] A. Khandani, J. Abounadi, E. Modiano, and L. Zheng, "Cooperative routing in static wireless networks," *IEEE Trans. Wireless Commun.*, vol. 55, no. 11, pp. 2185–2192, Nov. 2007.

[6] J. Zhang and Q. Zhang, "Cooperative routing in multi-source multi-destination multi-hop wireless networks," in *Proc. IEEE Infocom*, Phoenix, USA, Apr. 2008, pp. 2369–2377.

[7] A. S. Ibrahim, Z. Han, and K. J. R. Liu, "Distributed energy-efficient cooperative routing in wireless networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 10, pp. 3930–3941, Oct. 2008.

[8] A. Scaglione, D. L. Goeckel, and J. N. Laneman, "Cooperative communications in mobile ad-hoc networks: Rethinking the link abstraction," *IEEE Signal Process. Mag.*, vol. 23, no. 5, pp. 15–19, Sep. 2006.

[9] D. Tse and P. Viswanath, *Fundamentals of wireless communications*. Cambridge, UK: Cambridge University Press, 2005.

[10] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Trans. Inf. Theory*, vol. 46, no. 2, pp. 388–404, Mar. 2000.

[11] W. Yu and T. Lam, "Downlink beamforming with per-antenna power constraints," in *Proc. IEEE SPAWC*, New York, USA, Jun. 2005.

[12] K. Sundaresan, K. Ramachandran, and S. Rangarajan, "Optimal beam scheduling for multicasting in wireless networks," in *Proc. ACM Mobicom*, Beijing, China, Sep. 2009.

[13] A. Ozgur, O. Leveque, and D. Tse, "Hierarchical cooperation achieves optimal capacity scaling in ad hoc networks," *IEEE Trans. Inf. Theory*, vol. 53, no. 10, pp. 3549–3572, Oct. 2007.

[14] M. Franceschetti, M. Migliore, and P. Minero, "The capacity of wireless networks: information-theoretic and physical limits," *IEEE Trans. Inf. Theory*, vol. 55, no. 8, pp. 3413–3424, Aug. 2009.