Optimal Power Routing for End-to-end Outage Restricted Distributed MIMO Multi-hop Networks

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Abstract—**This paper investigates the optimal power routing problem in relay-based cooperative networks, where the relays are arbitrarily positioned. We generalize the standard shortest path routing algorithm (GSPRA) to find an minimum-power distributed MIMO multi-hop route from a source to a destination while satisfying a given e2e outage probability demand. The task of the proposed approach includes how to group relays to virtual antenna array (VAA) and discover the optimal multi-hop path. Instead of using per hop (or link) constraint, which is assumed by most of the existing routing algorithm, an e2e outage probability constraint is assumed for more relevance and freedom in practical systems. Under the concept of virtual node and virtual link, an efficient power allocation solution for general distributed MIMO multi-hop networks is used to calculate link costs for the shortest path algorithm. The proposed routing approach can fully exploit the merits of both cooperative communications and multi-hop transmissions. The significant power savings due to the proposed approach in comparison to the existing algorithms is demonstrated by numerical results.**

Index Terms—**Optimal power routing, asymmetric distributed MIMO, shortest path algorithm, outage probability, relaying.**

I. Introduction

After essentially research in the last years, the multi-hop transmission is well-known a promising technology to combat the large signal attenuations due to the large distances between transmitters and receivers. The energy-efficient routing problem over a multi-hop network is until now broadly investigated and well understood. Recently, there has been increasing interest in combining point-to-point MIMO techniques and multi-hop wireless relaying to achieve more reliable e2e communications. By the concept of virtual antenna array (VAA) spatially separated relaying nodes are allowed to utilize the capacity-enhancement approaches of MIMO techniques offering significant improvements for the data rate in multi-hop networks [1], e.g., by distributed space-time codes. Therefore, with the development of cooperative technologies like distributed MIMO concept, the existing routing algorithm need to be redesigned in order to meet the new challenge for the cooperative communications.

The goal of this paper is to establish which cooperative routing path ω from a source to a destination through several randomly positioned relays is with minimal power consumption while satisfying a given e2e outage probability constraint. Fig. 1 shows the cooperative routing under the concept of distributed MIMO multi-hop transmission, where one source communicates with one destination via a number of VAAs in multiple hops.

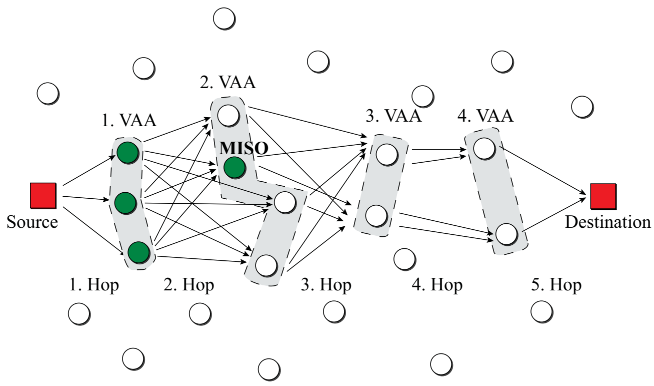

Fig. 1. Cooperative routing with distributed MIMO multi-hop structure.

Recently, the cooperative routing problem has been considered in [2], [3], [4]. In [2], the minimum energy cooperative path routing algorithm was introduced, where a cooperative shortest path algorithm was developed for cooperative routing in stationary wireless networks. In [3], the cooperative routing problem is studied for static wireless networks, where the multi-hop diversity technique is used to combine signals at the destination. The minimum power cooperative routing algorithm is proposed in [4], which makes full use of the cooperative communications while constructing the minimum-power route.

However, most of the existing cooperative routing approaches use per hop (or link) constraint to calculate the link cost, which is less relevant in e2e Quality-of-Service (QoS) based practical systems. Instead, we will consider the non-ergodic e2e outage probability as the measurement for the QoS in this paper. E2e QoS constraint achieves more freedom degrees as per link constraint, since by given an e2e QoS constraint we can also optimize the link constraints. Moreover, the majority of real-world wireless applications happen over non-ergodic slow fading channels, the ergodic capacity (or rate) is not applicable in strict sense.

In this paper, we consider the cooperative minimum power routing problem based on distributed MIMO multi-hop structure while satisfying a given e2e outage probability. In those works stated above, the routing algorithms are mainly based on

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the common triangle relay system (one source, one relay and one destination). Herein, the task of grouping relay nodes to VAAs is investigated to fully exploit the benefit of cooperative transmissions. Under the concept of virtual node and virtual link, the link cost can be calculated by an efficient power allocation solution for asymmetric distributed MIMO multi-hop networks, which is introduced by the authors in [5].

The remainder of the paper is organized as follows. In Section II the system model of the asymmetric distributed MIMO multi-hop scheme is introduced. In Section III we introduce the efficient power allocation solution briefly. In Section IV, the cooperative routing problem for distributed MIMO multi-hop network is discussed. Finally, some simulation results and conclusions are given in Section V and VI, respectively.

II. System Model and Cooperative Transmission

In this section, we describe the system model and the distributed MIMO multi-hop transmission scheme.

A. Cooperative Transmission

A given distributed MIMO multi-hop route ω is depicted in Fig. 1, where a source desires to communicates with a destination through $K-1$ VAAs in K hops. It is assumed that each relay has only one antenna and the orthogonal time-slotted transmission scheme is considered, i.e., time-diversion multiple-access (TDMA) between each hop. Due to the half-duplex constraint, one node can't transmit and receive signals simultaneously. Furthermore, the Decode-and-Forward (D&F) relaying protocol is applied at each relay [6].

The source transmits (or broadcasts) the signal to the first VAA at the first time slot. Each node at the first VAA decodes the received signal separately, i.e., there are no information exchange within the VAA during the decoding. Then each node re-encodes the information cooperatively according to an orthogonal space-time block code (OSTBC). An the next time slot, the first VAA transmits the signal to the second VAA. Each node at the second VAA forwards the signal to the next VAA in the same manner as in the first time slot. The signal is therefore "hopped" from one VAA to another VAA until the destination is reached [1]. Since each node within one VAA decodes the received signal separately but re-encodes the signal regarding the same space-time code word, the transmission within one hop can be modeled by several multiple-input single-output (MISO) systems as highlighted in Fig. 1.

Let k index the hop, t_k, r_k be the number of transmit nodes and receive nodes at the kth hop, respectively. The pathloss between node i of the $(k-1)$th VAA and node j of the kth VAA is defined by $1/d^{\epsilon}_{k,i,j}$, where $d_{k,i,j}$ denotes the distance and ϵ is the pathloss exponent within range of 2 to 5. We define $\mathbf{S}_k \in \mathbb{C}^{t_k \times T_k}$ as the OSTBC encoded signal transmitted from the t_k nodes at the kth hop. The received signal $\mathbf{y}_{k,j} \in \mathbb{C}^{1\times T_k}$ at the jth node is expressed as

$$\mathbf{y}_{k,j} = \mathbf{h}_{k,j} \cdot \mathbf{\Lambda}_{k,j} \cdot \mathbf{S}_k + \mathbf{n}_{k,j} \ , \tag{1}$$

with the diagonal matrix

$$\mathbf{\Lambda}_{k,j} = \mathrm{diag}\left\{ \sqrt{\frac{\mathcal{P}_{k,1}}{d^{\epsilon}_{k,1,j}}}, \cdots, \sqrt{\frac{\mathcal{P}_{k,t_k}}{d^{\epsilon}_{k,t_k,j}}} \right\} , \tag{2}$$

where $\mathbf{n}_{k,j} \sim \mathcal{N}_C(0, N_0) \in \mathbb{C}^{1\times T_k}$ is the Gaussian noise vector with power spectral density N_0 and $\mathcal{P}_{k,i}$ is the transmission power of the ith node at the kth hop. The channel from the t_k transmit nodes to the jth receive node is given by $\mathbf{h}_{k,j} \in \mathbb{C}^{1\times t_k}$, which obeys the Rayleigh fading statistics, i.e., they are complex zero-mean circular symmetric Gaussian distributed with variance 1.

Note that each MISO system considered in this paper is generally defined, i.e., each subchannel of the MISO system are with different pathlosses. We term such network as asymmetric network, which is realistic for practical applications.

III. Efficient Power Allocation for General Network Structure

In the sequel, we introduce an efficient power allocation for e2e outage probability restricted distributed MIMO multi-hop networks briefly. More details can be found in [5].

A. End-to-end Outage probability

As discussed in the system model, due to the D&F relaying protocol and non-cooperative receiving at the VAAs, the multi-hop transmission can be decomposed into several MISO systems. In order to calculate the e2e outage probability, we consider the outage probability per MISO system first.

The instantaneous achievable rate of an asymmetric MISO system with OSTBC can be expressed by

$$C_{k,j} = \rho_k W \log\left(1 + \frac{1}{\rho_k W N_0} \sum_{i=1}^{t_k} g_{k,i,j} |h_{k,i,j}|^2 \right) , \tag{3}$$

where $g_{k,i,j} = \mathcal{P}_{k,i}/d^{\epsilon}_{k,i,j}$ correspond to the elements of $\mathbf{\Lambda}_{k,j}$ given in (2). The variable ρ_k is the rate loss due to the OSTBC, e.g., $\rho_k = 1$ for Alamouti code with $t_k = 2$ and $\rho_k = 3/4$ for OSTBC with $t_k = 3, 4$ [7]. The outage probability $P_{\text{out},k,j} = \Pr(R > C_{k,j})$ describes the probability, that the capacity from the t_k nodes of VAA $k-1$ to node j of VAA k can not satisfy the rate R,

$$\begin{aligned} P_{\text{out},k,j} &= \Pr(R > C_{k,j}) \\ &= \Pr\left(\sum_{i=1}^{t_k} g_{k,i,j} |h_{k,i,j}|^2 < \left(2^{\frac{R}{\rho_k W}} - 1\right) \rho_k W N_0 \right) \\ &= \sum_{i=1}^{t_k} \prod_{\substack{i'=1 \\ i' \neq i}}^{t_k} \frac{g_{k,i,j}}{g_{k,i,j} - g_{k,i',j}} \left(1 - e^{-g^{-1}_{k,i,j} Q_k}\right) , \end{aligned} \tag{4}$$

where $Q_k = \left(2^{\frac{R}{\rho_k W}} - 1\right)\rho_k W N_0$. Due to the complexity of (4), we introduce two approximations to simplify the further analysis.

The variable $\sum_{i=1}^{t_k} g_{k,i,j} |h_{k,i,j}|^2$ in (4) describes a linear combination of t_k independent exponential distributed variables $|h_{k,i,j}|^2$ with different weights $g_{k,i,j}$. For low outage probabilities, it can be accurately approximated by a gamma distributed variable with shape t_k and scale given by the geometric mean $\prod_{i=1}^{t_k} g_{k,i,j}^{1/t_k}$ of all weights $g_{k,i,j}$ [8], [9]

$$\sum_{i=1}^{t_k} g_{k,i,j}|h_{k,i,j}|^2 \approx \text{Gamma}\left(t_k, \prod_{i=1}^{t_k} g_{k,i,j}^{1/t_k}\right) . \tag{5}$$

Therefore, we can transform the asymmetric MISO system with different weights $g_{k,i,j}$ to a symmetric MISO system with common weight $\prod_{i=1}^{t_k} g_{k,i,j}^{1/t_k}$. Hence, the outage probability $P_{\text{out},k,j}$ (4) is given by

$$\begin{aligned} P_{\text{out,Geo},k,j} &= \Pr\left(\prod_{i=1}^{t_k} g_{k,i,j}^{1/t_k} \sum_{i=1}^{t_k} |h_{k,i,j}|^2 < Q_k\right) \\ &= \Pr\left(\sum_{i=1}^{t_k} |h_{k,i,j}|^2 < \underbrace{Q_k \prod_{i=1}^{t_k} g_{k,i,j}^{-1/t_k}}_{x_{k,j}}\right) \\ &= \frac{\gamma(t_k, x_{k,j})}{\Gamma(t_k)} , \end{aligned} \tag{6}$$

where $\gamma(\cdot,\cdot)$ is the incomplete gamma function and $\Gamma(\cdot)$ denotes the gamma function. Since the low outage probability region is concerned for practical systems, the incomplete gamma function in (6) can be approximated by $\gamma(t_k, x_{k,j}) \approx x_{k,j}^{t_k} t_k^{-1}$ [10]. This leads to the simplified approximation for the outage probability (6)

$$\tilde{P}_{\text{out},k,j} = \frac{x_{k,j}^{t_k}}{\Gamma(t_k+1)} , \tag{7}$$

where the inequality $P_{\text{out},k,j} \leq P_{\text{out,Geo},k,j} \leq \tilde{P}_{\text{out},k,j}$ holds.

We assume that the e2e connection is in outage if any of the MISO systems is in outage. Moreover, since the signals are completely decoded at each VAA, the outage probability within each hop is mutually independent. Thus, the e2e outage probability is expressed as

$$P_{\text{e2e}} = 1 - \prod_{k=1}^{K} \prod_{j=1}^{r_k} (1 - P_{\text{out},k,j}) . \tag{8}$$

Furthermore, (8) can be approximated by a sum expression yielding the following e2e outage probability

$$\tilde{P}_{\text{e2e}} = \sum_{k=1}^{K} \sum_{j=1}^{r_k} \tilde{P}_{\text{out},k,j} = \sum_{k=1}^{K} \sum_{j=1}^{r_k} \frac{x_{k,j}^{t_k}}{\Gamma(t_k+1)} . \tag{9}$$

It can be proven that $\tilde{P}_{\text{e2e}}$ is an upper bound of P_{e2e} [11], i.e., $P_{\text{e2e}} \leq \tilde{P}_{\text{e2e}}$.

B. Convex Optimization Problem and Its Solution

The optimization problem that minimizes the total transmit power $\mathcal{P}_{\text{total}}$ while satisfying a given e2e outage probability e can be formulated as

$$\begin{aligned} &\text{minimize } \mathcal{P}_{\text{total}} = \sum_{k=1}^{K} \sum_{i=1}^{t_k} \mathcal{P}_{k,i} \\ &\text{subject to } P_{\text{e2e}} \leq e . \end{aligned} \tag{10}$$

Note that (10) can be shown to be convex for low e2e outage probability e [8]. Unfortunately, the optimization problem (10) doesn't have a closed-form solution in terms of the power per node. However, it can be solved by standard optimization tools leading to considerable complexity [12].

By replacing P_{e2e} in (10) with $\tilde{P}_{\text{e2e}}$ given in (9) the approximated optimization problem

$$\begin{aligned} &\text{minimize } \mathcal{P}_{\text{total}} = \sum_{k=1}^{K} \sum_{i=1}^{t_k} \mathcal{P}_{k,i} \\ &\text{subject to } \tilde{P}_{\text{e2e}} \leq e \end{aligned} \tag{11}$$

is achieved. The solution of this near-optimal power allocation problem leads to an increased total power consumption, but satisfies the original outage requirement $P_{\text{e2e}} \leq e$ as the more stringent constraint $\tilde{P}_{\text{e2e}} \geq P_{\text{e2e}}$ is considered. Furthermore, the near-optimal solution can be rapidly obtained by solving the constrained optimization problem (11) using Lagrange multipliers [5].

Due to the space limit in this paper, we omit the detailed proof of the efficient power allocation algorithm.

Theorem 1 (Near-optimal power allocation (NOPA)): In an asymmetric distributed MIMO multi-hop system with an arbitrary number of nodes t_k per VAA and a given e2e outage probability requirement e, the near-optimal power allocation $\mathcal{P}_{k,i}^*$ is given by

$$\mathcal{P}_{k,i}^* = \left(\sum_{j=1}^{r_k} D_{k,j}{}^{t_k}\right)^{\frac{1}{t_k+1}} \cdot (\Gamma(t_k+1)A)^{\frac{-1}{t_k+1}} , \tag{12}$$

where we define the abbreviation $D_{k,j} = Q_k \prod_{i=1}^{t_k} d_{k,i,j}^{\epsilon/t_k}$ and the parameter A is the non-negative real root of a high-order polynomial given by

$$\tilde{P}_{\text{e2e}} = \sum_{k=1}^{K} \sum_{j=1}^{r_k} \tilde{P}_{\text{out},k,j} = \sum_{k=1}^{K} \sum_{j=1}^{r_k} a_{k,j} A^{\frac{t_k}{t_k+1}} = e , \tag{13}$$

with coefficients

$$a_{k,j} = \Gamma(t_k+1)^{\frac{-1}{t_k+1}} D_{k,j}^{t_k} \left(\sum_{j=1}^{r_k} D_{k,j}^{t_k}\right)^{\frac{-t_k}{t_k+1}} . \tag{14}$$

Note that efficient methods of root searching like Newton can be used to determine A.

In general, we can define the total power consumption from the source to any node n as auxiliary function with an argument of routing path ω_n

$$\mathcal{P}_{\text{total},n} = f(\omega_n) = \sum_{k=1}^{K} \sum_{i=1}^{t_k} \mathcal{P}_{k,i} \text{ for route } \omega_n . \tag{15}$$

Therefore, (15) can be used to calculate the link cost for our routing algorithm.

IV. Cooperative Power Routing Algorithm

In this section we propose two distributed MIMO multi-hop routing algorithms as extensions to the shortest path algorithm [13].

A. Network Model

We consider a directed wireless network $G = (V, E)$ with node set V and edge set E. Given a source-destination pair S and D, the goal is to find the $S \to D$ route ω_D that minimizes the total transmission power while satisfying a specific e2e outage probability. Due to the broadcast nature of wireless medium, each node has connections to all the other nodes theoretically. We define the adjacency set $A(i)$ for node $i \in V$ which is the set of all edge (or link) incident from node i, written $A(i) = \{(i,j)|(i,j) \in E\}$. In order to describe a distributed MIMO multi-hop structure, a directed route ω_n from the source S to node n is given by

$$\omega_n = [S, \underbrace{\begin{bmatrix} i_{1,1} \\ \cdots \\ i_{1,t_1} \end{bmatrix}}_{1.\text{VAA}}, \cdots, \underbrace{\begin{bmatrix} i_{k,1} \\ \cdots \\ i_{k,t_k} \end{bmatrix}}_{k.\text{VAA}}, \cdots, \underbrace{\begin{bmatrix} i_{K-1,1} \\ \cdots \\ i_{K-1,t_k} \end{bmatrix}}_{(K-1).\text{VAA}}, n]. \quad (16)$$

B. Virtual Node and Virtual Link

The greatest challenge brought by the distributed MIMO concept to the routing problem is how to group potential relays to VAAs, since for such case the traditional shortest path algorithm is not valid anymore. To this end, the concept of virtual node and virtual link is introduced in order to adjust the shortest path algorithm for cooperative communications.

Since each VAA cooperates with each other to transmit signal regarding to an OSTBC, each VAA can be then viewed as a virtual node with several antennas, i.e., (16) becomes

$$\omega_n = [S, i'_1, \cdots, i'_k, \cdots, i'_{K-1}, n], \quad (17)$$

where i'_k describes the virtual node. As a result, the links from the source to one VAA, one VAA to another VAA, or one VAA to the destination can be seen as virtual links.

Under these definitions, we can generalize the short path algorithm to find the optimal distributed MIMO multi-hop route from potential relays.

C. Cooperative Add-on Routing Algorithm (CARA)

As mentioned before, most of the existing cooperative routing algorithm are simple extensions of the shortest path algorithm, which use the standard shortest path algorithm to find a basic route first and add relays to this route. Clearly, these routing algorithms do not fully exploit the advantages of cooperative communications. We term these algorithms as add-on approaches. For comparison, we also introduce such add-on approach for distributed MIMO multi-hop route, namely Cooperative Add-on Routing Algorithm (CARA).

Note that the proposed power allocation solution given in (15) is valid for any route ω from the source to the destination, e.g., the direct link or the traditional non-cooperative multi-hop route. Hence, (15) can be applied to calculate the non-cooperative multi-hop route by the standard shortest path algorithm at the first step. After obtaining this basic route, potential relays can be added to the intermediate relays to form VAAs. Table I describes the CARA algorithm in details.

Step I: shortest path algorithm w.r.t e2e outage probability constraint.
$\mathcal{P}_{\text{total},S} := 0$
$\mathcal{P}_{\text{total},j} := \infty, \forall j \in V - \{S\}$
LIST $:= V$
while LIST $\neq \emptyset$
  {node selection}
  let $i \in$ LIST be a node for which $\mathcal{P}_{\text{total},i} = \min\{\mathcal{P}_{\text{total},j} | j \in \text{LIST}\}$
  remove node i from LIST
  {link cost update}
  for each $(i,j) \in A(i)$
    $\omega_{j'} = [\omega_i, j]$
    if $\mathcal{P}_{\text{total},j} > \mathcal{P}_{\text{total},j'}$ **then**
      $\mathcal{P}_{\text{total},j} = \mathcal{P}_{\text{total},j'}$
      $\omega_j = [\omega_i, j]$

Step II: add-on process
ω_D is obtained from *Step I*
$\omega_D = [S, i_{1,1}, \cdots, i_{k,1}, \cdots, i_{K-1,1}, D]$.
LIST $:= V - \{n | n \in \omega_D\}$
for each $i_{k,1} \in \omega_D$
  {virtual node}
  $i'_k = i_{k,1}$
  {node selection}
  for each $i \in$ LIST
    group $i \in$ LIST and i'_k to form a VAA for a new route $\omega_{D'}$
    if $\mathcal{P}_{\text{total},D'} < \mathcal{P}_{\text{total},D}$ **then**
    $\mathcal{P}_{\text{total},D} = \mathcal{P}_{\text{total},D'}$
    {virtual node update}
    $(i'_k, i) \Rightarrow i'_k$
    $\omega_D = \omega_{D'}$
    remove node i from LIST

TABLE I
Cooperative Add-on Routing Algorithm (CARA).

D. Generalized Shortest Path Routing Algorithm (GSPRA)

In the sequel, we present a redesigned shortest path routing algorithm based on distributed MIMO multi-hop structure. Compared to the routing algorithm which is along the shortest non-cooperative path algorithm, the novel approach combines the route searching and VAA grouping directly to fully exploit the merits of distributed MIMO technique. Table II describes the GSPRA algorithm in details.

Generalized shortest path algorithm
$\mathcal{P}_{\text{total},S} := 0$
$\mathcal{P}_{\text{total},j} := \infty, \forall j \in V - \{S\}$
LIST $:= V$
while LIST $\neq \emptyset$
  {node selection}
  let $i \in$ LIST be a node for which $\mathcal{P}_{\text{total},i} = \min\{\mathcal{P}_{\text{total},j} | j \in \text{LIST}\}$
  remove node i from LIST
  {link cost update}
  for each $(i,j) \in A(i)$
    $\omega_{j'} = [\omega_i, j]$
    if $\mathcal{P}_{\text{total},j} > \mathcal{P}_{\text{total},j'}$ **then**
    {VAA grouping}
    for each $i \in$ LIST
      {virtual node}
      $i' = i$
      group $i \in$ LIST and i' to form a VAA for a new route $\omega_{D'}$
      if $\mathcal{P}_{\text{total},D'} < \mathcal{P}_{\text{total},D}$ **then**
      $\mathcal{P}_{\text{total},D} = \mathcal{P}_{\text{total},D'}$
      {virtual node update}
      $(i', i) \Rightarrow i'$
      $\omega_D = \omega_{D'}$
      remove node i from LIST

TABLE II
Generalized shortest path routing algorithm (GSPRA).

V. Performance Evaluation

The performance of the proposed cooperative power routing algorithm with e2e outage restricted distributed MIMO multi-hop route are assessed here. It is assumed that the e2e communication over $W = 5$ MHz should meet an e2e outage probability constraint of $e = 1\%$ where the path loss exponent ϵ is 3, and N_0 is -174 dBm/Hz. Note that the relays in the network are randomly positioned in one 4km $\times$ 4km area.

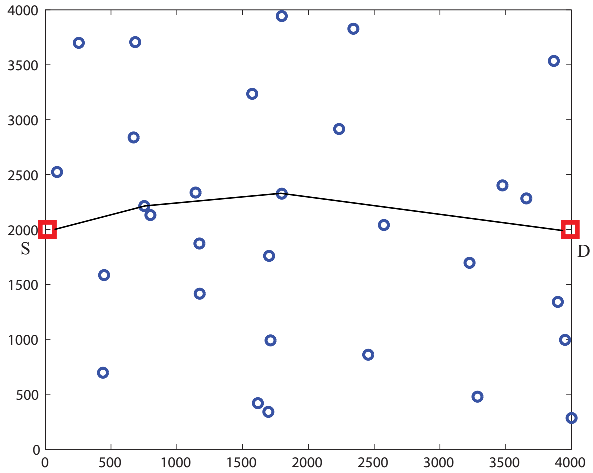

Fig. 2. Shortest non-cooperative multi-hop path.

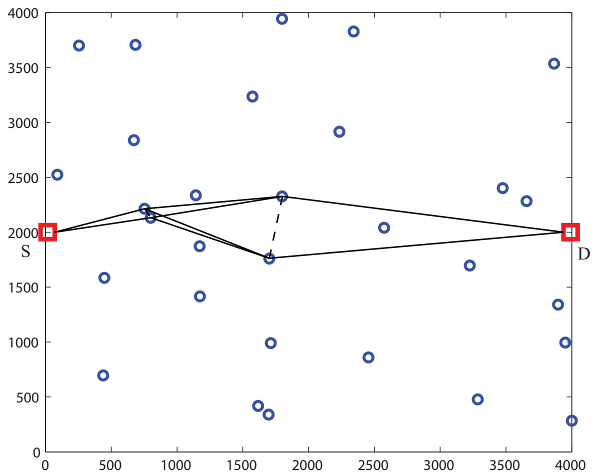

Fig. 3. Cooperative routing Shortest non-cooperative multi-hop path (CARA), where each dashed line represents one VAA.

Fig. 2, 3, 4 show the routing path calculated by shortest non-cooperative path algorithm, cooperative add-on routing algorithm and generalized shortest path algorithm for cooperative communications, respectively. As mentioned, the CARA approach is based on the basic shortest path and add relays to form VAAs as shown in Fig. 3. In contrast, the GSPRA derives a two-hop system with one two-node VAA.

Fig. 5 depicts the total power versus the data rate for direct transmission, standard shortest non-cooperative path

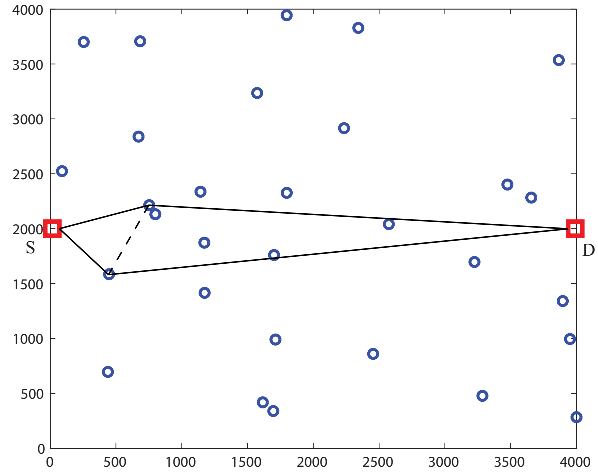

Fig. 4. Generalized shortest cooperative path routing (GSPRA), where each dashed line represents one VAA.

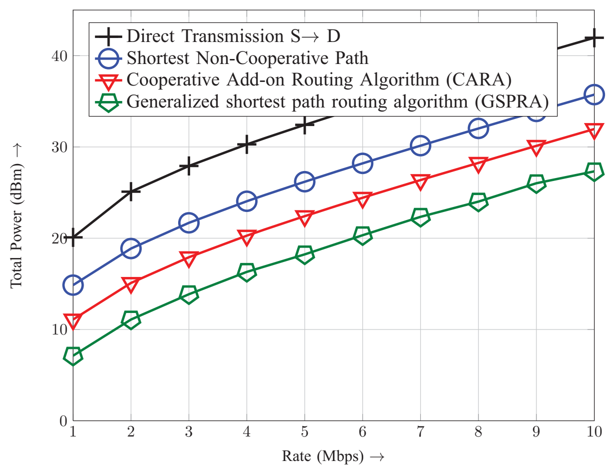

Fig. 5. $\mathcal{P}_{\text{total}}$ a) in mW and b) dBm for direct transmission, standard shortest non-cooperative path routing, cooperative add-on routing algorithm and generalized shortest cooperative path routing, respectively.

routing, cooperative add-on routing algorithm and generalized shortest cooperative path routing, respectively. As shown, both cooperative routing algorithms achieve significant power gain in comparison with the direct transmission and the non-cooperative multi-hop transmission. Moreover, the GSPRA scheme leads to power savings of more than 3 dBm comparing to the CARA scheme.

VI. Conclusion

In this paper, we investigated the cooperative power routing problem for relaying networks. By utilization the concept of distributed MIMO transmission, we have successfully derived two novel power routing algorithm with consideration of grouping dedicated relays to virtual antenna arrays. Hence, the capacity-enhancement MIMO techniques can be directly applied for VAAs, e.g., distributed space-time codes. Besides introducing a simple cooperative MIMO multi-hop routing algorithm along the shortest non-cooperative path routing algorithm, which has be assumed by most of the existing papers, the task of how to group relays to VAAs is accomplished in combination with the shortest path algorithm, i.e., we generalize the shortest path algorithm in order to support the challenge brought by cooperative communications. As shown in simulation results, the two approaches proposed here achieves significant power gain in comparison with the direct transmission and the non-cooperative multi-hop transmissions.

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