

A Novel MIMO DoF Model for Multi-hop Networks

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Abstract

The rapid advances of MIMO to date have mainly stayed at the physical layer or single-hop communications. Such fruits have not been fully reaped at the network level, particularly for multi-hop networks. This is mainly due to the lack of a tractable and accurate model that can characterize MIMO's powerful capabilities such as spatial multiplexing (SM) and interference cancellation (IC). Recently, a new DoF-based model was proposed to capture MIMO's SM and IC capabilities in multi-hop networks. This model is based on a novel node-ordering concept and only requires simple numeric computation on degrees-of-freedom (DoFs). In this short article, we review previous models for MIMO and then describe this new DoF model. This new DoF model has the potential to enable significant advances of MIMO research in the networking community.

I. INTRODUCTION

MIMO is widely considered as a major breakthrough in modern wireless communications [1], [2]. To date, MIMO has found applications in many wireless standards, such as wireless LAN (802.11n) and upcoming 4G systems. However, research advances in MIMO have been mainly limited at the physical (PHY) layer or for single-hop communications. Advances in multi-hop MIMO networks remain primitive and have not been well understood. The main reason for this stagnation is the lack of tractable and accurate MIMO models that can be readily employed by researchers in the networking community. The main challenge here is that mathematical characterization of MIMO's behavior involves complex matrix manipulations. Such matrix manipulations are

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required for the PHY layer signal processing in high dimensions (due to multiple antennas). But this poses a serious mathematical barrier in the design and analysis of algorithms and protocols for multi-hop networks.

Due to these difficulties, researchers have developed the so-called degree-of-freedom (DoF) models to analyze MIMO's spatial multiplexing (SM) and interference cancellation (IC) capabilities [3], [4], [5], [6], [7]. The concept of DoF was originally defined to represent the multiplexing gain of an MIMO channel in the information theory (IT) community. This DoF concept was then extended by the networking research community to characterize a node's spatial freedom provided by its multiple antennas. The main idea of DoF-based models is as follows: (i) The number of available DoFs at a node is equal to the number of its antennas; (ii) A node may use its DoFs for SM and IC, as long as its total DoF consumption does not exceed its available DoFs. Based on the specific IC schemes, the DoF-based models in the literature can be put in two categories: *conservative models* and *optimistic models*. The conservative models may shrink the DoF region unnecessarily by losing some feasible solutions. The optimistic models may incorrectly enlarge the DoF region by adding some solutions that turn out to be infeasible.

Recently, a new DoF-based model was proposed in [8]. The essence of this novel DoF-based model is a disciplined IC scheme based on a sequential ordered node list. Specifically, we introduce an ordering relationship among all the nodes in the network. Each node only consumes DoFs for canceling interference from/to those nodes before itself in the list, the interference to/from those nodes after itself in the list is to be considered by those nodes later. It was shown that this node ordering based IC model uses the DoF resources in a more efficient way when compared to the conservative models, since it eliminates any duplication in IC among the nodes by systematically determining which nodes are responsible for canceling a specific interference. More importantly, correct use of this model can guarantee the feasibility of its solutions, which is what is lacking when using the optimistic models.

The goal of this article is to offer a tutorial for this new DoF-based model to the networking research community. For readers who are interested in the mathematical foundation of this novel MIMO DoF model as well as its applications to multi-hop networks, we refer them to [8].



Fig. 1: An example that illustrates IC.

II. BACKGROUND AND EXISTING MIMO MODELS

Consider a multi-hop MIMO network consisting of a set of nodes, each equipped with multiple antennas. Within the network, suppose there are L possible links for data transmission. Due to interference, not all of these L links can be active at the same time. Suppose that scheduling operates in time slots, with each frame having T time slots. Within each time slot, a subset of links may be active. Denote $z_l[t]$ as the number of data streams on link l ($1 \leq l \leq L$) in time slot t ($1 \leq t \leq T$). In particular, $z_l[t] = 0$ indicates that link l is inactive in time slot t .

To transport $z_l[t]$ data streams on link l , one may employ linear precoding technique at the transmitter and linear decode (equalization) technique at the receiver. For each data stream, a transmitter uses a vector (called transmit vector) to precode this data stream, and the corresponding receiver uses a vector (called receive vector) to decode this data stream. In addition to SM, the freedom provided by multiple antennas at a node can also be used for IC. That is, a node with multiple antennas can cancel interference from/to its unintended nodes so that multiple links may be active simultaneously in the same vicinity. For example, consider two links in Fig. 1, where solid arrow lines represent directed links while the dashed arrow line represents interference. The interference from T_2 to R_1 can be canceled by either T_2 or R_1 so that both links can be active simultaneously.

In a given time slot t , a solution is a set of nonnegative integers that represent the number of data streams on each link, which can be denoted as $\varphi[t] = (z_1[t], z_2[t], \dots, z_L[t])$. Based on SM and IC, we can determine the feasibility of solution $\varphi[t]$ based on the following criterion.

Criterion 1: A solution $\varphi[t] = (z_1[t], z_2[t], \dots, z_L[t])$ is feasible if and only if there exist an encoding vector and a decoding vector for each data stream so that all data streams in $\varphi[t]$ can be transported free of interference based on SM and IC.

In this criterion, we assume that the channel state information (CSI) is globally available and the channel matrix between any two nodes has full rank. With Criterion 1, we check the feasibility of a solution $\varphi[t]$ by showing the existence of a set of transmit/receive vectors at each node so that all the data streams in $\varphi[t]$ are transported free of interference. However, this approach involves high-dimensional complex matrix manipulations

and is intractable for studying networking problems involving scheduling and routing.

On the other hand, the so-called DoF-based models avoid high-dimensional complex matrix manipulations. They are simple and practical to check the feasibility of a solution [3], [4], [5], [6], [7]. Note that although the concept of DoF was originally defined by the IT research community to represent the maximum SM gain (i.e., the maximum number of independent data streams) of an MIMO channel [9], it has been extended by the networking research community to characterize a node's capabilities of SM and IC. Specifically, the DoF represents a node's spatial freedom that can be used for SM and IC.

The basic idea of DoF-based models is as follows: (i) The number of available DoFs at a node is equal to the number of its antennas. (ii) A node consumes DoFs for SM. Specifically, a transmit node consumes DoFs to support the transmission of its data streams while a receive node consumes the same number of DoFs to support the reception of its desired data streams. (iii) A node consumes DoFs for IC. Specifically, a transmit node may cancel its interference to its neighboring receive nodes by consuming its DoFs. Likewise, a receive node may cancel the interference from its unintended transmit nodes by consuming its DoFs. (iv) A node can use some or all of its DoFs for SM and IC, as long as the total number of DoFs consumed for SM and IC does not exceed its available DoFs.

For all DoF-based models, the DoF consumption behaviors for SM are identical. These models differ in their IC behaviors. Based on how IC is performed, the DoF-based models in the literature can be put in two categories: *conservative models* and *optimistic models*.

Conservative DoF-based models. We call the models that may shrink the feasible solution space unnecessarily as conservative models. The loss of feasible solutions may be attributed to duplication in IC, restriction in receiver-side IC, or the use of some other predefined IC rules. Examples of the conservative models can be found in [3], [6], [7].

In [3], Bhatia and Li proposed a DoF-based model that required interference be canceled by both the transmitters and the receivers. Specifically, the DoF resources at a node may be consumed as follows:

- *Transmit node.* A transmit node consumes DoFs for both SM and IC. For SM, the number of consumed DoFs is equal to the number of its data streams to be transmitted. For IC, the number of consumed DoFs is equal to the total number of data streams that are received by those unintended receive nodes (within its interference range) from their own transmit nodes.

- *Receive node.* A receive node consumes DoFs for both SM and IC. For SM, the number of consumed DoFs is equal to the number of its desired data streams. For IC, the number of consumed DoFs is equal to the total number of data streams transmitted by those unintended transmit nodes whose interference ranges cover this receive node.

A solution is considered feasible if the DoF consumption (for SM and IC) at each node in the network does not exceed its total available DoFs. Due to duplication in IC at both transmit and receive nodes, a conservative model may lose some feasible solutions and has a smaller feasible solution space.

In [7], Sundaresan *et al.* proposed that the interference be canceled by the receive node only. Since they did not consider IC capability of a transmit node, their model failed to exploit the full design space for IC and thus results in a smaller feasible solution space. In [6], Park *et al.* considered the case where the links in the network become active sequentially. They proposed that the interference between two nodes be canceled by the node that becomes active later in the sequence. Such predefined IC rule again results in a smaller feasible solution space.

Optimistic DoF-based models. We call DoF models that may incorrectly enlarge the feasible solution space as optimistic models. The reason why these models may include infeasible solution is due to a lack of systematic or disciplined scheme for network-wide IC. Examples of the optimistic DoF model include [4], [5]. The difference between an optimistic model and a conservative model lies in how DoFs are used for IC. In the conservative model in [3], interference from a transmit node to an unintended receive node will consume DoFs at both nodes. Such duplication in IC is not necessary and leads to a waste of DoF resources. In the optimistic model, however, interference from a transmit node to an unintended receive node will only be canceled by one of the two nodes. If the interference is canceled by the transmit node, the number of DoFs consumed by this transmit node is equal to the number of data streams that are received by the unintended receive node. If the interference is canceled by the receive node, the number of DoFs consumed by this receive node is equal to the number of data streams that are transmitted by the unintended transmit node. Note that the number of DoFs consumed at transmit and receive nodes is likely to differ. So when using DoFs for IC, one needs to determine, for each pair of interfering nodes, which node is responsible for canceling the interference between them.

In the optimistic models [4], [5], to determine which node should be responsible for IC, one can model the network by a graph in which a vertex represents a node and an edge represents an interference. Each edge in the graph is colored by either blue or red. If an edge is blue, then the corresponding interference is canceled by the

transmit node; otherwise, the interference is canceled by the receive node. Then, the DoF resources at a node are used as follows:

- *Transmit node.* Its DoF consumption for SM is equal to the number of its data streams to be transmitted, and its DoF consumption for IC is equal to the total number of data streams at those receive nodes that have a blue edge connecting to this transmit node.
- *Receive node.* Its DoF consumption for SM is equal to the number of its desired data streams, and its DoF consumption for IC is equal to the total number of data streams at those transmit nodes that have a red edge connecting to this receive node.

In this DoF model, a solution is said to be feasible if and only if there exists a graph-coloring pattern so that the DoF consumption for SM and IC at each node does not exceed its total DoFs. This DoF model turns out to be “optimistic” as it may claim an infeasible solution (violating Criterion 1) as a feasible one.

III. A NOVEL NODE ORDERING BASED DOF MODEL

As discussed in Section II, conservative models may shrink the feasible solution space unnecessarily while optimistic models may incorrectly enlarge the feasible solution space. We believe the fundamental problem associated with both models is the absence of a correct systematic IC scheme for all nodes in the network. To address this problem, a new model was proposed in [8]. The essence of this new model is a novel “ordering” concept for all nodes in the network, where each node is associated with a position (order) in the list of all nodes in the network. By following this ordering, IC at each node can be done in a systematic and disciplined manner. The use of such ordering concept eliminates the possibility of duplication in IC and, at the same time, guarantees the feasibility of the final solution.

In this new model, at each node, the number of DoFs consumed for SM is the same as that for the conservative or optimistic model. The difference is in how IC is performed. In this new model, IC behavior at a node depends on its “position” in the ordered node list. For a given ordered node list, the number of DoFs consumed for IC at a node is as follows:

- *Transmit node.* A transmit node only needs to cancel its interference to those receive nodes that are before itself in the ordered node list. It does not need to consume DoFs to cancel its interference to those receive nodes that are after itself in the ordered node list. Interference from this transmit node to those receive nodes

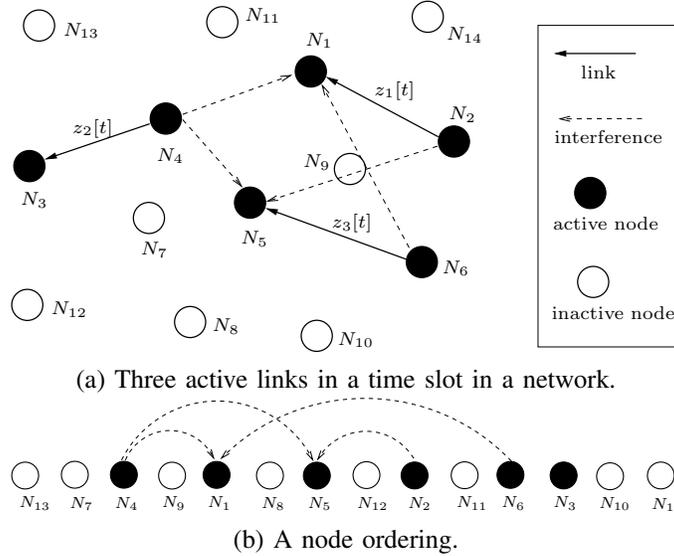


Fig. 2: An example illustrating node ordering and IC in a time slot.

after itself will be canceled by those receive nodes later. The number of DoFs consumed at this transmit node is equal to the total number of desired data streams received by those receive nodes (within this transmit node's interference range) that are before itself in the ordered node list.

- *Receive node.* A receive node only needs to cancel interference from those transmit nodes that are before itself in the ordered node list. It does not need to cancel interference from those transmit nodes that are after itself in the ordered node list. Interference from those transmit nodes after this node will be canceled by those transmit nodes later. The number of DoFs consumed at this receive node is equal to the total number of data streams transmitted by those transmit nodes (whose interference ranges cover this receive node) before this receive node in the ordered node list.

In this model, a solution $\varphi[t]$ is feasible in time slot t if there exists an ordered node list such that the DoF consumption for SM and IC at each node does not exceed its available DoFs. It is important to emphasize that the “ordering” concept is crucial to avoid any duplication in IC among the nodes in the network. Based on the ordering concept, for interference from a transmit node to a receive node, either the transmit or the receive node will cancel it, but not both. This ensures that the IC between the nodes are performed in an efficient manner. Further, it was proved in [8] that any solution considered feasible by this model also satisfies Criterion 1.

An example. As shown in Fig. 2(a), suppose that in time slot t , we have 3 links in the network that are active. Each node is equipped with two antennas. Denote the number of data streams on links (N_2, N_1) , (N_4, N_3) , and

TABLE I: Notation.

Symbol	Definition
B	A large constant integer
N	The number of nodes in the network
L	The number of links in the network
T	The number of time slots in a time frame
A_i	The number of antennas at node i
$\text{Tx}(l)$	The transmitter of link l
$\text{Rx}(l)$	The receiver of link l
$\mathcal{L}_i^{\text{in}}$	The set of incoming links at node i
$\mathcal{L}_i^{\text{out}}$	The set of outgoing links at node i
\mathcal{I}_i	The nodes within node i 's interference range
$x_i[t]$	A binary variable to indicate whether node i is a transmitter for some link in time slot t
$y_i[t]$	A binary variable to indicate whether node i is a receiver for some link in time slot t
$z_l[t]$	The number of data streams on link l in time slot t
$\pi[t]$	An ordering of nodes in the network in time slot t
$\pi_i[t]$	The position of node i in the node ordering $\pi[t]$
$\theta_{ji}[t]$	A binary variable to indicate whether node i is placed after node j in $\pi[t]$

(N_6, N_5) in time slot t as $z_1[t]$, $z_2[t]$, and $z_3[t]$, respectively. We want to check whether a specific solution, $\varphi[t] = (z_1[t], z_2[t], z_3[t]) = (1, 1, 1)$, is feasible. It is easy to see that at each active node, the DoF consumption for SM is one since each active link has one data stream. To determine the DoF consumption for IC at each active node, suppose that the ordered node list is $[N_{13}, N_7, N_4, N_9, N_1, N_8, N_5, N_{12}, N_2, N_{11}, N_6, N_3, N_{10}, N_{14}]$ as shown in Fig. 2(b). Based on this ordering, transmit node N_4 does not consume any DoF for IC (since it is the first active node in the list); receive node N_1 consumes one DoF to cancel the interference from transmit node N_4 ; receive node N_5 consumes one DoF to cancel the interference from transmit node N_4 ; transmit node N_2 consumes one DoF to cancel the interference to receive node N_5 ; and transmit node N_6 consumes one DoF to cancel the interference to receive node N_1 . In summary, the DoF consumption for IC at nodes N_1 , N_2 , N_5 , and N_6 is one while the DoF consumption for IC at other nodes is zero. Therefore, the DoF consumption for SM and IC at each active node is less than or equal to two, indicating that this solution is feasible.

Mathematical modeling. As shown in the above example, the ordering of a node plays a key role in DoF consumption for IC. So a natural question is: What is the optimal node ordering among the nodes? The answer is that an optimal ordering depends on the specific objective and other constraints in the optimization problem. An optimal ordering should be formulated as part of the optimization problem, the solution to which will give an optimal ordering.

We now describe a mathematical model for node ordering that can be put into an optimization problem. The notation used for this model is summarized in Table I. Denote N as the number of nodes in the network. Denote T as the number of time slots in a frame. Denote $\pi[t]$ as the order of the nodes in the network in time slot t . Denote $\pi_i[t]$ as the position of node i in the order $\pi[t]$, which may range from 1 to N . In the new DoF-based model, the “relative” ordering between two nodes determines which node is responsible for canceling the interference between them. To model the “relative” ordering between nodes i and j in $\pi[t]$, we introduce a binary variable $\theta_{ji}[t]$ and define it as follows: $\theta_{ji}[t] = 1$ if node j is before node i in $\pi[t]$ (not necessarily consecutive in $\pi[t]$); $\theta_{ji}[t] = 0$ otherwise. Thus, we can mathematically model the “relative” ordering of any two nodes in the network as follows [8]:

$$\pi_i[t] - N \cdot \theta_{ji}[t] + 1 \leq \pi_j[t] \leq \pi_i[t] - N \cdot \theta_{ji}[t] + N - 1, \quad (1 \leq i \leq N, j \in \mathcal{I}_i, 1 \leq t \leq T). \quad (1)$$

We can also model the DoF consumption constraints at each node based on the order $\pi[t]$. Denote A_i as the number of antennas at node i . We use a binary variable $x_i[t]$ to indicate whether node i is a transmitter for some link in time slot t . If node i is a transmitter in time slot t , then $x_i[t] = 1$; otherwise, $x_i[t] = 0$. We use another binary variable $y_i[t]$ to indicate whether node i is a receiver for some link in time slot t . If node i is a receiver in time slot t , then $y_i[t] = 1$; otherwise, $y_i[t] = 0$. Assuming half-duplex transceiver, a node cannot transmit and receive at the same time, indicating that $x_i[t]$ and $y_i[t]$ cannot be 1 simultaneously, i.e., $x_i[t] + y_i[t] \leq 1$. Denote \mathcal{I}_i as the set of nodes within the interference range of node i . Denote $\text{Tx}(l)$ and $\text{Rx}(l)$ as the transmit and receive nodes of link l , respectively. Denote $\mathcal{L}_i^{\text{out}}$ as the set of outgoing links at node i and $\mathcal{L}_i^{\text{in}}$ as the set of incoming links at node i . If node i is a transmitter in time slot t , then the number of its incoming data streams is zero and the total number of its outgoing data streams is $\sum_{l \in \mathcal{L}_i^{\text{out}}} z_l[t]$. If node i is a receiver in time slot t , then the number of its outgoing data streams is zero and the total number of its incoming data streams is $\sum_{l \in \mathcal{L}_i^{\text{in}}} z_l[t]$.

If node i is a transmitter in time slot t , then the number of its DoFs consumed for SM is $\sum_{l \in \mathcal{L}_i^{\text{out}}} z_l[t]$ and the number of its DoFs consumed for IC is $\sum_{j \in \mathcal{I}_i} \theta_{ji}[t] \sum_{k \in \mathcal{L}_j^{\text{in}}} z_k[t]$. The total number of its DoFs consumed for SM and IC cannot exceed its total available DoFs (i.e., A_i). Otherwise (i.e., node i is not a transmitter in time slot t), there is no constraint on $\sum_{j \in \mathcal{I}_i} \theta_{ji}[t] \sum_{k \in \mathcal{L}_j^{\text{in}}} z_k[t]$. To develop one constraint for both cases, we introduce a large integer constant B (e.g., $B = \sum_{i=1}^N A_i$) to ensure B is an upper bound for the number of DoFs

consumed for IC at node i . Then we have

$$\sum_{l \in \mathcal{L}_i^{\text{out}}} z_l[t] + \sum_{j \in \mathcal{I}_i} \theta_{ji}[t] \sum_{k \in \mathcal{L}_j^{\text{in}} \text{Tx}(k) \neq i} z_k[t] \leq A_i x_i[t] + (1 - x_i[t])B, \quad (1 \leq i \leq N, 1 \leq t \leq T). \quad (2)$$

Likewise, if node i is a receiver in time slot t , then the number of its DoFs consumed for SM is $\sum_{l \in \mathcal{L}_i^{\text{in}}} z_l[t]$ and the number of its DoF consumed for IC is $\sum_{j \in \mathcal{I}_i} \theta_{ji}[t] \sum_{k \in \mathcal{L}_j^{\text{out}} \text{Rx}(k) \neq i} z_k[t]$. The total number of its DoFs consumed for SM and IC should be less than or equal to its total available DoFs (i.e., A_i). Otherwise (i.e., node i is not a receiver in time slot t), there is no constraint on $\sum_{j \in \mathcal{I}_i} \theta_{ji}[t] \sum_{k \in \mathcal{L}_j^{\text{out}} \text{Rx}(k) \neq i} z_k[t]$. To establish one constraint for both cases, we have

$$\sum_{l \in \mathcal{L}_i^{\text{in}}} z_l[t] + \sum_{j \in \mathcal{I}_i} \theta_{ji}[t] \sum_{k \in \mathcal{L}_j^{\text{out}} \text{Rx}(k) \neq i} z_k[t] \leq A_i y_i[t] + (1 - y_i[t])B, \quad (1 \leq i \leq N, 1 \leq t \leq T). \quad (3)$$

Together, constraints (1), (2), and (3) give a mathematical characterization of the new DoF-based model. Constraint (1) characterizes an ordering among the nodes in the network. Constraint (2) ensures that the consumed DoFs for SM and IC at a transmit node do not exceed the available DoFs based on the node ordering. Constraint (3) ensures that the consumed DoFs for SM and IC at a receive node do not exceed the available DoFs based on the node ordering.

Applications in multi-hop networks. This new DoF model offers a useful tool to study various network-level performance optimization problems for a multi-hop MIMO network that were once considered difficult or even impossible. Applications of this new model can be found in [10], [11], [12], [13], [14], [15]. In [10], Qin *et al.* employed this model to study a throughput optimization problem in a multi-hop MIMO network. In [11], [12], Jiang *et al.* used this model and successfully established a capacity scaling law for a random multi-hop MIMO network. In [13], Zeng *et al.* showed that this model can be used in distributed multi-hop MIMO networks for network throughput optimization. In particular, the author proposed an algorithm to obtain the ordering for each node in a distributed network while ensuring the existence of a global node ordering. In [14], this model was used to study an MIMO-empowered cognitive radio network (CRN) and showed that a CRN with A antennas at each node achieves more than A -fold throughput increase than a CRN with a single antenna at each node. In [15], Yuan *et al.* employed this model to study the throughput performance of multi-hop CRN under the so-called “transparent coexistence” paradigm for spectrum sharing between primary and secondary nodes.

TABLE II: A comparison of the existing MIMO models.

	Matrix-based Models	DoF-based Models		
		Conservative Models	Optimistic Models	Ordering-based Model
Tractability	Intractable, require to find transmit/receive vectors for each stream	Tractable	Tractable	Tractable
Solution Feasibility	Yes	Yes	Maybe infeasible	Yes
Size of DoF Region	—	Small	Large	Large

IV. CONCLUSIONS

This article offered a concise survey of the DoF models for MIMO in the literature and discussed their limitations. A new DoF-based model that characterizes MIMO's SM and IC capabilities was presented. This novel model overcomes the limitations of previous DoF models and represents the state-of-the-art of MIMO DoF model for networking research. A comparison of this new model and other MIMO models in the literature is summarized in Table II. We hope this article can help bring this new DoF model to the attention of the research community so that further advances in multi-hop MIMO network research can be made that were once considered too difficult.

REFERENCES

- [1] E. Biglieri, R. Calderbank, A. Constantinides, A. Goldsmith, A. Paulraj, and H.V. Poor, *MIMO Wireless Communications*, Cambridge University Press, Jan. 2007.
- [2] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*, Cambridge University Press, 2005.
- [3] R. Bhatia and L. Li, "Throughput optimization of wireless mesh networks with MIMO links," in *Proc. IEEE INFOCOM*, Anchorage, AK, May 2007, pp. 2326–2330.
- [4] D.M. Blough, G. Resta, P. Santi, R. Srinivasan, and L.M. Cortes-Pena, "Optimal one-shot scheduling for MIMO networks," in *Proc. IEEE SECON*, Salt Lake City, UT, June 2011, pp. 404–412.
- [5] B. Hamdaoui and K.G. Shin, "Characterization and analysis of multi-hop wireless MIMO network throughput," in *Proc. ACM MobiHoc*, Montreal, Quebec, Canada, Sep. 2007, pp. 120–129.
- [6] J.-S. Park, A. Nandan, M. Gerla, and H. Lee, "SPACE-MAC: Enabling spatial reuse using MIMO channel-aware MAC," in *Proc. IEEE ICC*, Seoul, Korea, May 2005, pp. 3642–3646.
- [7] K. Sundaresan, R. Sivakumar, M. Ingram, and T.-Y. Chang, "Medium access control in ad hoc networks with MIMO links: Optimization considerations and algorithms," *IEEE Trans. on Mobile Computing*, vol. 3, no. 4, Oct. 2004, pp. 350–365.
- [8] Y. Shi, J. Liu, C. Jiang, C. Gao, and Y.T. Hou, "An optimal MIMO link model for multi-hop wireless networks," in *Proc. IEEE INFOCOM*, Shanghai, China, April 2011, pp. 1916–1924.

- [9] L. Zheng and D.N.C. Tse, "Diversity and multiplexing: A fundamental tradeoff in multiple-antenna channels," *IEEE Trans. on Information Theory*, vol. 49, no. 5, May 2003, pp. 1073–1096.
- [10] X. Qin, X. Yuan, Y. Shi, Y.T. Hou, W. Lou, and S.F. Midkiff, "On Throughput Maximization for a Multi-hop MIMO Network," in *Proc. IEEE International Conference on Mobile Ad-hoc and Sensor Systems (IEEE MASS)*, Hangzhou, China, Oct. 2013, pp. 37–45.
- [11] C. Jiang, Y. Shi, and Y.T. Hou, "On the asymptotic capacity of multi-hop MIMO ad hoc networks," *IEEE Trans. on Wireless Communications*, vol. 10, no. 4, April 2011, pp. 1032–1037.
- [12] C. Jiang, Y. Shi, Y.T. Hou, W. Lou, S. Kompella, and S.F. Midkiff, "Toward simple criteria to establish capacity scaling laws for wireless networks," in *Proc. IEEE INFOCOM*, Orlando, FL, March 2012, pp. 774–782.
- [13] H. Zeng, Y. Shi, Y.T. Hou, and W. Lou, "An efficient DoF scheduling algorithm for multi-hop MIMO networks," in *Proc. IEEE INFOCOM*, Turin, Italy, April 2013, pp. 1564–1554.
- [14] C. Gao, Y. Shi, Y.T. Hou, and S. Kompella, "On the throughput of MIMO-empowered multi-hop cognitive radio networks," *IEEE Trans. on Mobile Computing*, vol. 10, no. 11, Nov. 2011, pp. 1505–1519.
- [15] X. Yuan, C. Jiang, Y. Shi, Y.T. Hou, W. Lou, and S. Kompella, "Beyond interference avoidance: On transparent coexistence for multi-hop secondary CR networks," in *Proc. IEEE SECON*, New Orleans, LA, June, 2013, pp. 398–405.

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