Cooperative Interference Neutralization in Multi-hop Wireless Networks

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***Abstract*—Interference neutralization (IN) is regarded as a promising interference management techniques for multi-hop wireless networks. Yet most existing results of IN are limited to *two-hop* networks such as the relay-aided cellular network. Little progress has been made so far in the exploration of IN in generic *multi-hop* (more than two hops) networks. This paper aims to bridge this gap by developing an optimization framework for IN in a generic multi-hop network with the objective of maximizing the end-to-end throughput of multiple coexisting communication sessions. We first derive a mathematical model for IN in a special one-hop network to characterize the capability of IN, and then generalize this model to a multi-hop network. Based on the IN model, we develop a cross-layer optimization framework for a multi-hop network with the objective of fully translating the benefits of IN to the end-to-end throughput of the multi-hop sessions. To evaluate the performance of IN in multi-hop networks, we compare its performance against the case where IN is not employed. Simulation results show that the use of IN can significantly (more than 50%) increase the session throughput and, more notably, the throughput gain of IN increases with the node density and traffic intensity in the network.**

***Index Terms*—Multi-hop wireless networks, interference neutralization, interference cancellation, throughput optimization**

I. Introduction

Multi-hop communications are becoming increasingly important in wireless networks, and have been considered for practical use in some wireless systems such as wireless mesh networks (e.g., IEEE 802.11s [1]) and mobile ad hoc networks (MANET) [2]. One of the fundamental problems in multi-hop wireless networks is the management of interference among different data flows. To address this issue, different types of interference management techniques have been proposed and applied to the multi-hop networks with the objective of maximizing the network throughput under various network constraints (see, e.g., [4], [5], [6], [7], [8], [9], [10], [11]). Existing results show that advanced interference management techniques, especially when jointly optimized with the upper-layer protocols, can significantly improve the network performance.

Recently, a new interference management technique called interference neutralized (IN) was proposed to address the interference issue in multi-hop networks [12], [13], [14]. IN is a transmitter-side baseband signal precoding technique. It refers to a joint design of the baseband signals at the transmitters so that their emitted radio signals are self-nullified *in the air* at their unintended receivers while remaining resolvable at their intended receivers. It requires that multiple transmitting nodes have the same data for transmission. Due to this special requirement, IN is uniquely suited for interference management in multi-hop networks as the nodes can overhear the data from their neighboring nodes.

A. Literature Review

The terminology of IN was invented by Mohajer et al. in [12], [13], [14] when studying the two-hop relay networks. However, the similar idea has been around for many years under different names such as *multiuser zero-forcing*, *distributed zero-forcing*, and *orthogonalize-and-forward* (see, e.g., [15], [16]). Due to its special requirement that multiple transmitters have the same data information for transmission, the main research thread of IN (and its variations) is focused on the two-hop relay-aided networks. In [16], Rankov and Wittneben studied a $K \times N \times K$ relay interference network and showed that it requires at least $K(K-1)+1$ relay nodes to achieve IN at the destination nodes. In [12], Mohajer et al. proposed an IN scheme for a special two-hop relay networks (so-called ZZ network) and showed that their IN scheme can convey the maximum amount of information under deterministic channel models. Sequentially, they applied IN to the same networks, but under Gaussian channel model, to study the approximate network capacity in [13], [14]. Ho and Jorswieck in [17] studied an achievable rate region of the instantaneous interference relay channel when IN was employed at the relay nodes. In [18], Maier and Mathar explored the conditions for IN in full-duplex relay interference channel to ensure the resolvability of the desired signal at each destination.

Another research thread of IN is focused on the aligned interference neutralization (AIN) in two-hop interference MIMO networks. In [19], Gou et al. showed that the use of AIN with two symbol extension allows the $2 \times 2 \times 2$ interference channel to achieve the min-cut outer bound value of 2 DoFs. A similar AIN scheme was employed by Lee and Wang in [20], where they showed that AIN can achieve significant DoF gain in the two-user network with instantaneous relay. Vaze and Varanasi in [21] studied the DoF region of the $2 \times 2 \times 2$ relay network and showed that an AIN-based scheme can achieve the min-cut DoF outer-bound, no matter how many antennas the nodes have.

B. Goals of This Paper and Main Contributions

Although there already exist an abundance of IN results in the literature, most of them are limited to *two-hop* wireless networks and little progress has been made in the exploration of IN in the context of multi-hop (more than two hops) networks. This vacancy underscores both the technical challenges in this area and the critical need to bridge this gap. The goal of this paper is to make a concrete step toward advancing our understanding of IN in generic multi-hop (more than two hops) networks. We consider a multi-hop network that consists of a set of nodes, each of which has the same number of antennas. The network has a set of multi-hop unicast communication sessions. The routing path of each communication session has already been computed through some routing protocols (e.g., OSPF [22]). To transport data from the source node to the destination node for each session, we assume that the transmission scheduling is done in a time frame that consists of a set of time slots. Our objective is to maximize the end-to-end throughput of the sessions by exploiting the benefits of IN in the network. The main contributions of this paper are summarized as follows:

- We develop an mathematical model to characterize the capabilities of interference neutralization and cancellation (INC) in a special one-hop network. This model consists of two sets of constraints: (i) constraints at the transmitters to characterize their IN capability; (ii) constraints at each receiver to characterize its IC capability. We prove the feasibility of the mathematical model by showing that if those INC constraints are satisfied, we can always construct a precoding and decoding scheme at the physical layer so that the data streams on each link are transported free of interference.
- We generalize the INC model from the special one-hop network to a generic multi-hop network by incorporating the assisting-node selection and link-activity decision into the INC feasibility constraints. Based on the generalized INC constraints, we develop a set of constraints across multiple layers of the multi-hop network. Collectively, these cross-layer constraints form an INC optimization framework for session throughput maximization in the multi-hop network. Under this framework, IN can be exploited to the fullest extent for a target network performance objective.
- As an application of our INC optimization framework, we study a specific network throughput problem – maximizing the minimum end-to-end throughput for a set of multi-hop sessions. To evaluate the performance of IN, we compare it against the case where IN is not employed (but still with IC). Our simulation results show that the use of IN can increase the session throughput significantly (more than 50%) for most cases. Further, we find that the throughput gain of IN increases with the node density and traffic intensity in the network.

We note that the goal of this paper is not to develop a practical solution to implement IN in multi-hop wireless networks. Rather, this paper is focused on the exploration of the maximum possible performance gain of IN in multi-hop wireless networks without taking into account the communication overhead caused by CSI feedback and node coordination. Results from the optimization framework serve as a performance upper bound for IN and provide guidance on the future design of practical IN solutions.

C. Paper Organization

The remainder of this paper is organized as follows. In Section II, we develop an INC model for a set of one-hop links and prove its feasibility. In Section III, we generalize the INC model from one-hop to multi-hop scenarios and develop an INC optimization framework for multi-hop networks. Section IV evaluates the throughput gain of IN in multi-hop networks and Section V concludes this paper.

TABLE I
NOTATION.

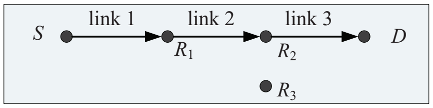
Symbol	Definition
$\mathcal{N}$	The set of nodes in the network
$\mathcal{N}_{\text{path}}$	The set of nodes involved in the routing paths
$\mathcal{N}_{\text{idle}}$	The set of nodes not involved in the routing paths
$\mathcal{L}$	The set of links along the routing paths
$\mathcal{F}$	The set of sessions in the network
$\mathcal{T}_l$	The set of transmitting nodes of link l
$\mathcal{R}_l$	The set of receiving nodes of link l
$\mathcal{P}_l$	The set of nodes that may serve as a transmitting node of link l
$\mathcal{Q}_l$	The set of nodes that may serve as a receiving node of link l
$\mathcal{S}_l$	The set of nodes that may be interfered by at least one transmitting node of link l
$\mathcal{A}_q$	The set of nodes that may serve as an assisting node for node q
$\mathcal{K}_j$	The set of links that have at least one of its transmitting nodes interfering with node j
$\mathcal{I}_i$	The set of nodes within the interference range of node i
$\mathcal{L}_q^{\text{in}}$	The set of incoming (active and inactive) links at node q
$\mathcal{L}_q^{\text{out}}$	The set of outgoing (active and inactive) links at node q
$\text{Tx}(l)$	The transmitter of link l
$\text{Rx}(l)$	The receiver of link l
$\mathbf{H}_{ji}$	The channel matrix between node j and node i
$\mathbf{u}_i^n$	The precoding vector for the nth stream at node i
$\mathbf{v}_j^m$	The decoding vector for the mth stream at node j
M	The number of antennas at each node
T	The number of time slots in a time frame
B	A large enough constant
$\lambda_{q,i}$	A binary indicator whether node i serves as an assisting node for node q
$r(f)$	The data rate of session f
$r_l(f)$	The amount of rate on link l that is used to session f
$z_l(t)$	The number of data streams on link l in time slot t
$\alpha_l(t)$	A binary indicator whether link l is active in time slot t
$\beta_{l,j}(t)$	A binary indicator whether the interference from the transmitters of link l to node j is neutralized in slot t
$\xi_{k,j}(t)$	A binary indicator whether node j needs to cancel the interference from the transmitters of link k in slot t
$\zeta_{k,j}(t)$	A temporary integer variable for linearization
$r_{\min}$	The minimum rate of the sessions in the network

II. Mathematical Modeling of INC

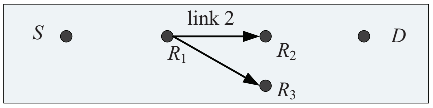
In this section, we first offer a primer of INC and then develop a mathematical modeling to characterize IN's and IC's capabilities in a special one-hop network. Results from the special one-hop network will lay the foundation for our study of INC in multi-hop networks. Table I lists the notation we use in this paper.

A. A Primer of INC

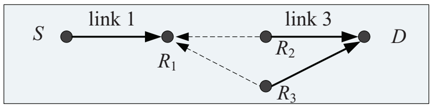
Interference Neutralization (IN): IN is a cooperative transmitter-side zero-forcing interference technique. It requires that multiple transmitters have the same data information for transmission. With the same data at multiple transmitters, IN jointly constructs the baseband signals at those transmitters to achieve two objectives: (i) nullifying their emitted radio signals



(a) A multi-hop network



(b) Scheduling in time slot 1



(c) Scheduling in time slot 2

Fig. 1. An example that illustrates the benefits of IN in a three-hop network.

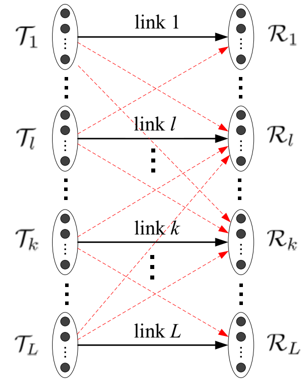


Fig. 2. A set of multipoint-to-multipoint links. Solid arrow represents data transmission and dashed line arrow represents interference.

in the air at their *unintended* receivers; and (ii) warranting the resolvability of their emitted radio signals at their *intended* receivers. Since IN can nullify the undesired radio signals (interference) at the unintended receiver, it can have more active concurrent links in the network and thereby improve the network throughput.

We use an example to illustrate the benefits of IN in multi-hop networks. Consider a three-hop network as shown in Fig. 1(a), which has a source node S, a destination node D, and 3 relay nodes between them. Each node has a single antenna. Suppose that the interference from the source node S is negligible at the destination node D due to the long-distance attenuation. Also suppose that the links are scheduled within a set of equal-length time slots and the amount of data on each link in a time slot is one unit. Then, for this network, under the interference avoidance scheme, it requires 3 time slots to transport one data unit on each link since any two links cannot be active in the same time slot. Therefore, the session throughput under the interference avoidance scheme is $1/3$. However, if we apply IN to this network, each link can transport one data unit within 2 time slots, thereby achieving a session throughput of $1/2$.

The IN scheme for this network is depicted in Fig. 1(b)–(c). In time slot 1, R_1 sends data to R_2 and R_3, as shown in Fig. 1(b). In time slot 2, S sends data to R_1 and, at the same time, R_2 and R_3 send data to D, as shown in Fig. 1(c). We now show that through a joint design of transmit signals at R_2 and R_3, their interference can be neutralized at R_1. Denote h_{ji} as the channel coefficient between R_j and R_i. Denote u_i as the signal precoding coefficient at R_i $(i = 2, 3)$. Then we construct the signal precoding coefficients at R_2 and R_3 by letting: $u_2 = h_{13}$ and $u_3 = -h_{12}$. It is easy to verify that by using the above amplifying coefficients at R_2 and R_3, the interference at R_1 will be neutralized: $h_{12}u_2x_3 + h_{13}u_3x_3 = 0$, where x_3 is the transmit signal at R_2 and R_3. Therefore, one data unit can be transported on each link within 2 time slots and the session throughput achieves $1/2$.

From the example we can see that IN exploits the idle nodes in the network to handle interference. The idle node (R_3) first overhears data information from the previous hop (R_1) and then exploits the overheard data information to help nullify the interference in the next hop (D). As such, IN fully uses the network resource so that the network throughput can be maximized.

Interference Cancellation (IC): IC in this paper refers to the signal design at each individual receiver by exploiting its multiple antennas to nullify its interfering signals and recover its desired signals. As such, IC capability is only considered at the receiving node and only available when the node has multiple antennas. Different from IN in the sense that it requires cooperation among multiple transmitters, IC does not require cooperation among different receivers.

B. *Feasibility Constraints of INC*

Before studying INC in multi-hop networks, we first study INC in a set of special multipoint-to-multipoint links as shown in Fig. 2. Results of INC in the set of one-hop links will lay the foundation for our study of INC in multi-hop networks. The connection between the special links and a multi-hop network will become clear later. Suppose that the nodes in the network have the same number of antennas, which we denote as M. Denote $\mathcal{L}$ as the set of links in the network, with L being its cardinality (i.e., $L = |\mathcal{L}|$). Different from the traditional link, which has only one transmitting node and only one receiving node, the link in this network may have *multiple* transmitting nodes and *multiple* receiving nodes. For link $l \in \mathcal{L}$, denote $\mathcal{T}_l$ as the set of its transmitting nodes and $\mathcal{R}_l$ as the set of its receiving nodes. We assume that the transmitting nodes in $\mathcal{T}_l$ have the same data streams for transmission and the receiving nodes in $\mathcal{R}_l$ want to decode the data streams from the transmitting nodes in $\mathcal{T}_l$ free of interference. Denote z_l as the number of data streams on link $l \in \mathcal{L}$. For each transmitting node $i \in \mathcal{T}_l$, denote $\{x_l^1, x_l^2, \cdots, x_l^{z_l}\}$ as the set of its outgoing data streams; denote $\mathbf{u}_i^n$ as the precoding vector of its outgoing data stream x_l^n, $n = 1, 2, \cdots, z_l$. We assume that the transmitting nodes in $\mathcal{T}_l$ have a fixed interference range and have the same interfering area. Their interference to those receiving nodes outside their interference area is negligible and will not be considered in our study.

Consider each receiving node $j \in \mathcal{R}_l$. Denote $\mathcal{K}_j$ as the set of links whose transmitting nodes (at least one of them) are interfering with receiving node j. Specifically, if receiving node j is within the interference range of at least one transmitting node in $\mathcal{T}_k$, then $k \in \mathcal{K}_j$; otherwise, $k \notin \mathcal{K}_j$. Denote $\mathbf{H}_{ji}$ as the channel matrix between receiving node j and transmitting node i. For a data transmission channel, we assume $\mathbf{H}_{ji} \neq \mathbf{0}$ for $i \in \mathcal{T}_l$ and $j \in \mathcal{R}_l$. For an interference channel, we assume

$$\hat{x}_l^m = (\mathbf{v}_j^m)^T \mathbf{y}_j = \underbrace{(\mathbf{v}_j^m)^T \Big(\sum_{i \in \mathcal{T}_l} \mathbf{H}_{ji} \mathbf{u}_i^m \Big) x_l^m}_{\text{Desired data stream}} + \underbrace{\sum_{n=1 \cdots z_l}^{n \neq m} (\mathbf{v}_j^m)^T \Big(\sum_{i \in \mathcal{T}_l} \mathbf{H}_{ji} \mathbf{u}_i^n \Big) x_l^n}_{\text{intra-link interference}} + \underbrace{\sum_{k \in \mathcal{K}_j} \sum_{n=1}^{z_k} (\mathbf{v}_j^m)^T \Big(\sum_{i \in \mathcal{T}_k} \mathbf{H}_{ji} \mathbf{u}_i^n \Big) x_k^n}_{\text{inter-link interference}} + \underbrace{(\mathbf{v}_j^m)^T \mathbf{w}_j}_{\text{noise}}. \quad (2)$$

$\mathbf{H}_{ji} \neq \mathbf{0}$ if receiving node j is within the interference range of transmitting node i and $\mathbf{H}_{ji} = \mathbf{0}$ otherwise. Then, at receiving node $j \in \mathcal{R}_l$, the received signal and interference can be written as:

$$\mathbf{y}_j = \underbrace{\sum_{i \in \mathcal{T}_l} \sum_{n=1}^{z_l} \mathbf{H}_{ji} \mathbf{u}_i^n x_l^n}_{\text{useful signals}} + \underbrace{\sum_{k \in \mathcal{K}_j} \sum_{i \in \mathcal{T}_k} \sum_{n=1}^{z_k} \mathbf{H}_{ji} \mathbf{u}_i^n x_k^n}_{\text{interference}} + \mathbf{w}_j, \quad (1)$$

where $\mathbf{w}_j$ is the noise vector at node j. In order to decode its desired data streams, we denote $\mathbf{v}_j^m$ as the decoding vector of its desirable data stream x_l^m, $m = 1, 2, \cdots, z_l$. Then the decoded data stream can be written as (2), where $(\cdot)^T$ is matrix transpose operation. In particular, when the node has a single antenna (i.e., $M = 1$), channel matrix $\mathbf{H}_{ji}$, precoding vector $\mathbf{u}_i^n$, and decoding vector $\mathbf{v}_j^m$ degrade to a complex coefficient (instead of being a complex vector or matrix).

Suppose that the noise is negligible compared to the signals and interference (i.e., high signal-to-noise ratio regime). Then we employ zero-forcing technique for each data stream at each receiving node with the aim of completely nullifying its interference. Based on (2), to ensure that each receiving node j can decode its desired data streams free of interference, one should jointly construct the precoding vectors and decoding vectors so that the following constraints are satisfied for $l \in \mathcal{L}$, $j \in \mathcal{R}_l$, and $m = 1, 2, \ldots, z_l$.

$$(\mathbf{v}_j^m)^T \Big(\sum_{i \in \mathcal{T}_l} \mathbf{H}_{ji} \mathbf{u}_i^m \Big) = 1; \quad (3a)$$

$$(\mathbf{v}_j^m)^T \Big(\sum_{i \in \mathcal{T}_l} \mathbf{H}_{ji} \mathbf{u}_i^n \Big) = 0, \quad 1 \leq n \leq z_l;\ m \neq n; \quad (3b)$$

$$(\mathbf{v}_j^m)^T \Big(\sum_{i \in \mathcal{T}_k} \mathbf{H}_{ji} \mathbf{u}_i^n \Big) = 0, \quad k \in \mathcal{K}_j; 1 \leq n \leq z_k; \quad (3c)$$

where (3a) ensures the success of receiving the desired data stream x_l^m, (3b) ensures the nullification of intra-link interference, and (3c) ensures the nullification of inter-link interference. Among these constraints, (3a) has 1 equation, (3b) has $(z_l - 1)$ equations, and (3c) has $|\mathcal{K}_j| \cdot z_l$ constraints. It is easy to see that nullifying the inter-link interference is the most demanding job as we need to make sure that the precoding and decoding vectors satisfy $|\mathcal{K}_j| \cdot z_l$ constraints.

Consider the inter-link interference in (3c). There are two approaches to nullify the inter-link interference: neutralization and cancellation. We summarize them as follows:

- *Neutralization*: IN refers to a joint design of the precoding vectors at the transmitting nodes of link $k \in \mathcal{K}_j$, so that the interference from the transmitting nodes of link k to receiving node $j \in \mathcal{R}_l$ is nullified, i.e., $\sum_{i \in \mathcal{T}_k} \mathbf{H}_{ji} \mathbf{u}_i^n = \mathbf{0}$ in (3c).

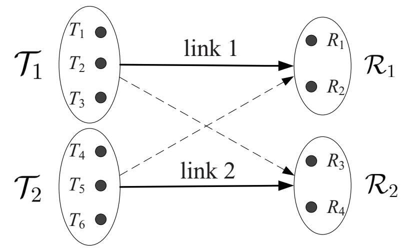


Fig. 3. An example that explains IN constraints. Solid arrow represents data transmission and dashed line arrow represents interference.

- *Cancellation*: IC refers to a sophisticated design of the decoding vectors at receiving node $j \in \mathcal{R}_l$, so that the un-neutralized interference from the transmitting nodes of link $k \in \mathcal{K}_j$ can be nullified, i.e., $(\mathbf{v}_l^m)^T \Big(\sum_{i \in \mathcal{T}_k} \mathbf{H}_{ji} \mathbf{u}_i^n \Big) = 0$ in (3c) when $\sum_{i \in \mathcal{T}_k} \mathbf{H}_{ji} \mathbf{u}_i^n \neq \mathbf{0}$.

In what follows, we explore IN constraints on the transmitter side and IC constraints on the receiver side so that each link $l \in \mathcal{L}$ can transport z_l data streams free of interference (i.e., one can always construct precoding and decoding vectors that satisfy (3) for $l \in \mathcal{L}$, $j \in \mathcal{R}_l$, and $m = 1, 2, \ldots, z_l$).

IN Constraints on Transmitter Side. To explore the constraints of IN on the transmitter side, we first study a small example and then extend our observations to the generic case.

Consider the two-link network as shown in Fig. 3, where each node has the same number of antennas (M antennas) and each link has three transmitting nodes and two receiving nodes. Both links have M data streams (i.e., $z_1 = z_2 = M$) and all nodes are in the same interference domain. Consider the three transmitting nodes in $\mathcal{T}_1$. Their outgoing data streams are desired at R_1 and R_2 but considered as interference at R_3 and R_4. We now show that the interference at the two receiving nodes in $\mathcal{R}_2$ can be neutralized through the joint design of precoding vectors at the three transmitting nodes in $\mathcal{T}_1$. Denote $\mathbf{y}_j^{\mathrm{S}}$ and $\mathbf{y}_j^{\mathrm{I}}$ as the desired signal and interference at receiving node j, respectively. Then we have

$$\mathbf{y}_1^{\mathrm{S}} = \sum_{n=1}^{z_1} \Big(\mathbf{H}_{11} \mathbf{u}_1^n + \mathbf{H}_{12} \mathbf{u}_2^n + \mathbf{H}_{13} \mathbf{u}_3^n \Big) x_1^n,$$

$$\mathbf{y}_2^{\mathrm{S}} = \sum_{n=1}^{z_1} \Big(\mathbf{H}_{21} \mathbf{u}_1^n + \mathbf{H}_{22} \mathbf{u}_2^n + \mathbf{H}_{23} \mathbf{u}_3^n \Big) x_1^n,$$

$$\mathbf{y}_3^{\mathrm{I}} = \sum_{n=1}^{z_1} \Big(\mathbf{H}_{31} \mathbf{u}_1^n + \mathbf{H}_{32} \mathbf{u}_2^n + \mathbf{H}_{33} \mathbf{u}_3^n \Big) x_1^n,$$

$$\mathbf{y}_4^{\mathrm{I}} = \sum_{n=1}^{z_1} \Big(\mathbf{H}_{41} \mathbf{u}_1^n + \mathbf{H}_{42} \mathbf{u}_2^n + \mathbf{H}_{43} \mathbf{u}_3^n \Big) x_1^n.$$

To neutralize the interference at the receiving nodes in $\mathcal{R}_2$, the precoding vectors at the transmitting nodes in $\mathcal{T}_1$ should meet the following conditions for $n = 1, 2, \cdots, z_1$.

$$\mathbf{H}_{11}\mathbf{u}_1^n + \mathbf{H}_{12}\mathbf{u}_2^n + \mathbf{H}_{13}\mathbf{u}_3^n \neq \mathbf{0}, \tag{4a}$$

$$\mathbf{H}_{21}\mathbf{u}_1^n + \mathbf{H}_{22}\mathbf{u}_2^n + \mathbf{H}_{23}\mathbf{u}_3^n \neq \mathbf{0}, \tag{4b}$$

$$\mathbf{H}_{31}\mathbf{u}_1^n + \mathbf{H}_{32}\mathbf{u}_2^n + \mathbf{H}_{33}\mathbf{u}_3^n = \mathbf{0}, \tag{4c}$$

$$\mathbf{H}_{41}\mathbf{u}_1^n + \mathbf{H}_{42}\mathbf{u}_2^n + \mathbf{H}_{43}\mathbf{u}_3^n = \mathbf{0}. \tag{4d}$$

Given that the channel matrices are independent of each other, the precoding vectors will satisfy conditions (4a)–(4b) almost surely if $\mathbf{u}_1^n$, $\mathbf{u}_2^n$, or $\mathbf{u}_3^n$ is a nonzero vector [23]. Therefore, to solve the problem in (4), we only need to focus on (4c)–(4d). By using the Gaussian elimination (also known as row reduction) algorithm, we can obtain one solution as follows:

$$\begin{aligned}
\mathbf{u}_3^n &= \mathbf{u}_{\text{ref}}^n, \\
\mathbf{u}_2^n &= \left(\mathbf{H}_{41}^{-1}\mathbf{H}_{42} - \mathbf{H}_{31}^{-1}\mathbf{H}_{32}\right)^{-1}\left(\mathbf{H}_{31}^{-1}\mathbf{H}_{22} - \mathbf{H}_{41}^{-1}\mathbf{H}_{43}\right)\mathbf{u}_{\text{ref}}^n, \\
\mathbf{u}_1^n &= \big[\left(\mathbf{H}_{31}^{-1}\mathbf{H}_{32}\right)\left(\mathbf{H}_{41}^{-1}\mathbf{H}_{42} - \mathbf{H}_{31}^{-1}\mathbf{H}_{32}\right)^{-1} \\
&\qquad \left(\mathbf{H}_{41}^{-1}\mathbf{H}_{43} - \mathbf{H}_{31}^{-1}\mathbf{H}_{22}\right) - \left(\mathbf{H}_{31}^{-1}\mathbf{H}_{33}\right)\big]\mathbf{u}_{\text{ref}}^n,
\end{aligned}$$

where $n = 1, 2, \cdots, z_l$ and $\{\mathbf{u}_{\text{ref}}^1, \cdots, \mathbf{u}_{\text{ref}}^M\}$ is a set of linearly independent nonzero vectors. It can be verified that by using these precoding vectors, the interference from the transmitting nodes in $\mathcal{T}_1$ can be neutralized at the two unintended receiving nodes in $\mathcal{R}_2$.

One observation from this example is that the success of IN relies on the fact that the number of transmitting nodes in $\mathcal{T}_1$ is larger than the number of receiving nodes in $\mathcal{R}_2$. We now extend this observation to the generic case in Fig. 2. Consider a link $l \in \mathcal{L}$ in the network. Denote $\mathcal{S}_l$ as the set of receiving nodes that are interfered by at least one transmitting node in $\mathcal{T}_l$. Denote $\beta_{l,j}$ as a binary variable to indicate whether the interference from the transmitting nodes in $\mathcal{T}_l$ to receiving node $j \in \mathcal{S}_l$ is neutralized. Specifically, $\beta_{l,j} = 1$ if the interference from the transmitting nodes in $\mathcal{T}_l$ to receiving node j is neutralized and 0 otherwise. Then we have the following lemma:

Lemma 1. Through the design of their precoding vectors, the transmitting nodes in $\mathcal{T}_l$ can always neutralize their interference for at least $|\mathcal{T}_l| - 1$ receiving nodes in $\mathcal{S}_l$.

The proof of this lemma is given in Appendix A. In the proof, we propose a Gauss–Jordan Elimination algorithm to construct the precoding vectors for the transmitting nodes in $\mathcal{T}_l$ so that their interference can be neutralized at those receiving nodes. Based on Lemma 1, we have the following constraints:

$$\sum_{j \in \mathcal{S}_l} \beta_{l,j} \leq |\mathcal{T}_l| - 1, \qquad l \in \mathcal{L}. \tag{5}$$

IC Constraints on Receiver Side. Consider a receiving node $j \in \mathcal{R}_l$ in Fig. 2. Recall that $\mathcal{K}_j$ is the set of links that have at least one transmitting node interfering with receiving node j. For a link $k \in \mathcal{K}_j$, if $\beta_{k,j} = 1$, then receiving node j does not need to take care of the interference from the transmitting nodes of link k since it has already been neutralized on the transmitter side. Otherwise (i.e., $\beta_{k,j} = 0$), receiving node j needs to cancel the interference from the transmitting nodes of link k through the design of the decoding vectors at receiving node j. To successfully decode its z_l data streams at receiving node $j \in \mathcal{R}_l$, we need to construct a decoding vector for each of its desired data stream so that (3) are satisfied. Then we have the following lemma:

Lemma 2. Through the design of its decoding vectors, each receiving node $j \in \mathcal{R}_l$ can decode its z_l desired data streams free of interference if the following constraint is satisfied:

$$z_l + \sum_{k \in \mathcal{K}_j} (1 - \beta_{k,j}) \cdot z_k \leq M, \qquad l \in \mathcal{L}, j \in \mathcal{R}_l. \tag{6}$$

The proof of this lemma is given in Appendix B.

INC Modeling Summary. Collectively, (5) and (6) constitute a mathematical model of INC, which can be used to check the feasibility of a given degree-of-freedom (DoF) vector $(z_1, z_2, \cdots, z_L)$ for a network in Fig. 2. Specifically, for any given DoF vector $(z_1, z_2, \cdots, z_L)$, if it satisfies (5) and (6), then one can always construct a set of precoding and decoding vectors that satisfy (3) for $l \in \mathcal{L}$, $j \in \mathcal{R}_l$, and $m = 1, 2, \ldots, z_l$. More concisely, we have the following theorem:

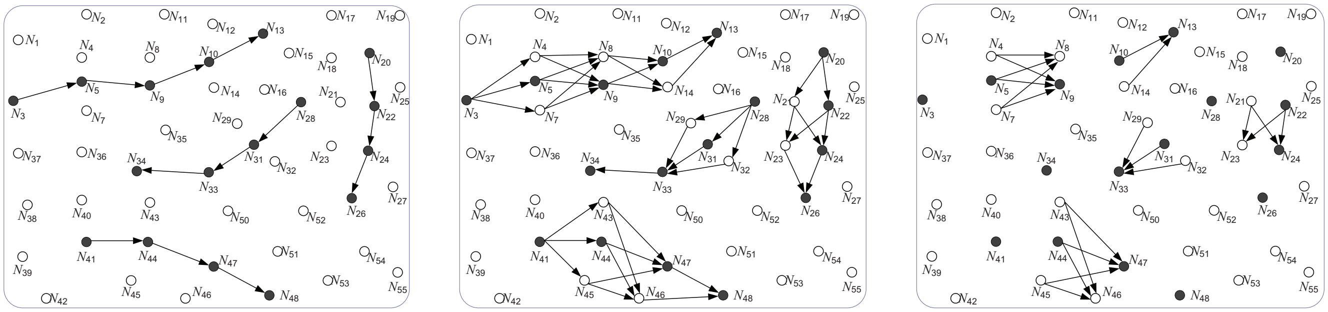
Theorem 1. Each link $l \in \mathcal{L}$ can transport z_l data streams from its transmitting nodes to its receiving nodes free of interference if (5) and (6) are satisfied.

The proof of this theorem is straightforward based on Lemma 1 and Lemma 2. We thus omit it. It is worth pointing out that our INC model is applicable to both single-antenna and multi-antenna networks. For a network with a single antenna at each node (i.e., $M = 1$), it does not have IC capability but it still has IN capability. This is because that the IN capability comes from the cooperation of multiple transmitters. Also, in the single-antenna case, the precoding and decoding vectors degrade to a complex number and the integer variable z_l degrades to a binary variable.

III. An INC Optimization Framework for Multi-hop Networks

In this section, we develop an optimization framework for INC in multi-hop networks. Consider a multi-hop network consisting of a set of nodes as shown in Fig. 4(a). Among the nodes there is a set $\mathcal{F}$ of multi-hop communication sessions, with $\text{src}(f)$ being the source node and $\text{dst}(f)$ being the destination node of session $f \in \mathcal{F}$. Denote $r(f)$ as the end-to-end data rate of session $f \in \mathcal{F}$. To transport data from a source node to its corresponding destination node, we assume that the routing path of each session has already been computed through some routing protocol (e.g., OSPF [22]). Based on the routing paths, the nodes in the network can be classified into two subsets: $\mathcal{N}_{\text{path}}$ and $\mathcal{N}_{\text{idle}}$, where $\mathcal{N}_{\text{path}}$ is the set of nodes on the routing paths (marked as solid circles in Fig. 4(a)) and $\mathcal{N}_{\text{idle}}$ is the rest of nodes (also called idle nodes, marked as empty circles in Fig. 4(a)). Denote $\mathcal{L}$ as the set of links along the routing paths of the sessions. For the links in $\mathcal{L}$, we assume that their transmission scheduling is done in a time frame that consists of T time slots.

For the communications in the multi-hop network in Fig. 4(a), we consider the cooperative case where the nodes in $\mathcal{N}_{\text{idle}}$ are willing to help the communications of the nodes in $\mathcal{N}_{\text{path}}$, as

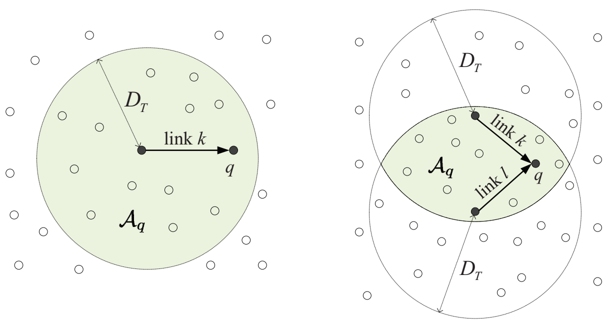


(a) A network with a set of session. Solid arrows represent routing path.

(b) Session communications with assisting nodes.

(c) Active transmitters and receivers in a time slot.

Fig. 4. Illustration of assisting node selection for IN in a wireless network with four multi-hop communication sessions. (Interferences are not shown in the figures.)



(a) Node q has a single incoming link

(b) Node q has multiple incoming links

Fig. 5. Two examples that illustrate the set $\mathcal{A}_q$ of possible assisting nodes for routing node q.

illustrated in Fig. 4(b). Consider idle node N_4 in Fig. 4(b) as an example. It serves as an assisting node for path node N_5. Specifically, it overhears data information from N_5's intended transmitter (i.e. N_3) whenever N_5 is a receiver; it also transmits the same data information as N_5 does whenever N_5 is transmitting. Similarly, idle node N_7 is another assisting node of path node N_5. Since N_4, N_5, and N_7 always have the same data information, they have the IN capability to nullify their interference to their unintended receivers when they are transmitting. Since they always have the same data information, they can neutralize their interference at some of their unintended receivers through the design of their precoding vectors. As an example, Fig. 4(c) depicts data transmissions in a time slot. Through jointly designing their precoding vectors, transmitting nodes N_4, N_5, and N_7 can neutralize their interference at receiving node N_{13} and N_{33}.

A. INC Constraints in Multi-hop Network

Assisting-Node Selection. Before extending the INC constraints to a multi-hop network, we first need to specify the set of transmitting nodes (i.e., $\mathcal{T}_l$) and the set of receiving nodes (i.e., $\mathcal{R}_l$) for each link $l \in \mathcal{L}$. Consider a node $q \in \mathcal{N}_{\text{path}}$ as shown in Fig. 5(a). We call an idle node $i \in \mathcal{N}_{\text{idle}}$ as an assisting node for node q if it behaves in the same way as node q (i.e., receiving and transmitting the same data streams as node q). Therefore, to be eligible for serving as an assisting node for node q, node i should be within the transmission range of node q's intended transmitting nodes. Fig. 5(a) illustrates the set of eligible assisting nodes for node q when node q has one incoming link and Fig. 5(b) illustrates the case where node q has two incoming links. More formally, by denoting $\mathcal{A}_q$ as the set of idle nodes that are eligible for serving as an assisting node for node q, we have

$$\mathcal{A}_q = \bigcap_{k \in \mathcal{L}_q^{\text{in}}} \left\{ i : d(i, \text{Tx}(k)) \le D_{\text{T}}, i \in \mathcal{N}_{\text{idle}} \right\}, \qquad q \in \mathcal{N}_{\text{path}},$$

where $d(i,j)$ is the distance between node i and node j, D_{T} is the transmission range of a transmitting node, $\mathcal{L}_q^{\text{in}}$ is the set of incoming links of node q, and $\text{Tx}(k)$ is the transmitting node of link k. In particular, if node q is the source node of a session, there is no node eligible to be its assisting node (i.e., $\mathcal{A}_q = \emptyset$).

Referring to Fig. 6, denote $\mathcal{P}_l$ as the set of all possible transmitting nodes of link l and denote $\mathcal{Q}_l$ as the set of all possible receiving nodes of link l. Based on the definition of $\mathcal{A}_q$, we have

$$\mathcal{P}_l = \mathcal{A}_{\text{Tx}(l)} \cup \{\text{Tx}(l)\},$$
$$\mathcal{Q}_l = \mathcal{A}_{\text{Rx}(l)} \cup \{\text{Rx}(l)\}.$$

For an idle node $i \in \mathcal{N}_{\text{idle}}$, it may be eligible to serve as an assisting node for multiple nodes in $\mathcal{N}_{\text{path}}$, as illustrated in Fig. 6. How to select the best serving node for an idle node $i \in \mathcal{N}_{\text{idle}}$ is a part of our optimization problem. Denote $\lambda_{q,i}$ as a binary variable to indicate whether or not node i serves as an assisting node for node $q \in \mathcal{N}_{\text{path}}$. Specifically, $\lambda_{q,i} = 1$ if node i serves as an assisting node for node q and 0 otherwise. Since a node $i \in \mathcal{N}_{\text{idle}}$ can serve as assisting node for at most one node in $\mathcal{N}_{\text{path}}$, we have the following constraints:

$$\sum_{q \in \mathcal{M}_i} \lambda_{q,i} \le 1, \qquad i \in \mathcal{N}_{\text{idle}}, \tag{7}$$

where $\mathcal{M}_i$ is the set of nodes in $\mathcal{N}_{\text{path}}$ for which node i is eligible to serve as an assisting node.

For notational convenience, we define a virtual variable $\lambda_{q,q}$ for node $q \in \mathcal{N}_{\text{path}}$ and force it to one to indicate that node q is always a transmitting (receiving) node of its outgoing (incoming) links. This constraint can be written as

$$\lambda_{q,q} = 1, \qquad q \in \mathcal{N}_{\text{path}}. \tag{8}$$

Based on the definition of $\mathcal{P}_l$, $\mathcal{Q}_l$, and $\lambda_{q,i}$, we have

$$\mathcal{T}_l = \left\{ i : i \in \mathcal{P}_l, \lambda_{\text{Tx}(l),i} = 1 \right\},$$

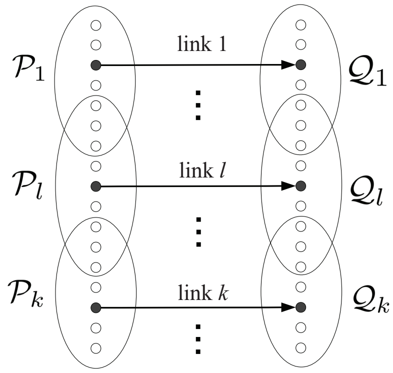


Fig. 6. The links in a multi-hop network with the possible assisting nodes. Solid circles represent routing nodes and empty circles represent idle nodes.

$$\mathcal{R}_l = \{i : i \in \mathcal{Q}_l, \lambda_{\mathrm{Rx}(l),i} = 1\}.$$

Generalized INC Constraints. Consider the network in Fig. 4 in a given time slot t. Due to the half-duplex and interference conflict, not every link can be active in the same time slot. Denote $\alpha_l(t)$ as a binary variable to indicate whether the link l is active in time slot t. Specifically, $\alpha_l(t) = 1$ if link l is active in time slot t and 0 otherwise. To generalize the INC model for a multi-hop network in time slot t, we need to incorporate variables $\lambda_{q,i}$ and $\alpha_l(t)$ into (5) and (6) so that the number of data streams on each link in time slot t can be characterized. Without causing ambiguity, we add index t to some defined variables to represent their values in time slot t. For example, $z_l(t)$ represents the number of data streams on link l in time slot t.

To generalize IN constraint (5), we consider a link $l \in \mathcal{L}$ in time slot t in Fig. 6. If link l is active (i.e., $\alpha_l(t) = 1$), then, based on (5), we have

$$\sum_{j \in \mathcal{S}_l} \beta_{l,j}(t) \le |\mathcal{T}_l| - 1 = \sum_{i \in \mathcal{P}_l} \lambda_{\mathrm{Tx}(l),i} - 1.$$

If link l is inactive (i.e., $\alpha_l(t) = 0$), there should be no constraint on $\beta_{l,j}(t)$ since the transmitting nodes of link l do not interfere with any nodes. Combining these two cases, we have the following constraints:

$$\sum_{j \in \mathcal{S}_l} \beta_{l,j}(t) \le \sum_{i \in \mathcal{P}_l} \lambda_{\mathrm{Tx}(l),i} - 1 + (1 - \alpha_l(t)) \cdot B, \quad l \in \mathcal{L}, 1 \le t \le T, \qquad (9)$$

where $\mathcal{S}_l$ is the set of nodes that are within the interference range of any possible transmitting node of link l (i.e., $\mathcal{S}_l = \cup_{i \in \mathcal{P}_l} \mathcal{I}_i$ with $\mathcal{I}_i$ being the set of nodes in the interference range of node i) and B is a large enough constant (e.g., $B = N \cdot M$).

We need one more constraint on the transmitter side. According to Lemma 1, constraint (5) can guarantee that at least one transmitting node of link l has nonzero transmit power, but it cannot guarantee that every transmitting node has a nonzero transmit power. Referring to Fig. 6, the receiving nodes of link l is only guaranteed to be within the transmission range of transmitting node $\mathrm{Tx}(l)$. Therefore, we need to make sure that for each active link $l \in \mathcal{L}$, the transmitting node $\mathrm{Tx}(l)$ has a nonzero transmit power. Based on the proof of Lemma 1, if the transmitting nodes of link l neutralize their interference only for those receiving nodes within the interference range of every transmitting node of link l, then the constructed precoding vectors would not be $\mathbf{0}$ and every transmitting node of link l has a nonzero transmit power. So we develop constraints to ensure that the transmitting nodes of link l neutralize their interference only for those receiving nodes within the interference range of every transmitting node of link l. Consider a transmitting node $i \in \mathcal{P}_l$ and a receiving node $j \in \mathcal{S}_l$. We define E_{ij} as a binary constant to indicate whether or not node j is within the interference range of node i. Specifically, $E_{ij} = 1$ if node j is within the interference range of node i and 0 otherwise. If node j is not within the interference range of node i (i.e., $E_{ij} = 0$), then we have $\beta_{l,j}(t) + \lambda_{\mathrm{Tx}(l),i} \le 1$. Otherwise, there is no additional constraint on $\beta_{l,j}(t)$ and $\lambda_{\mathrm{Tx}(l),i}$. Combining these two cases, we have

$$\beta_{l,j}(t) + \lambda_{\mathrm{Tx}(l),i} \le 1 + E_{ij}, \quad l \in \mathcal{L}, i \in \mathcal{P}_l, j \in \mathcal{S}_l, 1 \le t \le T. \qquad (10)$$

Now we consider the IC constraint on the receiver side. Before generalizing IC constraint (6), we first introduce a new binary variable $\xi_{k,j}(t)$ to indicate whether receiving node j needs to cancel the interference from the transmitting nodes of link k in time slot t. Specifically, $\xi_{k,j}(t) = 1$ if receiving node j needs to cancel the interference from the transmitting nodes of link k in time slot t and 0 otherwise. Referring to Fig. 6, we consider the transmitting nodes of link k and an unintended receiving node j in time slot t. Basically, there are two cases where receiving node j does not need to cancel the interference from the transmitting nodes of link k. First, receiving node j is out of the interference range of all the transmitting nodes of link k, i.e., $\sum_{i \in \mathcal{P}_k \cap \mathcal{I}_j} \lambda_{\mathrm{Tx}(k),i} = 0$ with $\mathcal{I}_j$ being the set of nodes within the interference range of node j. Second, the transmitting nodes of link k have already neutralized their interference for receiving node j, i.e., $\beta_{k,j}(t) = 1$. These two cases can be summarized as

$$\xi_{k,j}(t) = \begin{cases} 0 & \text{if } \sum\limits_{i \in \mathcal{P}_k \cap \mathcal{I}_j} \lambda_{\mathrm{Tx}(k),i} = 0 \text{ or } \beta_{k,j}(t) = 1, \\ 1 & \text{otherwise.} \end{cases} \qquad (11)$$

It can be verified that the relationship between $\xi_{k,j}(t)$, $\beta_{k,j}(t)$, and $\lambda_{\mathrm{Tx}(k),i}$ in the above expression can be equivalently interpreted as the following mathematical constraints:

$$\sum_{i \in \mathcal{P}_k \cap \mathcal{I}_j} \frac{\lambda_{\mathrm{Tx}(k),i}}{B} - \beta_{k,j}(t) \le \xi_{k,j}(t) \le \sum_{i \in \mathcal{P}_k \cap \mathcal{I}_j} \lambda_{\mathrm{Tx}(k),i}\,, \quad k \in \mathcal{L}, j \in \mathcal{S}_k, 1 \le t \le T, \qquad (12)$$

where $\xi_{k,j}(t)$ is a binary variable to indicate whether receiving node j needs to cancel the interference from the transmitting nodes of link k in time slot t; the right-hand side is a mathematical representation of whether receiving node j suffers from interference from the transmitting nodes of link k; and the left-hand side is a mathematical representation of whether the interference is nullified by IN. While the physical meanings of this constraint is not straightforward, it is easy to verify that, from the mathematical perspective, this constraint is equivalent to the summary of those two cases in (11).

Based on (12), we now generalize IC constraint (6) to multi-hop network in time slot t. Consider a receiving node $j \in \mathcal{Q}_l$

in Fig. 6. We now study its IC requirements by the following three cases:

- $\alpha_l(t) = 0$: In this case, link l is not active and thus node j does not need to decode the data streams on link l. Therefore, there should be no IC requirement at node j.
- $\lambda_{\mathrm{Rx}(l),j} = 0$: In this case, node j is not an active receiver of link l and thus it does not need to decode the data streams on link l. Therefore, there should be no IC requirement at node j.
- $\alpha_l(t) = 1$ and $\lambda_{\mathrm{Rx}(l),j} = 1$: In this case, it should be assured that node j is able to decode its desired data streams from the transmitting nodes of link l. Based on (6) in our INC model, we have $z_l(t) + \sum_{k\in\mathcal{L}}^{k\neq l} \xi_{k,j}(t)\cdot z_k(t) \le M$.

Combining these three cases, (6) in our INC model can be equivalently interpreted as the following constraints:

$$z_l(t) + \sum_{k\in\mathcal{L}}^{k\neq l} \xi_{k,j}(t)\cdot z_k(t) \le M + (2 - \alpha_l(t) - \lambda_{\mathrm{Rx}(l),j})\cdot B,$$
$$l\in\mathcal{L}, j\in\mathcal{Q}_l, 1\le t\le T, \quad (13)$$

where $z_l(t)$ on the left-hand side is the number of desired data streams for receiving node j; $\sum_{k\in\mathcal{L}}^{k\neq l}\xi_{k,j}(t)$ on the left-hand side is the number of interfering streams for receiving node j; $(2 - \alpha_l(t) - \lambda_{\mathrm{Rx}(l),j})$ on the right-hand side is an indicator of whether there is a need for decoding signals at receiving node j. In a nutshell, this constraint ensures that receiving node j has enough spatial DoFs to cancel its interference and recover its desired signals.

B. Cross-layer Optimization Constraints

Based on the INC constraints derived in Section III-A, we develop other necessary constraints to characterize the average end-to-end data rate of each session in T time slots.

Link Activity Constraints. For each node $q\in\mathcal{N}_{\mathrm{path}}$, we assume that it works with half-duplex radio, i.e., it cannot transmit and receive in the same time slot. We also assume that each node cannot be a transmitter or receiver of multiple links simultaneously. Denote $\mathcal{L}_q^{\mathrm{out}}$ as the set of outgoing links at node q. Recall that $\mathcal{L}_q^{\mathrm{in}}$ is the set of incoming links at node q. Then we have

$$\sum_{l\in\mathcal{L}_q^{\mathrm{out}}}\alpha_l(t) + \sum_{l\in\mathcal{L}_q^{\mathrm{in}}}\alpha_l(t) \le 1, \quad q\in\mathcal{N}_{\mathrm{path}}, 1\le t\le T. \quad (14)$$

Recall that $z_l(t)$ is the number of data streams on link l in time slot t. If link l is active (i.e., $\alpha_l(t)=1$), then we have $z_l(t)\ge 1$. Otherwise (i.e., $\alpha_l(t)=0$), we have $z_l(t)=0$. Therefore, we have

$$\alpha_l(t)\le z_l(t)\le M\cdot\alpha_l(t), \quad l\in\mathcal{L}, 1\le t\le T. \quad (15)$$

Link Rate Constraints. Consider a link $l\in\mathcal{L}$ in the network. It may be traversed by multiple sessions' routing paths. Denote $\mathcal{F}_l$ as the set of sessions whose routing paths traverse link l. Then the aggregate data rate requirement of link l is $\sum_{f\in\mathcal{F}_l} r(f)$. For the same link l, we assume that fixed modulation and coding scheme (MCS) is used for its data stream transmission and one data stream in one time slot corresponds to one unit data rate. Then the achievable data rate of link l (averaged over T time slots) is $\frac{1}{T}\sum_{t=1}^{T} z_l(t)$. Since the aggregate data rate requirement (for its traversing sessions) cannot exceed the achievable data rate, we have

$$\sum_{f\in\mathcal{F}_l} r(f) \le \frac{1}{T}\sum_{t=1}^{T} z_l(t), \quad l\in\mathcal{L}. \quad (16)$$

C. Put It Together and Linearization

Collectively, constraints (7)–(16) constitute our INC optimization framework for a multi-hop network. These constraints characterize the achievable data rate $r(f)$ of each session $f\in\mathcal{F}$, making the framework applicable to solve a wide range of throughput optimization problems in multi-hop wireless networks.

In a multi-hop network, suppose that the objective is to maximize the minimum rate among all sessions.[1] Defining $r_{\min}$ as the minimum rate among all sessions, we have

$$r_{\min}\le r(f), \quad f\in\mathcal{F}. \quad (17)$$

According to the constraints in our INC optimization framework, we can formulate this optimization problem as follows:

OPT-INC$^{\mathrm{raw}}$:	Max	$r_{\min}$
	S.t.	Assisting node selection: (7), (8);
		INC constraints: (9), (10), (12), (13);
		Link activity constraints: (14), (15);
		Link rate constraints: (16);
		Min rate constraints: (17).

In this optimization formulation, (13) is the only nonlinear constraint. To linearize (13), we define a new integer variable by letting $\zeta_{k,j}(t) = \xi_{k,j}(t)\cdot z_k(t)$ for $k\in\mathcal{L}$, $j\in\mathcal{S}_l$, and $t=1,2,\cdots,T$. Then (13) can be replaced with

$$z_l(t) + \sum_{k\in\mathcal{L}}^{k\neq l}\zeta_{k,j}(t) \le M + (2-\alpha_l(t)-\lambda_{\mathrm{Rx}(l),j})\cdot B,$$
$$l\in\mathcal{L}, j\in\mathcal{Q}_l, 1\le t\le T. \quad (18)$$

To ensure the equivalence of (13) and (18), we need to add $\zeta_{k,j}(t) = \xi_{k,j}(t)\cdot z_k(t)$ to the formulation, which can be equivalently interpreted to the following two linear constraints:

$$0\le\zeta_{k,j}(t)\le z_k(t), \quad k\in\mathcal{L}, j\in\mathcal{S}_k, 1\le t\le T. \quad (19)$$

$$z_k(t) + (\xi_{k,j}(t)-1)\cdot M \le \zeta_{k,j}(t) \le \xi_{k,j}(t)\cdot M,$$
$$k\in\mathcal{L}, j\in\mathcal{S}_k, 1\le t\le T. \quad (20)$$

In summary, by replacing nonlinear constraint (13) with (18)–(20), we have the following optimization problem:

OPT-INC:	Max	$r_{\min}$
	S.t.	(7)–(12), (14)–(20),

[1]Note that problems with other objectives such as maximizing sum of weighted rates or a proportional increase (scaling factor) of all session rates belongs to the same category and can be solved following the same token.

where M, T, and B are constants (depending on network setting, not optimization variables); $\alpha_l(t)$, $\lambda_{q,i}$, $\beta_{l,j}(t)$, and $\xi_{k,j}(t)$ are binary optimization variables; $z_l(t)$ and $\zeta_{k,j}(t)$ are non-negative optimization integers; $r_{\min}$ and $r(f)$ are non-negative continuous optimization variables. It should be noted that the linearization does not change the optimality of the problem, i.e., OPT-INC$^{\text{raw}}$ and OPT-INC have the same optimal objective value.

OPT-INC is a mixed-integer linear program (MILP). Although the theoretical worst-case complexity of solving a general MILP problem is exponential [24], [25], there exist highly efficient optimal and approximation algorithms (e.g., branch-and-bound with cutting planes [26]) and heuristic algorithms (e.g., sequential fixing algorithm [27], [28]). For small to moderate network size, an off-the-shelf solver such as CPLEX [29] may also be effective. Since our goal is to study the performance gain of INC in multi-hop networks (rather than developing a solution procedure), we will employ CPLEX solver to solve the optimization problems as it can serve our purpose appropriately.

D. Discussions of Practical Issues

Discussions of the practical issues related to IN are in order.

Synchronization. Practical use of IN in wireless networks requires a robust synchronization mechanism to synchronize all the nodes in both the time and frequency domains. Different approaches have been developed to synchronize the nodes in a multi-hop wireless network. For example, [30] proposed an efficient and scalable timing synchronization function for IEEE 802.11 networks in ad hoc mode. [31] proposed a clock synchronization algorithm for multi-hop wireless ad hoc networks. The IN scheme proposed in this paper can take advantage of the existing synchronization approaches for its implementation in real-world networks.

CSI Feedback. Implementation of IN in multi-hop wireless networks requires CSI on the transmitter side. To obtain CSI on the transmitter side, we can leverage the well-designed CSI feedback mechanisms in single-hop wireless networks such as WiFi and LTE. For example, Wi-Fi has defined a poll-based CSI feedback mechanism to support downlink MU-MIMO transmission [32], and LTE has specified a codebook-based CSI feedback mechanism for efficient spatial multiplexing [33]. Although these mechanisms were originally designed for single-hop networks, they can be used for the CSI feedback in multi-hop networks.

Node Coordination. IN is a cooperative transmitter-side interference management technique. It requires the fine-grained coordination among the nodes in each group (consisting of a routing node and all its assisting nodes) to jointly design their precoding vectors for interference nullification in the air. To achieve such coordination, special control channel should be established for the information exchange among the nodes in each group. We may customize the distributed coordination functions defined in 802.11 networks (e.g., [34]) to achieve coordination of the nodes in each group.

It should be noted that this paper is focused on the exploration of the maximum possible performance gain of IN in multi-hop wireless networks without taking into account the communication overhead induced by synchronization, CSI feedback and node coordination. How to address those practical issues to enable IN in real-world wireless networks is beyond the scope of this paper.

IV. Performance Evaluation

In this section, we evaluate the performance of IN in multi-hop networks using the optimization framework we developed in the previous section. Specifically, we study the optimal throughput of the sessions in a generic multi-hop network with INC and compare it against the case where IN is not employed (but still with IC). As a performance benchmark, we formulate the same problem but without IN (still with IC) to another optimization problem and denote it as OPT-IC, which is given in Appendix C.

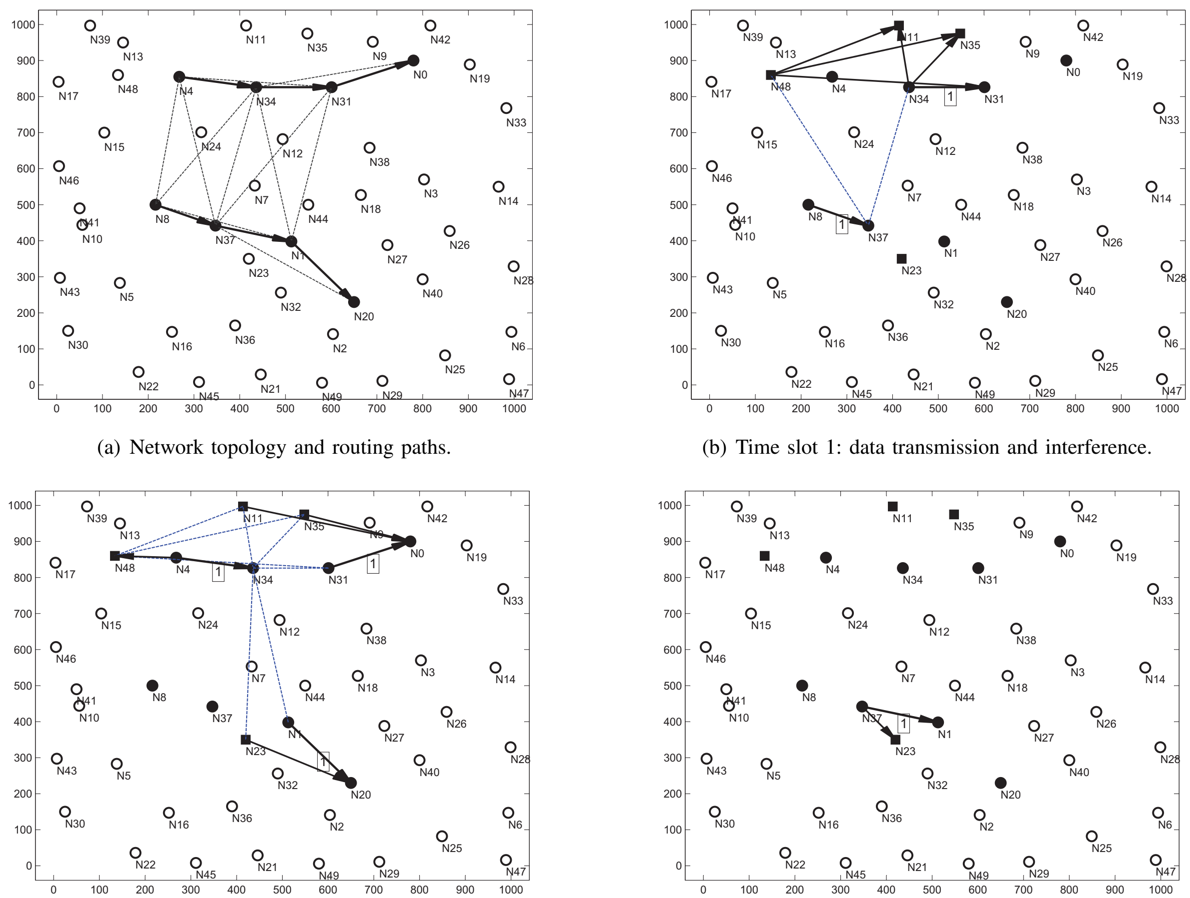
A. Simulation Setting

Without loss of generality, we normalize the units of distance, data rate, bandwidth, and time with appropriate dimension. We consider a multi-hop network consisting of a set of randomly generated nodes that are uniformly distributed in a 1000×1000 square region. Each node is equipped with the same number of antennas and the transmission range is assumed to be 250 (i.e., $D_{\text{T}} = 250$). There is a set of sessions in the network, with their source and destination nodes being randomly selected among all the nodes. For simplicity, the routing path from the source node of each session to its corresponding destination node is established by the shortest path (in terms of the number of hops). We assume each source node has persistent traffic for transmission. Unless otherwise stated, we assume that there are 10 time slots in a frame for scheduling.

B. Case Studies

IN in Single-Antenna Network. As a case study, we investigate a network instance as shown in Fig. 7(a). In addition to the parameters in Section IV-A, we also assume that the interference range, denoted as D_{R}, is twice of the transmission range (i.e., $D_{\text{R}} = 500$). There are 50 nodes and 2 sessions in this network instance, with the routing path being shown in the figure. For ease of exposition, we assume there are only 3 time slots for scheduling. We note that this network instance does not have IC capability because its nodes have only one antenna.

By solving OPT-IC for this network instance, we obtained the optimal objective value of 0. This indicates that, without IN, it is not possible to establish data communication for each session in 3 time slots. In contrast, by solving OPT-INC for this network instance, we obtained the optimal objective value of $1/3$. This means that, by employing IN, one can establish successful data communication for each session with an average rate of $1/3$. To see how IN manages to enable the communication for each session, let's scrutinize the optimization results in each time slot, which are exhibited in Fig. 7(b)–(d). In the figures, there are three types of symbols. Solid circles represent the nodes along the routing paths of the sessions, which we call *routing nodes*. Solid squares represent the nodes that are scheduled to help the transmission/reception of routing nodes, which we call *assisting nodes*. Empty circles represent the nodes that are not being scheduled for the communication. There are two



(a) Network topology and routing paths.

(b) Time slot 1: data transmission and interference.

(c) Time slot 2: data transmission and interference.

(d) Time slot 3: data transmission and interference.

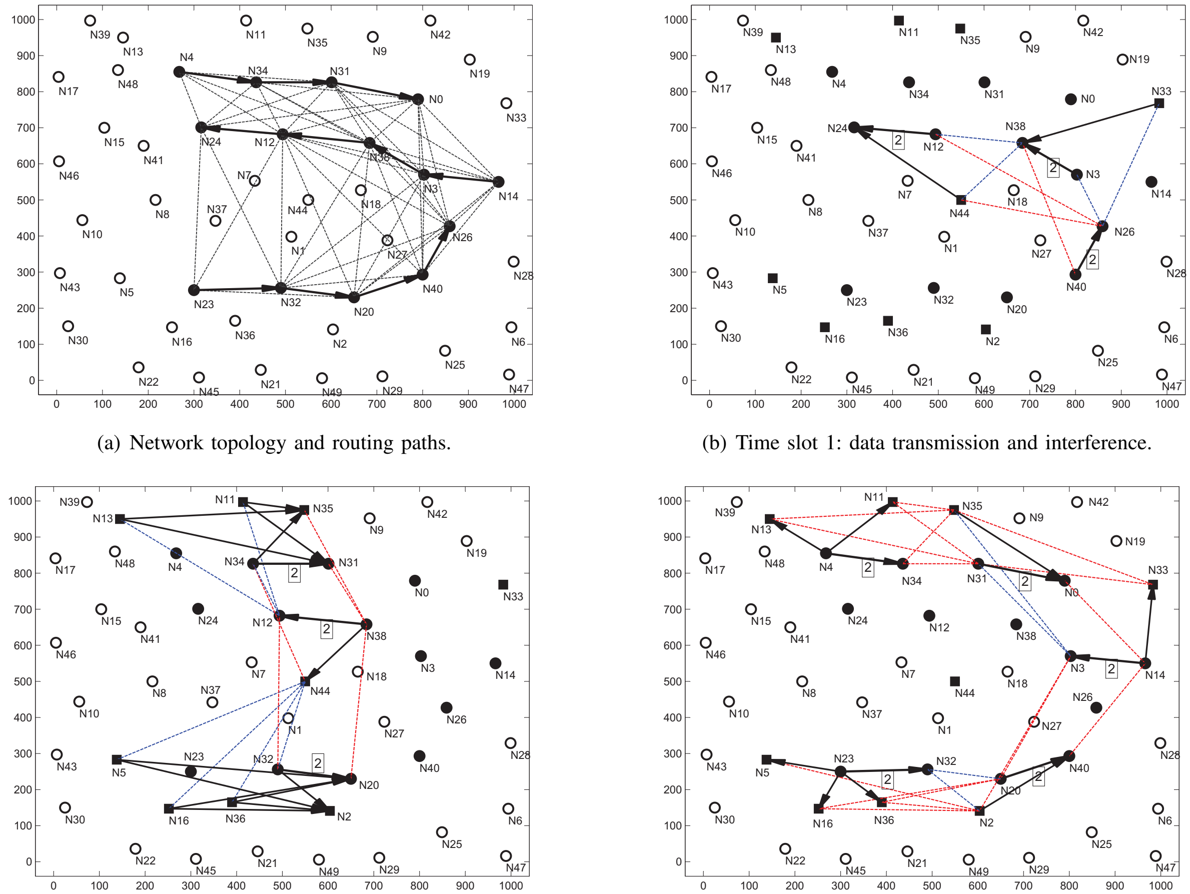
Fig. 7. A case study of IN in a multi-hop network where each node has a single antenna. Solid squares represent selected assisting nodes. Solid and dashed arrows represents data transmissions and interference, respectively.

categories of solid arrow links in the figures. The solid arrow line connecting two solid circles represents an active link along the routing paths, which we call *routing link*. The solid arrow line associated with at least one assisting node represents the data transmission for assisting node(s), which we call *assisting link*. In particular, the boxed number beneath a routing link represents the number of data streams on the routing link. The dashed slim line in the figures represents interference.

As shown in Fig. 7(b)–(d), there are 5 assisting nodes in the solution obtained by solving OPT-INC: N_{48} is the assisting node for routing node N_{34}; N_{11} and N_{35} are assisting nodes for routing node N_{31}; N_{23} and N_{44} are assisting nodes for routing node N_1. To see how these assisting nodes make IN possible, let's first look at time slot 1 in Fig. 7(b). In this time slot, there are 2 active routing links: (N_{34}, N_{31}) and (N_8, N_{37}), which could not be active in the same time slot if IN were not employed. Since N_{48} is an assisting node for N_{34}, it has the same transmit information as N_{34}. By jointly designing the precoding complex numbers at N_{34} and N_{48}, the interference from N_{34} and N_{48} can be neutralized at N_{37}, making it possible to transport data stream on routing link (N_8, N_{37}). One may wonder why assisting node N_{48} always has the same transmit information as routing node N_{34}. The reason is reflected in Fig. 7(c), where N_{48} and N_{34} are always receiving the same information from N_4. More generally, the IN constraints in our optimization framework ensure that every assisting node is able to successfully receive the same information as the routing node it serves. One may also wonder why assisting nodes N_{11} and N_{35} need to receive the information from N_{34} in Fig. 7(b). This can be explained by Fig. 7(c), where N_{11}, N_{35}, and N_{31} are required to neutralize their interference at both receivers N_{48} and N_{34}.

IN in multi-antenna Network. To see how IN performs in MIMO networks, we study a network instance consisting of 50 nodes as shown in Fig. 8(a), where each node has 4 antennas. There are 3 sessions in this network, with the routing path being shown in the figure. We assume that the interference range is twice of the transmission range and there are 3 time slots for scheduling (for ease of illustration). Since each node is equipped with multiple antennas, the network has IN capabilities on the transmitter side and IC capabilities on the receiver side.

By solving OPT-IC for this network instance, we obtained the optimal objective value of $1/3$. In contrast, by solving OPT-INC for this network instance, we obtained the optimal objective value of $2/3$. This means that the use of IN in this network can increase the session throughput by 100%. The scheduling results obtained by solving OPT-INC are shown in Fig. 8(b)–(d). Similar to Fig. 7, solid circles represent *routing nodes*, solid squares represent *assisting nodes*, and empty circles represent the nodes that are not being scheduled. Further, solid arrow line



(a) Network topology and routing paths.

(b) Time slot 1: data transmission and interference.

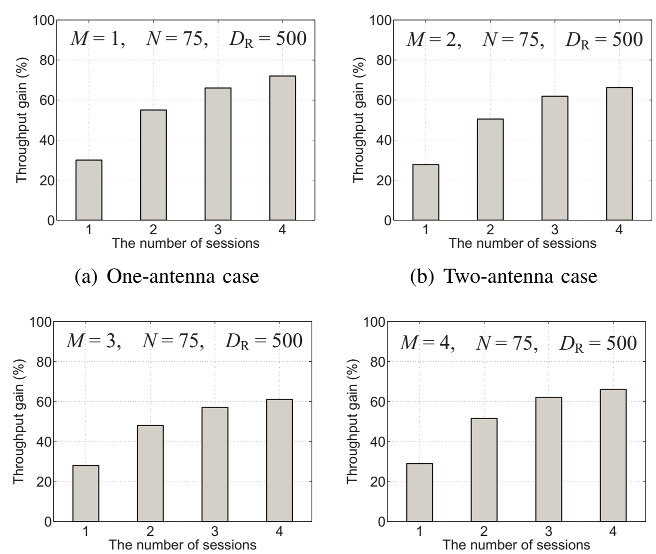
(c) Time slot 2: data transmission and interference.

(d) Time slot 3: data transmission and interference.

Fig. 8. A case study of IN in a multi-hop network where each node has four antennas. Solid squares represent selected assisting nodes. Solid and dashed arrows represents data transmissions and interference, respectively.

represents *routing link* and *assisting link* while dashed slim line represents interference. In particular, a blue dashed line means that this interference is nullified by IN on the transmitter side while a red dashed line means that this interference is nullified by IC on the receiver side.

To see how IN works with IC, let's look at the scheduling results in time slot 1 in Fig. 8(b) as an example. There are 3 active routing links in this time slot: (N_{12}, N_{24}), (N_3, N_{38}), and (N_{40}, N_{26}), each of which has 2 data streams. Consider routing link (N_3, N_{38}). Receive node N_{38} is interfered by nodes N_{12} and N_{44}. Since assisting node N_{44} has the same transmit information as routing node N_{12}, the interference from N_{12} and N_{44} can be nullified at receiving node N_{38} via IN on the transmitter side (and thus marked blue). Receive node N_{38} is also interfered by node N_{40}. Since each node has 4 antennas and each link has 2 data streams, this interference can be nullified by IC at receiving node N_{38} (and thus marked red). As a result, link (N_3, N_{38}) can transport 2 data streams free of interference. Similar IN and IC behaviors can be observed for other nodes in other time slots. We note that if IN were not employed, these 3 routing links could not transport 2 data streams as their IC capabilities are not enough to nullify all the interference.



(a) One-antenna case

(b) Two-antenna case

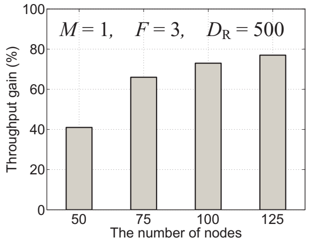
(c) Three-antenna case

(d) Four-antenna case

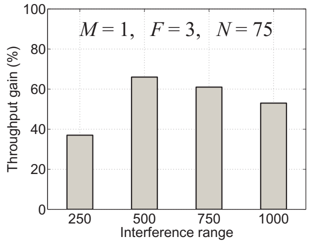
Fig. 9. The average throughput gain of IN versus the number of sessions, where M is the number of antennas, N is the total number of nodes, and D_R is the interference range.

C. Extensive Results

We now present extensive simulation results to show the throughput gain of IN in various networks. For each randomly



(a) Impact of node density



(b) Impact of interference range

Fig. 10. The average throughput gain of IN versus node density and interference range, where M is the number of antenna, N is the total number of nodes, F is the number of sessions, and $D_{\rm R}$ is the interference range.

generated network instance, the throughput gain of IN is obtained by $(\hat{r}^*_{\min} - \tilde{r}^*_{\min})/\tilde{r}^*_{\min}$, where $\hat{r}^*_{\min}$ and $\tilde{r}^*_{\min}$ are the optimal objective values by solving OPT-INC and OPT-IC for this network instance, respectively.

Impact of Traffic Volume. We first study the impact of traffic volume on the throughput gain of IN in the multi-hop network with 75 nodes and 500 interference range. Fig. 9(a) exhibits our simulation results for the network instances with one antenna at each node. The x-axis is the number of sessions in the network, ranging from 1 to 4. The y-axis is the average throughput gain of IN over 100 randomly generated network instances. From the figure we can see the significant throughput gain of IN in the two-, three-, and four-session cases. Furthermore, the throughput gain of IN amplifies when the number of sessions increases. The reason why IN has a relatively smaller gain in the one-session case ($\sim 30\%$) can be explained by the high probability of generating network instances with only one or two links, in which there is no room for performing IN. Another observation of the results in Fig. 9 is that the correlation between the throughput gain of IN and the number of antennas on each node is very weak. This is not surprising, because the throughput gain of IN comes from the participation of the assisting nodes rather than the multiple antennas on each node.

Impact of Node Density. We now study the impact of node density on the throughput gain of IN in the network with 3 sessions and 500 interference range. Fig. 10(a) presents our simulation results, where x-axis is the number of nodes in 1000×1000 square area and y-axis is the average throughput gain of IN over 100 network instances. From the figure we can see that the gain of IN increases with the node density. When the number of nodes increases from 50 to 75, there is a big improvement for the gain of IN. This is because the increase of node density brings a considerable new opportunity of IN for the network, thereby significantly improving the session throughput. But when the node density keeps increasing (from 75 to 125), the opportunity of IN saturates and the new room for IN becomes very limited, making the throughput improvement marginal.

Impact of Interference Range. We finally study the impact of interference range on the throughput gain of IN in the network with 75 nodes and 3 sessions. Fig. 10(b) presents our simulation results, where x-axis is the interference range and y-axis is the average throughput gain of IN over 100 network instances. We can see that the throughput gain of IN is not a monotonic function of the interference range. This non-monotonicity can be explained using the two consequences caused by the increase of interference range: (A) the IN capability becomes stronger as more idle nodes get involved in the communication; and (B) the amount of interferences in the network increases. Consequence A tends to increase the throughput while consequence B tends to decrease the throughput. When the interference range is less than 500, the throughput gain of IN increases as the interference range increases. This is because consequence A is more significant than consequence B in this range. When the interference range exceeds 500, the throughput gain of IN decreases as the interference range increases. This is because consequence B is more significant than consequence A when interference range exceeds 500.

V. Conclusions

While most of IN results in the literature are limited to two-hop networks, this paper made a concrete progress in advancing our understanding of IN in the context of large-scale multi-hop (more than two hops) networks. We developed an INC model for a set of one-hop links to characterize IN at their transmitters and IC at their receivers. We proved that as long as the constraints in our INC model are satisfied, there always exist precoding and decoding vectors so that the data streams on each link can be transported free of interference. Based on this INC model, we developed an INC optimization framework for a multi-hop network with a set of sessions. As an application of this framework, we studied a specific network throughput problem of maximizing the minimum end-to-end rate of the sessions. Simulation results show a significant throughput gain of IN in multi-hop networks. Furthermore, the throughput gain of IN increases with the number of nodes and sessions in the network.

Appendix A
Proof of Lemma 1

For ease of exposition, we denote $\mathcal{B}_l$ as a subset of $\mathcal{S}_l$. We prove this lemma by showing that if $|\mathcal{B}_l| \le |\mathcal{T}_l| - 1$, then the interference from the transmitting nodes in $\mathcal{T}_l$ to every receiving node in $\mathcal{B}_l$ can be neutralized through a joint design of their precoding vectors. To do so, we need to show that the following linear equation system has a solution for $n = 1, 2, \cdots, z_l$.

$$\sum_{i \in \mathcal{T}_l} \mathbf{H}_{ji} \mathbf{u}_i^n \neq \mathbf{0}, \qquad j \in \mathcal{R}_l; \tag{21a}$$

$$\sum_{i \in \mathcal{T}_l} \mathbf{H}_{ji} \mathbf{u}_i^n = \mathbf{0}, \qquad j \in \mathcal{B}_l; \tag{21b}$$

where $\mathbf{H}_{ji}$ is a given square matrix and $\mathbf{u}_i^n$ is a vector for design. Note that in our problem setting, $\mathbf{H}_{ji}$ is a nonzero matrix for $j \in \mathcal{R}_l$ and $i \in \mathcal{T}_l$ while $\mathbf{H}_{ji}$ may be a zero matrix for $j \in \mathcal{B}_l$ and $i \in \mathcal{T}_l$.

Given that any two channel matrices are independent of each other, a nonzero solution to the linear equations in (21b) will satisfy the linear equations in (21a) almost surely [23]. This means that we only need to show the existence of a nonzero solution to (21b). For the linear equations in (21b), there are $|\mathcal{B}_l| \cdot M$ linear constraints and $|\mathcal{T}_l| \cdot M$ variables. Since $|\mathcal{B}_l| < |\mathcal{T}_l|$, we know that (21b) has more variables than constraints.

Therefore, there exists a nonzero solution to (21b), which also satisfies (21a) almost surely.

We now propose a Gauss–Jordan elimination algorithm to construct the precoding vectors that satisfy (21b). With a bit abuse of notation, we index the transmitting nodes in $\mathcal{T}_l$ by $i = 1, 2, \cdots, I$ and index the receiving nodes in $\mathcal{B}_l$ by $j = 1, 2, \cdots, J$. By performing row reduction on the linear equations in (21b), we can obtain its reduced row echelon form as follows:

$$\begin{aligned} \mathbf{u}_1^n + \tilde{\mathbf{H}}_{12}\mathbf{u}_2^n + \tilde{\mathbf{H}}_{13}\mathbf{u}_3^n + \cdots + \tilde{\mathbf{H}}_{1(I-1)}\mathbf{u}_{(I-1)}^n + \tilde{\mathbf{H}}_{1I}\mathbf{u}_I^n &= \mathbf{0}, \\ \mathbf{u}_2^n + \tilde{\mathbf{H}}_{13}\mathbf{u}_3^n + \cdots + \tilde{\mathbf{H}}_{2(I-1)}\mathbf{u}_{(I-1)}^n + \tilde{\mathbf{H}}_{2I}\mathbf{u}_I^n &= \mathbf{0}, \\ \cdots \\ \mathbf{u}_{(I-1)}^n + \tilde{\mathbf{H}}_{JI}\mathbf{u}_I^n &= \mathbf{0}, \end{aligned} \tag{22}$$

where $\tilde{\mathbf{H}}_{ji}$ can be obtained by row operations. Note that $\tilde{\mathbf{H}}_{ji}$ may represent a zero matrix since it is the *reduced* row echelon form. We keep $\tilde{\mathbf{H}}_{ji}$ here for notational simplicity.

In the reduced row echelon form, if a vector is a leading vector with coefficient $\mathbf{1}$ for an equation, then it is a basic vector; otherwise, it is a free vector [35, Chapter 2]. Given that $|\mathcal{B}_l| < |\mathcal{T}_l|$, there exists at least one free vector in the reduced row echelon form. Denote $\mathcal{G}$ as the set of basic vectors and $\mathcal{H}$ as the set of free vectors. Then, the (precoding) vectors that satisfy (21b) can be constructed as follows:

$$\mathbf{u}_i^n = \begin{cases} \mathbf{u}_{\text{ref}}^n, & \text{for } \mathbf{u}_i^n \in \mathcal{H}, \\ -\sum\limits_{k=i+1}^{I} \tilde{\mathbf{H}}_{ik}\mathbf{u}_k^n, & \text{for } \mathbf{u}_i^n \in \mathcal{G}, \end{cases} \tag{23}$$

for $n = 1, 2, \cdots, z_l$, where $\{\mathbf{u}_{\text{ref}}^1, \cdots, \mathbf{u}_{\text{ref}}^M\}$ is a set of linearly independent nonzero vectors.

It is worth pointing out that in (23), the basic vector may be constructed to a zero vector, but the free vectors are always nonzero vector. Furthermore, if every receiving node in $\mathcal{B}_l$ is interfered by all the transmitting nodes in $\mathcal{T}_l$, then it can be verified that all the vectors constructed in (23) are nonzero vectors. This completes the proof.

Appendix B
Proof of Lemma 2

We prove this lemma by showing that at receiving node $j \in \mathcal{R}_l$, if (6) is satisfied, there exists a decoding vector $\mathbf{v}_j^m$ that meets (3) for $m = 1, 2, \cdots, z_l$. Consider the linear equations in (3), where channel $\mathbf{H}_{ji}$ is a given matrix, precoding vector $\mathbf{u}_i^n$ has already been constructed by (23), and decoding vector $\mathbf{v}_j^m$ has M complex variables. Now let's count the number of linear constraints in (3). Since (3a)–(3b) have z_l constraints and (3c) has $\sum_{k\in\mathcal{K}_j}(1-\beta_{k,j}) \cdot z_k$ constraints, the total number of nontrivial constraints in (3) is $z_l + \sum_{k\in\mathcal{K}_j}(1-\beta_{k,j}) \cdot z_k$, which is less than or equal to the number of variables in (3). Therefore, there always exists a solution to (3) if we can show that desired data stream direction $\sum_{i\in\mathcal{T}_l}\mathbf{H}_{ji}\mathbf{u}_i^m$ in (3a) is linear independent of intra-link interference directions $\cup_{n=1\cdots z_l}^{n\neq m}\{\sum_{i\in\mathcal{T}_l}\mathbf{H}_{ji}\mathbf{u}_i^n\}$ in (3b) and inter-link interference directions $\cup_{k\in\mathcal{K}_j}^{n=1\cdots z_k}\{\sum_{i\in\mathcal{T}_k}\mathbf{H}_{ji}\mathbf{u}_i^n\}$ in (3c).

Since any two channel matrices are independent of each other, it is not difficult to see that the desired data stream direction is linearly independent of the inter-link interference directions as they go through different channels. We then focus our argument on the intra-link interference. Based on (23), our precoding vector construction at transmitting node $i \in \mathcal{T}_l$ can be summarized by $\mathbf{u}_i^n = \mathbf{G}_i\mathbf{u}_{\text{ref}}^n$, where $\mathbf{G}_i$ is a $M \times M$ transformation matrix operation and it is independent of parameter n. Then we have

$$\begin{aligned} \dim\Big(\bigcup_{n=1}^{z_l}\big\{\sum_{i\in\mathcal{T}_l}\mathbf{H}_{ji}\mathbf{u}_i^n\big\}\Big) &= \dim\Big(\bigcup_{n=1}^{z_l}\big\{\sum_{i\in\mathcal{T}_l}\mathbf{H}_{ji}\mathbf{G}_i\mathbf{u}_{\text{ref}}^n\big\}\Big) \\ &\overset{(a)}{=} \dim\Big(\cup_{n=1}^{z_l}\big\{\mathbf{u}_{\text{ref}}^n\big\}\Big) \overset{(b)}{=} z_l, \end{aligned} \tag{24}$$

where (a) follows from the assumption that each channel matrix has full rank and (b) follows from our construction that $\{\mathbf{u}_{\text{ref}}^1, \cdots, \mathbf{u}_{\text{ref}}^M\}$ is a set of linearly independent vectors. (24) indicates that the desired data stream direction is also linearly independent of the intra-link interference directions. Therefore, there always exists a solution to (3) for $m = 1, 2, \cdots, z_l$. This complete the proof.

Appendix C
Problem Formulation without IN

As a performance benchmark, we formulate the same network throughput maximization problem but without employing IN. Specifically, we explore the throughput limits of the sessions in the network when employing IC at each receiving node (if it has multiple antennas). Similar to OPT-INC, we formulate this throughput maximization problem to an optimization problem by developing necessary constraints and then solve it using off-the-shelf optimization solver.

IC Constraints. Referring to Fig. 6, we develop the IC constraints in time slot t by considering two cases. For the first case, we consider an active link $l \in \mathcal{L}$ in the network, i.e., $\alpha_l(t) = 1$. Then receiving node $\text{Rx}(l)$ receives desired data streams from transmitting node $\text{Tx}(l)$ and interfering streams from the unintended transmitting nodes within its interference range. To ensure the success of decoding its desired data streams free of interference at receiving node $\text{Rx}(l)$, we have the following constraints:

$$z_l(t) + \sum_{k\in\mathcal{K}_{\text{Rx}(l)}} z_k(t) \leq M,$$

where $\mathcal{K}_{\text{Rx}(l)}$ is the set of links whose transmitting nodes are within the interference range of receiving node $\text{Rx}(l)$.

For the second case, we consider an inactive link $l \in \mathcal{L}$ in the network, i.e., $\alpha_l(t) = 0$. Since receiving node $\text{Rx}(l)$ does not need to decode any desired data streams, there is not IC requirement at this node. By introducing a large enough constant, we can combine these two cases by the following constraints:

$$z_l(t) + \sum_{k\in\mathcal{K}_{\text{Rx}(l)}} z_k(t) \leq M + (1-\alpha_l(t)) \cdot B, \qquad 1 \leq \mathcal{L}, 1 \leq t \leq T. \tag{25}$$

Following a similar approach of formulating OPT-INC, we can formulate the throughput maximization problem (with IC only) as follows:

OPT-IC: Max	$r_{\min}$	
S.t.	Link activity constraints: (14), (15);	
	IC constraints: (25);	
	Link rate constraints: (16);	
	Min rate constraints: (17);	

where M, T, and B are constants (not optimization variables); $\alpha_l(t)$ is binary optimization variable, $z_l(t)$ is non-negative optimization integer, $r_{\min}$, $r(f)$, and $r_l(f)$ are non-negative continuous optimization variables.

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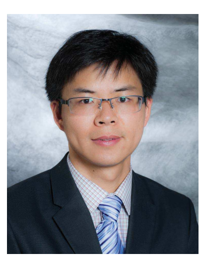

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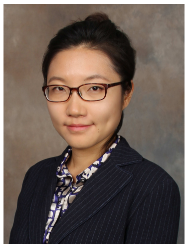

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