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On the integration of SIC and MIMO DoF for interference cancellation in wireless networks

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Abstract Recent advances in MIMO degree-of-freedom (DoF) models allowed MIMO research to penetrate the networking community. Independent from MIMO, successive interference cancellation (SIC) is a powerful physical layer technique used in multi-user detection. Based on the understanding of the strengths and weaknesses of MIMO DoF and SIC, we propose to have DoF-based interference cancellation (IC) and SIC help each other so that (i) precious DoF resources can be conserved through the use of SIC and (ii) the stringent SINR threshold criteria can be met through the use of DoF-based IC. In this paper, we develop the necessary mathematical models to realize the two ideas in a multi-hop wireless network. Together with scheduling and routing constraints, we develop a cross-layer optimization framework with joint DoF IC and SIC. By applying the framework on a throughput maximization problem, we find that SIC and DoF IC can indeed work in harmony and achieve the two ideas that we propose.

Keywords SIC · MIMO · DoF · Multi-hop · Interference cancellation · Wireless network

1 Introduction

MIMO has been widely adopted by the communications industry and the research community due to its capabilities of spatial multiplexing (SM) gain, interference cancellation (IC), and diversity gain. Until recently, research on MIMO has been limited at the physical (PHY) layer or for single-hop communications due to the lack of tractable MIMO models. Recent advances in MIMO degree-of-freedom (DoF) models removed this stagnation and allowed MIMO research to penetrate the networking community [1, 3, 12, 14, 23, 26]. The concept of DoF was originally defined to represent the multiplexing gain of a MIMO channel in the information theory (IT) community. This DoF concept was then extended by the networking community to characterize a node's spatial freedom provided by its multiple antennas. Under a DoF model, only simple numerical computation is needed to account for a node's resource allocation for SM and IC. The basic idea of DoF-based MIMO models is as follows [26]: (i) The number of available DoFs at a node is equal to the number of its antennas. A node may use its DoFs for either SM or IC. (ii) For SM, both transmit and receive nodes need to consume DoFs. For each data stream, both the transmit and receive nodes need to consume one DoF. (iii) For IC, either the transmit node or the receive node may consume DoFs. Clearly, under a DoF model, the number of available DoFs at a node is considered a precious recourse and must be utilized efficiently. In particular, when a node uses its DoFs for IC, its remaining DoFs for SM will be reduced. Therefore, there is a critical need to conserve DoFs for IC if one wishes to maximize the number of DoFs for SM.

Independent from MIMO, successive interference cancellation (SIC) is a powerful physical layer technique used in multi-user detection [14, 32]. It allows a receiver to take multiple interfering signals from different transmitters and decode each signal iteratively. In its simplest form, a receiver may decode the strongest signal from the aggregate received signals and considers all the other

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interfering signals as noise. If the strongest signal meets a SINR threshold, then it can be decoded successfully. Then the receiver subtracts it from the aggregate signals and repeats the process for the second strongest signal and so forth, until the desired signal is decoded successfully. Current research on exploiting SIC for single-antenna nodes in a wireless network can be found in [4, 9–11, 15, 17–21, 33, 36]. SIC has also been exploited in MIMO for point-to-point and multi-user communications (see related work in Sect. 6). Although attractive, SIC does have its limitations. Most notably, if the SINR threshold cannot be satisfied at any stage, the process cannot continue and the desired signal cannot be decoded.

Recognizing the strengths and weaknesses of MIMO DoF IC and SIC, we propose to have DoF IC and SIC help each other based on the following two ideas: (i) Since MIMO DoFs represent precious resources at the node, we shall exploit SIC for IC to conserve DoF resources; (ii) Since at a particular stage, SIC may fail to meet SINR threshold to successfully decode the signal, we may exploit MIMO DoF IC capability to selectively cancel a subset of interfering signals so that SIC can be successful at a receiver. In other words, we want to exploit SIC to conserve DoF resources while at the same time have DoF IC resolve the potential SINR barrier problem that SIC may encounter. The goal of this paper is to develop the mathematical models to realize these two ideas in a multi-hop wireless network.

The main contributions of this paper are as follows:

- This is the first paper that incorporates SIC under the MIMO DoF model with the goals of exploiting SIC for DoF resource conservation and employing DoF IC to selectively cancel a subset of interfering signals so that SIC can be successful to decode the desired signal. Note that our use of SIC in MIMO differs from SIC in multi-user MIMO communication (see Sect. 6) where there is no concern of exploiting MIMO's IC capability to remove the SINR threshold barrier that SIC may encounter.
- This is also the first paper that studies SIC under the MIMO DoF model for a multi-hop wireless network. In a multi-hop MIMO network, one needs to address the scheduling and flow routing problem. Coupling of both routing and scheduling with DoF allocation and SIC is clearly a nontrivial problem. Note that this problem differs from SIC in multi-user MIMO communication (see Sect. 6) where there is no concern of scheduling and routing.
- We propose a MIMO DoF IC scheme that incorporates SIC. Based on this scheme, we develop a model for DoF allocation at a transmitter and a receiver that incorporates SIC. We also develop a sequential SIC model when DoF IC is employed to cancel a subset of interfering signals that may hinder SIC from meeting its SINR decoding threshold. Both of these two models are developed for a multi-hop wireless network. Together with other scheduling and routing constraints, we develop an optimization framework for joint DoF IC and SIC in a multi-hop MIMO network.
- Through an application of the framework on a throughput maximization problem, we find that SIC and MIMO DoF IC can indeed work in harmony and help each other as we intended. When compared to a MIMO network where SIC is not used, there is a significant increase in throughput.

The remainder of this paper is organized as follows. In Sect. 2, we review a MIMO DoF model that we shall employ in this study. We also review the basic concept of SIC for the single-antenna case. Subsequently, we describe the motivation and basic idea of this paper, as well as the technical challenges that we will encounter. In Sect. 3, we extend the single-antenna SIC model to MIMO with multiple data streams from each user. In Sect. 4, we propose our MIMO SIC scheme and develop SIC in the MIMO DoF model for a multi-hop network, which is the core of this paper. In Sect. 5, we present a case study for a throughput maximization problem along with a performance comparison to the same problem when SIC is not used. Section 6 reviews related work. Section 7 concludes this paper.

2 SIC in MIMO: background and motivation

In this section, we first review a MIMO IC model that we will use in this study. Then we review the basic concept of SIC for single-antenna case. Based on this background, we motivate our idea of how SIC may be exploited to conserve DoF resources for MIMO IC.

2.1 MIMO DoF model

For notation, we denote vectors and matrices in bold-face lower and upper case letters, respectively. For matrix $\mathbf{G}$, $\mathbf{G}^T$ and $\mathbf{G}^\dagger$ denote transpose and Hermitian operations, respectively. $\|\mathbf{g}\|$ denotes the norm of vector $\mathbf{g}$. $\mathbf{g}^q$ denotes the q-th column of matrix $\mathbf{G}$. A diagonal matrix is denoted as $\mathrm{diag}\{\ldots\}$. Table 1 shows the notation used in this paper.

Consider a multi-hop MIMO network consisting of a set of nodes $\mathcal{N}$ which has N elements. Each node is assumed to have M antennas. Suppose that there are L possible links in the network. Denote $\mathrm{Tx}(l)$ and $\mathrm{Rx}(l)$ as the transmit and

Table 1 Notation

Symbol	Definition
M	Number of antennas at node each node
$\mathbf{H}_{ki}$	Channel fading matrix between transmitter k and receiver i
L_{ki}	Path-loss between node k and receiver node i
p_j	Transmit power of data streams from node j
$\mathbf{U}_k$	Precoding vector at transmitter node k
$\mathbf{x}_k$	Symbol vector at node k
$\mathbf{A}_k$	Diagonal transmit amplitude matrix at transmit node k
$\mathbf{n}$	Gaussian noise vector with power N_0
N_0	Noise power
$\mathbf{V}_{ji}$	Receive matrix to decode signal from node j at node i
$\mathbf{y}_{ji}$	Received signal vector at node i from node j
$\mathcal{I}_i$	Set of nodes within node i's interference range
L	Total number of links in the network
β	SIC SINR threshold
$\mathcal{L}_i^{\text{in}}$	Set of incoming links at node i
$\mathcal{L}_i^{\text{out}}$	Set of outgoing links at node i
N	Number of nodes in the network
$\mathcal{N}$	Set of nodes in the network
$\text{Rx}(l)$	Receiver of link l
$\text{Tx}(l)$	Transmitter of link l
$r(f)$	Rate of session f
$r_l(f)$	Rate for session f on link l
$w(f)$	Weight of session f
$x_i[t]$	Indicator variable to show if node i is a transmitter in time slot t
$y_i[t]$	Indicator variable to show if node i is a receiver in time slot t
$z_l(t)$	Number of data streams on link l in time slot t
$\pi_i[t]$	Node i's position in a node level ordering $\pi[t]$
$\theta_{ji}[t]$	A binary variable to indicate whether node$i$is placed after node j in $\pi[t]$
$\eta_{ji}[t]$	A binary variable to indicate interference from node$j$ is canceled at i by SIC in time slot t
$\gamma_{ji}[t]$	A binary variable to indicate interference from node j is canceled at i by MIMO-IC in time slot t
$\lambda_{ji}[t]$	A binary variable to indicate intended transmit node j at least transmits one data stream to receive node i in time slot t

receive nodes of link l, $1 \leq l \leq L$. We consider a time-slotted scheduling, where a time frame consists of T time slots. Depending on link scheduling, a subset of links will be active in time slot t, $1 \leq t \leq T$.

The basic idea of DoF-based MIMO models is as follows [26]: (i) The number of available DoFs at a node is equal to the number of its antennas. (ii) For SM, both transmit and receive nodes need to consume DoFs. For each data stream, both the transmit and receive nodes need to consume one DoF. (iii) For IC, either the transmit node or the receive node may consume DoFs. If a transmit node A is to cancel its interference to a receive node B, then it needs to consume x DoFs, where x is the number of DoFs that is being sent to node B (via SM) from B's intended transmitter. Likewise, if a receive node B is to cancel the interference from a transmit node A, then it needs to consume y DoFs, where y is the number of DoFs that is being sent by transmit node A (via SM) to A's intended receiver. (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.

Half-Duplex constraint. Although there has been significant advance on full duplex for single antenna node, there remain significant challenges to have a practical design for full duplex on a MIMO node. Therefore, we assume half duplex on a MIMO node in this paper. Denote $x_i[t]$ as a binary variable to indicate whether node $i \in \mathcal{N}$ is transmitting in time slot t, i.e., $x_i[t] = 1$ if node i is a transmitter in time slot t and 0 otherwise. Similarly, denote $y_i[t]$ as a binary variable to indicate whether node $i \in \mathcal{N}$ is receiving in time slot t, i.e., $y_i[t] = 1$ if node i is a receiver in time slot t and 0 otherwise. For half-duplex, we have the following constraint:

$$x_i[t] + y_i[t] \le 1, \quad (1 \le i \le N, 1 \le t \le T) . \tag{1}$$

Node's SM constraints. Denote $\mathcal{L}_i^{\text{in}}$ and $\mathcal{L}_i^{\text{out}}$ as the set of potential incoming and outgoing links at node i, respectively. Denote $z_{(l)}[t]$ as the number of data streams over link l. If node i is not a transmitter, then we have $\sum_{l \in \mathcal{L}_i^{\text{out}}} z_{(l)}[t] = 0$. Otherwise, the total number of outgoing streams should be positive and lesser than the number of antennas, i.e., $1 \le \sum_{l \in \mathcal{L}_i^{\text{out}}} z_{(l)}[t] \le M$. These two cases can be expressed in a compact form as follows:

$$x_i[t] \le \sum_{l \in \mathcal{L}_i^{\text{out}}} z_{(l)}[t] \le M x_i[t], \quad (1 \le i \le N, 1 \le t \le T) . \tag{2}$$

Similarly, depending on whether node i is an active receiver, we have the following constraint:

$$y_i[t] \le \sum_{l \in \mathcal{L}_i^{\text{in}}} z_{(l)}[t] \le M y_i[t], \quad (1 \le i \le N, 1 \le t \le T) . \tag{3}$$

Ordering constraint. In a multi-hop MIMO network, to avoid duplication in IC while ensuring feasibility of DoF allocation, Shi et al. [26] introduced a novel IC scheme among the nodes based on a node ordering concept. Under this scheme, all nodes in the network are put into a logical list with the position of the node in the list representing its order. Specifically, denote $\pi[t]$ as an ordered list of nodes in the network in time slot t and denote $\pi_i[t]$ as the position of node $i \in \mathcal{N}$ in $\pi[t]$. Then we have:

$$1 \le \pi_i[t] \le N, \quad (1 \le i \le N, 1 \le t \le T) . \tag{4}$$

To model the relative ordering between any two nodes i and j in $\pi[t]$, we define an indicator variable $\theta_{ji}[t]$ as follows:

$$\theta_{ji}[t] = \begin{cases} 1 & \text{if node } j \text{ is before node } i \text{ in } \pi[t], \\ 0 & \text{otherwise.} \end{cases}$$

Denote $\mathcal{I}_i$ as the set of nodes that are located within the interference range of transmitter i. Then the ordering relationship between any two nodes in the network can be represented by the following mathematical programming constraints [26]:

$$\pi_i[t] - N \cdot \theta_{ji}[t] + 1 \le \pi_j[t] \le \pi_i[t] - N \cdot \theta_{ji}[t] + N - 1, \\ (1 \le i \le N, j \in \mathcal{I}_i, 1 \le t \le T) . \tag{5}$$

Based on $\pi[t]$, each node in this list has the following responsibility in IC:

- *Transmit node.* If this node is a transmit node, then it 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 receive nodes after itself will be canceled by those receive nodes later. The number of DoFs consumed at this transmit node for IC is equal to the total number of desired data streams received by those receive nodes.
- *Receive node.* If this node is a receive node, then it 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 transmit nodes after this node will be canceled by those transmit nodes later. The number of DoFs consumed at this receive node for IC is equal to the total number of data streams transmitted by those transmit nodes.

The above IC rules can also be cast into mathematical programming constraints. Then the DoF constraint at a transmit node and a receive node for $(1 \le i \le N, 1 \le t \le T)$ can be written as follows [26]:

$$\sum_{l \in \mathcal{L}_i^{\text{out}}} z_{(l)}[t] + \sum_{j \in \mathcal{I}_i} \theta_{ji}[t] \sum_{k \in \mathcal{L}_j^{\text{in}}}^{\text{Tx}(k) \ne i} z_{(k)}[t] \le M x_i[t] + (1 - x_i[t]) B_i, \tag{6}$$

$$\sum_{k \in \mathcal{L}_i^{\text{in}}} z_{(k)}[t] + \sum_{j \in \mathcal{I}_i} \theta_{ji}[t] \sum_{l \in \mathcal{L}_j^{\text{out}}}^{\text{Rx}(l) \ne i} z_{(l)}[t] \le M \cdot y_i[t] + (1 - y_i[t]) B_i, \tag{7}$$

where B_i is a large constant and is no small than $\sum_{j \in \mathcal{I}_i} \theta_{ji}[t] \sum_{k \in \mathcal{L}_j^{\text{in}}}^{\text{Tx}(k) \ne i} z_{(k)}[t]$ and $\sum_{j \in \mathcal{I}_i} \theta_{ji}[t] \sum_{l \in \mathcal{L}_j^{\text{out}}}^{\text{Rx}(l) \ne i} z_{(l)}[t]$. For example, we can set $B_i = M \cdot |\mathcal{I}_i|$.

2.2 SIC under single-antenna node

SIC allows a receiver to take multiple interfering signals from different transmitters (see Fig. 1) and decode each one of them iteratively [32]. As shown in Fig. 2, for the composite received signal, the receiver attempts to decode the strongest signal and considers all other signals as interference. If the strongest signal is decoded successfully (upon meeting a certain SINR threshold), the receiver subtracts it from the original composite signal and then starts to decode the second strongest signal and so forth. The process continues until all signals are successfully decoded, or the SINR threshold cannot be satisfied at certain stage.

Without loss of generality, suppose that the power levels of the signals from the K transmitters received at node i are in nondecreasing order as $P_{1i} \le P_{2i} \le \ldots \le P_{Ki}$. Receive node i tries to decode signal from node n in the order of $K, K-1, \ldots n$. Then, the signal with received power P_{ni} can be decoded successfully if and only if

$$\begin{aligned}
&\text{Step 1 } \frac{P_{Ki}}{\sum_{l=1}^{K-1} P_{ki} + \sigma^2} \ge \beta, \\
&\text{Step 2 } \frac{P_{(K-1)i}}{\sum_{l=1}^{K-2} P_{ki} + \sigma^2} \ge \beta, \\
&\vdots \\
&\text{Step } (K-n+1) \frac{P_{ni}}{\sum_{l=1}^{n-1} P_{ki} + \sigma^2} \ge \beta, .
\end{aligned} \tag{8}$$

2.3 Motivation and basic idea

The above background on MIMO IC model and SIC model motivates us to propose the following ideas.

- *DoF IC to remove barrier signal in SIC.* For SIC, at any stage when the SINR threshold is no longer satisfied at a receiver, SIC will fail to continue. This is the limitation of SIC. But with MIMO IC capability, we could use a MIMO DoF (either at this receiver or the transmitter of this signal) to cancel this particular interference without decoding it. After this impeding interfering signal is removed, SIC can resume its decoding of the remaining signals from other transmitters. As an example, in (8), suppose in Step 1, the SINR threshold β for P_{Ki} is not satisfied. With DoF IC, either the transmitter K or receiver i can use 1 DoF to cancel this interfering signal, thereby allowing SIC to continue to work on the remaining signals. At any step when the SINR threshold β is no longer satisfied for some transmitter, we can apply the same DoF IC technique and remove this barrier signal, until the desired signal n is decoded successfully.

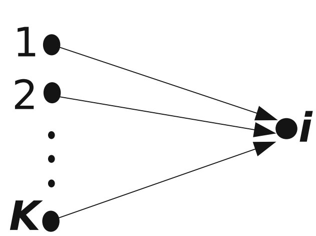

Fig. 1 A receiver with K concurrent transmitters

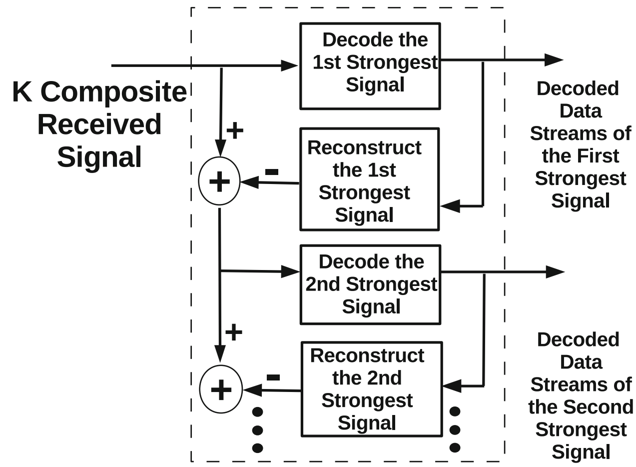

Fig. 2 A schematic of SIC

- *SIC to conserve DoFs in IC.* Likewise, before we expend precious DoFs for IC at a receive node, we could exploit SIC to its fullest extent at this receive node (to decode as many concurrent signals as possible). This exploitation of SIC capability will help conserve precious DoFs at the node. As an example, consider Fig. 3, where (T_1, R_1) and (T_2, R_2) are two pairs of transmitting and receive nodes in the network. Assume that all nodes share the same channel and are equipped with 4 antennas (with DoFs being 4 at each node). Suppose that both T_1 and T_2 wish to transmit 2 data streams to R_1 and R_2, respectively. For an ordered node list, say $\pi = (T_1, R_1, T_2, R_2)$, we need to expend 2, 2, 4, and 4 DoFs on T_1, R_1, T_2, R_2, respectively. Now, suppose that we employ SIC decoder at both receivers R_1 and R_2. Then it may be possible that the interference from T_2 be handled by SIC at R_1, allowing T_2 to save 2 DoFs for canceling its interference to R_1. Likewise, it may be possible that the interference from T_1 be handled by SIC at R_2, allowing R_2 to save 2 DoFs for canceling the interference from T_1. That is, when SIC is successful at R_1 and R_2, we only need to expend 2 DoFs on T_1, R_1, T_2, R_2, respectively.

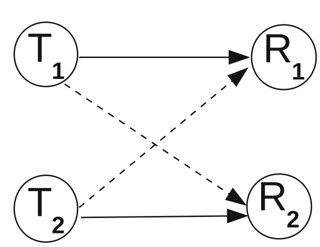

Fig. 3 A simple example illustrating how SIC can help conserve DoFs for IC

The above two ideas and examples illustrate the benefits of using DoF IC and SIC jointly for interference management. The goal of this paper is to establish its theoretical foundation. To do so, it is important to understand the underlying technical challenges.

2.4 Technical challenges

Although there has been active research on the MIMO DoF model (e.g. [1, 3, 12, 23, 26, 28, 38]) and SIC in wireless networks (e.g. [4, 11, 15, 17, 20, 32, 33]), they are mostly done independently, without exploiting the potential mutual benefits when used jointly to overcome each other's limitations. Although MIMO and SIC have been studied in the context of MIMO-MMSE-SIC in both the information theory (IT) and communications (COMM) communities (see, e.g., [2, 6, 7, 30]), SIC is not explicitly considered as a technique to conserve DoFs in IC; likewise, neither are DoFs explicitly used to remove large interference signal to meet SINR threshold. As a result, there is hardly any result in the literature addressing the ideas that we are proposing in this paper — bundling MIMO DoF and SIC to overcome each other's limitation in IC.

The main technical challenges that we need to address are as follows:

- The calculation of SINR at each stage of SIC requires received power from both intended and unintended transmitters. Such information is given explicitly in a single antenna SIC model. However, MIMO DoF model, which is a protocol model by nature, does not explicitly offer such receive power information. As a result, it is necessary to dig into the MIMO matrix model (inherently a physical model) and extract relevant parameters for power calculation. Such an intertwined approach in studying joint SIC and MIMO DoF models is not trivial.
- Once we know how to calculate SINR for SIC with MIMO, the next challenge is how to model SIC capability into MIMO's DoF constraints (at both transmitter and receiver). Coupling SIC with MIMO IC in mathematical programming is intrinsically complex and would call for effective reformulation techniques to ensure the tractability of the final formulation. Again, this is a challenging problem.
- Finally, instead of limiting ourselves to point-to-point or single-hop communications, we are interested in studying joint SIC and MIMO IC in the general context of a multi-hop wireless network. In a multi-hop environment, a MIMO-SIC scheme is also coupled with the upper layer scheduling and routing algorithms. These upper layer algorithms determine, in each time slot, the set of transmitters, the set of receivers, the set of links, and the number of data streams. The joint DoF-SIC scheme shall again be jointly designed with these upper layer scheduling and routing algorithms. As expected, such a mathematical formulation is intrinsically complex and usually results in a challenging problem.

3 SIC in MIMO

In Sects. 3 and 4, we address the above problems. In this section, we extend SIC model in (8) for single-antenna system to MIMO. In the next section, we present a mathematical modeling of employing SIC in the MIMO DoF model.

3.1 Calculating SINR in MIMO

Consider the multiuser MIMO model in Fig. 4, where there are multiple transmit nodes and one receive node. We assume that nodes are symbol synchronous and each node $j \in \mathcal{I}_i$ may transmit up to M data streams. For a given symbol time, the data streams from transmit node j are denoted by a vector of symbols $\mathbf{x}_j = [x_j^1, x_j^2, \ldots, x_j^M]^T$. We assume if transmit node j has fewer data streams than M, then the remaining elements of $\mathbf{x}_j$ are filled with zeros.

The complex MIMO signal from transmitter j received at node i (after passing through a linear receiver) can be written as:

$$\mathbf{y}_{ji} = L_{ji}\mathbf{V}_{ji}^{\dagger}\mathbf{H}_{ji}^{\dagger}\mathbf{U}_j\mathbf{A}_j\mathbf{x}_j + \sum_{k\in\mathcal{I}_i, k\neq j} L_{ki}\mathbf{V}_{ji}^{\dagger}\mathbf{H}_{ki}^{\dagger}\mathbf{U}_k\mathbf{A}_k\mathbf{x}_k + \mathbf{V}_{ji}^{\dagger}\mathbf{n}_i \ , \quad (9)$$

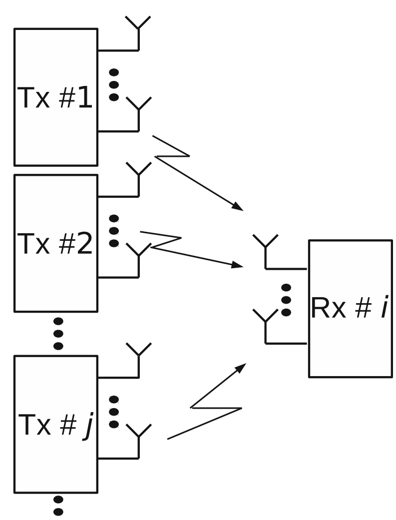

Fig. 4 System configuration of a multiuser MIMO system

where $\mathbf{H}_{ki} \in \mathbb{C}^{M\times M}$ is the channel matrix between transmit node k and receive node i and is normalized to mean power 1, L_{ji} is the path-loss factor between j and i, $\mathbf{U}_k \in \mathbb{C}^{M\times M}$ is the unitary transmit precoding matrix at transmit node k, $\mathbf{A}_j \in \mathbb{R}^{M\times M}$, $\mathbf{A}_j = \mathrm{diag}\{\sqrt{p_j}, \sqrt{p_j}, \ldots, \sqrt{p_j}\}$ is the real-valued diagonal transmit amplitude matrix. $\mathbf{V}_{ji} \in \mathbb{C}^{M\times M}$ is the unitary receive matrix at node i for decoding data streams from node j, and $\mathbf{n}_i \in \mathbb{C}^{M\times 1}$ is the white Gaussian noise vector with variance N_0 per element.

Depending on the transmit precoder and receiver matrices, SINR can be calculated [29, 35]. Assuming data streams are uncorrelated, SINR for the q-th element in $\mathbf{y}_{ji}$ is:

$$\mathrm{SINR}^q_{ji} = \frac{p_j \cdot L^2_{ji} \|\mathbf{v}^{q\dagger}_{ji} \mathbf{H}^{\dagger}_{ji} \mathbf{u}^q_j\|^2}{\sum_{k\in\mathcal{I}_i, k\neq j} p_k L^2_{ki} \|\mathbf{v}^{q\dagger}_{ji} \mathbf{H}^{\dagger}_{ki} \mathbf{U}_k\|^2 + N_0 \|\mathbf{v}^q_{ji}\|^2} .$$

Since $\mathbf{V}_{ji}$ is a unitary matrix, we have $\|\mathbf{v}^q_{ji}\|^2 = 1$. Therefore,

$$\mathrm{SINR}^q_{ji} = \frac{p_j \cdot L^2_{ji} \|\mathbf{v}^{q\dagger}_{ji} \mathbf{H}^{\dagger}_{ji} \mathbf{u}^q_j\|^2}{\sum_{k\in\mathcal{I}_i, k\neq j} p_k L^2_{ki} \|\mathbf{v}^{q\dagger}_{ji} \mathbf{H}^{\dagger}_{ki} \mathbf{U}_k\|^2 + N_0} . \tag{10}$$

3.2 Sequential constraints for MIMO-SIC

In (8), we showed a mathematical model for SIC in a single-antenna system. For MIMO, there are usually multiple data streams from a transmit node. Performing SIC at data stream level across different transmit nodes is not compatible to the MIMO DoF model, as the latter is intrinsically a node-based model. Instead, we choose to decode *aggregate* data streams on a per transmit node level in this paper. That is, we use the minimum SINR among all data streams from the same transmitter as the worst-case aggregate SINR for this transmit node. Note that there is no interference among data streams from node j to node i due to SM. Thus, if the worst-case (with the smallest SINR) data stream from node j is decodable, all other data streams from node j must also be decodable. Therefore, all data streams from transmit node j are decodable at receive node i if

$$\frac{p_j \cdot L^2_{ji} \cdot \min_q \|\mathbf{v}^{q\dagger}_{ji} \mathbf{H}^{\dagger}_{ji} \mathbf{u}^q_j\|^2}{\sum_{k\in\mathcal{I}_i, k\neq j} p_k L^2_{ki} \cdot \max_q \|\mathbf{v}^{q\dagger}_{ji} \mathbf{H}^{\dagger}_{ki} \mathbf{U}_k\|^2 + N_0} \geq \beta . \tag{11}$$

Denote $C_{ji} = \min_q \|\mathbf{v}^{q\dagger}_{ji} \mathbf{H}^{\dagger}_{ji} \mathbf{u}^q_j\|^2$ and $D_{jki} = \max_q \|\mathbf{v}^{q\dagger}_{ji} \mathbf{H}^{\dagger}_{ki} \mathbf{U}_k\|^2$. To have SIC operate on the node level with aggregate data streams, without loss of generality, suppose that the minimum received power levels of the data streams from each of the K transmit nodes at node i are listed in non-decreasing order as $p_1 \cdot L^2_{1i} \cdot C_{1i} \leq \ldots \leq p_n \cdot L^2_{ni} \leq \ldots \leq p_K \cdot L^2_{Ki} \cdot C_{Ki}$, where $p_n \cdot L^2_{ni}$ corresponds to the minimum received power from intended transmit node n while the others correspond to minimum received power of unintended transmit nodes. Based on SIC, receiver i will decode the signals in the order of $K, K-1, \ldots n$ (i.e., the strongest signal first, until the intended transmit node n, inclusive). That is, the set of data streams from intended transmitter node n is decodable if

$$\begin{aligned}
&\text{Step 1} \quad \frac{p_K \cdot L^2_{Ki} \cdot C_{Ki}}{\sum_{k=1}^{K-1} p_k L^2_{ki} \cdot D_{Kki} + N_0} \geq \beta, \\
&\text{Step 2} \quad \frac{p_{(K-1)} \cdot L^2_{(K-1)i} \cdot C_{(K-1)i}}{\sum_{k=1}^{K-2} p_k L^2_{ki} \cdot D_{(K-1)ki} + N_0} \geq \beta, \\
&\vdots \\
&\text{Step } (K-n+1) \quad \frac{p_n \cdot L^2_{ni}}{\sum_{k=1}^{n-1} p_k L^2_{ki} \cdot D_{nki} + N_0} \geq \beta ,
\end{aligned} \tag{12}$$

where for intended transmit node n, $C_{ni} = 1$ due to SM requirements.

Note that although (12) shows the iterative SIC process, it is not written in a mathematical program. To address this issue, we adopt a similar approach as in [15] by defining the so-called *residual SINR* (or r-SINR). r-SINR is a compact expression to calculate SINR value for the transmit-receive pair under consideration after all the transmit nodes with stronger received signals have been successfully decoded. Specifically, for the aggregate data streams from transmit node j to receive node i in time slot t, we define r-SINR $_{ji}[t]$ as follows:

$$\text{r-SINR}_{ji}[t] = \frac{p_j \cdot L^2_{ji} \cdot C_{ji}}{\sum_{k\in\mathcal{I}_i, k\neq j}^{p_k L^2_{ki} \cdot C_{ki} \leq p_j L^2_{ji} \cdot C_{ji}} p_k \cdot L^2_{ki} \cdot D_{jki} + N_0} , \tag{13}$$

where the summation in the denominator includes all transmit nodes k with weaker received signals than j.

4 SIC in MIMO DOF model

A receive node may receive signals from multiple transmit nodes, including both signals from the intended transmit node and interference from any unintended transmit node. In the proposed scheme, receive node i divides the signals from these transmit nodes into five sets:

Set 1 Signals from unintended transmit nodes that are canceled by DoFs at the transmit nodes;

Set 2 Signals from unintended transmit nodes that are canceled by DoFs at receive node i;

Set 3 Signals from unintended transmit nodes that are decoded and subtracted from the composite received signals by SIC at receive node i before the intended transmit node (i.e., the received powers from these transmit nodes are greater than the powers from the intended transmit node n);

Set 4 Signals from intended transmit node n.

Set 5 Signals from unintended transmit nodes that are treated as noise during SIC at receive node i (i.e., the received powers from these transmit nodes are less than the powers from the intended transmit node n);

For the signals from an unintended transmitter to receive node i, the question of which sets (1, 2, 3, or 5) the signals belong to will be solved by an optimization problem. The goal of this section is to define and formulate the decision variables into the necessary constraints for DoF IC and SIC. Figure 5 shows how the signals from the intended transmitter (Set 4) are successfully decoded at receive node i. First, set 1 signals are canceled at the transmitter side. The remaining composite signals from sets 2, 3, 4 and 5 are received at Rx node i. As shown in the figure, Rx node has one reconfigurable receive matrix, which is updated iteratively during SIC. In each SIC iteration (except the last iteration), Rx node performs DoF IC and SIC as follows. In the first iteration, Rx node configures its receive matrix to perform DoF IC for signals in set 2. Then it decodes the strongest received signal (minimum received power among the data streams from a transmit node) in the union of sets 3, 4 and 5 by SM while treating the remaining signals in sets 3, 4 and 5 as noise. The decoded signals are reconstructed and subtracted from the composite signal before the next iteration. The process goes on from iteration to iteration. In the last iteration, the Rx node will decode the signals from the intended transmitter (set 4) while treating the signals in set 5 as noise. The output from the last iteration are the signals from the intended transmitter. In the rest of this section, we show mathematically how the DoF IC model and SIC model can be coupled together. First, we need to introduce some notations.

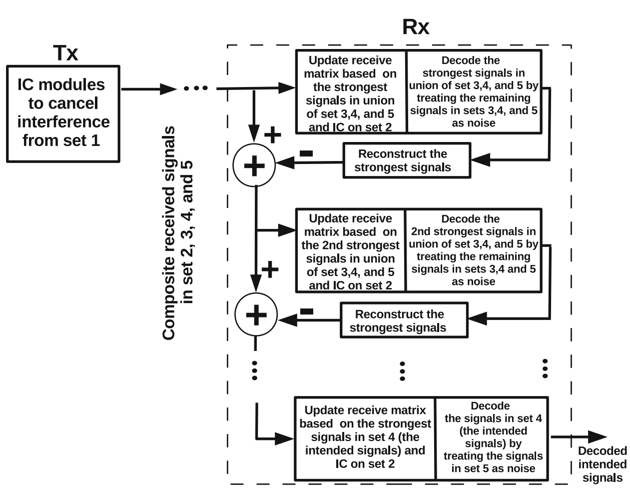

Fig. 5 A schematic of the proposed DoF-SIC scheme

Indicator variables for DoF IC and SIC. For the 5 sets of signals, we define three binary indicator variables $\gamma_{ji}[t]$ (for sets 1 and 2), $\eta_{ji}[t]$ (for sets 3 and 5) and $\lambda_{ji}[t]$ (for set 4) as follows:

- $\gamma_{ji}[t]$: a binary variable. $\gamma_{ji}[t] = 1$ if the interference from unintended transmit node j to receive node i is canceled by DoF (either at transmit node j or receive node i), and 0 otherwise. Note that when $\gamma_{ji}[t] = 1$, it does not tell which node does the IC with DoF (transmit node j or receive node i). For that, we need the value of $\theta_{ji}[t]$. Also note that, if $\gamma_{ji}[t] = 1$, then we have $x_j[t] = 1$ and $y_i[t] = 1$. This sufficient condition can be modeled by the following constraints:

$$x_j[t] \geq \gamma_{ji}[t], \quad (1 \leq i \leq N, j \in \mathcal{I}_i, 1 \leq t \leq T)\,, \tag{14}$$

$$y_i[t] \geq \gamma_{ji}[t], \quad (1 \leq i \leq N, j \in \mathcal{I}_i, 1 \leq t \leq T)\,. \tag{15}$$

- $\eta_{ji}[t]$: a binary variable. $\eta_{ji}[t] = 1$ if the interference from unintended transmit node j to receive node i is canceled by SIC (or being treated as noise), and 0 otherwise. Also note that, if $\eta_{ji}[t] = 1$, then we have $x_j[t] = 1$ and $y_i[t] = 1$. This sufficient condition can be modeled by the following constraints:

$$x_j[t] \geq \eta_{ji}[t], \quad (1 \leq i \leq N, j \in \mathcal{I}_i, 1 \leq t \leq T)\,, \tag{16}$$

$$y_i[t] \geq \eta_{ji}[t], \quad (1 \leq i \leq N, j \in \mathcal{I}_i, 1 \leq t \leq T)\,. \tag{17}$$

Also note that, if $x_j[t] = y_i[t] = 1$, then we have $\eta_{ji}[t] + \gamma_{ji}[t] = 1$. This sufficient condition can be modeled by the following constraints:

$$x_j[t] + y_i[t] - 1 \leq \eta_{ji}[t] + \gamma_{ji}[t] \leq 1, \quad (1 \leq i \leq N, j \in \mathcal{I}_i, 1 \leq t \leq T)\,. \tag{18}$$

- $\lambda_{ji}[t]$: a binary variable. $\lambda_{ji}[t] = 1$ if intended transmit node j transmits *at least* one data stream successfully to receive node i via SM, and 0 otherwise. For SM, we have:

$$\lambda_{ji}[t] \leq z_l[t] \leq M \cdot \lambda_{ji}[t], \quad (1 \leq l \leq L, j = \text{ Tx } (l), i = \text{ Rx } (l), 1 \leq t \leq T)\,. \tag{19}$$

Coupling SIC with MIMO DoF model. With the above definitions for $\gamma_{ji}[t]$, $\eta_{ji}[t]$ and $\lambda_{ji}[t]$, the DoF consumption constraints in (6) and (7) for a transmit node and a receive node can be extended by taking into account SIC as follows. When node i is a transmit node, then the DoF consumption at this node must satisfy:

$$\sum_{l \in \mathcal{L}_i^{\text{out}}} z_{(l)}[t] + \sum_{j \in \mathcal{I}_i} \theta_{ji}[t]\gamma_{ij}[t] \sum_{k \in \mathcal{L}_j^{\text{in}}}^{\text{Tx}(k) \neq i} z_{(k)}[t] \le M x_i[t] + (1 - x_i[t])B_i, (1 \le i \le N, 1 \le t \le T). \quad (20)$$

Note that in the above expression, the use of $\gamma_{ij}[t]$ limits the accounting of DoFs (used in IC) only to those interfering data streams that are canceled by transmit node i. Similarly, when node i is a receive node, then the DoF consumption at this node must satisfy:

$$\sum_{k \in \mathcal{L}_i^{\text{in}}} z_{(k)}[t] + \sum_{j \in \mathcal{I}_i} \theta_{ji}[t]\gamma_{ji}[t] \sum_{l \in \mathcal{L}_j^{\text{out}}}^{\text{Rx}(l) \neq i} z_{(l)}[t] \le M y_i[t] + (1 - y_i[t])B_i, (1 \le i \le N, 1 \le t \le T). \quad (21)$$

Sequential SIC model with DoF IC. In Sect. 3, we developed MIMO SIC constraint (13) without DoF IC consideration. With DoF IC, the potential barrier signals that do not meet threshold β can now be removed and SIC can continue to decode. We incorporate DoF IC into the r-SINR definition in (13) through the $\eta_{ji}[t]$ and $\lambda_{ji}[t]$ variables, which allows us to account for only those interfering signals that are to be handled by SIC (i.e., not canceled by DoF IC). So r-SINR $_{ji}[t]$ can be re-defined as follows:

$$\text{r-SINR}_{ji}[t] = \frac{p_j \cdot L_{ji}^2 \cdot C_{ji}}{\sum\limits_{k \in \mathcal{I}_i, k \neq j, \eta_{ki}[t]=1 \text{or} \lambda_{ki}[t]=1}^{p_k L_{ki}^2 \cdot C_{ki} \le p_j L_{ji}^2 \cdot C_{ji}} p_k \cdot L_{ki}^2 \cdot D_{jki} + N_0} . \quad (22)$$

When j is the intended transmit node, i.e., $j = n$, $C_{ni} = 1$ due to SM, r-SINR $_{ni}[t]$ is:

$$\text{r-SINR}_{ni}[t] = \frac{p_n \cdot L_{ni}^2}{\sum\limits_{k \in \mathcal{I}_i, k \neq n, \eta_{ki}[t]=1}^{p_k L_{ki}^2 \cdot C_{ki} \le p_n L_{ni}^2} p_k \cdot L_{ki}^2 \cdot D_{nki} + N_0} . \quad (23)$$

Note that if $\lambda_{ni}[t] = 1$ (i.e., we have at least one data stream from intended transmit node n to receive node i), then we must have:

- (i) The r-SINR $_{ji}$'s of all stronger received signals from other transmit nodes j with $\eta_{ji}[t] = 1$ are no less than the SINR threshold β; and
- (ii) The r-SINR $_{ni}[t]$ of the intended signals from node n to node i is no less than the SINR threshold β.

That is, if $\lambda_{ni}[t] = 1$, we have

$$\text{r-SINR}_{ji}[t] \ge \beta, \quad (1 \le i \le N, j \in \mathcal{I}_i, \eta_{ji}[t] = 1, p_j L_{ji}^2 C_{ji} > p_n L_{ni}^2, 1 \le t \le T) , \quad (24)$$

$$\text{r-SINR}_{ni}[t] \ge \beta, \quad (1 \le i \le N, n \in \mathcal{I}_i, 1 \le t \le T) . \quad (25)$$

Note that r-SINR $_{ji}[t]$ and r-SINR $_{ni}[t]$ in above constraints refers to definitions (22) and (23), respectively.

5 Case study: a throughput maximization problem

In Sects. 2 to 4, we established key models for MIMO-SIC. In this section, we show how these models can be used to study networking problems. Let's consider a typical throughput maximization problem in a multi-hop MIMO network. Suppose there is a set of active sessions $\mathcal{F}$. Denote $r(f)$ as the rate of session $f \in \mathcal{F}$ and $r_{\min}$ as the minimum session rate, i.e., $r_{\min} = \min_{f \in \mathcal{F}} r(f)$. Our objective is to maximize the minimum session rate $r_{\min}$ among all sessions $\mathcal{F}$.

To formulate this problem, we need to have flow routing constraints and link capacity constraints, in addition to those constraints in Sects. 2 to 4.

Flow routing constraints. Denote $r_l(f)$ as the amount of data rate on link l that is attributed to session $f \in \mathcal{F}$. Denote $s(f)$ and $d(f)$ as the source and destination nodes of session $f \in \mathcal{F}$, respectively. Then at source node, $s(f)$, $f \in \mathcal{F}$, we have the following flow balance:

$$\sum_{l \in \mathcal{L}_i^{\text{out}}} r_l(f) = r(f), \quad (i = s(f), f \in \mathcal{F}) . \quad (26)$$

At any intermediate relay node, we have

$$\sum_{l \in \mathcal{L}_i^{\text{in}}} r_l(f) = \sum_{l \in \mathcal{L}_i^{\text{out}}} r_l(f), \quad (1 \le i \le N, i \ne s(f), i \ne d(f), f \in \mathcal{F}) . \quad (27)$$

At a destination node, we have

$$\sum_{l \in \mathcal{L}_i^{\text{in}}} r_l(f) = r(f), \quad (i = d(f), f \in \mathcal{F}) . \quad (28)$$

It can be easily verified that if (26) and (27) are satisfied, then (28) is also satisfied. Therefore, it is sufficient to have (26) and (27).

Link capacity constraints. For simplicity, we assume the granularity of the data rate is DoF per time slot. Since the aggregate data rate on link l cannot exceed the link's average rate, we have

$$\sum_{f \in \mathcal{F}} r_l(f) \le \frac{1}{T} \sum_{t=1}^{T} z_{(l)}[t], \quad (1 \le l \le L) \tag{29}$$

where the right-hand-side represents the average throughput on link l over a frame (T time slots).

Putting all the constraints together, we have the following formulation for the throughput maximization problem:

Table 2 Source node and destination node in the 25-node network

Session f	Source node $s(f)$	Dest. node $d(f)$
1	0	20
2	9	17
3	21	2
4	15	14

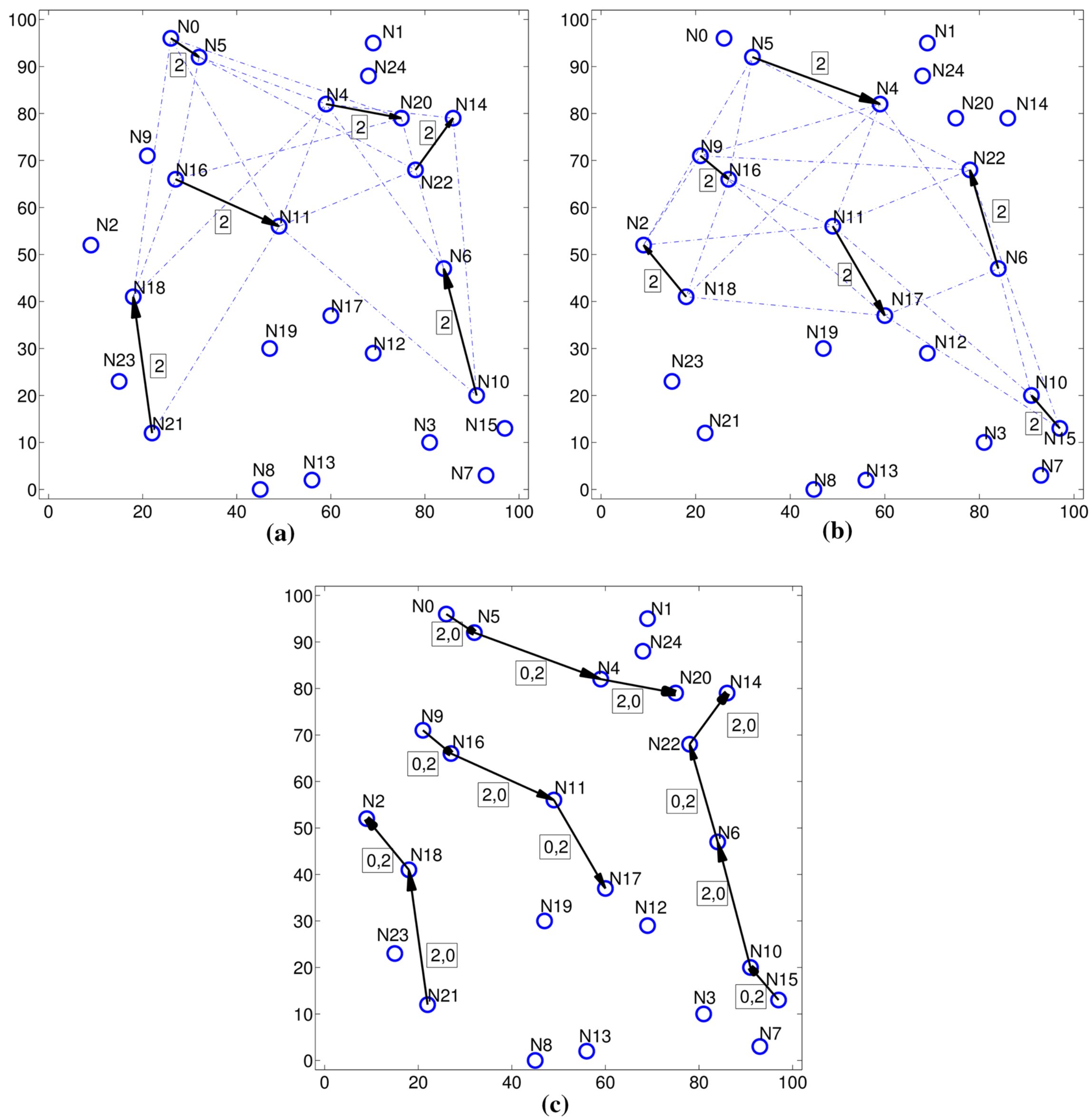

Fig. 6 **a** and **b** show scheduled links, DoFs allocation on each link, and interference pattern in time slots 1 and 2, respectively. A *solid arrow line* represents a directed transmission link (with the number of data streams on the link shown in a *box*) and a *dashed arrow line* represents an interference. **c** shows the combined results for both time slots (with the number of data streams for each time slot on the link shown in a *box*) **a** Time slot 1 **b** Time slot 2 **c** Combined results

$$
\begin{aligned}
\textbf{TMP} \quad \max \quad & r_{\min} \\
\text{s.t.} \quad & r_{\min} \le r(f) \qquad (f \in \mathcal{F}); \\
& \text{Half duplex constraint} : (1); \\
& \text{Node's SM constraints} : (2), (3); \\
& \text{Node ordering constraints} : (4), (5); \\
& \text{DoF consumption with SIC} : (14) - 18), (20) - (21); \\
& \text{Sequential SIC with IC} : (19), (24), (25); \\
& \text{Flow balance constraints} : (26), (27); \\
& \text{Link capacity constraints} : (29).
\end{aligned}
$$

In the formulation, $M, N, T, B_i, p_j, L_{ji}^2, \beta, N_0, C_{ji}$ and D_{jki} are constants[1] and $x_i[t]$, $y_i[t]$, $z_{(l)}[t]$, $\pi_i[t]$, $\theta_{ji}[t]$, $\eta_{ji}[t]$, $\gamma_{ji}[t]$,$\lambda_{ji}[t]$, $r_l(f)$, $r(f)$ are variables. Through reformulation on (20), (21), (24) and (25) (see "Appendix"), TMP can be reformulated into a mixed integer linear program (MILP). Although the theoretical worst-case complexity to a general MILP problem is exponential [8, 24], there exist highly efficient heuristics (e.g., sequential fixing algorithm [13] Chapter 10]) to solve it. Another approach is to apply an off-the-shelf solver (CPLEX [40]), which we find can handle up to a moderate-sized network successfully. Since the main goal of this paper is to explore DoF IC and SIC jointly, it is sufficient to demonstrate our results with moderate-sized networks. Therefore, we will use CPLEX to solve MILP.

5.1 A 25-node example

The goal of this effort is twofold. First, we want to show how a solution to the TMP formulation looks like for an example network. By examine the details of our solution for an example network, one could gain some quantitative understanding of the interaction between DoF IC and SIC. Second, we want to perform a comparison study between our joint DoF IC and SIC framework and that without SIC.

We consider a randomly generated multi-hop wireless network with 25 nodes that are distributed in a 100×100 area. For generality, we normalize all units for distance, data rate, bandwidth, and power with appropriate dimensions. At the network layer, minimum-hop routing is employed. There are 4 active sessions in the network with each session's source node and destination node given in Table 2. Each node is equipped with $M = 4$ antennas. The transmit power for each data stream at a node is set to 1. The path-loss factor L_{ji}^2 between nodes i and j is $L_{ji}^2 = d_{ji}^{-\alpha}$, where d_{ji} is the distance between the two nodes and $\alpha = 3$ is the path-loss index. The power of ambient noise is $N_0 = 10^{-6}$. The average value of C_{ji} is 0.3460. The worst case upper bound value for D_{jki} is 7.3753. For the 25-node network, we apply CPLEX solver for the TMP formulation. In [33], it was recommended that SIC be used with direct sequence spread spectrum (DSSS). We follow this approach and assume DSSS's spreading gain is 3. We assume $\beta = 1.2$ and $T = 2$ time-slots.

Figure 6 shows the set of active links and the number of data streams per link in each time slot in the solution. Table 3 shows the details of SIC and DoF IC in each time slot. The first column identifies the time slot (1 or 2). The second column shows the active receivers in each time slot. The third column shows the transmitters (both desired and interfering) with respect to the receiver. The fourth column shows the number of DoFs for SM on the intended link (with 0 indicating interference). The fifth column shows whether the interference from the transmitter is handled by SIC (through SINR calculation). The last column shows whether the interference is canceled by DoF IC on the transmitter side or receiver side.

To show the benefits of the joint DoF IC and SIC scheme, we compare our solution to that without SIC. The achievable objective value is 1 under the proposed joint

Table 3 Details of SIC and DoF IC on each link in each time slot

Time slot 1					Time slot 2				
Rx	Tx	SM	SIC	IC	Rx	Tx	SM	SIC	IC
N_5	N_0	2		0	N_2	N_5	0	✓	0
	N_4	0	✓	0		N_9	0	✓	0
	N_{16}	0	✓	0		N_{11}	0	✓	0
	N_{22}	0	✓	0		N_{18}	2		0
N_6	N_4	0	✓	0	N_4	N_5	2		0
	N_{10}	2		0		N_6	0		2 at Rx
	N_{22}	0		2 at Rx		N_9	0		2 at Tx
N_{11}	N_0	0	✓	0		N_{11}	0		2 at Tx
	N_4	0		2 at Rx		N_{18}	0	✓	0
	N_{10}	0		2 at Tx	N_{10}	N_6	0	✓	0
	N_{16}	2		0		N_{11}	0	✓	0
	N_{21}	0		2 at Tx		N_{15}	2		0
	N_{22}	0		2 at Tx	N_{16}	N_5	0	✓	0
N_{14}	N_4	0	✓	0		N_9	2		0
	N_{10}	0	✓	1		N_{11}	0		2 at Tx
	N_{22}	2		0		N_{18}	0	✓	0
N_{18}	N_0	0	✓	0	N_{17}	N_6	0		2 at Tx
	N_4	0		2 at Tx		N_9	0	✓	0
	N_{16}	0		2 at Rx		N_{11}	2		0
	N_{21}	2		0		N_{15}	0	✓	0
N_{20}	N_0	0	✓	0		N_{18}	0		2 at Rx
	N_4	2		0	N_{22}	N_5	0		2 at Tx
	N_{16}	0	✓	0		N_6	2		0
	N_{22}	0		2 at Tx		N_9	0		2 at Rx
						N_{11}	0	✓	0

[1] For the purpose of this paper, we set C_{ji} to its average value over a large number of realizations and D_{jki} to its worst case bound.

Table 4 Objective values under joint scheme and DoF IC only scheme for 25-node network over 50 instances

IDX	DoF IC and SIC	DoF IC only	Incr %	IDX and SIC	DoF IC	DoF IC only	Incr %
1	1	0.5	100	26	1	0.5	100
2	1	0.5	100	27	1	0.5	100
3	1	0.5	100	28	2	1	100
4	1	0.5	100	29	1	0.5	100
5	1	0.5	100	30	1	0.5	100
6	1	0.5	100	31	1	0.5	100
7	1	0.5	100	32	1	0.5	100
8	1	0.5	100	33	1	0.5	100
9	1	0.5	100	34	1	0.5	100
10	1	0.5	100	35	1	0.5	100
11	0.5	0.5	0	36	1	0.5	100
12	0.5	0.5	0	37	1	0.5	100
13	0.5	0.5	0	38	1	0.5	100
14	1	0.5	100	39	1	0.5	100
15	2	1	100	40	1	0.5	100
16	1	0.5	100	41	2	1	100
17	0.5	0.5	0	42	1	0.5	100
18	0.5	0.5	0	43	1	0.5	100
19	2	0.5	300	44	1	0.5	100
20	1	0.5	100	45	1	0.5	100
21	1	0.5	100	46	1	0.5	100
22	1	0.5	100	47	0.5	0.5	0
23	1	0.5	100	48	0.5	0.5	0
24	1	0.5	100	49	0.5	0.5	0
25	1	0.5	100	50	1	0.5	100

DoF IC and SIC scheme and it is 0.5 when SIC is not used. The increase in throughput is therefore 100%.

5.2 Complete results

The previous section gives results for a 25-node example network. In this section, we provide three additional sets of results. First, we perform the same study for 25-node network, but for 50 randomly generated network instances, with each session's source and destination nodes being randomly selected among the nodes. Table 4 shows the results for both the proposed joint scheme and DoF IC only scheme. We find that the average percentage increase over the 50 instances is 87.75%.

Next, we perform the study on 50-node network randomly deployed in 150×150 area. There are 4 sessions in each network instance, with each session's source and destination nodes being randomly selected among the nodes.

Figures 7 and 8 demonstrate the objective values under the two schemes when the number of time slots is 2 and 4, respectively. In the case when there are only 2 time slots, the average percentage increase in objective value under the joint scheme is 86.66%, while the average percentage increase is 65% when there are 4 time slots. This decrease is intuitive as more time slots will offer more room for scheduling, thus alleviating the DoF resource shortage issue in DoF IC only scheme.

6 Related work

Related work on single-antenna SIC and MIMO DoF IC has been described in Sect. 1. In this section, we focus our review on related work that employs SIC in MIMO.

For point-to-point MIMO communication, there has been extensive research on SIC based receivers to decode received data streams. The first MIMO SIC for point-to-point MIMO communication was D-BLAST by Foschini [6]. The use of SIC helps boost the performance of a MIMO receiver by decoding and subtracting each data stream successively. The boost in power gain comes from increased SINR at each stage. It was shown in [6] that a receiver based on minimum mean-square-error (MMSE) outperforms zero forcing in terms of mitigating both

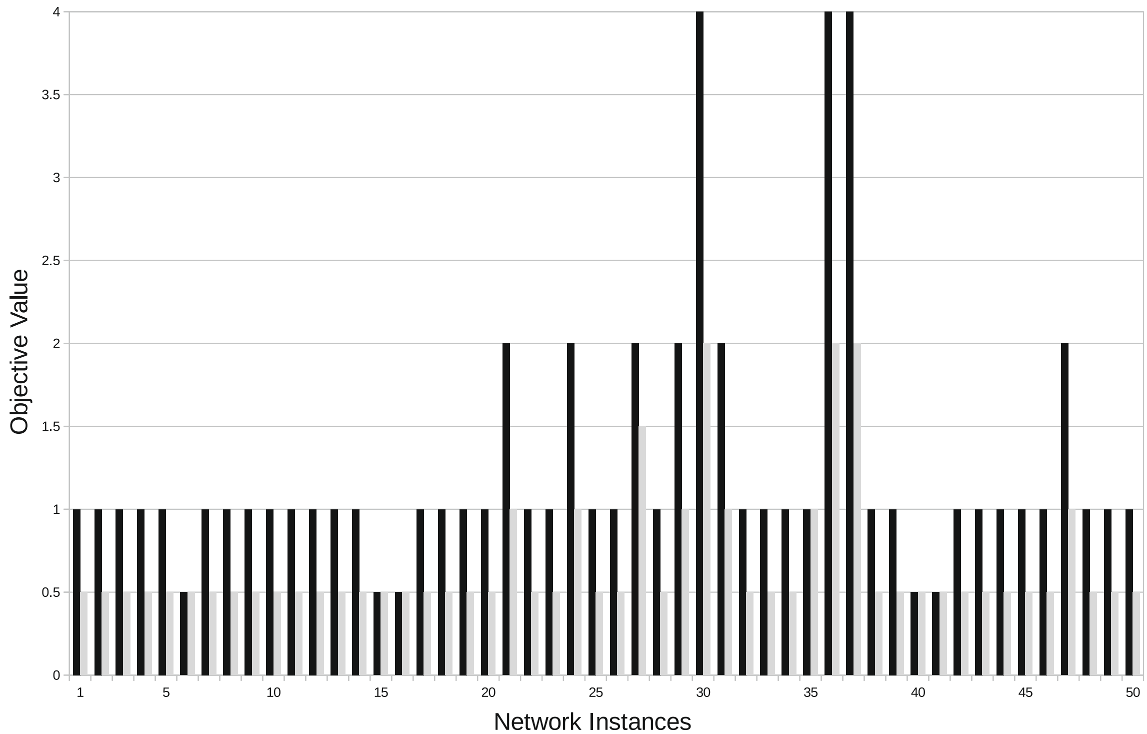

Fig. 7 Objective values under joint scheme (represented by *black bars*) and DoF IC only scheme (represented by *gray bars*) for 50-node network over 50 instances. Number of time slot is 2

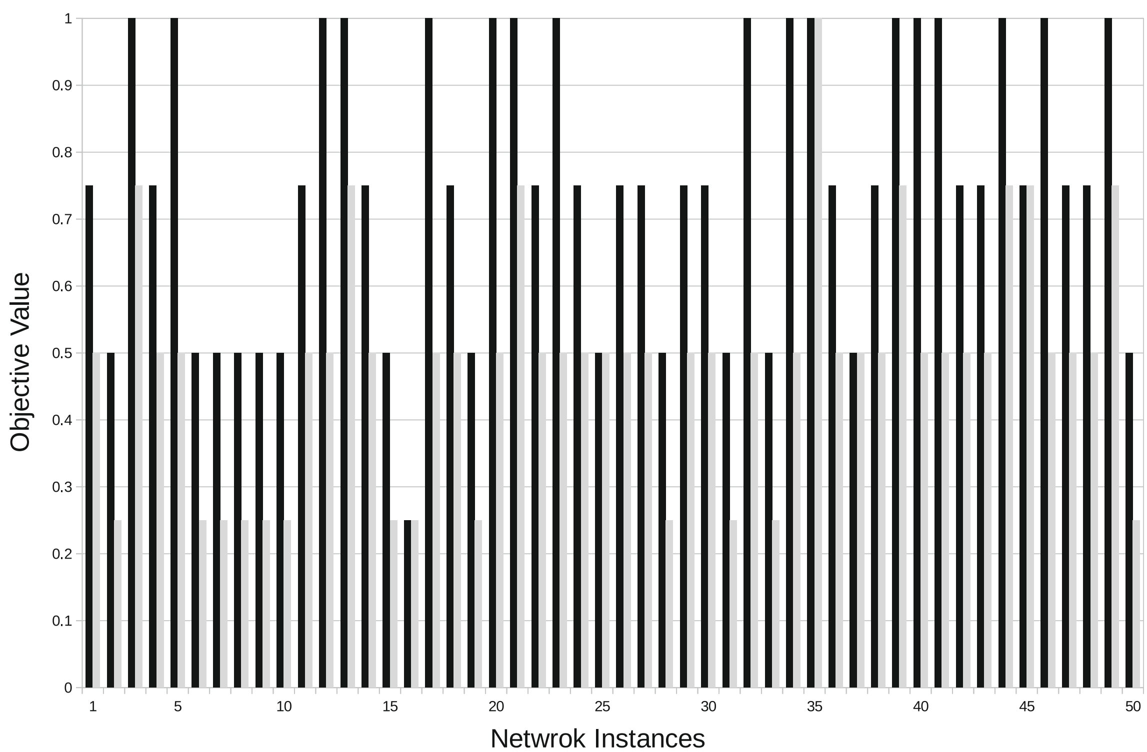

Fig. 8 Objective values under joint scheme (represented by *black bars*) and DoF IC only scheme (represented by *gray bars*) for 50-node network over 50 instances. Number of time slot is 4

interference and noise. The optimality of MMSE in conjunction with SIC was shown in [31] by Varanasi et al. A simplified version of D-BLAST, called V-BLAST, was proposed by Wolniansky et al. in [34]. A number of performance studies of V-BLAST and MIMO-MMSE SIC in the context of point-to-point MIMO communication can be found in [5, 16, 22, 37, 39].

In multi-user MIMO with SIC, although the incoming data streams may come from different MIMO transmitters, the receiver design is still similar to that for the point-to-point MIMO SIC receiver. That is, V-BLAST architecture remains prevalent in the design of multi-user MIMO-SIC receiver (e.g., [27]). Although the MMSE based receiver is prevalent in single-user and multi-user MIMO SIC, it is not tractable when we study MIMO SIC in a multi-hop network environment. This is because when scheduling algorithm is unknown (part of the optimization problem), the number of variables and constraints become prohibitively large when MMSE is employed in a multi-hop network with MIMO SIC. Due to this reason, we do not employ MMSE in our MIMO SIC receiver and instead employ the simple DoF model, which is based on zero-forcing. In this sense, DoF based MIMO SIC design may only achieve sub-optimal. But it offers an excellent starting point to understand the potential of SIC in a multi-hop MIMO network.

In [9], Gelal et al. studied how to maximally exploit SIC in multi-user MIMO networks through selection of a subset of links that can be concurrently active in each receiver's neighborhood. The proposed algorithms attempt to divide the network into a minimum number of sub-topologies where the set of links in each sub-topology can be active simultaneously. In [9], MIMO's capability is limited to selection diversity on the receiver side, while SM and IC capabilities are not considered. Further, it is not clear how the proposed the algorithm can be extended to address end-to-end data flow routing via multiple hops in the network.

7 Conclusions

DoF is an important concept to characterize a node's resource for SM and IC in a MIMO network. SIC is a powerful technique for IC and has the potential to conserve DoF resources once employed in a MIMO network. However, SIC's effectiveness is limited by its stringent SINR threshold criteria. This paper investigated how to conserve DoF resources and meet SIC's SINR threshold criteria by jointly exploiting the strengths of each technique. We developed the necessary mathematical models to characterize (i) how precious DoF resources can be conserved through the use of SIC and (ii) how the stringent SINR threshold criteria can be met through the use of DoF-based IC. Our modeling work was done in a general multi-hop MIMO network, which by default included scheduling and routing for user traffic sessions. Based on our cross-layer mathematical models, we studied a throughput maximization problem and confirmed that SIC and DoF IC can indeed achieve the two benefits that proposed in this paper.

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Appendix: Reformulation

Reformulation of (20) and (21). First, we introduce binary variables $\kappa_{ji}[t]$ and $\beta_{ji}[t]$ to replace $\theta_{ji}[t]\cdot\gamma_{ij}[t]$ and $\theta_{ji}[t]\cdot\gamma_{ji}[t]$. That is, $\kappa_{ji}[t]=\theta_{ji}[t]\cdot\gamma_{ij}[t]$ and $\beta_{ji}[t]=\theta_{ji}[t]\cdot\gamma_{ji}[t]$. This change of variables will introduce the following new constraints for $\kappa_{ji}[t]$ and $\beta_{ji}[t]$:

$$\kappa_{ji}[t]\geq\theta_{ji}[t]+\gamma_{ij}[t]-1,(1\leq i\leq N,j\in\mathcal{I}_i,1\leq t\leq T),\tag{30}$$

$$\theta_{ji}[t]\geq\kappa_{ji}[t],(1\leq i\leq N,j\in\mathcal{I}_i,1\leq t\leq T),\tag{31}$$

$$\gamma_{ij}[t]\geq\kappa_{ji}[t],(1\leq i\leq N,j\in\mathcal{I}_i,1\leq t\leq T),\tag{32}$$

$$\beta_{ji}[t]\geq\theta_{ji}[t]+\gamma_{ji}[t]-1,(1\leq i\leq N,j\in\mathcal{I}_i,1\leq t\leq T),\tag{33}$$

$$\theta_{ji}[t]\geq\beta_{ji}[t],(1\leq i\leq N,j\in\mathcal{I}_i,1\leq t\leq T),\tag{34}$$

$$\gamma_{ji}[t]\geq\beta_{ji}[t],(1\leq i\leq N,j\in\mathcal{I}_i,1\leq t\leq T).\tag{35}$$

Now we can rewrite constraints (20) and (21) for $(1\leq i\leq N,1\leq t\leq T)$ as

$$\sum_{l\in\mathcal{L}_i^{\text{out}}}z_{(l)}[t]+\sum_{j\in\mathcal{I}_i}\kappa_{ji}[t]\sum_{k\in\mathcal{L}_j^{\text{in}}}^{\text{Tx}(k)\neq i}z_{(k)}[t]\leq M\cdot x_i[t]+(1-x_i[t])B_i\ .\tag{36}$$

$$\sum_{k\in\mathcal{L}_i^{\text{in}}}z_{(k)}[t]+\sum_{j\in\mathcal{I}_i}\beta_{ji}[t]\sum_{l\in\mathcal{L}_j^{\text{out}}}^{\text{Rx}(l)\neq i}z_{(l)}[t]\leq M\cdot y_i[t]+(1-y_i[t])B_i\ .\tag{37}$$

Note that we still have nonlinear terms in (36) and (37), i.e., $\kappa_{ji}[t]\sum_{k\in\mathcal{L}_j^{\text{in}}}^{\text{Tx}(k)\neq i} z_{(k)}[t]$ and $\beta_{ji}[t]\sum_{l\in\mathcal{L}_j^{\text{out}}}^{\text{Rx}(l)\neq i} z_{(l)}[t]$. To reformulate these nonlinear terms, we again introduce new variables and adding new constraints. Specifically, we define new integer variable $\psi_{ji}[t]=\kappa_{ji}[t]\cdot\sum_{k\in\mathcal{L}_j^{\text{in}}}^{\text{Tx}(k)\neq i} z_{(l)}[t]$. Then (36) can be rewritten as

$$\sum_{i\in\mathcal{L}_i^{\text{out}}} z_{(l)}[t]+\sum_{j\in\mathcal{I}_i}\psi_{ji}[t]\le M\cdot x_i[t]+(1-x_i[t])B_i \quad (1\le i\le N, 1\le t\le T)\ , \tag{38}$$

along with new constraints for $\psi_{ji}[t]$ for $(1\le i\le N, j\in\mathcal{I}_i, 1\le t\le T)$.

$$\psi_{ji}[t]\le\sum_{k\in\mathcal{L}_j^{\text{in}}}^{\text{Tx}(k)\neq i} z_{(k)}[t]\ , \tag{39}$$

$$\psi_{ji}[t]\le M\cdot\kappa_{ji}[t]\ , \tag{40}$$

$$\psi_{ji}[t]\ge M\cdot\kappa_{ji}[t]+\sum_{k\in\mathcal{L}_j^{\text{in}}}^{\text{Tx}(k)\neq i} z_{(k)}[t]-M\ . \tag{41}$$

Similarly, for (37), we define new variable $\epsilon_{ji}[t]=\beta_{ji}[t]\sum_{l\in\mathcal{L}_j^{\text{out}}}^{\text{Rx}(l)\neq i} z_{(l)}[t]$. Then (37) can be rewritten as:

$$\sum_{i\in\mathcal{L}_i^{\text{in}}} z_{(l)}[t]+\sum_{j\in\mathcal{I}_i}\epsilon_{ji}[t]\le M\cdot y_i[t]+(1-y_i[t])B_i \quad (1\le i\le N, 1\le t\le T)\ , \tag{42}$$

along with new constraints for $\epsilon_{ji}[t]$ for $(1\le i\le N, j\in\mathcal{I}_i, 1\le t\le T)$,

$$\epsilon_{ji}[t]\le\sum_{l\in\mathcal{L}_j^{\text{out}}}^{\text{Rx}(l)\neq i} z_{(l)}[t]\ , \tag{43}$$

$$\epsilon_{ji}[t]\le M\cdot\beta_{ji}[t]\ , \tag{44}$$

$$\epsilon_{ji}[t]\ge M\cdot\beta_{ji}[t]+\sum_{l\in\mathcal{L}_j^{\text{out}}}^{\text{Rx}(l)\neq i} z_{(l)}[t]-M\ . \tag{45}$$

Reformulation of (24) and (25). The two sets of constraints in (24) and (25) are stated in the form of sufficient conditions rather than mathematical programming. To reformulate both, we first move $\eta_{ji}[t]=1$ out of the range in (24) by treating it as part of the sufficient condition. That is, if ($\eta_{ji}[t]=1$ *and* $\lambda_{ni}[t]=1$) then r-SINR $_{ji}[t]\ge\beta$ for $(1\le i\le N, j\in\mathcal{I}_i, p_jL_{ji}^2\cdot C_{ji}>p_nL_{ni}^2, 1\le t\le T)$. To combine $\eta_{ji}[t]=1$ and $\lambda_{ni}[t]=1$ into one condition, we introduce a binary variable $\delta_{(ji),(ni)}[t]$, where $\delta_{(ji),(ni)}[t]=1$ *if and only if* ($\eta_{ji}[t]=1$ *and* $\lambda_{ni}[t]=1$) for $(1\le i\le N, (n,j)\in\mathcal{I}_i, p_jL_{ji}^2\cdot C_{ji}>p_nL_{ni}^2, 1\le t\le T)$. This logical condition can be expressed in mathematical form as following:

$$\delta_{(ji),(ni)}[t]\ge\eta_{ji}[t]+\lambda_{ni}[t]-1\ , \tag{46}$$

$$\eta_{ji}[t]\ge\delta_{(ji),(ni)}[t]\ , \tag{47}$$

$$\lambda_{ni}[t]\ge\delta_{(ji),(ni)}[t]\ . \tag{48}$$

Now, we can re-write MIMO SIC sequential SINR constraints derived in (24) and (25) based on the above newly defined variables and substituting r-SINR definitions for intended and unintended transmissions in (23) and (22), respectively. For $(1\le i\le N, (n,j)\in\mathcal{I}_i, p_jL_{ji}^2\cdot C_{ji}>p_nL_{ni}^2, 1\le t\le T)$,

$$\text{if } \delta_{(ji),(ni)}[t]=1 \text{ then } \frac{p_j\cdot L_{ji}^2\cdot C_{ji}}{\sum_{k\in\mathcal{I}_i,k\neq j,\eta_{ki}[t]=1 \text{ or } \lambda_{ki}[t]=1}^{p_kL_{ki}^2\cdot C_{ki}\le p_jL_{ji}^2\cdot C_{ji}} p_k\cdot L_{ki}^2\cdot D_{jki}+N_0}\ge\beta\ , \tag{49}$$

and for $(1\le i\le N, n\in\mathcal{I}_i, 1\le t\le T)$,

$$\text{if } \lambda_{ni}[t]=1 \text{ then } \frac{p_nL_{ni}^2}{\sum_{k\in\mathcal{I}_i,k\neq n,\eta_{ki}=1}^{p_kL_{ki}^2\cdot C_{ki}\le p_nL_{ni}^2} p_k\cdot L_{ki}^2\cdot D_{nki}+N_0}\ge\beta\ . \tag{50}$$

The logical constraints (49) and (50) can now be reformulated into mathematical form. For $(1\le i\le N, (n,j)\in\mathcal{I}_i, p_jL_{ji}^2\cdot C_{ji}>p_nL_{ni}^2, 1\le t\le T)$,

$$\frac{\delta_{(ji),(ni)}[t]\cdot p_j\cdot L_{ji}^2\cdot C_{ji}+(1-\delta_{(ji),(ni)}[t])\cdot G'}{\sum_{k\in\mathcal{I}_i,k\neq j}^{p_kL_{ki}^2\cdot C_{ki}\le p_jL_{ji}^2\cdot C_{ji}} p_k\cdot L_{ki}^2\cdot\eta_{ki}[t]\cdot D_{jki}+\lambda_{ni}[t]\cdot p_n\cdot L_{ni}^2\cdot D_{jni}+N_0}\ge\beta\ , \tag{51}$$

and for $(1\le i\le N, n\in\mathcal{I}_i, 1\le t\le T)$,

$$\frac{\lambda_{ni}[t]\cdot p_j\cdot L_{ji}^2+(1-\lambda_{ni}[t])\cdot G}{\sum_{k\in\mathcal{I}_i k\neq n}^{p_kL_{ki}^2\cdot C_{ki}\le p_nL_{ni}^2} p_k\cdot L_{ki}^2\cdot\eta_{ki}[t]\cdot D_{nki}+N_0}\ge\beta\ . \tag{52}$$

where G' is an upper bound of $\beta\cdot(\sum_{k\in\mathcal{I}_i,k\neq j}^{p_kL_{ki}^2\cdot C_{ki}\le p_jL_{ji}^2\cdot C_{ji}}\eta_{ki}[t]\cdot p_k\cdot L_{ki}^2\cdot D_{jki}+\lambda_{ni}[t]\cdot p_n\cdot L_{ni}^2\cdot D_{jni}+N_0)$ to ensure that the constraint holds whenever $\delta_{(ji),(ni)}[t]=0$. Define $G'=\beta\cdot(\sum_{k\in\mathcal{I}_i,k\neq j}p_k\cdot L_{ki}^2\cdot D_{jki}+N_0)$. Then

$$G'\ge\beta\cdot(\sum_{k\in\mathcal{I}_i,k\neq j}^{p_kL_{ki}^2\cdot C_{ki}\le p_jL_{ji}^2\cdot C_{ji}}\eta_{ki}[t]\cdot p_k\cdot L_{ki}^2\cdot D_{jki}+\lambda_{ni}[t]\cdot p_n\cdot L_{ni}^2\cdot D_{jni}+N_0).$$

Similarly, G is an upper bound of $\beta\cdot(\sum\sum_{k\in\mathcal{I}_i,k\neq n}^{p_kL_{ki}^2\cdot C_{ki}\le p_nL_{ni}^2}\eta_{ki}[t]\cdot p_k\cdot L_{ki}^2\cdot D_{nki}+N_0)$ to ensure that the constraint holds whenever $\lambda_{ni}[t]=0$. Define $G=\beta\cdot(\sum_{k\in\mathcal{I}_i,k\neq n}p_k\cdot L_{ki}^2\cdot D_{nki}+N_0)$. Then $G\ge\beta\cdot(\sum_{k\in\mathcal{I}_i,k\neq n}^{p_kL_{ki}^2\cdot C_{ki}\le p_nL_{ni}^2}\eta_{ki}[t]\cdot p_k\cdot L_{ki}^2\cdot D_{nki}+N_0)$.

In summary we replace (20), (21), (24), and (25) with (30)–(35), (38)–(41), (42)–(45), (51), and (52) in the original formulation **TMP**. The resulting optimization problem which we denote **R-TMP**, can be written as

$$\begin{aligned}
\mathbf{R-TMP}\quad & \max\ r_{\min} \\
\text{s.t.}\quad & r_{\min} \le r(f) \qquad (f \in \mathcal{F}); \\
& \text{Half duplex constraint}: (1); \\
& \text{Node activity constraints}: (2),(3); \\
& \text{Node ordering constraints}: (4),(5); \\
& \text{DoF consumption with SIC}: (14)-18),(30)-(35),(38)-(45); \\
& \text{Sequential SIC with IC}: (19),(46)-(48),(51),(52); \\
& \text{Flow balance constraints}: (26),(27); \\
& \text{Link capacity constraints}: (29); \\
& \text{Variables}: x_i[t], y_i[t], z_{(l)}[t], \pi_i[t], \theta_{ji}[t], \eta_{ji}[t], \gamma_{ji}[t], \lambda_{ji}[t], \\
& \psi_{ji}[t], \kappa_{ji}[t], \epsilon_{ji}[t], \beta_{ji}[t], \delta_{(ji),(ni)}[t], r_l(f), r(f); \\
& \text{Constants}: M, N, T, B_i, p_j, L_{ji}^2, \beta, N_0, G, G', C_{ji}, D_{jki}.
\end{aligned}$$

R-TMP is a mixed-integer linear problem (MILP). Therefore, we can apply a solver such as CPLEX [40] to obtain a solution efficiently.

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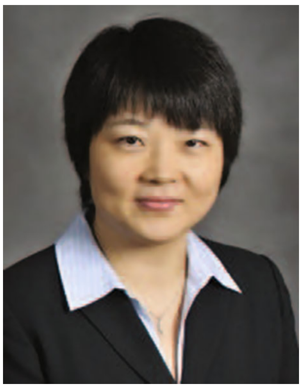

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