Cooperative Interference Mitigation for Heterogeneous Multi-hop MIMO Wireless Networks

Yantian Hou* Ming Li* Xu Yuan† Y. Thomas Hou† Wenjing Lou†
* Utah State University, USA
† Virginia Polytechnic Institute and State University, USA

***Abstract*—This paper explores a new paradigm for the coexistence among heterogeneous multi-hop networks in unplanned deployment settings, called *cooperative cross-technology interference mitigation* (CIM). CIM exploits recent advancements in physical layer technologies such as *technology-independent interference cancellation* (TIIC), making it possible for disparate networks to cooperatively mitigate the interference to each other to enhance everyone's performance, even if they possess different wireless technologies. This paper offers a thorough study of the CIM paradigm for unplanned multi-hop networks. We first propose a novel cooperative TIIC mechanism based on only channel ratio information, and then establish a tractable model to accurately characterize the CIM behaviors of both networks. We develop a bi-criteria optimization formulation to maximize both networks' throughputs, and propose a new methodology to compute the *Pareto-optimal throughput curve* as performance bound. Simulation results show that CIM provides significant performance gains to both networks compared with the traditional interference-avoidance paradigm.**

I. Introduction

The ever-growing number of wireless systems and the scarcity for available spectrum necessitates highly efficient spectrum sharing among disparate wireless networks [1]. Many of them are heterogenous in hardware capabilities, wireless technologies, or protocol standards, and are expected to overlap with each other in both frequency and space. This inevitably leads to *cross-technology interference* (CTI), which can be detrimental to the performance of co-locating networks if it is not properly mitigated [6], [10], [16], [19]. Some examples of existing and future radio devices/networks that create CTI include: IEEE 802.11 (WiFi), 802.15.4 (ZigBee), 802.16 (WiMax), and Bluetooth in the ISM bands, IEEE 802.22 (WRAN) and IEEE 802.11af (WLAN) in the TV white space, etc. Often, there is no central administration or planning for the coexistence of such networks. To enable spectrum sharing, current approaches mostly follow the *interference-avoidance* paradigm, where transmissions are separated in frequency, time, or space in order to share bandwidth among different networks, rather than to reduce or eliminate interference.

On the other hand, interference cancellation (IC) has emerged as a powerful physical layer approach to mitigate interference [30]. IC is enabled by the use of smart antennas (MIMO), which uses signal processing techniques to minimize or completely cancel interference from/to other links. MIMO is gaining popularity in commercial and future systems such as 802.11n, 802.16, and 802.11af. With IC, concurrent transmissions of two or more links are possible, as long as the interference among them is properly cancelled at the corresponding receivers. Recent advances in Technology-Independent Multiple-Output (TIMO) [11] even enable the cancellation of the CTI to/from a interferer with a completely different wireless technology. Intuitively, it is possible for two or more heterogeneous networks to cooperatively cancel/mitigate the interference to each other if they (or as long as one of them) are equipped with MIMO, such that everyone's performance can be enhanced simultaneously. We call this the *cooperative cross-technology interference mitigation* (CIM) paradigm.

Past research has mostly focused on exploiting MIMO IC to enhance throughput within standalone and homogeneous wireless networks [2], [3], [13], [28]. However, to date, its potential for interference mitigation across two or more heterogenous multi-hop networks has not been well understood. There is a lack of both feasibility study and theoretical guidelines on the performance limits of CIM. Recently IC has been adopted to fulfil the "transparent coexistence" or *underlay* paradigm in cognitive radio networks [31], in that the secondary network should cancel their interference to/from the primary networks to satisfy FCC policy. However, in this paradigm the responsibility for IC is always assigned to the secondary network, which is only half of the story. This is suitable to a *planned* deployment but not *unplanned* ones (e.g., secondary networks), where there is no predefined priority among networks which adds uncertainty, and they have competing interests which cannot be solved by single-objective optimization. Moreover, coexistence between multi-hop networks with *heterogeneous* wireless technologies has not been studied yet.

The goal of this paper is to explore the theoretical limits of the CIM paradigm for coexisting heterogeneous multi-hop networks. We consider an unplanned deployment setting, where each network aims at maximizing its own throughput while adopting the CIM paradigm to cooperatively cancel their interference to each other. To characterize the performance bounds, the *Pareto-optimal throughput curve* should be found, which contains all the points such that both networks cannot simultaneously increase their throughput. Deriving this curve is important for two reasons. (1) It provides to network designers the whole spectrum of optimal throughput tradeoff between another coexisting network, so that any desirable working point on the curve can be quickly found without re-computing an optimization problem every time. (2) It can guide practical protocol design, especially the design and evaluation of the performance-approaching protocols.

It is challenging to realize CIM from both theoretical and practical aspects. The Pareto-optimal throughput curve is equivalent to the outer bound of capacity region of the two networks. However, so far even the capacity region of single multi-hop MIMO network remains an open problem due to the intractability of previous models. On the practical side, the main challenges come from system heterogeneity. For networks with different wireless technologies, their PHY layer and signal structures are disparate, thus the full channel state information (CSI) cannot be obtained. The existing approach [11] is not general enough to realize arbitrary IC under the CIM paradigm in the multi-hop setting. Novel approaches to enable IC across heterogeneous networks are needed.

To this end, we first propose a novel cooperative technology-independent IC (TIIC) scheme across different technologies based on only partial CSI (channel ratio information), in order to deal with system heterogeneity. We show the feasibility of our TIIC scheme in multi-hop networks, which is also more general than TIMO [11] in terms of DoF constraints. Then we propose a tractable model for CIM that accurately captures both networks' *bilateral cooperative IC decisions, link scheduling, and various forms of system heterogeneity*, based on recent advances in MIMO link layer modeling. Then we formulate a bi-criteria optimization problem with mixed integer linear (MILP) constraints to maximize both networks' throughput. In order to characterize the Pareto-optimal throughput curve as performance bound, we exploit the inherent properties of the formulation which reveal it to be a *stair-shape* function. Our new methodology enables the derivation of the *exact throughput curve* without solving a large number of MILP problems. It is the *first tractable approach to compute the capacity region of two multi-hop MIMO networks* (in the DoF sense).

The rest of this paper is organized as follows. In Section II, we give necessary background on MIMO and the motivation. Section III describes our proposed technique to deal with cross-technology IC. In Section IV, we present the modeling of the CIM paradigm and formulate the bi-criteria optimization problem to find the performance bound. In Section V, we give our approach to find the optimal throughput curve. Section VI presents the simulation evaluation results. Section VII discusses related works, and Section VIII concludes the paper.

II. Background and Motivation

MIMO Background. There are two key techniques enabled by MIMO communication: spatial multiplexing (SM) and interference cancellation (IC). The degrees of freedom (DoF) [30] at a node represent the available number of interference-free signaling dimensions. SM refers to transmitting multiple streams simultaneously on a single MIMO link using multiple DoFs, which is upper limited by $min(A_t, A_r)$ where A_t and A_r are the antenna numbers at the transmitter and receiver sides, respectively. IC refers to a node's capability to cancel unintended interference using some of its DoFs, which can be done either by a transmitter or receiver. Assume transmitter t's link carries s_t streams and another receiver r's link carries s_r

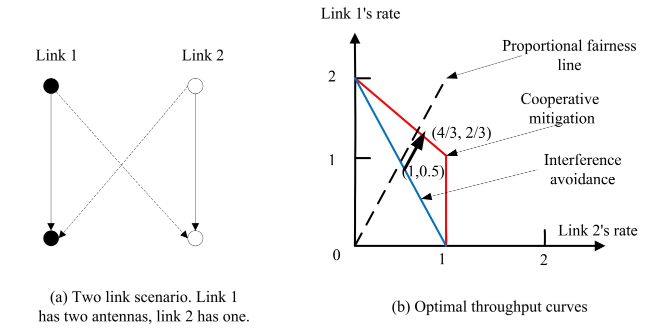


Fig. 1. Cooperative MIMO interference mitigation can increase the throughput of both links.

streams. For transmitter side IC, the number of DoFs required at t is equal to s_r (i.e., t can cancel its interference at r iff. $A_t - s_t \geq s_r$). For receiver side IC, the number of DoFs required at a receiver is equal to s_t (i.e., r can cancel t's signal iff. $A_r - s_r \geq s_t$). To achieve SM and IC, antenna weights are assigned to transmitters and receivers such that the signals received will be combined in the desired way.

Traditional IC techniques depend on full channel state information (CSI) at each node which is usually estimated via training symbols in an OFDM packet. However, with the CTI from a different wireless technology, the full CSI may not be obtained (or very costly to obtain) due to the generally unknown signal structure. If the other wireless network also uses OFDM as the PHY layer and its preamble is known, then we can assume full CSI is available. But in reality this requires prior knowledge of the protocol standard of various coexisting networks, which incurs significant overhead and cannot handle new systems. Fortunately, Gollakota et al. [11] proposed Technology-Independent Multiple-Output (TIMO), which enables an 802.11 MIMO link to completely cancel the high power and wide-bandwidth interference to/from a non-802.11 device (e.g., a ZigBee sensor and microwave oven), by only measuring the *channel ratio* information. TIMO is *agnostic* to the interferer's technology, making it possible to enhance coexistence among *heterogeneous* networks.

Motivation. The advancement of both MIMO and TIMO IC makes it possible for two or more coexisting networks to cooperatively enhance everyone's throughput. Fig. 2 illustrates this idea using a simple two interfering link setting. Link 1 is equipped with two antennas at both transmitter and receiver sides, while link 2 only has one antenna (different technology). Assume we use TDMA with an *infinite* number of slots, and define each link's throughput to be the average number of streams transmitted (or DoF for SM) over time. Fig. 1 (b) shows their optimal throughput curve, which is derived from the convex hull of all the possible base rate combinations: $(2, 0), (1, 1), (1, 0), (0, 1), (0, 0)$. Suppose we want to achieve proportional fairness, and let the ratio between the throughput of two links to be the same as that of their maximum throughput without interference (i.e., 2:1). Under the interference-avoidance paradigm, the Pareto-optimal fair throughput pair is $(1, 0.5)$. In contrast, under CIM (link 1 uses both transmitter and receiver side IC), the new pair is $(\frac{4}{3}, \frac{2}{3})$, which is achieved by sending $(1, 1), (1, 1), (2, 0)$ streams during three consecutive slots for each link. Note that this also requires link 2 to cooperate by not transmitting during the third slot. This example clearly shows the potential of using IC for CIM.

To enable such cooperation between heterogeneous multi-hop networks, global information of active sessions and the interference graph in both networks needs to be known. This can be difficult in unplanned deployments, as there lacks a common communication channel (CCC) between networks with different protocol standards. However, it is possible to obtain such information without a CCC. For example, Zhang and Shin [34] proposed GapSense, a lightweight protocol to coordinate among heterogeneous wireless devices based on energy sensing. It can be regarded as a side channel using implicit communication. In reality, we can assume each network has a central controller or base station, and these controllers can exchange necessary information for CIM using implicit communications. The performance bounds for each network form a Pareto-optimal curve. In reality, to choose from one working point on the curve, two networks can make agreements based on certain criteria like fairness (max-min or proportional) or max total rate. This can be achieved because we assume that the networks are cooperative. In the case that networks are selfish and may deviate from cooperation, a game-theoretic approach is needed which will be left for our future work.

Key Challenges. There involves a unique set of challenges to realize CIM in a multi-hop network setting. (1) So far TIMO has only been applied to the single-link setting with non-cooperative CTI, and it is limited to canceling only one concurrent and co-channel CTI source [11], which reduces concurrent transmission opportunities. In a multi-hop network, there can be multiple simultaneous active links in each network which cause interfere to a link in the other network. How can we develop a feasible and general IC approach to cancel multiple concurrent interferers across different wireless technologies, without knowing the CTI's protocol type and signal structure? (2) To theoretically model and quantify the performance limit of CIM among heterogeneous MIMO networks, the intrinsic complexity involves both networks' cooperative link scheduling, MIMO DoF allocation for spatial multiplexing (SM), IC for both intra- and inter-network. The model must capture network heterogeneity: different PHY technologies, number of antennas, transmit power, data rates, etc. (3) Networks have competing interests such that each wants to maximize its own throughput. One may think of extending the capacity region concept to derive the Pareto-optimal throughput curve of the "combined network". Previously, Toumpis and Goldsmith studied the capacity region of SISO multi-hop wireless networks [29], which showed the region can be derived from the convex hull of a set of base rate matrices via arbitrary time-sharing. However it remains open for MIMO ad hoc networks due to the intractability of SNR model. Even if we adopt a DoF model but still use the convex hull based approach, there are numerous combinations that constitute the feasible base rate pairs of the two networks, which involves enumerating not only the link scheduling but also DoF allocation on each link. To the best of our knowledge, this problem also remains open to date.

III. Cooperative IC Across Different Technologies

In this section, we propose a cooperative technology-independent IC (TIIC) scheme to handle the interference cancellation to/from an arbitrary number of concurrent and co-channel CTI sources (subject to the DoF constraints at a node).

Overview. First we give an overview of our approach. Consider a scenario with one communication link k where the transmitter and receiver both have A antennas, and one or more active CTI links (interferers) $l_1, ..., l_M$ from another network with a different technology. We first assume each CTI link only has one antenna (e.g., ZigBee sensor or Bluetooth device). Different from TIMO [11] which assumes the CTI source is non-cooperative (thus a receiver needs to estimate the *channel ratio* β in the presence of the concurrent transmission of interference signal), we assume the CTI links and the MIMO link are cooperative. The goal is to make only one of the interferer's signal present at a time such that the receiver/transmitter can compute the interferers' channel ratios directly. This can be done by each interferer sending a short probing packet (PP) at different times (while link k is silent). For example, suppose TDMA is used, at the beginning of each time slot, all the active transmitters in a 802.15.4 network can schedule their PPs such that each is transmitted within a non-overlapping mini-slot (M in total). After the probing from l_i, the channel ratios $\{\beta_i(j) = \frac{h_i(j)}{h_i(1)}\}_{j\in[2,A]}$ are obtained by taking the ratio of the received symbols on each antenna, where $h_i(j)$ is the (frequency version) channel gain from l_i to link k's receiver's jth antenna. After all the probing, the signal-of-interest s and interference signals may transmit concurrently.

Feasibility of Cross-Technology Cooperative IC. Next we show the feasibility of the cooperative IC. We adopt the matrix representation of MIMO IC based on the Zero-Forcing beamforming (ZFBF) [26], which is used by previous works [17], [23]. W.l.o.g., consider the cross-technology interference from the transmitter $\mathrm{Tx}(l)$ of a link l to receiver $\mathrm{Rx}(k)$ in a slot t, where node i has A_i antennas. For each active link l, denote z_l as the number of data streams and s_{li} the signal of stream i ($1 \le i \le z_l$). Denote $\mathbf{H}_{(l,k)}$ the $A_{\mathrm{Tx}(l)} \times A_{\mathrm{Rx}(k)}$ channel gain matrix between nodes $\mathrm{Tx}(l)$ and $\mathrm{Rx}(k)$ which is full-rank (assuming a rich scattering environment). Let transmitter $\mathrm{Tx}(l)$'s transmit weight vectors be $\mathbf{u}_{li}, 1 \le i \le z_l$, and receiver $\mathrm{Rx}(k)$'s receive weight vectors be $\mathbf{v}_{kj}, 1 \le j \le z_k$. The interference to data stream j on link k is:

$$\Big(\sum_{i=1}^{z_l} \mathbf{u}_{li} s_{li}\Big)^T \mathbf{H}_{(l,k)} \mathbf{v}_{kj} = \sum_{i=1}^{z_l} ((\mathbf{u}_{li})^T \mathbf{H}_{(l,k)} \mathbf{v}_{kj}) \cdot s_{li}.$$

To cancel this interference, the following constraints should be satisfied:

$$(\mathbf{u}_{li})^T \mathbf{H}_{(l,k)} \mathbf{v}_{kj} = 0 \quad (1 \le i \le z_l, 1 \le j \le z_k). \tag{1}$$

However, the complete matrix $\mathbf{H}_{(l,k)}$ is unknown due to different technology. In the special case we discussed above where link l has only one antenna, we have $z_l = 1$ and $\mathbf{u}_{li}$ equals to a constant while $\mathbf{H}_{(l,k)}$ is an $A_{\text{Rx}(k)}$ dimensional vector $\mathbf{h}_{(l,k)}$. Then we get $\sum_{d=1}^{A_{\text{Rx}(k)}} h_{(l,k)}(d) \cdot v_{kj}(d) = 0$. Since $v_{kj1} \neq 0$, if we divide $h_{(l,k)}(1)$ on both left and right side, we obtain

$$\mathbf{h}_{(l,k)} \cdot \mathbf{v}_{kj} = v_{kj}(1) + \sum_{d=2}^{A_{\text{Rx}(k)}} \beta_l(d) v_{kj}(d) = 0 \quad (1 \leq j \leq z_k), \tag{2}$$

where $\beta_l(d) = \frac{h_{(l,k)}(d)}{h_{(l,k)}(1)}$, $2 \leq d \leq A_{\text{Rx}(k)}$. Note that, Eq. (2) is equivalent to Eq. (1) thus it does not change the rank of the coefficient matrix of $\mathbf{v}_{kj}$. This means, the degree-of-freedom consumed by all constraints in Eq. (2) is unchanged.

When the CTI links have multiple antennas, we need to define "*extended channel ratio*" β'. Observe that in Eq. (1), $(\mathbf{u}_{li})^T \mathbf{H}_{(l,k)} = \mathbf{h'}_{(l,k)}$ which is an $A_{\text{Rx}(k)}$ dimensional vector, where $h'_{(l,k)}(d) = \sum_{j'=1}^{A_{\text{Tx}(l)}} u_{1i}(j') \cdot h_{(l,k)}(j', d)$ $(h'_{(l,k)}(1) \neq 0$ with high probability). Then,

$$\beta'_l(d) = \frac{h'_{(l,k)}(d)}{h'_{(l,k)}(1)}, \quad (2 \leq d \leq A_{\text{Rx}(k)}). \tag{3}$$

The extended channel ratio can be obtained in a similar way to the channel ratio. In the beginning of a slot, the active CTI link l sends a weighted probing signal $\mathbf{u}_{1i} \cdot s_l$ during each mini-slot $i (1 \leq i \leq z_l)$ where s_l is the probe packet, and z_l is the intended number of streams to transmit on l. The received signal vector on all the antennas of $\text{Rx}(k)$ is $(\mathbf{u}_{1i})^T \mathbf{H}_{(l,k)} s_l = \mathbf{h'}_{(l,k)} s_l$. Then, dividing the signal on the dth antenna by that of the 1st antenna yields exactly $\beta'_l(d)$.

The above describes the use of receiver side IC, which means the CTI transmitter $\text{Tx}(l)$ determines its transmit vectors $\mathbf{u}_{1i}$ first, and the receiver $\text{Rx}(k)$ decides its receive vectors $\mathbf{v}_{kj}$ later. The same approach can be easily extended to transmitter side IC ($\text{Tx}(k)$ cancels its CTI to $\text{Rx}(l)$), which can be achieved by letting the receiver $\text{Rx}(l)$ transmit a probing signal (e.g., a CTS packet in the beginning of a slot, or an ACK packet in the end), under the assumption of channel reciprocity [11]. If the channel is static the probing overhead can be amortized.

DoF Criterion. In general, we consider two multi-hop networks with different technologies. Similar to [23], let there be a global "node ordering" π among the nodes in the "combined network"; denote $\pi_{\text{Tx}(l)}$ and $\pi_{\text{Rx}(k)}$ as the positions of nodes $\text{Tx}(l)$ and $\text{Rx}(k)$ in π, respectively. Because in our channel ratio based IC scheme, every IC constraint equation is equivalent to the original one by a constant factor, the number of consumed DoFs of a vector due to a set of linear constraints among its elements is unchanged compared with normal IC with full CSI. Based on Lemma 5 in [23], we have the following lemma:

Lemma 1: Consider the cross-technology interference from Tx(l)'s z_l streams to Rx(k)'s z_k streams. Based on only channel ratio information, from the IC constraints in Eq. (1), we have (i) if $\pi_{Tx(l)} > \pi_{Rx(k)}$, then the number of DoFs consumed by IC are z_k and 0 at Tx(l) and Rx(k), respectively. If $A_{Tx(l)} = 1$ and $z_k \geq 1$, then $z_l = 0$ at Tx(l). (ii) If $\pi_{Tx(l)} < \pi_{Rx(k)}$, then the number of DoFs consumed by IC are 0 and z_l at Tx(l) and Rx(k), respectively.

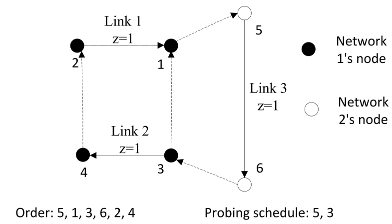


Fig. 2. An example realization of cooperative TIIC between three links (two from the same network). All links have two antennas and transmit one stream. Dotted lines represent the direction of IC on interfered links.

Such an ordering is both sufficient and necessary to ensure the feasibility of the above cross-technology IC scheme, and the node order also determines the probing order. Interestingly, we have the following observation.

Observation 1: A node needs to perform probing in a time slot t iff. it is active in t and is pointed "to" by an IC relation where both endpoints are in different networks. A probing schedule of channel ratio measurement maps to the set of all the need-to-probe nodes ordered by their node ordering for IC.

Fig. 2 shows a simple example with three links. The node ordering is $(5, 1, 3, 6, 2, 4)$, and the cross-network probing schedule is $(5, 3)$ (only two mini-slots are needed). Intra-network IC needs little overhead for estimating the CSI so it is neglected. In this way, the interference among all the links can be cancelled, independent to the wireless technology used. Compared with TIMO, our approach is cooperative, simpler, and is not limited to handle a single concurrent and co-channel CTI source thus is more general.

IV. Modeling and Formulation

In this and the next section, we systematically study the performance bounds of two (or more) heterogeneous multi-hop MIMO wireless networks under the CIM paradigm. Due to the absence of central administration, we consider each network aiming at maximizing its own throughput, assuming they cooperatively cancel/mitigate the interference to/from each other. However, the networks' objectives conflict with each other because of their mutual interference. Thus, we will develop a *bi-criteria optimization* framework, and characterize the *Pareto-optimal throughput curve* rather than a single optimal point. In order to be tractable, we adopt a recent DoF model from [23], and assume that time is slotted and finite instead of continuous assumed in capacity region research. Since arbitrary time sharing is not supported by a finite number of slots T, our result can be regarded as a lower bound to the case when $T \to \infty$ (however it is exact under our formulation).

A. Mathematical Modeling

System Model. Consider two unplanned multi-hop wireless networks $\mathcal{N}_1 = (V_1, E_1)$ and $\mathcal{N}_2 = (V_2, E_2)$ with heterogeneous technologies that interfere with each other, and $N_1 = \|V_1\|$ and $N_2 = \|V_2\|$. Assume the nodes in at least one network possess MIMO capability (e.g., an 802.11n ad hoc network v.s. WiMax, or ZigBee with SISO links). The MIMO nodes also uses our cooperative TIIC scheme to cancel the CTI from/to another network of different technology[1]. The networks operate in the same band, and we consider T time slots to be available to both networks[2]. Let $\mathcal{F}_i$ represent the set of multi-hop sessions in network i, and $r(f)$ denotes the rate of session $r \in \mathcal{F}_i$. Assume routing is given and denote $\mathcal{L}_i$ the set of active links in network i. Let $z_l(t)$ be the number of data streams transmitted over link $l \in \mathcal{L}_i$ during slot t. If a network is SISO, then $z_l(t) = 1$ when link l is active during slot t, otherwise $z_l(t) = 0$. Each network's goal is to maximize its own utility (function of session rates: $\sum_{f \in \mathcal{F}_i} h[r(f)]$) while using CIM.

Modeling the CIM Paradigm. We describe the general case where both networks are MIMO. To model channel access, we consider half-duplex transceivers for both networks. Denote binary variables $x_i(t)$ and $y_i(t)$ ($i \in V_1 \cup V_2, 1 \le t \le T$) as if node i transmits or receives at slot t. We have:

$$x_i(t) + y_i(t) \le 1 \qquad (i \in V_1 \cup V_2, 1 \le t \le T) \tag{4}$$

To realize CIM, both networks should use some of its resources to mitigate the interference with each other. For a MIMO network, each node can use MIMO IC to cancel the interference either to/from other nodes within the same network, and to/from nodes in the other network. While for a SISO network, it is not able to carry out any IC. Thus its cooperative behavior can be regarded as refrain from transmitting on a subset of its links that will interfere with the MIMO network during each slot, through link scheduling. The main complexity of the problem is due to the lack of predefined order/priority between any two networks so the responsibility of cooperation is in both networks in general. There are numerous combinations as to how the nodes should cancel the interference to/from links in its own network, and to/from the other network, and scheduling its transmission to not interfere with another network in case of SISO.

To this end, we adopt a recent MIMO link layer model [23], which introduces an ordering among the nodes for DoF allocation to ensure the feasibility of IC and avoid unnecessary duplication of IC. By inserting a formulation of the ordering relationship into a specific optimization problem, an optimal ordering can be found. In our case, a global order of nodes in both networks needs to be established in each time slot. Denote $1 \le \pi_i(t) \le N = N_1 + N_2$ as the absolute ordering of node i in slot t, and $\theta_{ji}(t)$ as the relative order between nodes j and i ($\theta_{ji}(t) = 1$ if j is before i and 0 otherwise). Then we have the following relationship:

$$\pi_i(t) - N \cdot \theta_{ji}(t) + 1 \le \pi_j(t) \le \pi_i(t) - N \cdot \theta_{ji}(t) + N - 1, \quad i, j \in V_1 \cup V_2, 1 \le t \le T \tag{5}$$

Next we describe the constraints for DoF consumption at each node, which includes DoFs spent for spatial multiplexing (SM), intra- and inter-network IC. With the above MIMO link model, a transmitter i needs only to cancel the interference to the set of neighboring nodes $\mathcal{I}_i \subset V_1 \cup V_2$ (within its interference range) that are before itself in the ordered list, and the DoF spent is equal to the number of streams received by those interfered nodes. A similar rule is used for a receiver. If node i is transmitting/receiving, its DoF consumptions cannot exceed the total number of DoFs of itself. Denote $\mathcal{L}_{i,out}$ and $\mathcal{L}_{i,in}$ as the set of outgoing and incoming links from node i, respectively. The transmitter side DoF constraints are:

$$x_i(t) \le \sum_{l \in \mathcal{L}_{i,out}} z_l(t) + [\sum_{j \in \mathcal{I}_i, j \in V_1 \cup V_2} (\theta_{j,i}(t) \sum_{k \in \mathcal{L}_{j,in}}^{Tx(k) \neq i} z_k(t))] x_i(t) \le A_i x_i(t), \quad i \in V_1 \cup V_2, 1 \le t \le T \tag{6}$$

The receiver sides' DoF constraints are similar:

$$y_i(t) \le \sum_{l \in \mathcal{L}_{i,in}} z_l(t) + [\sum_{j \in \mathcal{I}_i, j \in V_1 \cup V_2} (\theta_{j,i}(t) \sum_{k \in \mathcal{L}_{j,out}}^{Rx(k) \neq i} z_k(t))] y_i(t) \le A_i y_i(t) \quad i \in V_1 \cup V_2, 1 \le t \le T \tag{7}$$

Note that, these constraints are also satisfied under SISO($A_i = 1$). This is because a SISO node either transmits/receives or not (for latter case, either $x_i = \sum_{l \in \mathcal{L}_{i,out}} z_l(t) = 0$, or $y_i = \sum_{l \in \mathcal{L}_{i,in}} z_l(t) = 0$). The above also captures the cross-network IC using the proposed cooperative TIIC scheme, which satisfies the same DoF constraints for transmitters/receivers (we neglect the probing overhead for theoretical analysis).

For the link capacity model, to reflect heterogeneous data rates, we multiply a different constant weight for each network (one DoF corresponds to 1 unit of data):

$$c_l = w_n \cdot \frac{1}{T} \sum_{t=1}^{T} z_l(t), \ \forall l \in \mathcal{L}_n, n \in \{1, 2\}, 1 \le t \le T \tag{8}$$

Reformulation. In order to convert the non-linear constraints into linear ones, we reformulate Eqs. 6 and 7 into the following. First, by imposing an upper bound (large constant) $B = \sum_{j \in \mathcal{I}_i, j \in V_1 \cup V_2} \sum_{k \in \mathcal{L}_{j,in}}^{Tx(k) \neq i} A_k$, and $B' = \sum_{j \in \mathcal{I}_i, j \in V_1 \cup V_2} \sum_{k \in \mathcal{L}_{j,out}}^{Tx(k) \neq i} A_k$, where $\mathcal{I}_i$ is the interference node set of link i, Eq. 6 can be converted into Eq. 9, and Eq. 7 can be converted into Eq. 10.

$$\sum_{l \in \mathcal{L}_{i,out}} z_l(t) + [\sum_{j \in \mathcal{I}_i, j \in V_1 \cup V_2} (\theta_{j,i}(t) \sum_{k \in \mathcal{L}_{j,in}}^{Tx(k) \neq i} z_k(t))] \le x_i(t) \cdot A_i + (1 - x_i(t)) B, \quad i \in V_1 \cup V_2, 1 \le t \le T \tag{9}$$

$$\sum_{l \in \mathcal{L}_{i,in}} z_l(t) + [\sum_{j \in \mathcal{I}_i, j \in V_1 \cup V_2} (\theta_{j,i}(t) \sum_{k \in \mathcal{L}_{j,out}}^{Rx(k) \neq i} z_k(t))] \le y_i(t) \cdot A_i + (1 - y_i(t)) B', \quad i \in V_1 \cup V_2, 1 \le t \le T \tag{10}$$

[1]We assume that the networks' technologies are unknown to each other, thus complete CSI across networks is not obtainable.

[2]This reflects that spectrum is crowded. We can also extend this to model an additional set of channel resources.

Then, we apply the Reformulation-Linearization Technique (RLT) [22] to transform the above to linear constraints. Specifically, define $\lambda_{j,i}(t) = \theta_{j,i}(t) \sum_{k\in\mathcal{L}_{j,in}}^{Tx(k)\neq i} z_k(t)$, Eq. 9 can be rewritten as:

$$\sum_{l\in\mathcal{L}_{i,out}} z_l(t) + \sum_{j\in\mathcal{I}_i, j\in V_1\cup V_2} \lambda_{j,i}(t) \leq x_i(t)\cdot A_i + (1-x_i(t))B,$$
$$i \in V_1 \cup V_2, 1 \leq t \leq T \quad (11)$$

Because we also have $\theta_{j,i}(t) \geq 0$, $1-\theta_{j,i}(t) \geq 0$, $\sum_{k\in\mathcal{L}_{j,in}}^{Tx(k)\neq i} z_k(t) \geq 0$ and $A_j - \sum_{k\in\mathcal{L}_{j,in}}^{Tx(k)\neq i} z_k(t) \geq 0$, we can obtain the following linear constraints by multiplying them together:

$$\lambda_{j,i}(t) \geq 0, \quad (12)$$
$$\lambda_{j,i}(t) \leq A_j \cdot \theta_{j,i}(t), \quad (13)$$
$$\lambda_{j,i}(t) \leq \sum_{k\in\mathcal{L}_{j,in}}^{Tx(k)\neq i} z_k(t), \quad (14)$$
$$\lambda_{j,i}(t) \geq A_j \cdot \theta_{j,i}(t) - A_j + \sum_{k\in\mathcal{L}_{j,in}}^{Tx(k)\neq i} z_k(t), \quad (15)$$

for all $i \in V_1 \cup V_2, j \in \mathcal{I}_i, 1 \leq t \leq T$. Eqs. 11-15 are equivalent with Eq. 9. Similarly, define $\mu_{j,i}(t) = \theta_{j,i}(t) \sum_{k\in\mathcal{L}_{j,out}}^{Rx(k)\neq i} z_k(t)$, Eq. 10 can be replaced by:

$$\sum_{l\in\mathcal{L}_{i,in}} z_l(t) + \sum_{j\in\mathcal{I}_i, j\in V_1\cup V_2} \mu_{j,i}(t) \leq y_i(t)\cdot A_i + (1-y_i(t))B', \quad (16)$$

$$\mu_{j,i}(t) \geq 0, \quad (17)$$
$$\mu_{j,i}(t) \leq A_j \cdot \theta_{j,i}(t), \quad (18)$$
$$\mu_{j,i}(t) \leq \sum_{k\in\mathcal{L}_{j,out}}^{Rx(k)\neq i} z_k(t), \quad (19)$$
$$\mu_{j,i}(t) \geq A_j \cdot \theta_{j,i}(t) - A_j + \sum_{k\in\mathcal{L}_{j,out}}^{Rx(k)\neq i} z_k(t), \quad (20)$$

where $i \in V_1 \cup V_2, j \in \mathcal{I}_i, 1 \leq t \leq T$.

B. Formulation

The mathematical formulation of the throughput maximization problem of both networks can be casted into Fig. 3, which can be converted to a bi-criteria mixed-integer linear program (MILP). $h(\cdot)$ is a network utility function representing the objective.

As shown in the formulation, the objective is to maximize both networks' utilities simultaneously while satisfying all constraints. The optimization variables include: network 1 and 2's session rates $r(f)$ and $r(g)$, $\pi_i(t)$, $\theta_{ji}(t)$, $z_l(t)$, $x_i(t), y_i(t)$, and

$$\max U_1 = \sum_{f\in\mathcal{F}_1} h[r(f)]$$
$$\max U_2 = \sum_{g\in\mathcal{F}_2} h[r(g)]$$

s.t. (for both networks)

Half duplex constraints:(4);

Node ordering constraints:(5);

Transmitter/receiver DoF constraints:$(11)-(15), (16)-(20)$;

Flow balance constraints;

Flow rate $\leq$ link capacity;

Link capacity model:(8)

Fig. 3. Original bi-criteria optimization formulation (MOPT).

additional variables $\lambda_{ji}(t)$, $\mu_{j,i}(t)$ in the reformulated problem. Even the single-objective version of the above MILP problem is NP-hard in the worst case. However, we will show that this can be converted into multiple (a small number of) single-objective MILP problems, where there exist highly efficient optimal [21] or approximation algorithms such as sequential fixing algorithms [31] to solve it.

V. Pareto-Optimal Throughput Curve

In this section, we explore a novel approach to find the optimal throughput curve of two heterogeneous multi-hop MIMO networks. We consider the linear case[3] where $h[r(f)] = \alpha_1 \cdot r(f)$ and $h[r(g)] = \alpha_2 \cdot r(g)$, such that $\sum_{f\in\mathcal{F}_1} h[r(f)]$ and $\sum_{g\in\mathcal{F}_2} h[r(g)]$ represent the weighted throughput of each network, respectively.

We want to find all the *Pareto-optimal* utility pairs (U_1, U_2) such that there does *not* exist another solution (U_1', U_2') such that $U_1' \geq U_1$ and $U_2' \geq U_2$. By fixing one objective ($U_1 = u_1$) and find the optimal value of the other (U_2), that is to solve a single optimization problem:

$$OPT(u_1): \max U_2, \quad (21)$$
$$\text{s.t.} U_1 = u_1, \text{and all constraints in MOPT},$$

one can obtain a one-to-one mapping $U_2 = f(u_1)$ which defines an optimal throughput curve containing all the *weakly Pareto-optimal* points. A weakly Pareto-optimal point is a utility pair (U_1, U_2) such that there does *not* exist another solution (U_1', U_2') such that $U_1' > U_1$ and $U_2' > U_2$. A Pareto-optimal point is also weakly Pareto-optimal, but not vice versa.

Since U_1 and U_2 are continuous, a naive approach to approximate the curve is to discretize $[0, U_{max}]$ into a large number of equal intervals, solve $OPT(u_1)$ for each discrete u_1, and connect the corresponding optimal values of U_2 via line segments. However, each instance is an MILP problem (NP-hard in general), thus this method incurs high complexity and does not give any performance guarantee.

Instead of brute-force or trying approximation approaches, through exploiting the property of the curve itself, we find that the exact curve can be obtained (under our formulation).

[3]Non-linear utility functions will be our future work.

Firstly, it is easy to see the curve is *non-increasing* with U_1, because when U_1 increases the interference to $\mathcal{N}_2$ also increases. Interestingly, we have the following Theorem which gives the basis of our method:

Theorem 1: When T is finite, the optimal throughput curve $U_2 = f(u_1)$ is a stair-shape non-continuous function, and the minimum unit stair width is $\alpha_1 \cdot w_1/T$.

Proof: The basic idea can be explained by perturbation analysis. Observe that the form of Eq. (8) is $c_l = kw_1/T$ where $k \geq 0$ is an integer which increment by a least step of one. First we assume that there is only one flow in each network, and the link capacity constraints are $r(f) \leq c_l$, $\forall l$ on f, $r(g) \leq c_l$, and $\forall l$ on g. Also, $u_1 = \alpha_1 \cdot r(f) = \alpha_1 \cdot \min\{c_l\}_{\forall l \text{ on } f}$, $u_2 = \alpha_2 \cdot r(g) = \alpha_2 \cdot \min\{c_l\}_{\forall l \text{ on } g}$ which increment by least steps of $\alpha_1 w_1/T$ and $\alpha_2 w_2/T$, respectively. Suppose $(k-1)\alpha_1 \cdot w_1/T < u_1 < k\alpha_1 \cdot w_1/T$, and a small increase δ is applied to u_1 so that $u_1' = u_1 + \delta$. If $u_1' < \alpha_1 \cdot kw_1/T$, it does not violate any constraint in $\mathcal{N}_1$'s own network, thus all the variables in $\mathcal{N}_1$ remain unchanged. Consequently, none of the constraints in $OPT(u_1)$ are violated, therefore the optimal U_2 remains unchanged.

In the general case of multiple flows contained in each network, each session can be independent or share links with other sessions. The two networks' objective functions become $\alpha_1 \cdot \sum_{f \in \mathcal{F}_1} r(f)$ and $\alpha_2 \cdot \sum_{g \in \mathcal{F}_2} r(g)$, respectively. The link capacity constraints become $\sum_{f \text{ traverse } l} r(f) \leq c_l$, $\forall l \in \mathcal{L}_1$, and $\sum_{g \text{ traverse } l} r(g) \leq c_l$, $\forall l \in \mathcal{L}_2$, respectively. In general, $\alpha_1 \cdot r(f)$, $\forall f \in \mathcal{F}_1$ is upper constrained by a set of linear expressions in the form of either $\alpha_1 \cdot r(f) \leq \alpha_1 \cdot \min\{c_l\}_{\forall l \text{ on } f}$ (in case of independent flow) or $\alpha_1 \cdot \sum_{f \text{ traverse } l} r(f) \leq \alpha_1 \cdot \min\{c_l\}_{\forall l \in \mathcal{L}_1}$ (in case of flow link sharing), which all increments by least step of $\alpha_1 w_1/T$. Thus, the upper bound to their linear combination $U_1 = \alpha_1 \cdot \sum_{f \in \mathcal{F}_1} r(f)$ also increments by least step of $\alpha_1 w_1/T$. Therefore, if U_1 changes by a small amount without violating the current upper bound, the optimal U_2 remains unchanged. Imagine increasing network A's utility $\sum_{f \in \mathcal{F}_1} \alpha_1 \cdot r(f)$ to a edge point, which means increasing a little amount δ will break the constraint $\alpha_1 \cdot \frac{1}{T} \sum_{t=1}^{T} z_l(t)$ on a link l. We could increase other links' rate $r_k(f)$ to their edge points while keeping $\sum_{f \in \mathcal{F}_1} \alpha_1 \cdot r(f)$ unchanged, thus the overall stream number in this network must be $N - \delta$, in which N is a integer. Therefore the network's rate at this point is $(N - \delta) \cdot \alpha_1 \cdot w_1/T$. ∎

The above means we need only to compute the points on the curve where $U_1 = \alpha_1 w_1 k/T, 0 \leq k \leq k_{max}$, and connect them using stair shape line segments. Each computation corresponds to solving one $OPT(u_1)$ instance. But the following theorem shows it is not necessary to cover all $0 \leq k \leq k_{max}$:

Theorem 2: There exists two saturation points $(U_{1s}, U_{2s}), (U_{1s}', U_{2s}')$ on the optimal throughput curve $f(u_1)$ where $U_{1s} \leq U_{1s}'$ and $U_{2s} \geq U_{2s}'$, such that $f(u_1) = U_{2s}$ for $u_1 \in [0, U_{1s}]$ and $f^{-1}(u_2) = U_{1s}'$ for $u_2 \in [0, U_{2s}']$.

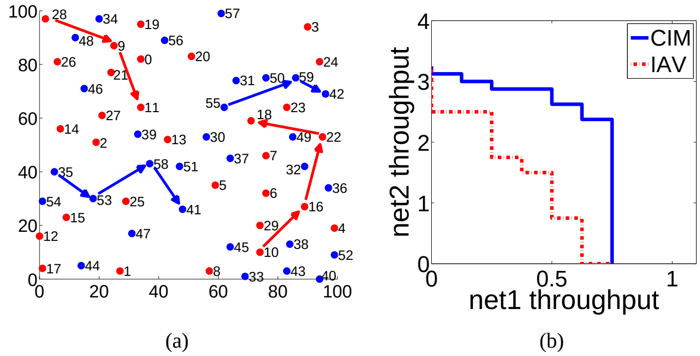


Fig. 4. (a) Active sessions in two heterogeneous networks (blue: Net 1, red: Net 2). (b) The optimal throughput curve for the two networks under CIM and IAV.

Proof: We only need to prove that when $u_2 = \max\{U_2\}$, $u_1 = OPT(u_2) \geq 0$. This is easy to see, because in general $\mathcal{N}_1$ and $\mathcal{N}_1$ are not completely interfered with each other, so there are still some available links in $\mathcal{N}_1$ that can deliver positive flow(s). Similarly, if $u_1 = \max\{U_1\}$, $u_2 = OPT(u_1) \geq 0$. ∎

Therefore, we can further reduce computation complexity by first identifying two saturation points on the curve (which can be obtained by only two instances of $OPT(\max\{U_1\})$ and $OPT(\max\{U_2\})$), then focusing on finding the curve points between them. Our method can also be extended to more than two networks, where the curve becomes multi-dimensional.

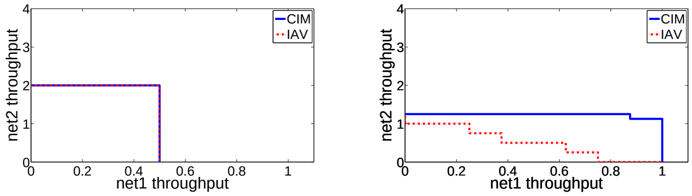
VI. Evaluation

In this section, we use numerical results to show the gain of CIM compared with the Interference Avoidance (IAV) paradigm, where each network only cancels/mitigates the interference within itself but not to/from another network. We also examine the impacts of various types of interference scenarios and network heterogeneity.

A. A Case Study

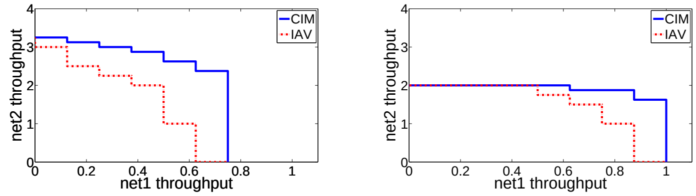
We use a case study to show the gain of the CIM paradigm. Consider two multi-hop networks (topology and sessions shown in Fig. 4 (a)) with 30 nodes each, deployed in a 100×100 area. Networks 1 and 2 both have two active sessions (14 active nodes in total) and min-hop routing is used. We assume network 1 is a traditional SISO network, while network 2 is equipped with MIMO (4 antennas per node). For simplicity, assume $w_1 = w_2 = 1$ and $\alpha_1 = \alpha_2 = 1$. All nodes' transmission and interference range are 30 and 50, respectively. There is one band and $T = 8$ time slots available. We use CPLEX to solve for the exact solution of each $OPT(u_1)$ instance. The results are generated by an Intel 4 core i5-2400 with a 3.1GHz CPU and 8GB RAM.

The derived stair-shape curve is shown in Fig. 4 (b). The blue line denotes the curve when using CIM, and the red line denotes the one using IAV. It can be seen that the minimum unit step is $1/8$. Obviously, for every point on the IAV's curve, one can find another point on the CIM's curve which Pareto-dominates the former, thus both networks' throughputs are



(a) (b)

Fig. 5. In (a), Network 1 has 1 session: 45 → 38 →52. Network 2 has 1 session: 26 → 0 → 20. In (b), Network 1 has 1 session: 50 → 30. Network 2 has 1 session: 21 → 27 → 13 → 5.



(a) (b)

Fig. 6. In (a), Network 1 has 2 sessions:35 → 53 → 47, 37 → 49 → 36. Network 2 has 2 sessions: 10 → 16 → 22 → 18, 12 → 15 → 25. In (b), Network 1 has 2 sessions: 41 → 51 → 55, 48 → 34 → 56. Network 2 has 2 sessions: 8 → 10 → 4, 5 → 7 → 23.

enhanced compared with IAV. All computations for the curve finished within reasonable amount of time.

To verify the networks' cooperative behavior under CIM, we select the maximum total-throughput point $(0.5, 2.875)$ on the curve as an example. It can be derived by drawing a line with slope of -1 and find the tangential point with the curve. This point reflects the maximum overall benefit of both networks.

In Table. I, we list the stream allocation during all the slots for all the links. First, we can verify that all interference is cancelled. For example, in slot 7, links $58 \to 41, 9 \to 11, 10 \to 16, 22 \to 18$ are active. The interference graph is $58 \Rightarrow 11, 58 \Rightarrow 18, 10 \Rightarrow 18, 22 \Rightarrow 16$. Nodes $9, 11$ use 3 out of their 4 total DoFs for SM, with the remaining 1 DoF used for cancelling the CTI from node 58. Similarly, node $22, 18, 10, 16$ all spare some DoFs for CIM.

Second, from the node ordering we can see how cooperation is done. For example, $\theta_{58,11} = 1$, which means node 11 applies receiver side IC to cancel the CTI from node 58. On the other hand, $\theta_{18,59} = 1$, thus node 59 in network 1 should cancel its CTI to node 18 in network 2. As the nodes in network 1 has only one antenna, node 59 will keep silent. Interestingly, we find that more of network 2's nodes tend to be ordered behind network 1's, because the former has more DoF resources.

Various other points can be easily identified from the curve. For max-min fairness (MMF), the throughput pair is $(0.75, 2.375)$ – the top-right corner point. In this specific case, MMF is realized by network 2 solely canceling its CTI to/from network 1. The proportional fairness point is $(0.625, 2.5)$, if we define the ratio to be $1 : 4$ (antenna numbers).

B. Impact of Different Interference Degrees

We further compare CIM's performance with that of IAV's, by changing the extent to which both networks interfere with each other. For example, we alter the nearest distance between the active sessions in both networks.

In Fig. 5, we choose two scenarios containing one session in each network, while Fig. 6 contains results from two scenarios with multiple sessions in each network. In Fig. 5 (a), the two sessions are far apart so as to not interfere with each other, while in Fig. 5 (b) they are near enough to fully interfere with each other. But in Fig. 6 (a), the interference degree is higher than that of Fig. 6 (b). We can observe in Fig. 5 (a), the curves derived by CIM and IAV are exactly the same. In contrast, the two curves separate in Fig. 5 (b). The gap between two curves is larger in Fig. 6 (a) than in Fig. 6 (b). The above shows that

Sessions	Link	Time Slot	DoF of SM	Max Allowable Rate
Session1-1	35 → 53	4	1	0.25
		5	1	
	53 → 58	0	1	0.25
		2	1	
	58 → 41	1	1	0.25
		7	1	
Session1-2	55 → 59	4	1	0.25
		5	1	
	59 → 42	1	1	0.25
		2	1	
Session2-1	28 → 9	0	4	1.75
		2	4	
		4	3	
		5	3	
	9 → 11	1	3	1.75
		3	4	
		6	4	
		7	3	
Session2-2	10 → 16	0	2	1.125
		1	2	
		3	4	
		7	1	
	16 → 22	2	3	1.125
		4	3	
		5	3	
	22 → 18	0	2	1.125
		1	1	
		6	4	
		7	2	

TABLE I
LINK STREAM ALLOCATION IN EACH SLOT AT THE MAXIMUM TOTAL THROUGHPUT POINT

more benefit can be gained by CIM compared with IAV as two networks mutually interfere to a larger degree.

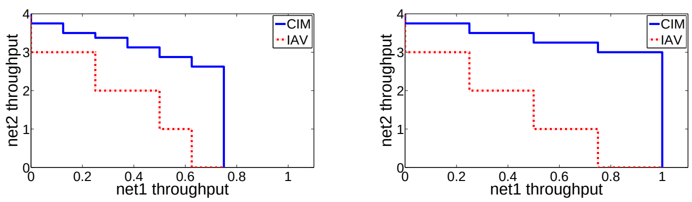
We then randomly generate 50 scenarios to show the better performance of CIM compared with IAV in an average sense. Again we pick the maximum total-throughput point of two networks, and compare the total throughput. Network 1 and Network 2 are equipped with 2 and 4 antennas respectively to reflect heterogeneity. The results are shown in Table. II. It can be seen that the maximum total throughput under CIM is significantly larger than the ones under IAV in some cases. In other cases, the total throughput is the same for these two paradigms. Again, this is due to different interference degrees among the sessions in different networks as their distance varies. Similar results can be obtained under other throughput allocation criteria such as max-min or proportional fairness, which are not elaborated in this paper.

C. Impact of Network Heterogeneity

We also show the effectiveness of CIM in more heterogeneous network scenarios, by considering different transmit powers and data rates. The former changes transmission and interference ranges. This is to reflect reality, such as 802.11 v.s. 802.15.4 networks.

Scenarios	CIM	IAV	Scenarios	CIM	IAV
0	3.5	2.75	25	4.625	4.625
1	4.25	4	26	4.5	4
2	8	7.5	27	4	4
3	6	6	28	5	5
4	4	4	29	4.625	4
5	3	2	30	4	4
6	10	10	31	7	6
7	4.25	4	32	2.125	2
8	4.625	4.625	33	5.25	5.25
9	8	8	34	5	4
10	2	2	35	4.125	4
11	5.25	5.25	36	2	2
12	3.25	3.25	37	3	2
13	3.75	3	38	4	4
14	5	4	39	2.125	2
15	6	6	40	6	6
16	4.625	4.625	41	6	6
17	2.375	2	42	6	6
18	6	6	43	4	4
19	6	6	44	4.125	4
20	4	4	45	2.5	2.5
21	6.75	6.5	46	6	6
22	2.5	2.5	47	4.625	4
23	2.5	2.5	48	4	4
24	5.25	5.25	49	3	2.5

TABLE II
MAX. TOTAL THROUGHPUT COMPARISON BETWEEN CIM AND IAV



(a) (b)

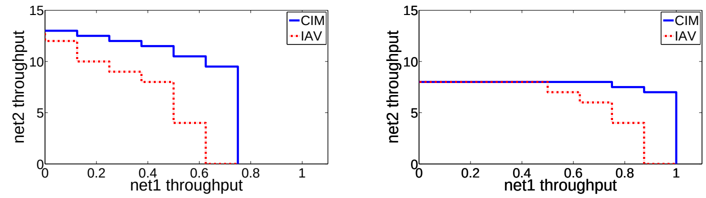
Fig. 7. In (a) and (b), Network 1 has 2 sessions:39 → 51 → 41, 55 → 50 → 59 → 42. Network 2 has 2 sessions: 28 → 0 → 27, 10 → 16 → 18. For (a), the transmission ranges are (20,40), the interference ranges are (30,60). For (b), the transmission ranges are (33,40) the ranges are (50,60)

In Fig. 7 (a), we set the transmission ranges for networks 1 and 2 to be 20 and 40, and the interference ranges to be 30 and 60, respectively. In Fig. 7 (b), we increase network 1's transmission range to 33, interference range to 50. One can see that both the throughput region and the gap between CIM and IAV enlarges in Fig. 7 (b). There are two insights: (1) larger transmission range decreases hop count thus increases one's own throughput; (2) Both networks have larger incentives to cooperate when the interference is more symmetric based on their higher simultaneous gains compared with IAV.

For different data rates, suppose $w_2 = 4w_1$ (such as 1Mbps in WiFi and 250kbps in ZigBee) instead of $w_2 = w_1$. The results are shown in Fig. 8. Compared with Fig. 6, essentially the throughput curve scales by a factor of 4 in the y-axis.

VII. Related Works

In the information theoretic community, prior works mainly focused on characterizing the MIMO channel capacity for Gaussian interference channels, either using the Shannon capacity [9] or degree-of-freedom based approach [4], [15]. However, results are mostly limited to very simple settings such as node/link pairs or *single-hop* communications. Even for a single



(a) (b)

Fig. 8. In (a), Network 1 has 2 sessions:35 → 53 → 47, 37 → 49 → 36. Network 2 has 2 sessions: 10 → 16 → 22 → 18, 12 → 15 → 25. In (b), Network 1 has 2 sessions: 41 → 51 → 55, 48 → 34 → 56. Network 2 has 2 sessions: 8 → 10 → 4, 5 → 7 → 23.

multi-hop MIMO network, the exact capacity in the traditional Shannon sense is an open problem.

The networking community, on the other hand, has explored MIMO IC and SM to optimize the performance of multi-hop wireless networks [2], [3], [13], [28]. Degree-of-freedom (DoF) is a typical model for MIMO links due to its analytical tractability. Some of them only considered either transmitter or receiver side cancellation [7], [13], [18] which is a conservative model (sufficient but not necessary), while several works modeled both possibilities [3], [27] but tend to be opportunistic (necessary but not sufficient). To date, there is no DoF model that is both sufficient and necessary. In fact, Shi et al. showed that finding an optimal DoF model is still an open problem [24]. To ensure feasibility of IC, in this paper we adopt the DoF model proposed by Liu et al. [17] based on node ordering.

However, the above works only studied the standalone network setting, which concerns only *internal-interference* from within the same network. There is very limited work that apply MIMO IC techniques to mitigate *external interference* for multi-hop wireless networks. For spectrum sharing in the unlicensed bands, (e.g., WiFi, ZigBee and Bluetooth etc.), past research has mostly adopted the interference-avoidance approach to mitigate external CTI or enhance network coexistence [14], [16], [19], [33], which separates transmissions in space, time or frequency. In the 802.11-based WLAN literature, most works only attempt to efficiently share the bandwidth of a wireless channel through channel allocation [5] or channel bonding [25]. Recently, Blough [8] applied MIMO IC to deal with inter-cell interference in densely deployed WLANs. However, their study focused on simple one-hop networks. Similarly, in the femtocell literature, cooperative processing [32] and interference alignment [12], [20] has been adopted to mitigation inter-cell interference (also unplanned deployments). Again, those are limited to one-hop networks. Moreover, all the above works only apply to homogeneous networks with the same protocol standards. In contrast, this paper studies the external CTI mitigation for heterogeneous multi-hop networks.

Recently, in cognitive radio networks, Yuan et al. proposed to realize the "transparent coexistence" or "underlay" paradigm between multi-hop secondary and primary networks using MIMO IC [31]. However, this paradigm is suitable for a planned deployment but not for unplanned ones (e.g., networks in the unlicensed bands), where there is no predefined priority nor central control and each network has its own interest.

Hence, simple extension of the optimization framework in [31] is not applicable to the unplanned setting.

VIII. Conclusions and Future Work

This paper offered a thorough study of the cooperative cross-technology interference mitigation (CIM) paradigm for heterogeneous multi-hop networks in unplanned settings. The main technical challenges are due to the lack of a predefined network priority in unplanned deployments, and various forms of network heterogeneity. We first show that general technology-independent interference cancellation is feasible for heterogeneous multi-hop networks with different protocol standards, and then establish a tractable theoretical framework to characterize the performance bounds of CIM via deriving the Parato-optimal throughput curve. Through extensive simulation results we show that the CIM paradigm can offer significant performance gains in throughput and spectrum efficiency to both networks compared with the traditional interference-avoidance paradigm. The models and results in this paper will guide practical CIM protocol design, and pave the way to ultimately change the coexistence paradigm for unplanned heterogeneous networks in unlicensed bands and TV white spaces.

In the future, we plan to extend our model to capture more factors of system heterogeneity, such as different bandwidth. We will also investigate the incentives for cooperation in a distributed setting assuming selfish networks, and fully distributed CIM protocols that approach the theoretical performance limits without explicit communication between networks.

Acknowledgments

The authors would like to thank Dejun Yang, Huacheng Zeng and Qiben Yan for helpful discussions.

References

[1] J. Bernhard, J. Reed, and J. M. Park. Final report of the national science foundation workshop on. enhancing access to the radio spectrum (ears). *http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503480*, 2010.

[2] R. Bhatia and L. Li. Throughput optimization of wireless mesh networks with mimo links. In *IEEE INFOCOM 2007*, pages 2326–2330, 2007.

[3] D. Blough, G. Resta, P. Santi, R. Srinivasan, and L. Cortes-Pena. Optimal one-shot scheduling for mimo networks. In *IEEE SECON*, pages 404–412, 2011.

[4] V. Cadambe and S. Jafar. Interference alignment and degrees of freedom of the k -user interference channel. *Information Theory, IEEE Transactions on*, 54(8):3425–3441, 2008.

[5] S. Chieochan, E. Hossain, and J. Diamond. Channel assignment schemes for infrastructure-based 802.11 wlans: A survey. *Communications Surveys Tutorials, IEEE*, 12(1):124–136, 2010.

[6] K. Chowdhury and I. Akyildiz. Interferer classification, channel selection and transmission adaptation for wireless sensor networks. In *Communications, 2009. ICC '09. IEEE International Conference on*, pages 1 –5, june 2009.

[7] S. Chu and X. Wang. Adaptive and distributed scheduling in heterogeneous mimo-based ad hoc networks. In *IEEE MASS '09*, pages 217–226, 2009.

[8] L. M. Cortes-Pena and D. M. Blough. Distributed mimo interference cancellation for interfering wireless networks: Protocol and initial simulation. *http://www.cercs.gatech.edu/tech-reports/tr2013/git-cercs-13-02.pdf*, Feb. 2013.

[9] R. Etkin, D. Tse, and H. Wang. Gaussian interference channel capacity to within one bit. *Information Theory, IEEE Transactions on*, 54(12):5534–5562, 2008.

[10] G. Fang, E. Dutkiewicz, K. Yu, R. Vesilo, and Y. Yu. Distributed inter-network interference coordination for wireless body area networks. In *IEEE GLOBECOM 2010*, pages 1 –5, dec. 2010.

[11] S. Gollakota, F. Adib, D. Katabi, and S. Seshan. Clearing the rf smog: making 802.11n robust to cross-technology interference. In *ACM SIGCOMM 2011*, pages 170–181, New York, NY, USA, 2011. ACM.

[12] B. Guler and A. Yener. Interference alignment for cooperative mimo femtocell networks. In *IEEE GLOBECOM 2011*, pages 1–5, 2011.

[13] B. Hamdaoui and K. G. Shin. Characterization and analysis of multi-hop wireless mimo network throughput. In *ACM MobiHoc '07*, pages 120–129, New York, NY, USA, 2007. ACM.

[14] J. Huang, G. Xing, G. Zhou, and R. Zhou. Beyond co-existence: Exploiting wifi white space for zigbee performance assurance. In *IEEE ICNP '10*, pages 305–314, 2010.

[15] S. Jafar and M. Fakhereddin. Degrees of freedom for the mimo interference channel. *Information Theory, IEEE Transactions on*, 53(7):2637–2642, 2007.

[16] C. Liang, N. Priyantha, J. Liu, and A. Terzis. Surviving wi-fi interference in low power zigbee networks. In *Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems*, pages 309–322. ACM, 2010.

[17] J. Liu, Y. Shi, and Y. Hou. A tractable and accurate cross-layer model for multi-hop mimo networks. In *INFOCOM, 2010 Proceedings IEEE*, pages 1–9, 2010.

[18] B. Mumey, J. Tang, and T. Hahn. Algorithmic aspects of communications in multihop wireless networks with mimo links. In *IEEE ICC*, pages 1–6, 2010.

[19] R. Shah and L. Nachman. Interference detection and mitigation in ieee 802.15. 4 networks. In *IEEE IPSN'08*, pages 553–554. IEEE Computer Society, 2008.

[20] S. Sharma, S. Chatzinotas, and B. Ottersten. Interference alignment for spectral coexistence of heterogeneous networks. *EURASIP Journal on Wireless Communications and Networking*, 2013(1):1–14, 2013.

[21] S. Sharma, Y. Shi, Y. Hou, H. Sherali, and S. Kompella. Cooperative communications in multi-hop wireless networks: Joint flow routing and relay node assignment. In *INFOCOM, 2010 Proceedings IEEE*, pages 1–9, 2010.

[22] H. D. Sherali and W. P. Adams. *A Reformulation-Linearization Technique for Solving Discrete and Continuous Nonconvex Problems*. Springer, 2010.

[23] Y. Shi, J. Liu, C. Jiang, C. Gao, and Y. Hou. An optimal link layer model for multi-hop mimo networks. In *INFOCOM, 2011 Proceedings IEEE*, pages 1916–1924, 2011.

[24] Y. Shi, H. Zeng, C. Jiang, and Y. T. Hou. An open problem in dof-based models for multi-hop mimo networks. In *IEEE WIRELESS COMMUNICATIONS LETTERS*, 2013.

[25] V. Shrivastava, S. Rayanchu, J. Yoonj, and S. Banerjee. 802.11n under the microscope. In *ACM IMC'08*, pages 105–110, New York, NY, USA, 2008. ACM.

[26] Q. Spencer, A. Swindlehurst, and M. Haardt. Zero-forcing methods for downlink spatial multiplexing in multiuser mimo channels. *Signal Processing, IEEE Transactions on*, 52(2):461–471, 2004.

[27] R. Srinivasan, D. Blough, and P. Santi. Optimal one-shot stream scheduling for mimo links in a single collision domain. In *IEEE SECON '09*, pages 1–9, 2009.

[28] K. Sundaresan, R. Sivakumar, M.-A. Ingram, and T.-Y. Chang. Medium access control in ad hoc networks with mimo links: optimization considerations and algorithms. *Mobile Computing, IEEE Transactions on*, 3(4):350–365, 2004.

[29] S. Toumpis and A. Goldsmith. Capacity regions for wireless ad hoc networks. *Wireless Communications, IEEE Transactions on*, 2(4):736–748, 2003.

[30] D. Tse and P. Viswanath. *Fundamentals of wireless communication*. Cambridge University Press, New York, NY, USA, 2005.

[31] X. Yuan, C. Jiang, Y. Shi, Y. Hou, W. Lou, and S. Kompella. Beyond interference avoidance: On transparent coexistence for multi-hop secondary cr networks. In *Proc. IEEE SECON*, pages 1–9, 2013.

[32] H. Zhang and H. Dai. Cochannel interference mitigation and cooperative processing in downlink multicell multiuser mimo networks. *EURASIP Journal on Wireless Communications and Networking*, 2004(2):202654, 2004.

[33] X. Zhang and K. Shin. Enabling coexistence of heterogeneous wireless systems: Case for zigbee and wifi. In *Proc. of ACM MobiHoc*, 2011.

[34] X. Zhang and K. G. Shin. Gap sense: Lightweight coordination of heterogeneous wireless devices. In *INFOCOM, 2013 Proceedings IEEE*, 2013.