Cooperative Cross-Technology Interference Mitigation for Heterogeneous Multi-hop Networks

Yantian Hou*   Ming Li*   Xu Yuan†   Y. Thomas Hou†   Wenjing Lou†

* Utah State University, UT, USA

† Virginia Polytechnic Institute and State University, VA, USA

Abstract—This paper explores a new paradigm for the coexistence among heterogeneous multi-hop networks in unplanned deployment settings, called cooperative interference mitigation (CIM). CIM exploits recent advancements in physical layer technologies such as technology-independent multiple output (TIMO), 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 show the feasibility of CIM among heterogeneous multi-hop networks by exploiting only channel ratio information, and then establish a tractable model to accurately characterize the CIM behaviors of both networks. We also develop a bi-criteria optimization formulation to maximize both networks' throughput, 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], [17], [20]. 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 [31]. 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) [12] 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], [14], [29]. 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 study on both the feasibility and theoretical performance limits of CIM. Recently IC has been adopted to fulfil the "transparent coexistence" or *underlay* paradigm in cognitive radio networks [32], 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 for a *planned* deployment but not for *unplanned* ones (e.g., networks in the unlicensed bands), where there is no predefined priority among networks, and each network has a competing interest which cannot be solved by single-objective optimization. Moreover, interference cancellation among multi-hop networks with *heterogeneous* wireless technologies has not been systematically 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 other coexisting networks, 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 TIMO approach [12] is based on measuring channel ratio, which works for simple single-hop settings but the feasibility of IC under arbitrary multi-hop setting is unknown.

To this end, we first explore the feasibility of CIM among heterogeneous multi-hop networks with different technologies by exploiting only partial CSI (or channel ratio information, CRI). Specifically, we show that compared with full CSI, such CRI does not affect the satisfiability of DoF constraints (or computability of transmit/receive vectors) in each network. We discuss possible methods to measure CRI and achieve cooperative technology-independent interference cancellation (TIIC). 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* under a finite number of slots, without solving a large number of MILP problems. It can be regarded as a lower-bound to the outer-bound of 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) [31] 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

(a) Two link scenario. Link 1 has two antennas, link 2 has one.
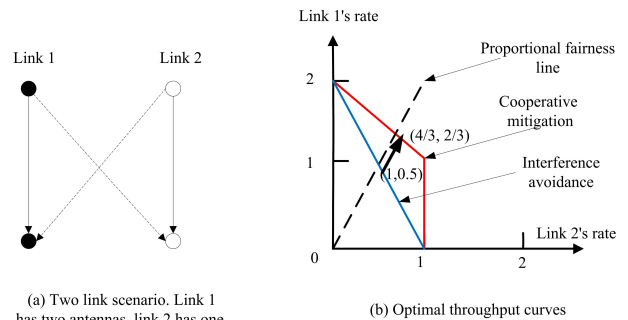
(b) Optimal throughput curves

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

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 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. [12] 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 among heterogeneous multi-hop networks, information including active sessions and the interference graph in each network needs to be shared with others. 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 [35] 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) How to cancel the interference from/to nodes in another multi-hop network of different wireless technology without having the full CSI? So far TIMO has only been applied to the single-link and non-cooperative setting, but its feasibility in multi-hop networks is unexplored. 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. Then how can the transmit/receive vectors of multiple active nodes can be designed to satisfy all nodes' DoF constraints? (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 [30], 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. FEASIBILITY OF COOPERATIVE TIIC AMONG MULTI-HOP NETWORKS

In this section, we study the feasibility of realizing cooperative TIIC across heterogeneous multi-hop networks. Specifically, considering the basic scenario of two coexisting networks, whether the links' transmissions in both networks can be scheduled such that all the interference from/to each other can be cancelled (subject to the DoF constraints at each node)? In the case of a single MIMO network, it has been shown feasible [2], [3], [14], [18], [24], [29] that links can cancel all the interference in the same network by allocating their transmission DoFs for SM and IC. However, the previous results are derived under the assumption of full CSI. To deal with cross-technology interference, only partial CSI can be obtained (such as channel ratio in TIMO [12]). Thus the natural question is, can MIMO and TIMO work together in heterogeneous multi-hop networks (use the former for intra-network IC and the latter for inter-network IC)?

TIIC based on Channel Ratio Information (CRI). We first give a theoretical treatment of TIIC based on CRI. We adopt the matrix representation of MIMO IC based on the Zero-Forcing beamforming (ZFBF) [27], which is used by previous works [18], [24]. W.l.o.g., consider the cross-technology interference from the transmitter $\text{Tx}(l)$ of a link l to receiver $\text{Rx}(k)$, 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 ($1 \leq i \leq z_l$). Denote $\mathbf{H}_{(l,k)}$ the $A_{\text{Tx}(l)} \times A_{\text{Rx}(k)}$ channel gain matrix between nodes $\text{Tx}(l)$ and $\text{Rx}(k)$ which is full-rank (assuming a rich scattering environment). Let transmitter $\text{Tx}(l)$'s transmit weight vectors be $\mathbf{u}_{li}, 1 \leq i \leq z_l$, and receiver $\text{Rx}(k)$'s receive weight vectors be $\mathbf{v}_{kj}, 1 \leq j \leq z_k$. 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:

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

However, the complete matrix $\mathbf{H}_{(l,k)}$ is unknown due to different technology. In the special case 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 $h_{(l,k)}(1) \neq 0$ w.h.p., if we divide $h_{(l,k)}(1)$ on both left and right sides, we obtain

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

$$(2)$$

where the "*channel ratio*" between link l's transmitter and link k's receiver is defined as: $\beta_{l,k}(d) = \frac{h_{(l,k)}(d)}{h_{(l,k)}(1)}$, $2 \le d \le A_{\text{Rx}(k)}$. 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-freedoms consumed by all constraints in Eq. (2) are unchanged. Note that, similar results can be derived for transmitter-side IC.

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 $h'_{(l,k)}(d) = \sum_{j'=1}^{A_{\text{Tx}(l)}} u_{li}(j') \cdot h_{(l,k)}(j',d)$, where $h'_{(l,k)}(1) \ne 0$ with high probability. Then,

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

Similar to Eq. (2), by replacing $\mathbf{h}_{(l,k)}$ with $\mathbf{h}'_{(l,k)}$ and $\beta_{l,k}(d)$ with $\beta'_{l,k}(d)$, the DoFs consumed are unchanged. Hereafter, we use *channel ratio information* (CRI) to refer to the union of channel ratio and extended channel ratio.

DoF Criterion. Now we explore the feasibility of TIIC in general for two multi-hop networks. Assume there is 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 a CRI-based TIIC 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 standard IC with full CSI. Based on Lemma 5 in [24], 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 CRI, 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 $z_k \ge 1$, 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.

The proof is straightforward. Such a node ordering is both sufficient and necessary to ensure the feasibility of transmit/receive vector allocation on each link, thus showing that the CRI-based TIIC can be used in multi-hop networks along with standard IC with full CSI.

Measuring the Channel Ratio Information. In order to obtain the CRI, TIMO can be used to measure the channel ratio for single antenna interference sources. Its current implementation is limited to single concurrent and co-channel interferer. Extending to multiple interferers is possible but the IC algorithm will be more complex. Therefore, we propose an alternative, cooperative approach to suit the CIM paradigm.

Our idea is to ensure only one of the interferer's signal is present at a time such that the channel ratios can be measured directly. We assume time is slotted (e.g., TDMA is used), which is necessary for optimized transmission scheduling. Each interferer sends a short probing packet (PP) at different times sequentially. Suppose there are M active nodes in total in one slot according to link scheduling, each of them can broadcast
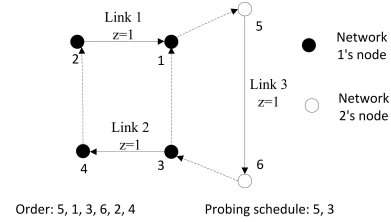

Fig. 2. An example realization of cooperative TIIC between three links (two from the same network). All links have two antennas and transmit one stream. Dotted lines represent the direction of IC on interfered links.

a PP within a non-overlapping mini-slot (M in total). Upon each probing, the channel ratios on each interfered node are obtained by taking the ratio of the received symbols on each antenna. After all the probing, the signal-of-interest and interference signals may transmit concurrently.

The extended channel ratio can be obtained in a similar way as the channel ratio. An active node on link l sends a weighted probing signal $\mathbf{u}_{li} \cdot s_l$ during each mini-slot $i (1 \le i \le z_l)$ 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 $(\mathbf{u}_{li})^T \mathbf{H}_{(l,k)} s_l = \mathbf{h}'_{(l,k)} s_l$. Then, dividing the signal on the dth antenna by that of the 1st antenna yields $\beta'_{l,k}(d)$.

The above describes the use of receiver side IC, which means the CTI transmitter $\text{Tx}(l)$ determines its transmit vectors $\mathbf{u}_{li}$ 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 $\text{Rx}(l)$), for which the receiver $\text{Rx}(l)$ transmits a probing signal, and then $\text{Tx}(k)$ can estimate the CRI based on channel reciprocity [12].

Interestingly, the probing order can be derived from the node order π, since a higher-priority node must decide its vector first.

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 CRI measurement is given by 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 of the wireless technology used.

Discussion. Here we discuss the overhead of our CRI-based cooperative TIIC scheme. First, the exchange of network flow information and interference graph (input to the optimization problem) is done at the beginning, which is a one-time overhead and can be amortized. Second, regarding probing signals, the number of mini-slots needed in the worst case is $(A_1 \cdot N_1 + A_2 \cdot N_2)$, where A_i is the number of antennas for each node in the ith network. In reality it can be much smaller because not all active nodes are involved in cross-network interference. Besides, the probing frequency depends on the channel coherence time, which is typically hundreds of milliseconds in static indoor environments [11]. In that case, the overhead can be amortized over multiple data slots. Third, time synchronization among networks is only required in our analytical optimization framework, which can be relaxed in

practice. For example, if a CSMA-like MAC protocol is used in both networks, neither probing and synchronization are needed. CRI measurement can be done by opportunistically exploiting overheard non-interfered signals from RTS/CTS/Data/ACK packets.

Next, we illustrate the overhead using a concrete example. Assume that network 1 and 2 has N_1 and N_2 nodes respectively. The first interference graph detecting phase needs all nodes to report their interference graph to the controller. This phase is needed only at the beginning, thus is a one-time overhead. The main overhead is sending the probing packets to calculate channel ratio. In the worst case, each node i will send A_i streams which is its available amount of DOF. Thus the worst time overhead is $N_1 * A_1$ and $N_2 * A_2$ for the two networks respectively. In reality node i doesn't need to send A_i probes if it is not allocated A_i streams to transmit. Therefore, we can see the overall time overhead is $O(N_1 + N_2)$ in the worst case. This overhead is acceptable as long as the sizes of networks are not large. In some scenarios, the overhead could be further reduced. For instance, in the networks shown in Fig. 4 (a), networks 1 and 2 both have 7 nodes. The nodes in network 1 and 2 has one and four antennas respectively. As the nodes in network 1 are not able to do any IC, thus network 2 does not needs to send probes to let network 1's nodes measure the CRI. The channel measurement within its own network uses normal preambles which causes much less overhead than the probing, and can be neglected. Therefore we only consider the overhead caused by network 1. We use slot 7 (as in Table. 1) as example and we can see only nodes 58 and 41 are active. Therefore only 2 probing packets need to be sent by network 1, which causes only $2 * 0.5 = 1$ ms time overhead. Even if the channel coherence time is as small as 10ms, this overhead only accounts for 10% of the time.

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 [24], 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:

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

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 [24], 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

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the following relationship:

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

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:

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

The receiver sides' DoF constraints are similar:

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

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):

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

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.

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

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

Then, we apply the Reformulation-Linearization Technique (RLT) [23] 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:

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

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

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

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

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

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).

(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 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 [22] or approximation algorithms such as sequential fixing algorithms [32] 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:

$$OPT(u_1) : \max U_2, \qquad (21)$$

$$\text{s.t.} U_1 = u_1, \text{and all constraints in MOPT},$$

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

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

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). 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 $(N - \delta) \cdot \alpha_1 \cdot w_1/T$. ∎

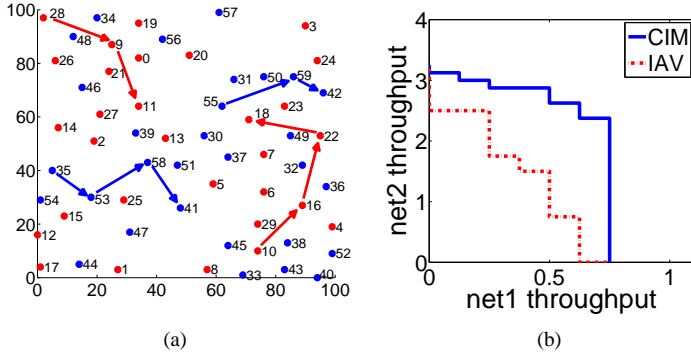The above means we need only to compute the points on the

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.

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

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

curve where $U_1 = \alpha_1 w_1 k / T, 0 \le k \le k_{max}$, 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 $0 \le k \le k_{max}$:

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

Proof: We only need to prove that when $u_2 = \max\{U_2\}$, $u_1 = OPT(u_2) \ge 0$. 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 $u_1 = \max\{U_1\}$, $u_2 = OPT(u_1) \ge 0$. ∎

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.
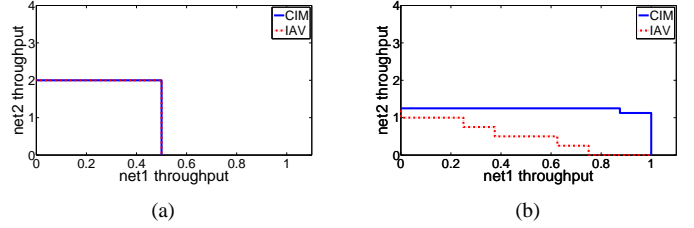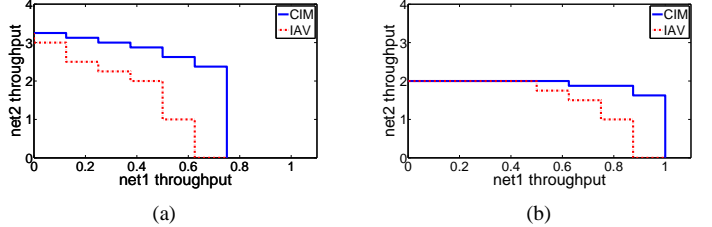
The derived stair-shape curve is shown in Fig. 4 (b). The blue line denotes the curve when using CIM, and the red line denotes the one using IAV. It can be seen that the minimum unit step is $1/8$. Obviously, for every point on the IAV's curve, one can find another point on the CIM's curve which Pareto-dominates the former, thus both networks' throughputs are 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 $58 \Rightarrow 11, 58 \Rightarrow 18, 10 \Rightarrow 18, 22 \Rightarrow 16, 10 \Rightarrow 41$. 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

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

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

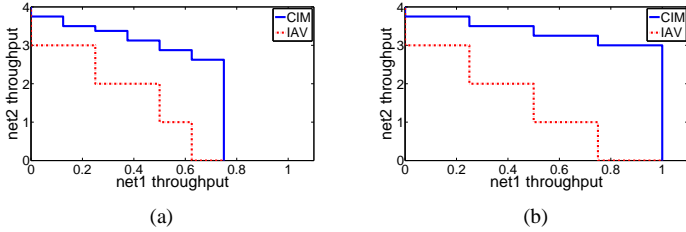MAX. TOTAL THROUGHPUT COMPARISON BETWEEN CIM AND IAV

(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)
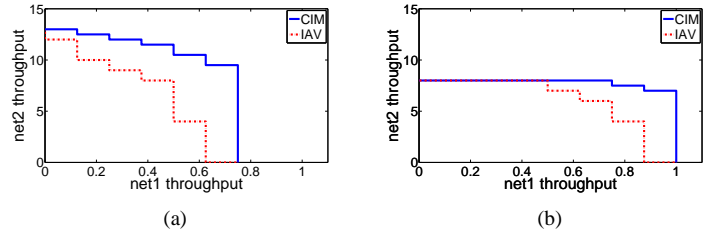

(a)   (b)

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.

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 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.

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], [16]. However, results are mostly limited to very simple settings such as node/link pairs or *single-hop* communications. Even for a single 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], [14], [29]. 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], [14], [19] which is a conservative model (sufficient but not necessary), while several works modeled both possibilities [3], [28] 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 [25]. To ensure feasibility of IC, in this paper we adopt the DoF model proposed by Liu et al. [18] 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 [15], [17], [20], [34], 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 [26]. 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 [33] and interference alignment [13], [21] 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 [32]. 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 [32] 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.

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