Cooperative Interference Mitigation for Heterogeneous Multi-Hop Wireless Networks Coexistence

Yantian Hou, *Student Member, IEEE*, Ming Li, *Member, IEEE*, Xu Yuan, *Member, IEEE*,
Y. Thomas Hou, *Fellow, IEEE*, and Wenjing Lou, *Fellow, IEEE*

***Abstract*— This paper studies the coexistence of heterogeneous multi-hop networks, which use different physical-layer technologies. We propose a new paradigm, called cooperative interference mitigation (CIM), which exploits recent advancement in interference cancellation (IC), such as technology-independent multiple output. CIM makes it possible for disparate networks to cooperatively mitigate the interference to/from each other to enhance everyone's performance. We first show the feasibility of CIM among heterogeneous multi-hop networks by exploiting only channel-ratio information. Then, we establish two tractable models to characterize the CIM behaviors of both networks by using full IC and receiver-side IC only. We propose two bi-criteria optimization problems aiming at maximizing both networks' throughput, while cooperatively canceling the interference between them based on our two models. Several simulations are carried out to compare the Pareto-optimal throughput curves by using our CIM paradigms and traditional interference-avoidance (IAV) paradigm. By comparing the results from CIM and IAV, we show that CIM could remarkably improve the coexisting networks' throughput in different network settings.**

***Index Terms*— Multi-hop wireless networks, throughput optimization, wireless MIMO.**

I. INTRODUCTION

WITH the ever-growing number of wireless systems, the problem of spectrum scarcity is becoming more important than ever. To utilize the spectrum resources more thoroughly, we need highly efficient spectrum-sharing technologies in wireless networks [1], in which the networks are heterogenous in hardware capabilities, wireless technologies, or protocol standards, and overlap with each other in the same frequency and space domains. The overlapping of disparate networks in the same spectrum band inevitably leads to *cross-technology interference* (CTI). 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. The CTI can be detrimental to the performance of co-locating networks if it is not properly mitigated [5], [14], [18], [21]. However, the CTI is harder to handle than *same-technology interference* due to the differences in physical-layer technology, thus making the communication and coordination among cross-technology devices infeasible. Therefore, it is practically infeasible to use central administration or planning for the coexistence of such networks (unless we use some multi-protocol devices as controller and coordinator, which inevitably exacerbates both hardware and communication overhead). To enable spectrum sharing, current approaches mostly follow the *Interference Avoidance* (IAV) paradigm, where different transmissions are separated in frequency, time, or space domains to avoid collisions, rather than to reduce or eliminate interference.

Recently, interference cancellation (IC) has emerged as a powerful physical-layer approach to mitigate interference [32]. IC is enabled by the use of smart antennas (MIMO), which uses signal processing techniques to minimize or completely cancel the interference from other links. MIMO is gaining popularity in commercial and future systems such as 802.11n, 802.16, and 802.11af. By using IC, we can successfully transmit multiple streams concurrently, as long as the interferences generated are properly canceled at all receivers. Interference alignment (IAL) [3], [12] is a recent advance of IC, which aligns different interferences along the same directions, thus allowing the receiver to cancel all interferences with fewer degree-of-freedom (DoF), By using IAL, the receiver could spend more DoFs on its own transmission, instead of spending on IC. Recent advances in Technology-Independent Multiple-Output (TIMO) [11] even enables the cancellation of the CTI to/from a interferer with a completely different wireless technology. Intuitively, it is possible for two or more multi-hop heterogeneous networks to cooperatively cancel/mitigate the interference to/from each other as long as 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.

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Y. Hou is with the University of Arizona, Tucson, AZ 85719 USA and Utah State University, Logan, UT 84322 USA (e-mail: yantian.hou@aggiemail.usu.edu).

M. Li is with the University of Arizona, Tucson, AZ 85719 USA (e-mail: ming.li@arizona.edu).

X. Yuan, Y. T. Hou, and W. Lou are with the Virginia Polytechnic Institute and State University, Blacksburg, VA 24061 USA (e-mail: xuy10@vt.edu; thou@vt.edu; wjlou@vt.edu).

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Previous works have mostly focused on exploiting MIMO IC to enhance throughput within standalone and homogeneous wireless networks [2], [7], [13], [30]. 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 fulfill the "transparent coexistence" or *underlay* paradigm in cognitive radio networks [33], in that the secondary networks should cancel their interferences 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. The work in [34] analyzes the throughput under IAL, and compares it with the one using only traditional IC. However, it also only studied the throughput optimization within a single network without any competing interests. Moreover, interference cancellation among multi-hop networks with *heterogeneous* wireless technologies has not been systematically studied yet.

Our goal in this paper is to explore the theoretical performance limit for coexisting heterogeneous multi-hop networks by using CIM paradigm, and compare it with the one by using traditional Interference Avoidance (IAV) paradigm. We consider an unplanned deployment setting, where each network aims at maximizing its own throughput while adopting the CIM paradigm to cooperatively cancel its interference to/from the other. To characterize the performance bounds, the *Pareto-optimal throughput curve* should be found, which is the set of all the points such that both networks cannot simultaneously increase their throughput. The meaning of this Pareto-optimal throughput curve is two-fold: (1) It provides to network designers the quantitative performance-enhancement analysis by using CIM paradigm under arbitrary network settings, such as routing, protocols, and device DoFs. (2) It can guide practical coexisting distributed-algorithm's design, as our Pareto-optimal curve could be used as the theoretical performance bound.

The difficulty of realizing CIM comes from both theoretical and practical aspects. Theoretically, 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 as an open problem due to the intractability of previous models. Practically, the main challenge is caused by system heterogeneity, as the devices with different physical layers cannot communicate with each other. In this case, the full channel state information (CSI) between disparate devices cannot be obtained as the packets cannot be decoded. The existing TIMO approach [11] 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.

In this paper, we first explore the feasibility of CIM among heterogeneous multi-hop networks 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 practical methods to measure CRI and achieve cooperative technology-independent interference cancellation (TIIC). Then we propose two tractable models for CIM that accurately capture both networks' *bilateral cooperative IC decisions, link scheduling, and various forms of system heterogeneity*, based on recent advances in MIMO link-layer modeling. One of our models captures full IC (CIM-FIC) which considers both transmitter-side and receiver-side IC, while the other model only captures traditional receiver-side cancellation (CIM-RIC). Furthermore, for our CIM-FIC model, we theoretically analyze its ability to support interference alignment and use an example to prove it. Based on our CIM models, we formulate two bi-criteria optimization problems, in which both coexisting networks maximize their own respective throughput. As both of our problems are mixed integer linear programming (MILP) problems, we rely on the Reformulation-Linearization Technique (RLT) to reformulate them. In order to find the Pareto-optimal curve efficiently, we exploit the inherent stair-shape property determined by our model, thus avoiding to solve a large number of MILP problems, which is extremely time-consuming in practice. The derived curve under our model could be regarded as a lower bound to the outer bound of the capacity region of two multi-hop heterogeneous networks in the DoF sense.

The rest of this paper is organized as follows. Section II discusses related works. In Section III, we give necessary background on MIMO and the motivation. Section IV describes our technology-independent interference cancellation (TIIC) and its feasibility in multi-hop networks. In Section V, we present the modelings of the CIM paradigms and the formulations of our two bi-criteria optimization problems. In Section VI, we introduce our approach to efficiently derive the optimal-throughput curve by exploiting its stair-shape property. Section VII presents the evaluation results, and Section VIII concludes the paper.

II. RELATED WORK

In the information theoretic community, previous work mostly focused on characterizing the MIMO channel capacity for Gaussian interference channels, either using the Shannon capacity [9] or DoF based approach [3], [17]. 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.

On the other hand, the networking community has explored MIMO IC and SM to optimize the performance of multi-hop wireless networks [2], [7], [13], [30]. Degree-of-freedom is a typical model for MIMO links due to its analytical tractability. Some of them only considered either transmitter-side or receiver-side cancellation [6], [13], [19] which is a conservative model (sufficient but not necessary), while several works modeled both possibilities [7], [29] 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 [26]. To ensure feasibility of IC, in this paper we adopt the DoF model proposed in [25] based on node ordering.

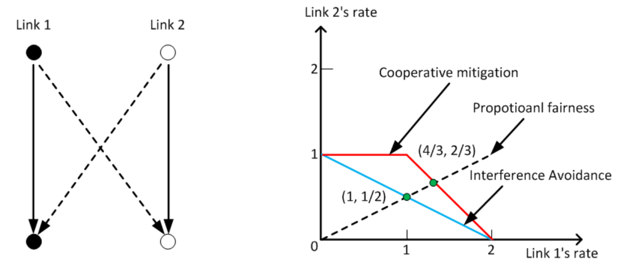
However, the above work only studied the standalone network setting, which concerns only *internal-interference* from within the same network. There is very limited work that applies MIMO IC techniques to mitigate *external interference* for multi-hop wireless networks. For spectrum sharing in the unlicensed 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], [18], [21], [36], 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 [4] or channel bonding [27]. Recently, Cortés-Peña and 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 [35] and interference alignment [20], [22] 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 (CRN), Yuan et al. proposed the "transparent-coexistence underlay" paradigm between multi-hop secondary and primary networks using MIMO IC [33]. 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 [33] is not applicable to the unplanned setting. Zeng *et al.* in [34] studies the networks' throughput by using interference alignment. In this work the authors designed a tractable model which captures the IAL in single multi-hop networks. However, they also didn't study the coexisting of two multi-hop networks. Besides, instead of their non-ordering model, we adopt a ordering one, which makes the calculation of transmit/receive vector feasible in practical multi-hop networks.

III. BACKGROUND AND MOTIVATION

A. MIMO Background

There are two key techniques enabled by MIMO communication: spatial multiplexing (SM) and interference cancellation (IC). The DoF [32] 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 streams. For transmitter-side IC, the number of DoF 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. $A_r - s_r \geq s_t$). As an advance of IC, the IAL is built upon receiver-side IC, which aligns the interferences from different transmitters along the same directions in the receiver's nulling space. As a result, the receiver could deal with multiple aligned interfering streams as if dealing with fewer streams. 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.



(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.

IC depends 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 at 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.

B. Motivation

The advancement of both MIMO and TIMO makes it possible for two or more coexisting networks to cooperatively enhance everyone's throughput. Fig. 1 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. Assume we divide time into multiple slots, and define each link's throughput to be the average number of streams transmitted (or DoF for SM) over all time slots. 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 throughput ratio of two links to be the same as that of their maximum throughput without interference (i.e., 2:1, equaling to the ratio of their antenna numbers). 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 by using 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 [37] 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 feasible 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 both networks are selfish and may deviate from cooperation, a game-theoretic approach is needed which will be left for our future work.

C. Key Challenges

It 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 running 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 generating interference to a link of the other network. Then how to design the transmit/receive vectors 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 [31], which showed the region can be derived from the convex hull of a set of base-rate points 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, the deriving of base-rate pairs is still non-trivial as we need to enumerate 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.

IV. FEASIBILITY OF COOPERATIVE TIIC AMONG MULTI-HOP NETWORKS

In this section, we study the feasibility of realizing cooperative TIIC across heterogeneous multi-hop networks, which is the essence in our CIM paradigms. Specifically, considering the basic scenario of two coexisting networks, is it possible to schedule the links' transmissions in both networks such that all the interference from/to each other can be canceled (subject to the DoF constraints at each node)? In the case of a single MIMO network, it has been shown feasible [2], [7], [13], [25], [30], [33] 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 [11]). Thus the natural question is, is it possible to make MIMO and TIMO work together in heterogeneous multi-hop networks (use the former for intra-network IC and the latter for inter-network IC)?

A. 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) [28], which is used by previous works [25]. W.l.o.g., consider the cross-technology interference from the transmitter $Tx(l)$ of a link l to receiver $Rx(k)$, 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 $(1 \le i \le z_l)$. Denote $\mathbf{H}_{(l,k)}$ the $A_{Tx(l)} \times A_{Rx(k)}$ channel gain matrix between nodes $Tx(l)$ and $Rx(k)$ which is full-rank (assuming a rich scattering environment). Let transmitter $Tx(l)$'s transmitting-weight vectors be $\mathbf{u}_{li}$, $1 \le i \le z_l$, and receiver $Rx(k)$'s receiving-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:

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

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 $A_{\mathrm{Rx}(k)}$ dimensional vector $\mathbf{h}_{(l,k)}$. Then we get $\sum_{d=1}^{A_{\mathrm{Rx}(k)}} h_{(l,k)}(d) \cdot v_{kj}(d) = 0$. 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

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

where the "*channel ratio*" between link l's transmitter and link k's receiver is defined as: $\beta_{l,k}(d) = \frac{h_{(l,k)}(d)}{h_{(l,k)}(1)}$, $2 \leq d \leq A_{\mathrm{Rx}(k)}$. 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 DoF consumed by all constraints in Eq. (2) is unchanged. It has been shown in TIMO that we are able to solve Eq. (2), i.e. to find $\mathbf{v}_{kj}$ such that the interference from node l is canceled, as long as we can get $\beta_{l,k}(d)$, which can be easily realized by broadcasting the vector $\mathbf{u}_{li}$ in probing packet before data transmission. The deriving of channel ratio information $\beta_{l,k}(d)$ in multi-hop networks will be introduced later. Note that, under channel-reciprocity model, 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 $A_{\mathrm{Rx}(k)}$ dimensional vector, where $h'_{(l,k)}(d) = \sum_{j'=1}^{A_{\mathrm{Tx}(l)}} u_{li}(j') \cdot h_{(l,k)}(j', d)$, where $h'_{(l,k)}(1) \neq 0$ with high probability. Then,

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

By replacing $\mathbf{h}_{(l,k)}$ with $\mathbf{h}'_{(l,k)}$ and $\beta_{l,k}(d)$ with $\beta'_{l,k}(d)$ in Eq. (2), we can use the same methodology as that in TIMO to derive $\mathbf{v}_{kj}$ in the multi-antenna CTI case.

Hereafter, we use *channel ratio information* (CRI) to refer to the union of channel ratio and extended channel ratio.

B. DoF Criterion

Next we analyze the DoF consumption in our multi-hop networks. First, we consider the coexisting of two single-link networks. Assume link 1 and link 2 are transmitting s_1 and s_2 streams respectively. W.l.o.g, we assume link $Rx(1)$ tries to cancel the interference from link $Tx(2)$. Because in a CRI-based TIIC scheme, every IC-constraint equation is equivalent to the original one by a constant factor (e.g. (1) and (2)), the number of consumed DoF of a node due to a set of linear constraints is unchanged compared with the one with full CSI. Therefore the consumed DoF will be s_2 at $Rx(1)$, as each interfering stream generates one equation, thus consume one DoF. Then, we assume link 2 tries to cancel its interference towards $Rx(1)$. In this case, the DoF consumed will be s_1 at $Tx(2)$.

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 $\pi_{Tx(l)}$ and $\pi_{Rx(k)}$ as the positions of nodes $Tx(l)$ and $Rx(k)$ in the node-ordering list, respectively. Based on [26, Lemma 5], 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 $z_k \geq 1$, 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.

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.

C. Measuring the Channel Ratio Information in Multi-Hop Networks

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 within one slot according to link scheduling, each of them can broadcast 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 probings, 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 $\mathbf{u}_{li}^T \cdot s_p$ during each mini-slot $i (1 \leq i \leq z_l)$ where s_p 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 Rx(k) is $(\mathbf{u}_{li})^T \mathbf{H}_{(l,k)} s_p = \mathbf{h}'_{(l,k)} s_p$. 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 Tx(l) determines its transmit vectors $\mathbf{u}_{li}$ first, and the receiver Rx(k) decides its receive vectors $\mathbf{v}_{kj}$ afterwards. The same approach can be easily extended to transmitter-side IC (Tx(k) cancels its CTI to Rx(l)), for which the receiver Rx(l) transmits a probing signal, and then Tx(k) can estimate the CRI based on channel reciprocity [11].

The probing order is determined by the node order π. This is because that the order π must be followed when determining vector $\mathbf{u}$, $\mathbf{v}$ [25], and the probing behavior logically plays a '*vector-notifying*' role in practice.

D. Feasibility of IAL

After elaborating the importance of node-ordering in our CIM paradigm. Next, we show that node-ordering is an effective mechanism to achieve IAL in practice.

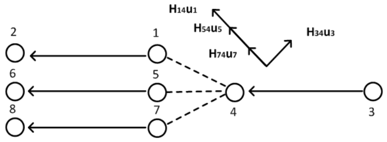


Fig. 2. Example of interference alignment by using our CIM paradigm. Dash lines denote the interference. Each node has two antennas. Node 1, 3, 5, 7 could transmit 1 stream respectively. The streams transmitted by node 1, 5, 7 are aligned along the same direction.

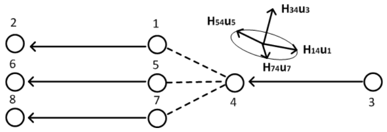


Fig. 3. Example of interference alignment by using our CIM paradigm. Dash lines denote the interference. Each node has two antennas except node 4 which has 3 antennas. Node 1, 3, 5, 7 could transmit 1 stream respectively. The streams transmitted by node 1, 5, 7 are casted into the nulling space of node 4.

In Fig. 2, assume each node's order is the same as its index number, i.e. node i's order is also i. At an arbitrary time point, assuming node 1 transmits one stream to node 2. By using our CIM, it will broadcast a probing packet using its transmitting vector $\mathbf{u}_1$ to all other nodes. Note that as node 1 has highest priority in the global order π, its vector $\mathbf{u}_1$ could be arbitrarily chosen. Based on the channel ratio information β measured on all its antennas, node 4 will compute its receiving vector $\mathbf{v}_4$ satisfying $\mathbf{u}_1^T\mathbf{H}_{1,4}\mathbf{v}_4 = \mathbf{0}$, then broadcast a probing packet using the receiving vector $\mathbf{v}_4$. Next the nodes $5, 7$ will use the same methodology to derive $\mathbf{u}_{5/7}$, such that $\mathbf{u}_{5/7}^T\mathbf{H}_{5/7,4}\mathbf{v}_4 = \mathbf{0}$. In this way, we can see that node 5 and 7 align their interfering streams $\mathbf{u}_5$, $\mathbf{u}_7$ along the direction of $\mathbf{u}_1$.

The example in Fig. 2 is a special case where IAL is achieved by using our ordering mechanism. However, we don't claim that our ordering mechanism could achieve IAL in all cases. E.g., in Fig. 3, assuming all settings are the same as in Fig. 2, except that node 4 has three antennas. In this case, all interfering streams from node $1, 5, 7$ are casted into node 4's nulling space, which is a two-dimensional plane. In general, we have the following theorem:

Theorem 1: Under any feasible ordering π, the interference alignment is supported by our CIM-FIC model, i.e., given a node ordering π, any feasible DoF allocation using IAL could be equivalently derived using CIM-FIC.

The proof is in Appendix. The basic idea of this theorem is that the IAL is feasible under our CIM model as long as it is feasible given any ordering π. Note that our CIM paradigm supports IAL only under full-IC (FIC) model, as IAL is feasible only if transmitter-side IC is feasible.

E. 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 DoFs for each node in the ith network. In reality it can be much smaller because not all active nodes are involved in cross-technology interference. Besides, the probing frequency depends on the channel coherence time, which is typically hundreds of milliseconds in static indoor environments [10]. 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 nor synchronization is needed. CRI measurement can be done by opportunistically exploiting overheard non-interfered signals from RTS/CTS/Data/ACK packets.

V. 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 [25], 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 $T \to \infty$.

A. Mathematical Modeling

1) System Model: Consider two unplanned multi-hop wireless networks $\mathcal{N}_1 = (\mathcal{V}_1, \mathcal{E}_1)$ and $\mathcal{N}_2 = (\mathcal{V}_2, \mathcal{E}_2)$ with heterogeneous technologies that interfere with each other, and $N_1 = \|\mathcal{V}_1\|$ and $N_2 = \|\mathcal{V}_2\|$. Assume the nodes in at least one network possesses MIMO capability (e.g., an 802.11n ad hoc network v.s. WiMax, or ZigBee with SISO links). The MIMO nodes also use our cooperative TIIC scheme to cancel the CTI from/to another disparate network using different technology.[1] The networks operate in the same band, and we consider T time slots are 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 $f \in \mathcal{F}_i$. 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.

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[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.

2) Modeling the CIM Paradigm With Full IC: In the full-IC model, we assume both transmitter and receiver have the ability to perform interference cancellation. 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 $y_i(t)$ $(i \in \mathcal{V}_1 \cup \mathcal{V}_2, 1 \leq t \leq T)$ as if node i transmits or receives at slot t. We have:

$$x_i(t) + y_i(t) \leq \ 1 \quad (i \in \mathcal{V}_1 \cup \mathcal{V}_2, 1 \leq t \leq T) \tag{4}$$

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, or 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 refraining 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 [25], 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 $1 \leq \pi_i(t) \leq N = N_1 + N_2$ as the global 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:

$$\pi_i(t) - N \cdot \theta_{ji}(t) + 1 \leq \pi_j(t) \leq \pi_i(t) - N \cdot \theta_{ji}(t) + N - 1, \quad (i, j \in \mathcal{V}_1 \cup \mathcal{V}_2, 1 \leq t \leq T) \tag{5}$$

Next we describe the constraints for DoF consumption at each node, which include DoFs spent on 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 $\mathcal{I}_i \subset \mathcal{V}_1 \cup \mathcal{V}_2$ (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:

$$\begin{aligned} x_i(t) \leq \sum_{l \in \mathcal{L}_{i,out}} z_l(t) + [\sum_{j \in \mathcal{I}_i} (\theta_{j,i}(t) \sum_{k \in \mathcal{L}_{j,in}}^{Tx(k) \neq i} z_k(t))] x_i(t) \\ \leq A_i x_i(t), \quad (i \in \mathcal{V}_1 \cup \mathcal{V}_2, 1 \leq t \leq T) \end{aligned} \tag{6}$$

The receiver-side's DoF constraints are similar:

$$\begin{aligned} y_i(t) \leq \sum_{l \in \mathcal{L}_{i,in}} z_l(t) + [\sum_{j \in \mathcal{I}_i} (\theta_{j,i}(t) \sum_{k \in \mathcal{L}_{j,out}}^{Rx(k) \neq i} z_k(t))] y_i(t) \\ \leq A_i y_i(t), \quad (i \in \mathcal{V}_1 \cup \mathcal{V}_2, 1 \leq t \leq T) \end{aligned} \tag{7}$$

By analyzing the constraint (7), we can clearly see that the IAL is supported intrinsically by our model. In the component $[\sum_{j \in \mathcal{I}_i} (\theta_{j,i}(t) \sum_{k \in \mathcal{L}_{j,out}}^{Rx(k) \neq i} z_k(t))]$, it can be seen that only the interferences from transmitting nodes j that are prior to node i in the ordering list π are canceled by i using receiver-side IC. The streams from nodes j that are behind i in ordering list π are not canceled thus will not consume any DoF at node i. As a result, these non-interfering streams must be casted into the nulling space of node i, in which *aligning along one direction* is a special case.

Note that, the constraints (6) and (7) are also satisfied under SISO ($A_i = 1$). This is because a SISO node either transmits/receives or keeps silent (for latter case, either $x_i = \sum_{l \in \mathcal{L}_{i,out}} z_l(t) = 0$, or $y_i = \sum_{l \in \mathcal{L}_{i,in}} z_l(t) = 0$).

For the link-capacity model, to reflect heterogeneous data rates, we multiply with a different constant weight w_n for each network:

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

Then we have the flow-rate constraints for each session of our two coexisting networks:

$$r(f) \leqslant c_l \quad (\forall l \ \in f, f \in \mathcal{F}_1), \quad r(g) \leqslant c_l \quad (\forall l \ \in g, g \in \mathcal{F}_2) \tag{9}$$

3) Modeling the CIM Paradigm With Receiver-Side IC: The model of CIM with only receiver-side IC is different with the one using full IC in terms of receiver-side's DoF constraint. In the previous model, multiple streams from different transmitters could be casted into the receiver's nulling space. However, in the receiver-side-IC model, all interfering streams are handled by receiver, thus each interfering stream will consume one DoF at the receiver. To eliminate transmitter-side IC, we just need to modify the receiver-side IC constraint by assuming all incoming-interfering streams should be canceled by every receiver i. Based on the analysis in [34], we modify the receiver's DoF constraint:

$$\begin{aligned} y_i(t) \leq [\sum_{l \in \mathcal{L}_{i,in}} z_l(t) + \sum_{j \in \mathcal{I}_{i,in}} \alpha_{ji}(t)] \cdot y_i(t) \leq A_i y_i(t), \\ (i \in V_1 \cup V_2, 1 \leq t \leq T) \end{aligned} \tag{10}$$

in which the variant $\alpha_{ij}(t)$ denotes the number of interfering streams from transmitter i to receiver j. The definition of $\alpha_{ij}(t)$ is given as follows:

$$\alpha_{ij}(t) = y_j(t) \cdot \sum_{l \in \mathcal{L}_{i,out}}^{Rx(l) \neq j} z_l(t), \ (j \in \mathcal{I}_i, 1 \leqslant i \leqslant N, 1 \leqslant t \leqslant T) \tag{11}$$

4) 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) $B = \sum_{j\in\mathcal{I}_i}\sum_{k\in\mathcal{L}_{j,in}}^{Tx(k)\neq i} A_k$, and $B' = \sum_{j\in\mathcal{I}_i}\sum_{k\in\mathcal{L}_{j,out}}^{Tx(k)\neq i} A_k$, where $\mathcal{I}_i$ is the interference node set of link i, Eq. (6) can be converted into Eq. (12), and Eq. (7) can be converted into Eq. (13).

$$\sum_{l\in\mathcal{L}_{i,out}} z_l(t) + [\sum_{j\in\mathcal{I}_i}(\theta_{j,i}(t)\sum_{k\in\mathcal{L}_{j,in}}^{Tx(k)\neq i} z_k(t))] \\ \leq x_i(t)\cdot A_i + \ (1-x_i(t))B, \quad (i\in\mathcal{V}_1\cup\mathcal{V}_2,\ 1\leq t\leq T) \tag{12}$$

$$\sum_{l\in\mathcal{L}_{i,in}} z_l(t) + [\sum_{j\in\mathcal{I}_i}(\theta_{j,i}(t)\sum_{k\in\mathcal{L}_{j,out}}^{Rx(k)\neq i} z_k(t))] \\ \leq y_i(t)\cdot A_i + \ (1-y_i(t))B', \quad (i\in\mathcal{V}_1\cup\mathcal{V}_2, 1\leq t\leq T) \tag{13}$$

Then, we apply the Reformulation-Linearization Technique (RLT) [24] 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. (12) can be rewritten as:

$$\sum_{l\in\mathcal{L}_{i,out}} z_l(t) + \sum_{j\in\mathcal{I}_i}\lambda_{j,i}(t) \leq x_i(t)\cdot A_i + \ (1-x_i(t))B, \\ (i\in\mathcal{V}_1\cup\mathcal{V}_2, 1\leq t\leq T) \tag{14}$$

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:

$$\lambda_{j,i}(t) \geq 0, \tag{15}$$

$$\lambda_{j,i}(t) \leq A_j\cdot\theta_{j,i}(t), \tag{16}$$

$$\lambda_{j,i}(t) \leq \sum_{k\in\mathcal{L}_{j,in}}^{Tx(k)\neq i} z_k(t), \tag{17}$$

$$\lambda_{j,i}(t) \geq A_j\cdot\theta_{j,i}(t) - A_j + \sum_{k\in\mathcal{L}_{j,in}}^{Tx(k)\neq i} z_k(t), \tag{18}$$

for all $i \in \mathcal{V}_1\cup\mathcal{V}_2, j \in \mathcal{I}_i, 1\leq t\leq T$. Eqs. (14)-(18) are equivalent with Eq. (12). 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. (13) can be replaced by:

$$\sum_{l\in\mathcal{L}_{i,in}} z_l(t) + \sum_{j\in\mathcal{I}_i}\mu_{j,i}(t) \leq y_i(t)\cdot A_i + \ (1-y_i(t))B', \\ (i\in\mathcal{V}_1\cup\mathcal{V}_2,\ 1\leq t\leq T) \tag{19}$$

$$\mu_{j,i}(t) \geq 0, \tag{20}$$

$$\mu_{j,i}(t) \leq A_j\cdot\theta_{j,i}(t), \tag{21}$$

$$\mu_{j,i}(t) \leq \sum_{k\in\mathcal{L}_{j,out}}^{Rx(k)\neq i} z_k(t), \tag{22}$$

$$\mu_{j,i}(t) \geq A_j\cdot\theta_{j,i}(t) - A_j + \sum_{k\in\mathcal{L}_{j,out}}^{Rx(k)\neq i} z_k(t), \tag{23}$$

where $i\in\mathcal{V}_1\cup\mathcal{V}_2,\ j\in\mathcal{I}_i,\ 1\leq t\leq T$.

$$\begin{aligned} &\max\ U_1 = \sum_{f\in\mathcal{F}_1} h[r(f)] \\ &\max\ U_2 = \sum_{g\in\mathcal{F}_2} h[r(g)] \\ &\quad \text{s.t. (for both networks)} \\ &\qquad \text{Half duplex constraints:}(4); \\ &\qquad \text{Node ordering constraints:}(5); \\ &\qquad \text{Tx/Rx DoF constraints:}(14)-(18), (19)-(23); \\ &\qquad \text{Flow rate} \leq \text{link capacity:}(9); \\ &\qquad \text{Link capacity model:}(8) \end{aligned}$$

Fig. 4. Original bi-criteria optimization formulation with FIC (BOPT-FIC).

$$\begin{aligned} &\max\ U_1 = \sum_{f\in\mathcal{F}_1} h[r(f)] \\ &\max\ U_2 = \sum_{g\in\mathcal{F}_2} h[r(g)] \\ &\quad \text{s.t. (for both networks)} \\ &\qquad \text{Half duplex constraints:}(4); \\ &\qquad \text{Node ordering constraints:}(5); \\ &\qquad \text{Tx DoF constraints:}(14)-(18); \\ &\qquad \text{Rx DoF constraints:}(10); \\ &\qquad \text{Interference degree:}(24, 25); \\ &\qquad \text{Flow rate} \leq \text{link capacity:}(9); \\ &\qquad \text{Link capacity model:}(8) \end{aligned}$$

Fig. 5. Original bi-criteria optimization formulation with RIC (BOPT-RIC).

The constraint in (11) is also nonlinear. Again, by choosing a large constant $B \geqslant A_i$, we use RLT to transform it into two equivalent linear constraints:

$$0 \leqslant \sum_{\mathcal{L}_{i,out}}^{Rx(l)\neq j} z_l(t) - \alpha_{ij}(t) \leqslant \ (1-y_j(t))\cdot B, \\ (j\in\mathcal{I}_i,\ 1\leqslant i\ \leqslant N,\ 1\leqslant t\ \leqslant\ T) \tag{24}$$

$$0 \leqslant \alpha_{ij}(t) \leqslant y_j(t)\cdot B, \quad (j\in\mathcal{I}_i, 1\leqslant i\leqslant N, 1\leqslant t\leqslant T). \tag{25}$$

B. Formulation

The mathematical formulations of the throughput maximization problems with FIC and RIC are shown in Fig. 4 and Fig. 5 respectively, which are bi-criteria mixed-integer linear programing (MILP) problems. In the objective function, $h(\cdot)$ denotes network utility function.

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 $r(g)$, the ordering variables $\pi_i(t)$ and $\theta_{ji}(t)$, link stream variable $z_l(t)$, node activity variables $x_i(t)$ and $y_i(t)$, and additional variables $\lambda_{ji}(t)$ and $\mu_{j,i}(t)$ in the reformulated problem. The challenge is that even the single-objective version of the general MILP problem is NP-hard. We will show that this can be converted into multiple (a small number of) single-objective MILP problems, where there exists highly efficient optimal and approximation algorithms such as branch-and-bound with cutting planes [23], or heuristic algorithms such as sequential fixing algorithms [33] to solve it. We use the off-the-shelf solver CPLEX to solve the MILP problems in our case.

VI. 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 $h[r(f)] = d_1 \cdot r(f)$ and $h[r(g)] = d_2 \cdot r(g)$, 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. Here d_1, d_2 are two constants.

We want to find all the *Pareto-optimal* throughput pairs (u_1, u_2) where there does *not* exists 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:

$$\begin{aligned} OPT(u_1): \quad & \max u_2, \\ & \text{s.t. } u_1 = u_1^*, \quad \text{and constraints in} \\ & \qquad\qquad \text{BOPT-FIC/BOPT-RIC} \end{aligned} \tag{26}$$

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 throughput pair (u_1, u_2) where 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.

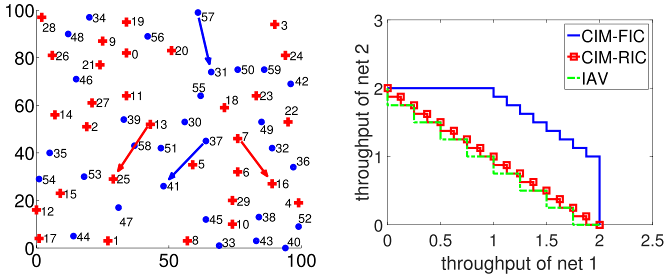
Since u_1 and u_2 are continuous, a naive approach to approximate the curve is to discretize $[0, u_{1,max}]$ into a large number of equal intervals, solve $OPT(u_1)$ for each discrete u_1, and connect the corresponding optimal values u_2 via line segments. However, each instance is an MILP problem (NP-hard 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). Firstly, it is easy to see the curve is *non-increasing* with u_1, because when u_1 increases the interference to network 2 also increases. Interestingly, we have the following Theorem which gives the basis of our method:

Theorem 2: 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 $d_1 \cdot w_1/T$.

The proof is in Appendix. This theorem means that we only need to compute the points on the curve where $u_1 = d_1 w_1 k/T$, $0 \leq k \leq k_{max}$, 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 3: There exists two special Pareto-optimal points (u_{1s}, u_{2s}), (u_{1s}', u_{2s}') on the optimal throughput curve that $u_{2s} = u_{2,max}$ and $u_{1s}' = u_{1,max}'$.



(a) (b)

Fig. 6. (a) Active sessions in two heterogeneous networks (dot: Net 1, cross: Net 2). (b) The optimal throughput curve for the two networks under CIM and IAV.

The proof is in Appendix. Given theorem 3, we can further reduce computation complexity by first identifying two Pareto-optimal 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.

VII. EVALUATION

In this section, we use numerical results to show the throughput gain by using our CIM with full IC and receiver-side IC. We compare our CIM paradigm with the interference-avoidance 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 brought by CIM paradigm. Consider two multi-hop networks (topology and sessions shown in Fig. 6 (a)) with 30 nodes each, deployed in a 100 × 100 area. Networks 1 and 2 both have two active sessions (8 active nodes in total) and min-hop routing is used. We assume both networks have two antennas for each node. For simplicity, assume $w_1 = w_2 = 1$ and $d_1 = d_2 = 1$. All nodes' transmission and interference ranges are 30 and 50, respectively. All networks coexist in one frequency band. Time is divided into 8 slots. 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. 6 (b). The blue line denotes the curve when using CIM with FIC, and the red line denotes the one using CIM with RIC. The throughput curve derived by IAV is drawn in green line. It can be seen that the minimum unit step is 1/8. Obviously, one can find that every point on the IAV's curve is Pareto-dominated by two points on CIM-FIC's and CIM-RIC's curves respectively, which verifies the large throughput gain from IAV. Besides, the throughput curve of CIM-FIC also dominates the one of CIM-RIC, which shows the performance enhancement brought by transmitter-side IC.

To verify the networks' cooperative behavior under CIM, we randomly pick a set of points from the curve with network 1's throughput equaling to 1.25.

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

TABLE I

LINK STREAM ALLOCATION IN EACH SLOT

Sessions	Path Link	FIC Slot	DoF of SM	Rate	RIC Slot	DoF of SM	Rate
Session1-1	57 → 31	0	1	0.75	0	2	0.25
		2	1		x	x	
		4	1		x	x	
		5	1		x	x	
		6	1		x	x	
		7	1		x	x	
Session1-2	37 → 41	1	1	1	1	1	0.5
		2	1		2	1	
		3	1		4	1	
		4	1		5	1	
		5	1		x	x	
		6	1		x	x	
		7	1		x	x	
		8	1		x	x	
Session2-1	7 → 16	0	1	0.625	3	2	0.375
		1	1		6	1	
		3	1		x	x	
		4	1		x	x	
		5	1		x	x	
Session2-2	13 → 25	1	1	0.625	1	1	0.875
		2	1		2	1	
		3	1		4	1	
		6	1		5	1	
		7	1		6	1	
		x	x		7	2	

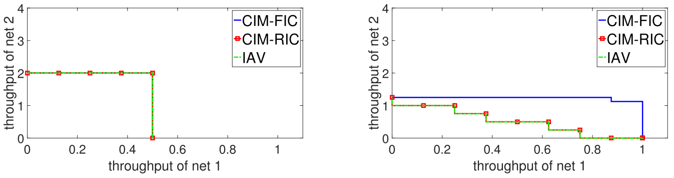
In Table I, we list the stream allocation during all the slots for all the links. In this table, ‘x’ denotes that no stream is allocated in the corresponding time slot. First, we can verify that all interferences are canceled. For example, in slot 2, links $37 \rightarrow 41, 13 \rightarrow 25$ are active in CIM-RIC. Both nodes use 1 out of their 2 total DoFs for SM. By analyzing the node ordering $\theta_{41,13}$ and $\theta_{37,25}$, we found that node 41 cancels the interference from node 13 while node 37 canceling its interference to node 25. We can see that no alignment is applied here. For CIM-FIC, using slot 2 as well, link $57 \rightarrow 31$, $37 \rightarrow 41$, $13 \rightarrow 25$ are active, with one stream transmitting on each link. We can see that the IAL is applied in this slot as node 31 receives one stream while dealing with the interferences from node 13 and 37 simultaneously. This is only possible when the two interfering streams are aligned in one direction, otherwise node 31 can’t handle three streams concurrently (1 receiving stream and 2 interfering streams) with only two antennas.

Various special points can be identified on this curve. For max-min fairness (MMF), the optimal throughput-pair obtained is $(1.5,\ 1.5)$ when using CIM-FIC, compared with $(1, 1)$ by using IAV. For proportional fairness, the optimal throughput-pair is also $(1.5,\ 1.5)$ due to the symmetric antenna numbers in our example (both networks have 2 antennas for each node).

B. Impact of Different Interference Degrees

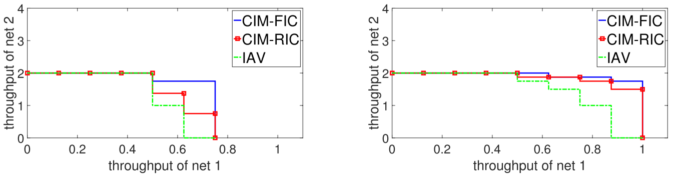
We further compare CIM’s performance with that of IAV’s, by changing the extent to which both networks interfere with each other. For example, we change the distance between the two networks to study the interference’s impact on throughputs.

In Fig. 7, we choose two scenarios containing one session in each network, while Fig. 8 illustrates two scenarios containing 2 sessions in each network. In Fig. 7 (a), the two sessions are far apart so as to not interfere with each other, while in Fig. 7 (b) they are near enough to severely interfere with each other. In Fig. 8 (a), the interference degree is approximately equal to that of Fig. 8 (b). We can observe in Fig. 7 (a), the curves derived by CIM and IAV are exactly the same. The reason is that when the two networks don’t interfere with each other, the interference cancellation ability becomes needless as there is no interference needs to be canceled. In contrast, the throughput ranges derived by CIM-FIC and CIM-RIC are larger than the one by IAV shown in Fig. 7 (b). This is because when interference emerges in the networks, there exist some transmission opportunities that could be only utilized by performing IC rather than IAV. The higher interference degree is, more such type of opportunities we have. The gaps between CIM and IAV are nearly the same in Fig. 8(a) and Fig. 8(b), though the CIM-RIC brings more benefits in (b) due to its slightly more-crowded network setting. These two sets of results successfully verified that FIC and RIC could enhance both networks’ throughputs which coexist in the same space and frequency domain.



(a) (b)

Fig. 7. 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 → 2 → 13 → 5.



(a) (b)

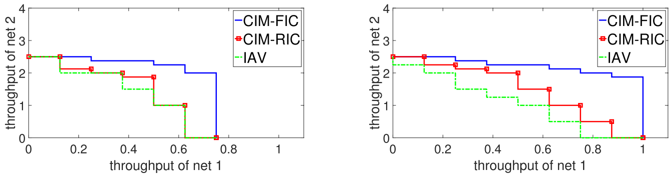
Fig. 8. In (a), Network 1 has 2 sessions:35 → 53 → 47, 37 → 32 → 36. Network 2 has 2 sessions: 10 → 5 → 18, 12 → 1 → 25. In (b), Network 1 has 2 sessions: 41 → 30 → 55, 48 → 34 → 56. Network 2 has 2 sessions: 8 → 10 → 4, 5 → 7 → 23.

We randomly generate 50 scenarios to show the better performances brought by our CIM paradigms compared with the one using IAV in an average sense. We calculate the maximum overall throughput of both networks. Network 1 and Network 2 are equipped with 1 and 4 antennas respectively to reflect heterogeneity. All sessions are randomly generated within the range shown in Fig. 6 (a). The results are presented in Table II. It can be seen that the maximum overall throughputs under CIM paradigms are significantly larger than the ones under IAV in some cases. By using FIC and RIC, the overall throughput are never lower than the ones using IAV. Similar results can be obtained under other throughput-allocation criteria such as max-min or proportional fairness, which are not elaborated in this paper. All computations for the curve finished within reasonable amount of time ranging from less than one second to tens of seconds, with an average of $13.1s$.

TABLE II

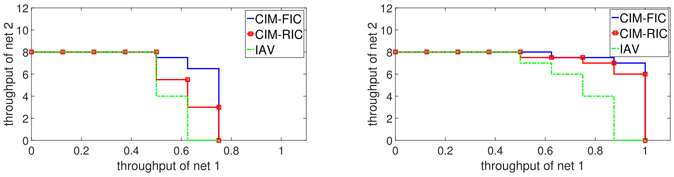
MAX. TOTAL THROUGHPUT COMPARISON BETWEEN CIM AND IAV

Scenarios	CIM-FIC	CIM-RIC	IAV	Scenarios	CIM-FIC	CIM-RIC	IAV
0	3.25	2.5	2.5	25	4.25	4.25	4.25
1	4	4	4	26	4.25	4.25	4
2	6	6	6	27	4	4	4
3	5	5	5	28	4.5	4.5	4.5
4	4	4	4	29	2.5	2.5	2.5
5	2.75	2.5	2.5	30	4	4	4
6	9	9	9	31	6.5	6	6
7	4	4	4	32	2	2	2
8	4.25	4.25	4.25	33	5.25	5.25	5.25
9	8	8	8	34	3.5	3	3
10	2	2	2	35	4	4	4
11	4	4	4	36	5	5	5
12	6	6	6	37	2.5	2	2
13	3	2.625	2.5	38	4	4	4
14	4	4	4	39	2	2	2
15	5	5	5	40	3	3	3
16	4.25	4.25	4.25	41	4	4	4
17	2.25	2	2	42	4	4	4
18	5	5	5	43	4	4	4
19	6	6	6	44	4	4	4
20	4	4	4	45	5	5	5
21	2.125	2	1.875	46	4.5	4.5	4.5
22	4.25	4.25	4.25	47	5	5	5
23	2.125	2.125	2	48	8	8	8
24	5.25	5.25	5.25	49	2.5	2.5	2.5



(a) (b)

Fig. 9. In (a), Network 1 has 2 sessions: 39 → 51 → 41, 55 → 50 → 59 → 42. Network 2 has 2 sessions: 28 → 0 → 27, 10 → 5 → 18. In (b), Network 1 has 2 sessions: 39 → 41, 55 → 31 → 42. Network 2 has 2 sessions: 28 → 0 → 27, 10 → 5 → 18. For (a), the transmission ranges are (20 ,40), the interference ranges are (30, 60). For (b), the transmission ranges are (33,40), the interference ranges are (50, 60).



(a) (b)

Fig. 10. In (a), Network 1 has 2 sessions:35 → 53 → 47, 37 → 32 → 36. Network 2 has 2 sessions: 10 → 5 → 18, 12 → 1 → 25. In (b), Network 1 has 2 sessions: 41 → 30 → 55, 48 → 34 → 56. Network 2 has 2 sessions: 8 → 10 → 4, 5 → 7 → 23.

C. Impact of Network Heterogeneity

We test our CIM paradigms in several other heterogeneous aspects, such as different transmit power/range and data rates. This heterogeneity exists in practical coexisting environment, such as the coexisting of 802.11 with 802.15.4 networks.

In Fig. 9 (a), we set the transmission ranges for networks 1 and 2 as 20 and 40, and the interference ranges as 30 and 60, respectively. In Fig. 9(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 enlarge in Fig. 9 (b). There are two insights: (1) larger transmission range decreases hop count thus increases one's own throughput; (2) When the mutual interference degree is higher, more gains could be obtained by using CIM paradigms, thus making the coexisting networks more willing to cooperatively mitigate the interference. 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. 10. Compared with Fig. 8, the throughput curve scales by a factor of 4 in the y-axis.

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 (TIIC) is feasible for heterogeneous multi-hop networks with different protocol standards, and then introduce our two CIM models with different interference cancellation (IC) techniques. We characterize the performance bounds of CIM via deriving the Parato-optimal throughput curve. Through extensive simulation results we show that the CIM paradigms with full IC and receiver-side IC can both offer significant performance gains in throughput to the coexisting networks compared with the traditional interference-avoidance (IAV) 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 work, we will investigate the incentives of cooperation for multiple independent networks, and study the coexisting problem with a game-theoretical approach.

APPENDIX

A. Proof of Theorem 1

Proof: The proof is straightforward. Assume there exists an ordering π, under which IAL is feasible. For each IAL relation, there must be one receiver (e.g. j) and more than two interfering transmitters (e.g. i, k). Assume the node j receives z_j streams while the other nodes performing IAL. Among all the interfering streams being canceled at j, there is a set of streams $\mathbf{u}_{i,m}$, $\mathbf{u}_{k,m'}$ which are not aligned (i.e. they are canceled by receiver-side IC). We call them *basis* streams and define the DoF consumed by the basis streams at node j as α_j. For these streams, we have $\mathbf{u}_{i,m}^T \mathbf{H}_{i,j} \mathbf{v}_{j,n} = 0, \forall m, n$, and/or $\mathbf{u}_{k,m'}^T \mathbf{H}_{k,j} \mathbf{v}_{j,n} = 0, \forall m', n$. For the set of aligned streams $\mathbf{u}_{i,x}$, $\mathbf{u}_{k,x'}$, we have $\mathbf{u}_{i,x}^T \mathbf{H}_{i,j} = \mathbf{u}_{k,m'}^T \mathbf{H}_{k,j}$ and/or $\mathbf{u}_{i,m}^T \mathbf{H}_{i,j} = \mathbf{u}_{k,x'}^T \mathbf{H}_{k,j}$, $\exists m$ or m'. As these aligned streams are also casted into j's nulling space, we automatically have $\mathbf{u}_{i,x}^T \mathbf{H}_{i,j} \mathbf{v}_{j,n} = 0$, $\forall n$ and $\mathbf{u}_{k,x'}^T \mathbf{H}_{k,j} \mathbf{v}_{j,n} = 0$, $\forall n$.

Now we show that IAL is equivalent with our CIM-FIC in terms of DoF consumption in this case. We modify the ordering π, by setting the receiver j prior to all other nodes in the new ordering π'. According to CIM-FIC, node j determines its receiving vectors first. We make it broadcast the exact receiving vectors $\mathbf{v}_{j,n}$ such that $\mathbf{u}_{i,m}^T \mathbf{H}_{i,j} \mathbf{v}_{j,n} = 0, \forall m$ and $\mathbf{u}_{k,m'}^T \mathbf{H}_{k,j} \mathbf{v}_{j,n} = 0, \forall m'$. Therefore, the number of DoF consumed is still α_j, i.e. the DoF consumption is unchanged for node j.

For all interfering transmitters (i, k), they will perform transmitter-side IC instead of IAL. The nodes i, k will calculate $\mathbf{u}_i$ and $\mathbf{u}_k$, such that $\mathbf{u}_i^T\mathbf{H}_{i,j}\mathbf{v}_{j,n} = 0$ and $\mathbf{u}_k^T\mathbf{H}_{k,j}\mathbf{v}_{j,n} = 0$. Apparently, $\mathbf{u}_{i,m}, \mathbf{u}_{i,x}, \mathbf{u}_{k,m'}, \mathbf{u}_{k,x'}, \forall m, m', x, x'$ are all feasible solutions thus the DoF consumptions are unchanged for node i, k. Therefore, the DoF allocation using IAL is a feasible solution under our CIM-FIC model, as long as IAL is feasible given a global ordering π.

B. Proof of Theorem 2

Proof: The basic idea can be explained by perturbation analysis. Observe that the form of Eq. (8) is $c_l = k\omega_n/T$ where $k \geq 0$ is an integer which increases with a minimum 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, $u_1 = d_1 \cdot r(f) = d_1 \cdot \min\{c_l\}_{\forall l \text{on } f}$, $u_2 = d_2 \cdot r(g) = d_2 \cdot \min\{c_l\}_{\forall l \text{ on } g}$ which increment by least steps of $d_1\omega_1/T$ and $d_2\omega_2/T$, respectively. Suppose $(k-1)d_1 \cdot \omega_1/T < u_1 < kd_1 \cdot \omega_1/T$, and a small increase δ is applied to u_1 so that $u_1' = u_1 + \delta$. If $u_1' < d_1 \cdot k\omega_1/T$, 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 $d_1 \cdot \sum_{f \in \mathcal{F}_1} r(f)$ and $d_2 \cdot \sum_{g \in \mathcal{F}_2} r(g)$, 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, $d_1 \cdot r(f)$, $\forall f \in \mathcal{F}_1$ is upper constrained by a set of linear expressions in the form of either $d_1 \cdot r(f) \leq d_1 \cdot \min\{c_l\}_{\forall l \text{ on } f}$ (in case of independent flow) or $d_1 \cdot \sum_{f \text{ traverse } l} r(f) \leq d_1 \cdot \min\{c_l\}_{\forall l \in \mathcal{L}_1}$ (in case of flow link sharing), which all increments by least step of $d_1\omega_1/T$. Thus, the upper bound to their linear combination $u_1 = d_1 \cdot \sum_{f \in \mathcal{F}_1} r(f)$ also increments by least step of $d_1\omega_1/T$. 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 $\sum_{f \in \mathcal{F}_1} d_1 \cdot r(f)$ to a edge point, which means increasing a little amount δ will break the constraint $d_1 \cdot \frac{1}{T}\sum_{t=1}^{T} z_l(t)$ on a link l. We could increase other links' rate $r_k(f)$ to their edge points while keeping $\sum_{f \in \mathcal{F}_1} d_1 \cdot r(f)$ 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 $(N - \delta) \cdot d_1 \cdot \omega_1/T$.

C. Proof of Theorem 3

Proof: To prove this theorem, we first show that the function $f()$ of the Pareto-optimal curve is a monotone decreasing function. This is very easy to see, as the increasing of one network Φ's throughput definitely generates more interference to the other network Ψ, thus generating tighter constraint to limit its throughput. Second, we show that the increasing of network Φ's throughput doesn't necessarily decrease the other network Ψ's throughput. This is because the network Ψ could adjust its scheduling to digest the interference from network Φ. Starting from the original point, by increasing one network's throughput (e.g. u_Φ), we can always find a point $u_{\Psi s}$ such that any tiny increasing on u_Φ will decrease the value of u_Ψ. Therefore we derive $u_{\Phi s}$ and its corresponding $u_{\Psi s}$. Using same methodology we can get the other pair ($u'_{\Phi s}$ and $u'_{\Psi s}$).

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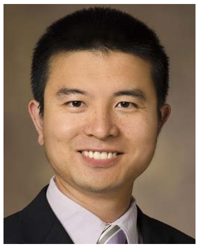
Yantian Hou (S'13) received the B.S. and M.S. degrees from the Electrical Engineering Department, Beijing University of Aeronautics and Astronautics, in 2009 and 2012, respectively. He is currently pursuing the Ph.D. degree with the Computer Science Department, Utah State University. He is also a Visiting Student with the Electrical and Computer Engineering Department, University of Arizona. His research interests include wireless network and security, and applied cryptography.



Ming Li (M'11) received the Ph.D. degree from the Worcester Polytechnic Institute, in 2011. He was an Assistant Professor with the Computer Science Department, Utah State University, from 2011 to 2015. He is currently an Associate Professor with the Department of Electrical and Computer Engineering, University of Arizona. His main research interests are wireless networks and cyber security, with current emphasis on wireless network optimization, wireless and spectrum security, and cyber-physical system security. He is a member of ACM. He received the NSF Early Faculty Development (CAREER) Award in 2014, and the ONR Young Investigator Program Award in 2016.

Xu Yuan (S'13–M'16) received the B.S. degree in computer science from Nankai University, Tianjin, China, in 2009. He is currently pursuing the Ph.D. degree with the Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA. His current research interest focuses on algorithm design and optimization for cognitive radio networks.

Y. Thomas Hou (F'14) received the Ph.D. degree from the NYU Tandon School of Engineering, in 1998. He is currently a Bradley Distinguished Professor of Electrical and Computer Engineering with the Virginia Polytechnic Institute and State University, Blacksburg, VA, USA. He has authored two graduate textbooks entitled *Applied Optimization Methods for Wireless Networks* (Cambridge University Press, 2014) and *Cognitive Radio Communications and Networks: Principles and Practices* (Academic Press/Elsevier, 2009). He holds five U.S. patents. His current research focuses on developing innovative solutions to complex cross-layer optimization problems in wireless and mobile networks. His research was recognized by five best paper awards from the IEEE and two paper awards from ACM. He is currently an Editor of the IEEE TRANSACTIONS ON NETWORKING/*ACM Transactions on Networking* and *ACM Transactions on Sensor Networks*. He is the Steering Committee Chair of the IEEE INFOCOM Conference and a member of the IEEE Communications Society Board of Governors. He is also a Distinguished Lecturer of the IEEE Communications Society.

Wenjing Lou (F'15) received the Ph.D. degree in electrical and computer engineering from the University of Florida, in 2003. From 2003 to 2011, she was a Faculty Member with the Worcester Polytechnic Institute. She has been a Professor with Virginia Tech since 2011.

Her current research interests focus on privacy protection techniques in networked information systems and cross-layer security enhancement in wireless networks, by exploiting intrinsic wireless networking and communication properties.

Prof. Lou has served as a Program Director of the U.S. National Science Foundation since 2014, where she is involved in the Networking Technology and Systems program and the Secure and Trustworthy Cyberspace program.