Interference Alignment for Multi-hop Wireless Networks: Challenges and Research Directions

Huacheng Zeng† Feng Tian‡ Y. Thomas Hou† Wenjing Lou† Scott F. Midkiff†
† Virginia Polytechnic Institute and State University, USA
‡ Nanjing University of Posts and Telecommunications, China

Abstract

Interference alignment (IA) has been widely regarded as a promising technique to handle mutual interference in wireless networks. Although there have been many studies on IA, most of the results are limited to the single-hop scenario. To date, research of IA in the networking community remains scarce. This stagnation underscores both the technical barrier in this area and the critical need to fill in this gap. This article offers a tutorial of three different forms of IA—spatial, temporal, and frequency, with a focus on their respective challenges, recent advances, and open problems in multi-hop wireless networks. We hope this article can bring state-of-the-art knowledge on IA to the wireless networking community.

I. Introduction

Interference alignment (IA) is widely regarded as a major advance in interference management in recent years. The basic idea of IA is to jointly construct the signals at transmitters, so that the constructed signals overlap at their unintended receivers but remain decodable at their intended receivers. Consider the MIMO network in Fig. 1 as an example. Suppose that each node has two antennas and there are four active transmissions: $T_1 \to R_1$, $T_2 \to R_2$, $T_3 \to R_3$, and $T_4 \to R_4$. Each transmission carries one data stream. By jointly designing the precoding vectors at transmitters T_1, T_2, and T_3, we can have the three interfering streams at R_4 aligned to the same direction, making it possible for R_4 to decode its desired data stream from T_4 free of interference.

Since its debut, IA has gained tremendous momentum and has been applied to a variety of channels and networks. In [1], Cadambe and Jafar proved that by using IA, the K-user interference channel can achieve $K/2$ degrees of

Corresponding author: Y.T. Hou (thou@vt.edu).

freedom (DoFs), indicating that each user can get one half of channel utilization regardless of the number of users. In [2], Suh and Tse studied IA in cellular networks and showed that IA was an extremely effective technique to cancel inter-cell interference. In [3], Gomadam et al. proposed an iterative algorithm that utilizes the reciprocity of wireless networks to achieve IA with only local channel knowledge at a node. Recently, the feasibility and practicality of IA have been validated in [4], [5]. In [4], Gollakotta et al. demonstrated experimentally that the use of IA can increase the average throughput by 1.5 times for the downlink and 2 times for the uplink in a 2×2 MIMO WLAN. In [5], El Ayach et al. implemented IA in a MIMO-OFDM testbed and showed a considerable throughput gain that was made possible by IA.

Although there have been many studies on IA in the literature, most results are limited to the single-hop scenario (e.g., the K-user interference channel and cellular networks). Results for IA in multi-hop networks remain scarce. This stagnation is mainly due to the complexity of IA in a multi-hop network. Specifically, IA requires a meticulous design of the signals at the transmitters to enable the alignment of interference and to ensure the resolvability of desired signals at each receiver. However, in a multi-hop network environment, there may exist a large number of nodes with random topology, making it difficult to achieve alignment. Further, IA at the physical (PHY) layer is also complicated by its coupling with upper-layer scheduling and routing decisions, bringing in further challenges to exploit the benefits of IA in a network environment. The lack of results of IA in multi-hop networks underscores both the technical barriers and the critical need to address those challenges. The goal of this article is to offer an overview of IA in the spatial, temporal, and frequency domains, with a focus on its respective challenges, new results, and open problems in the context of multi-hop networks.

The remainder of the article is organized as follows. In Section II to IV, we survey IA in the spatial, temporal, and frequency domains, respectively. In each section, we first explain the basic concept of IA in its respective domain and then offer a discussion of new results and open problems in the context of multi-hop networks. Finally, Section V concludes this article.

TABLE I: A summary of S-IA, T-IA, and F-IA.

	Application Domain	CSI at TX	Coordination among TX	SNR Requirement	Channel Requirement
S-IA	MIMO networks	Required	Required	High SNR regime	Full-rank and independent channels
T-IA	Networks with large propagation delays (e.g., UWA networks)	Required	Required	All SNR regime	No requirement
F-IA	OFDM networks	Required	Required	High SNR regime	Full-rank and frequency-selective channels

II. Spatial-Domain IA

To achieve IA in the spatial domain, each node is expected to be equipped with multiple antennas. Spatial-domain IA (S-IA) refers to a joint construction of transmit signals at the transmitters (by precoding their outgoing data streams onto their multiple antennas) so that at each receiver, the interfering (undesired) streams are overlapped in the spatial domain while the desired data streams remain resolvable. Since the interfering streams are overlapped at a receiver, the dimension of the interference subspace is reduced, making it possible to receive more concurrent data streams free of interference at this receiver. A summary of S-IA is given in Table I. In what follows, we use an example to illustrate the potential benefits of S-IA.

An Example. Consider the 3-link network in Fig. 2(a), where each node has two antennas. When S-IA is not employed, at most two independent data streams can be transported concurrently from the transmitters to the receivers, since all nodes are in the same interference domain. But by using S-IA, three independent data streams can be transported free of interference, with one data stream on each link. To see how this is possible, let's consider the receivers. For each receiver, it has one desired data stream and two interfering streams. Since each receiver has only two antennas, it can decode its desired data stream free of interference only if the two interfering streams are aligned in the same direction. At transmitter T_i, denote $\mathbf{u}_i^k$ as the precoding vector for the kth stream. Denote $\mathbf{H}_{ji}$ as the spatial-domain channel matrix between receiver R_j and transmitter T_i. Then, a possible precoding scheme that can achieve the desired IA at all three receivers is as follows:

$$
\begin{aligned}
&\mathbf{u}_1^1 = \mathrm{eigvec}(\mathbf{H}_{21}^{-1}\mathbf{H}_{23}\mathbf{H}_{13}^{-1}\mathbf{H}_{12}\mathbf{H}_{32}^{-1}\mathbf{H}_{31}),\\
&\mathbf{u}_2^1 = \mathbf{H}_{32}^{-1}\mathbf{H}_{31}\mathbf{u}_1^1,\\
&\mathbf{u}_3^1 = \mathbf{H}_{23}^{-1}\mathbf{H}_{21}\mathbf{u}_1^1,
\end{aligned}
$$

where $\mathrm{eigvec}(\mathbf{H})$ is an eigenvector of square matrix $\mathbf{H}$. It can be verified that by using the above precoding vectors, the interfering streams will be aligned in the same direction and the desired data stream will lie in an independent direction (free of interference) at all three receivers, as shown in the figure. Therefore, three independent data streams can be transported simultaneously from the transmitters to the receivers.

S-IA in Multi-hop Networks. The above example demonstrated the benefits of S-IA in a single-hop network. A comprehensive study of S-IA in single-hop networks can be found in [6]. To show how the potential benefits of S-IA can be tapped in a multi-hop network, let's consider the two-hop network in Fig. 2(b). There are three sessions in this network: $S_1 \to R_1 \to D_1$, $S_2 \to R_2 \to D_2$, and $S_3 \to R_3 \to D_3$. Each node has two antennas and works in half duplex. All the nodes are in the same interference domain and there are two time slots for transmission scheduling.

For this two-hop network, it has six links in total. If S-IA is not employed, any three out of the six links cannot be active in the same time slot due to the half-duplex and interference constraints. Therefore, it is impossible to transport any data stream for all the three sessions in two time slots. However, if S-IA is employed in this network, each link can transport one data stream in two time slots. This can be achieved by simply assigning links $\{1, 3, 5\}$ in the first time slot and links $\{2, 4, 6\}$ in the second time slot. Based on the results in the previous example (see Fig. 2(a)), the use of S-IA allows links $\{1, 3, 5\}$ to transport three data streams in the first time slot and links $\{2, 4, 6\}$ to transport three data streams in the second time slot. Therefore, each session can achieve one data stream in two time slots.

As we may see from the examples in Fig. 2, it is not a trivial task to design a S-IA scheme for a single-hop

TABLE II: A summary of challenges and open problems for S-IA, T-IA, and F-IA.

<table>
<tr><th rowspan="2"></th><th colspan="2">Challenges</th><th colspan="2">Open problems</th></tr>
<tr><th>Common</th><th>Unique</th><th>Common</th><th>Unique</th></tr>
<tr><td>S-IA</td><td rowspan="3">• Guarantee IA feasibility at the PHY layer
• Jointly design IA with scheduling and routing algorithms</td><td>• Cooperation mechanism to achieve S-IA</td><td rowspan="3">• Design an optimal IA scheme that maximizes network throughput</td><td>• Design S-IA without CSI or with partial CSI
• Design S-IA to maximize data rate</td></tr>
<tr><td>T-IA</td><td>• Require synchronization and propagation delay information
• Design distributed T-IA scheme</td><td>• Achieve time synchronization and obtain propagation delay information</td></tr>
<tr><td>F-IA</td><td>• Large F-IA design space
• Cooperation mechanism to achieve F-IA</td><td>• Impact of network topology on performance of F-IA
• Apply F-IA to CR network
• Jointly apply F-IA and S-IA to MIMO-OFDM network</td></tr>
</table>

network and it is even more challenging to design a S-IA scheme for a multi-hop network. Referring to Table II, we summarize some of the challenges as follows:

- *Cooperation mechanism.* Due to the complex interference relationship among the nodes, designing a S-IA that works among all nodes in the network is not an easy task. This is because S-IA is intrinsically a local scheme. Such a local scheme may not pan out in a network environment as it lacks the global coordination mechanism among the nodes beyond its local group.
- *Guarantee feasibility.* Once a S-IA scheme is designed, ensuring its feasibility at the PHY layer is not a trivial task. To guarantee feasibility at the PHY layer, one needs to show that there exist a precoding vector and a decoding vector for each data stream in the network, so that all the data streams can be transported free of interference. Proving the existence of such precoding and decoding vectors for each data stream in a given S-IA scheme is not an easy task.
- *Coupling with scheduling and routing.* In a multi-hop network environment, a S-IA scheme is tightly coupled with the upper-layer scheduling and routing algorithms. The upper-layer algorithms determine, for each time slot, the set of transmitters, the set of receivers, the set of links, and the number of data streams on each link. To maximize its benefits, a S-IA scheme must be jointly designed with the upper-layer scheduling and routing algorithms. But this is a challenging task.

Recent advances of S-IA in multi-hop networks can be found in [7], [8]. In [7], Li et al. discussed S-IA with several example scenarios to illustrate its potential benefits. However, in their proposed algorithm, the key requirements of S-IA (i.e., how to construct signals at transmitters so that these signals overlap at their unintended receivers while remaining resolvable at their intended receivers) were not considered. With the absence of this critical component, their proposed algorithm did not offer major advance of S-IA in multi-hop networks. In [8], Zeng et al. developed a S-IA model for a multi-hop network where each node is assumed to have the same number of antennas. This model consists of a set of simple constraints that characterize the number of data streams on each link in the network. Instead of dealing with complex design of precoding and decoding vectors at the PHY layer, the constraints in the S-IA model only requires simple algebraic addition and subtraction operations. They proved the feasibility of this S-IA model by showing that as long as those simple constraints are satisfied, there always exists a set of precoding and decoding vectors so that the data streams on each link can be transported free of interference at the PHY layer. Such a S-IA model allows us to study S-IA in a network environment without getting involved into complex design of precoding and decoding vectors at the PHY layer. Based on this S-IA model, they developed a cross-layer S-IA optimization framework to exploit the benefits of S-IA for throughput maximization in a multi-hop MIMO network. Through numerical resutls, it was shown in [8] that the use of S-IA can significantly increase (an average of 43%) the end-to-end session throughput in a general multi-hop network when compared to the case where S-IA was not employed.

Open Problems. The results in [8] offered a first step to exploit S-IA in multi-hop networks. Many problems (including those challenges discussed earlier) remain open. Referring to Table II, we summarize some of them as follows: (i) How to design an optimal S-IA scheme for a multi-hop network is an open problem. An optimal scheme would be of great interest from both theoretical and practical perspectives. (ii) How to design an efficient or even optimal S-IA scheme for a MIMO network without CSI (or with only partial CSI) at transmitters is another open problem. Most of the existing results on S-IA rely on the assumption that global CSI is available at transmitters. Relaxing this assumption is an important step toward applying S-IA to practical multi-hop networks. (iii) How to bridge the gap between data stream and data rate in a S-IA scheme is an open problem. Most of the existing S-IA

TABLE III: Propagation delays (normalized with respect to an OFDM symbol duration, e.g., 85.5 ms) between transmitter T_i ($i = 1, 2, 3, 4$) and receiver R_j ($j = 1, 2, 3, 4$).

Node	R_1	R_2	R_3	R_4
T_1	3.9	8.0	13.1	18.0
T_2	8.0	3.9	6.7	11.2
T_3	13.1	6.7	3.9	6.4
T_4	18.0	11.2	6.4	3.9

schemes were meticulously designed to maximize the number of concurrent data streams in a MIMO network. However, more data streams does not necessarily mean higher data rates, especially in the low- or mid-SINR (e.g., less than 20dB) regime. Bridging this gap is important to achieve the ultimate performance objective of a network, which is typically measured in bit rate.

III. Temporal-Domain IA

Unlike S-IA, temporal-domain IA (T-IA) does not require each node in the network to have multiple antennas. To achieve T-IA, one may jointly design the transmit signals at the transmitters in the temporal domain (by packing symbols into appropriate time intervals) so that at each receiver, the interfering signals are overlapped in some time intervals while the desired signals are free of interference.[1] In [10], Grokop et al. proposed a T-IA scheme based on the propagation delays between transmitters and receivers. They showed that by using the T-IA scheme, the spectral efficiency of the K-user interference channel can grow linearly with K if the channel bandwidth is sufficiently large. A similar result was independently developed by Cadambe and Jafar in [11]. In [13], Chitre et al. developed scheduling algorithms to exploit the benefits of T-IA for throughput improvement in a multi-user network with large propagation delays. A summary of T-IA is given in Table I. In what follows, we use an example to illustrate the potential benefit of T-IA.

An Example. Consider the 4-link underwater acoustic (UWA) network in Fig. 3(a), where the solid arrow line represents data transmission and the dashed arrow line represents interference. The propagation delays between a transmitter and a receiver can be computed based on the distances given in Fig. 3(a) and the speed of sound in

[1]There exist various forms of T-IA in the literature and we focus on the form of T-IA that is based on propagation delays in this section.

water (1500 m/s). We assume that the data transmission at each transmitter is done in time slots. Each time slot consists of 15 OFDM symbols and each OFDM symbol is of 85.5 ms time duration [12]. Then the normalized propagation delays (with respect to the OFDM symbol time duration) between transmitters and receivers can be computed, as listed in Table III.

Suppose that we schedule OFDM symbol payload at each transmitter as shown in Fig. 3(b), where the shadowed intervals represent payload while blank intervals represent idle time. Then for each receiver, it receives one desired symbol stream and three interfering symbol streams. Based on their respective propagation delays in Table III, the received desired and interfering symbol streams at each receiver are shown in Fig. 4. We can see that, thanks to the propagation delays, the desired symbol stream at each receiver is completely separated from the interfering streams in the temporal domain. For example, at receiver R_1 (see Fig. 4(a)), the desired symbols from transmitter T_1 are completely free of interference. On the other hand, there is temporal overlap among the payload symbols from their transmitters T_2, T_3, and T_4. Similar separation of desired symbols and alignment of interfering symbols occur at receivers R_2, R_3, and R_4.

Quantitatively, we have a total of 21 payload symbols that are successfully transported in a time slot in this network. If there were no propagation delays (and thus no T-IA), at most 15 payload symbols can be transported in a time slot since all links are in the same interference domain. Therefore, T-IA allows 6 more symbols to be transported over 15 symbol intervals, offering an increase of 40% in spectral efficiency.

T-IA in Multi-hop Networks. As the above example shows, the essence of T-IA is a coordinated design of scheduling algorithm to exploit the propagation delays between transmitters and receivers so that at each receiver, the interfering symbols may overlap while the desired symbols are free of interference. To extend T-IA from single-hop to multi-hop networks, a more sophisticated T-IA scheduling is needed to coordinate the nodes on a network scale. Designing such a network-wide T-IA scheduling is not a trivial task. In addition to the common challenges in Table II, we identify some challenges that are unique for T-IA as follows:

- *Synchronization and propagation delay information.* As showed in Fig. 3, the success of T-IA relies on the time synchronization and the availability of propagation delay information at the transmitters. In practical networks, however, the transmitters may not be perfectly synchronized and the propagation delay information may not be accurate. Therefore, how to design a T-IA scheduling that is robust to synchronization error and inaccurate delay information is a challenging problem.

- *Distributed T-IA design.* For most multi-hop networks, perfect coordination among the nodes may not be possible and thus a distributed T-IA scheduling algorithm is preferred. But designing a distributed T-IA scheduling algorithm with a fast convergence time and low overhead is not a trivial problem.

Recent advances of T-IA in multi-hop networks can be found in [14], where Zeng et al. developed an analytical T-IA model with a set of constraints that guarantee T-IA feasibility (i.e., desired data symbols are free of interference in the temporal domain at each receiver) at the PHY layer. Based on this model, they developed a T-IA scheduling algorithm, nicknamed Shark-IA, to maximally overlap interference in a multi-hop UWA network. They further showed that their proposed Shark-IA algorithm is amenable to local operations and may be further developed for distributed implementation. It was shown in [14] that the Shark-IA algorithm can offer considerable throughput gain (e.g., 40% in some cases) when compared to an idealized benchmark algorithm with perfect scheduling and zero propagation delays.

Open Problems. While [14] offered preliminary results of T-IA in multi-hop networks, research of T-IA in the context of multi-hop networks is still in its infancy. In addition to the common open problems listed in Table II, we identify some other open problems for T-IA as follows: (i) Existing T-IA schemes require reasonably accurate propagation delay information between the transmitters and receivers. This may be achievable for a static network. But for a mobile ad hoc network, such information is hard to estimate due to node mobility. How to apply T-IA to a mobile ad hoc network is an open problem. (ii) Besides the propagation-delay-based T-IA, there also exist other forms of T-IA (e.g., achieving T-IA by jointly precoding transmit signals over a set of time slots in [1]). There is little result on how to exploit the potential benefits of those forms of T-IA in multi-hop networks.

IV. Frequency-Domain IA

Frequency-domain IA (F-IA) refers to a joint construction of transmit signals at the transmitters by precoding their outgoing data streams onto a set of frequency subcarriers (instead of a set of time intervals or a set of antenna elements) so that at each receiver, its interfering streams are overlapped in the frequency domain while its desired data streams remain resolvable. Different from S-IA, F-IA does not require the network to have multiple antennas at each node. Instead, it requires the network to have multiple orthogonal frequency channels such as OFDM subcarriers. F-IA was first studied for cellular networks by Suh and Tse in [2], in which they proved that a F-IA scheme could achieve $K/(\sqrt[G-1]{K}+1)^{G-1}$ DoFs for each cell, where G is the number of cells and K is the number of users in a cell. As the number of users in a cell becomes large ($K \rightarrow +\infty$), each cell can achieve one DoF, meaning that each cell (base station) can serve its users as if there were no interference in the network. In [15], Suh et al. extended their F-IA scheme to the downlink of a cellular network and showed that their F-IA scheme works for the network where feedback information is limited in a cell. In [16], Zeng et al. developed a F-IA model with a set of constraints for a cellular network with heterogeneous setting. They proved the feasibility of their F-IA model by showing that one can always construct a precoding vector and a decoding vector for each data stream as long as the constraints in their F-IA model are satisfied. A summary of F-IA is given in Table I. In what follows, we use an example to illustrate the idea of F-IA.

An Example. Consider the 4-link network in Fig. 5, where each node has a single antenna. For ease of illustration, we assume that there are 3 orthogonal frequency subcarriers for data transmission. Since all the transmitters and receivers are in the same interference domain, putting more than one data streams on a subcarrier will inevitably cause collision on that subcarrier. Therefore, when F-IA is not employed, at most 3 independent data streams (one on each subcarrier) can be transported from the transmitters to the receivers. That is, at most 3 out of the 4 links can be active and at least 1 link is idle. Now we show that the use of F-IA allows 4 independent data streams to be transported free of interference, with one data stream on each link.

Denote $\mathbf{H}_{ji}$ as the frequency-domain channel matrix between receiver R_j and transmitter T_i. Due to the orthogonality and independence of the frequency subcarriers, $\mathbf{H}_{ji}$ is assumed to be a full-rank diagonal matrix and its kth diagonal entry is channel coefficient of the kth subcarrier. Denote $\mathbf{u}_i^k$ as the precoding vector for the kth outgoing stream at transmitter T_i. For each receiver, it has 2 desired data streams and 2 interfering streams. Since the receiver has only 3 frequency subcarriers, it can decode both its desired data streams free of interference only if its two interfering streams are aligned in the same direction. One precoding scheme that can achieve the desired alignment at both receivers is as follows:

$$\begin{aligned}
&\mathbf{u}_1^1 = \mathbf{u}_{\text{ref}}, \\
&\mathbf{u}_2^1 = \mathbf{H}_{22}^{-1}\mathbf{H}_{21}\mathbf{u}_1, \\
&\mathbf{u}_3^1 = \mathbf{u}_{\text{ref}}, \\
&\mathbf{u}_4^1 = \mathbf{H}_{24}^{-1}\mathbf{H}_{23}\mathbf{u}_3,
\end{aligned}$$

where $\mathbf{u}_{\text{ref}}$ is a 3×1 reference vector with nonzero entries. By using the above precoding vectors, it can be verified that at each receiver, the two interfering streams will be aligned in the same direction and the two desired data streams will lie in two independent directions, as shown in the figure. Therefore, 4 independent data streams can be transported free of interference over 3 frequency subcarriers in this network.

The above example appears similar in structure to that for S-IA. But there is a fundamental difference between S-IA and F-IA. The design of F-IA relies on orthogonal frequency channels, which are represented by a diagonal matrix with each diagonal entry being the channel coefficient of a frequency subcarrier. In contrast, the design of S-IA relies on the spatial channel, which is represented by a full (instead of diagonal) matrix with each entry being the channel coefficient from a transmit antenna to a receive antenna. Due to this fundamental difference, a direct extension of an IA scheme from the spatial domain to the frequency domain by simply treating an antenna element as a frequency subcarrier is not plausible and may result in an infeasible solution. So a separate design of F-IA scheme for multi-hop networks is necessary.

F-IA in Multi-hop Networks. As shown in Table II, it is not an easy task to ensure F-IA feasibility at the PHY layer when jointly designing F-IA with upper-layer algorithms. In addition, we identify some other challenges in designing F-IA scheme for multi-hop networks as follows:

- *Large design space.* In a multi-hop network with OFDM modulation, there is a large number of frequency subcarriers available (e.g., 512 or 1024). Such a large pool of subcarriers offers a large space for the design of a F-IA scheme. To achieve any optimization objective in such a large design space is not an easy problem.
- *Centralized coordination.* Since a F-IA scheme requires centralized coordination, it is not a trivial task to implement a F-IA scheme that works a multi-hop network with a large number of nodes and complex transmission/interference pattern.

Open Problems. To the best of our knowledge, there is no result of F-IA in multi-hop networks. Many problems, including those aforementioned challenges, remain open. In addition to the common open problem listed in Table II, we identify some other open problems: (i) The relationship between F-IA and the network topology is an open problem. Preliminary results (see, e.g., [2]) indicate the throughput gain of F-IA is highly dependent on the network topology. More research efforts are required to explore F-IA in various network topologies, including both infrastructure-based networks (e.g., cellular networks and WLAN) and infrastructure-less networks (e.g., multi-hop ad hoc and mesh networks). (ii) How to apply F-IA to cognitive radio (CR) networks is an open problem. Due to its flexibility, CR networks may be adopted for future wireless communications. However, the heterogeneity of available frequency bands at each node in a CR network is likely to pose a challenge to the design of F-IA schemes, as the latter typically assumes a homogeneous set of frequency channels among the nodes. (iii) How to jointly perform F-IA and S-IA in MIMO-OFDM networks is an interesting but an open problem. Nowadays, MIMO-OFDM has been widely deployed in wireless networks. Such a hybrid technology offers the possibility of performing IA in both spatial and frequency domains. How to combine the best of both worlds with the maximum benefits is an open problem.

V. Conclusions

This magazine article offers a concise overview of three forms of IA. For each form of IA, we explained its basic idea and discussed its status in multi-hop networks, including technical challenges, recent advances, and open problems. Summaries of the three IA techniques are given in Tables I and II. We hope this article can help bring further research efforts from the research community so that major advances of IA can be made for multi-hop wireless networks in the future.

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BIOGRAPHIES

HUACHENG ZENG [S'09] (zeng@vt.edu) received his B.E. and M.S. degrees in Electrical Engineering from Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 2007 and 2010, respectively. He received his Ph.D. degree in Computer Engineering from Virginia Tech, Blacksburg, VA, in 2015. He was a recipient of ACM WUWNET 2014 Best Student Paper Award.

FENG TIAN (tianfeng1979@gmail.com) is an Associate Professor at Nanjing University of Posts and Telecommunications, Nanjing, China. He received his Ph.D. degree in Signal and Information Processing from the same university in 2008. He is a visting scholar at Virginia Tech, USA from 2013-2015. His research focuses on performance optimization and algorithm design for wireless networks.

Y. THOMAS HOU [S'91–M'98–SM'04–F'14] (thou@vt.edu) is Bradley Distinguished Professor of Electrical and Computer Engineering at Virginia Tech, Blacksburg, VA. He received his Ph.D. degree in Electrical Engineering from New York University (NYU) Polytechnic School of Engineering in 1998. Prof. Hou's research focuses on developing innovative solutions to complex problems that arise in wireless networks. He is an IEEE Fellow and an ACM Distinguished Scientist. He is the Chair of IEEE INFOCOM Steering Committee and a Distinguished Lecturer of the IEEE Communications Society.

WENJING LOU [S'01–M'03–SM'08–F'15] (wjlou@vt.edu) is a Professor in the Department of Computer Science at Virginia Tech, USA. She received her Ph.D. degree in Electrical and Computer Engineering from the University of Florida in 2003. Prof. Lou's research interests include cyber security and wireless networks. She is on the editorial boards of a number of IEEE transactions. She is an IEEE Fellow and the Steering Committee Chair of IEEE Conference on Communications and Network Security (CNS). Prof. Lou is currently on IPA assignment as a program director at the US National Science Foundation.

SCOTT F. MIDKIFF [S'82–M'85–SM'92] (midkiff@vt.edu) is a professor in the Bradley Department of Electrical and Computer Engineering and currently serves as Vice President for Information Technology and Chief Information Officer at Virginia Tech, Blacksburg, VA, USA. He received his Ph.D. degree in Electrical Engineering from Duke University, Durham, NC. During 2006–2009, he served as a program director at the US National Science Foundation. His research interests include wireless networks, network services for pervasive computing, and cyber-physical systems.

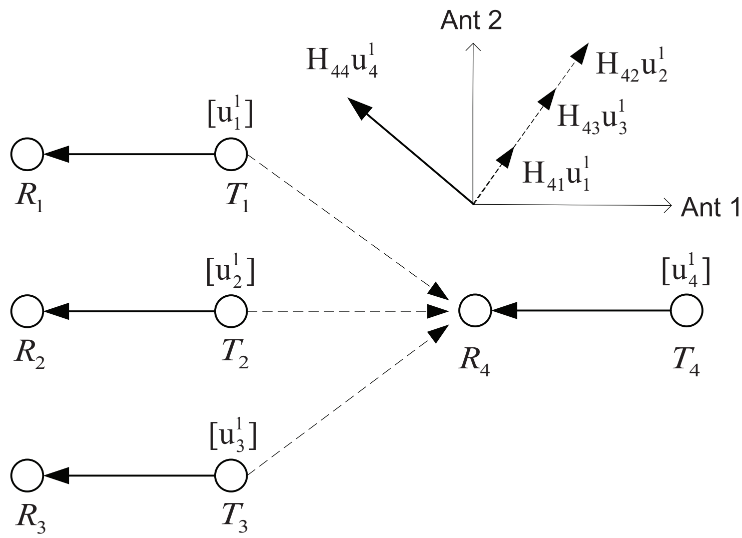
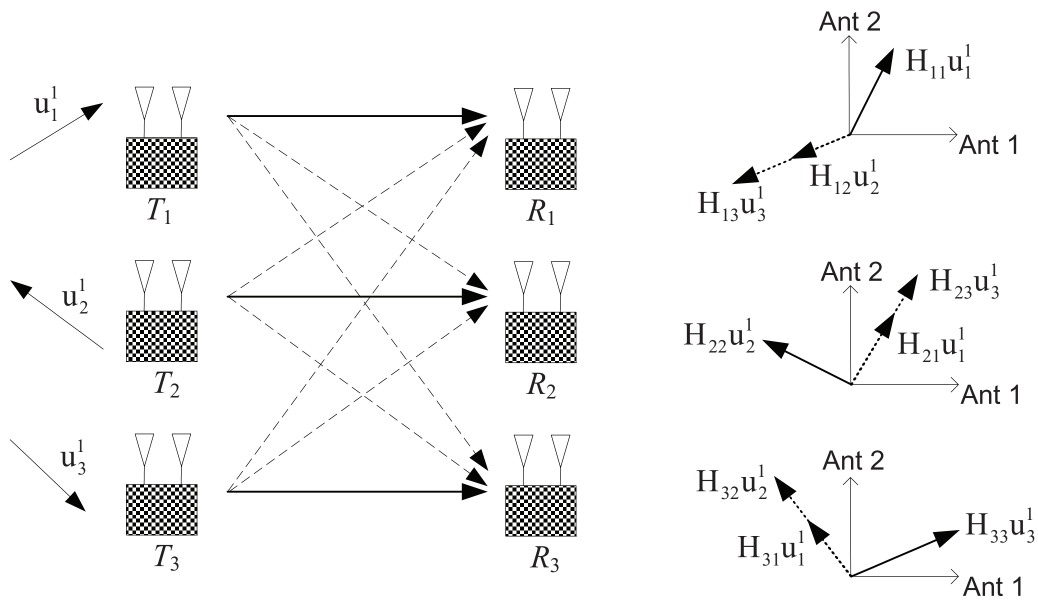
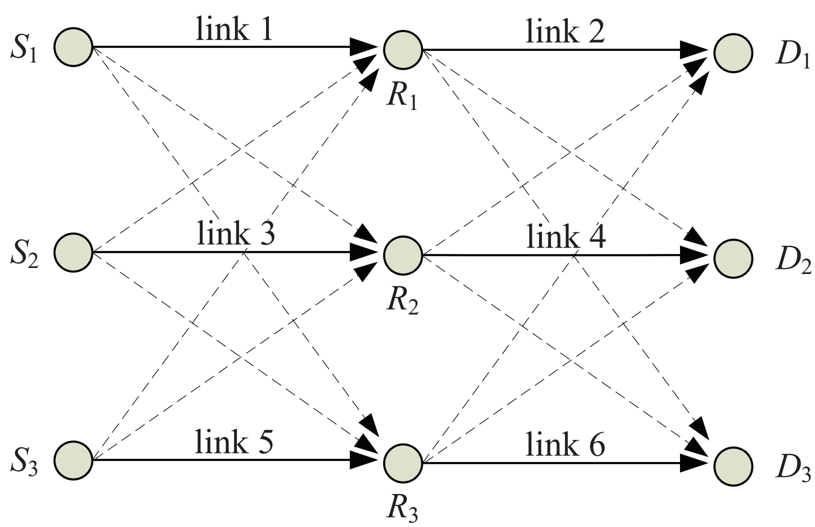


Fig. 1: An example illustrating IA in the spatial domain. A solid arrow line represents data transmission while a dashed arrow line represents interference. Vector $\mathbf{u}_i^k$ is the precoding vector of the kth stream at T_i. Matrix $\mathbf{H}_{ji}$ is the spatial channel between R_j and T_i.

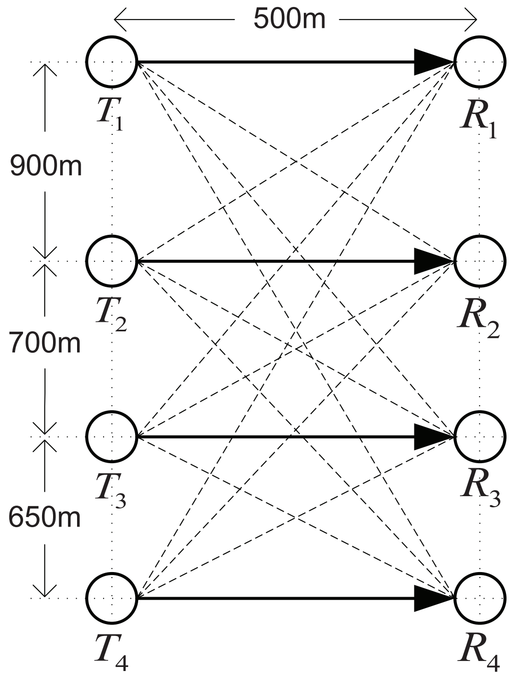


(a) S-IA in one-hop network

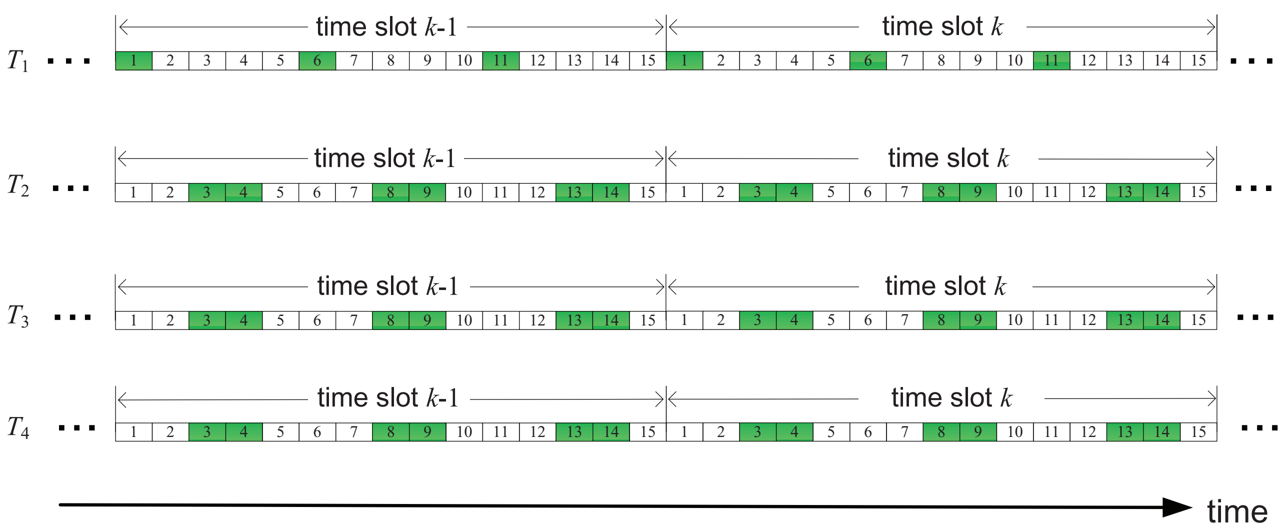


(b) S-IA in multi-hop network

Fig. 2: Illustration of S-IA in both single-hop and multi-hop networks. A solid arrow line represents directed link while a dashed arrow line represents directed interference.

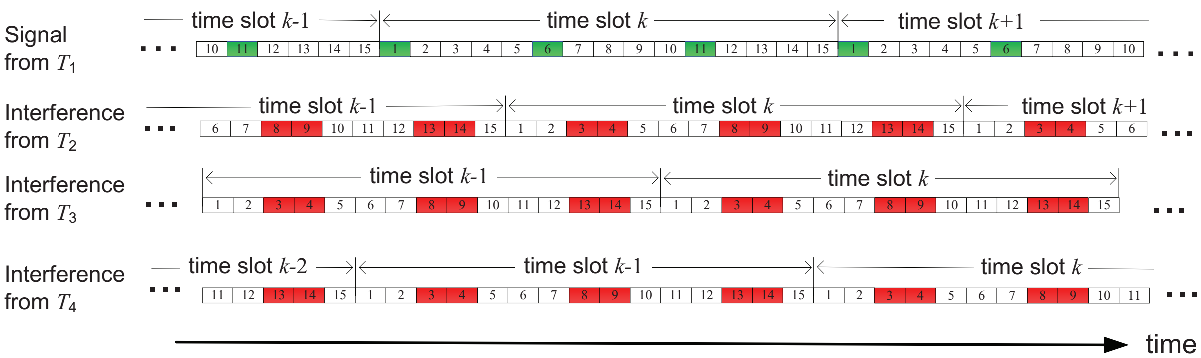


(a) Received signal and interference at receiver R_1

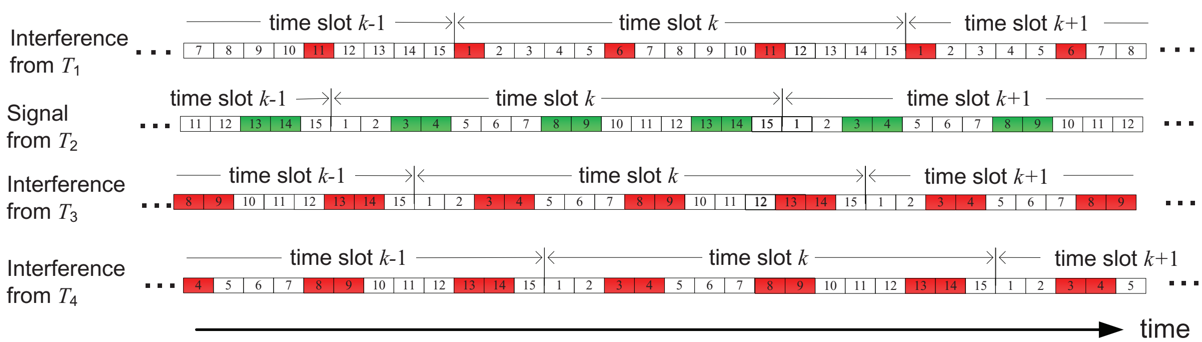


(b) Received signal and interference at receiver R_2

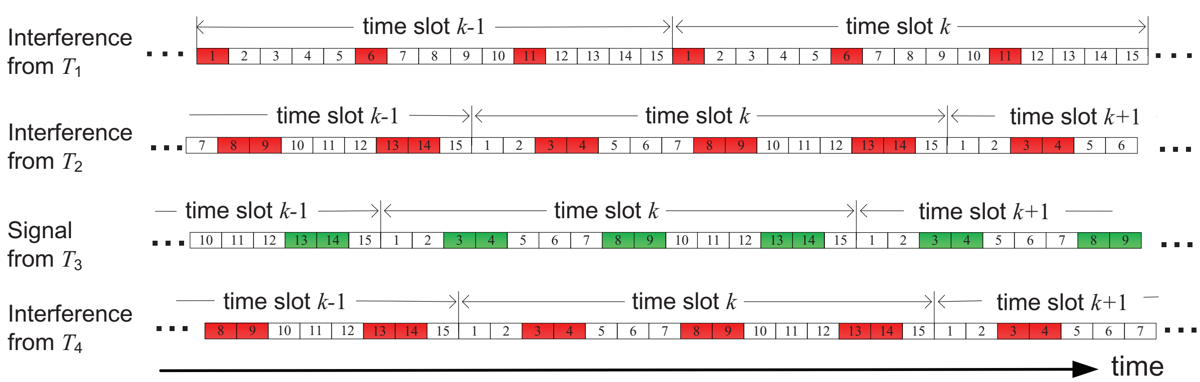
Fig. 3: A schedule of payloads at each transmitter.



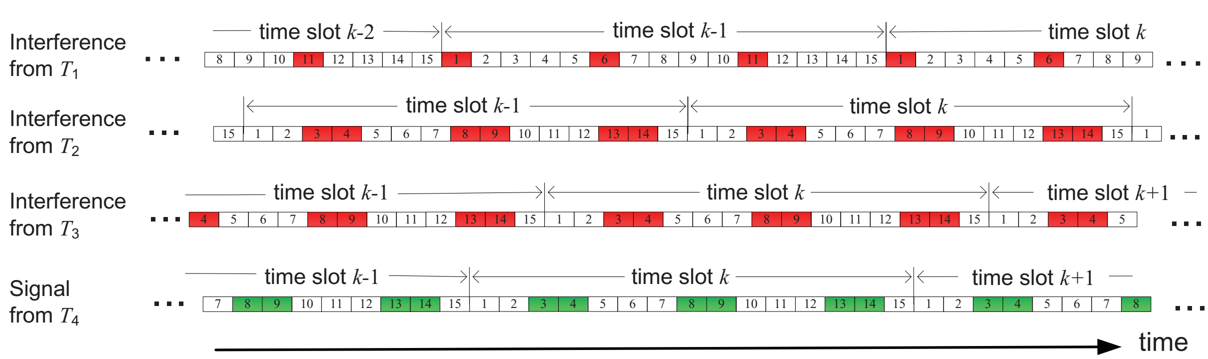
(a) Received signal and interference at receiver R_1



(b) Received signal and interference at receiver R_2



(c) Received signal and interference at receiver R_3



(d) Received signal and interference at receiver R_4

Fig. 4: Received signal and interference at each receiver.

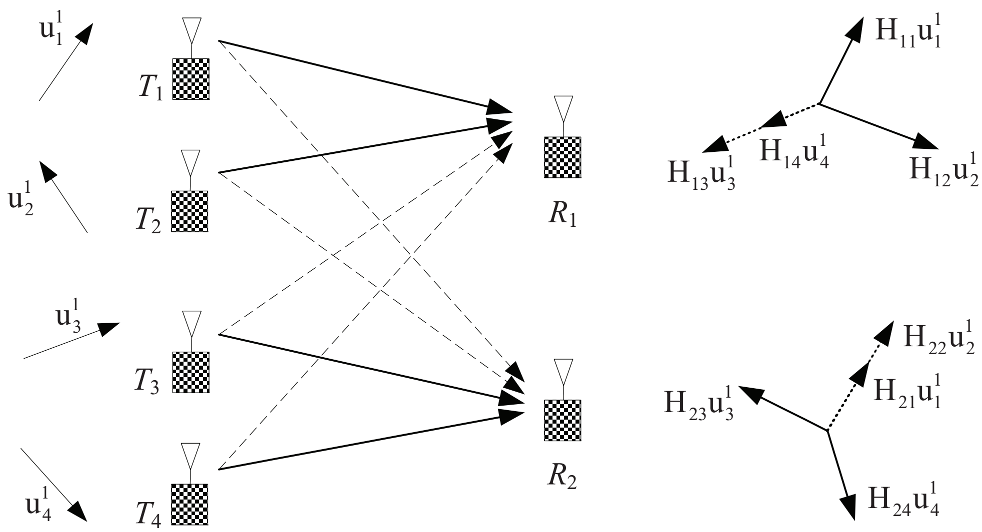


Fig. 5: An example of IA in the frequency domain. A solid arrow line represents data transmission while a dashed arrow line represents interference.