Advanced Interference Management Technique: Potential and Limitations

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Abstract—Interference management has the potential to improve spectrum efficiency in current and next generation wireless systems (e.g. 3GPP LTE and IEEE 802.11). Recently, new paradigms for interference management have emerged to tackle interference in a general class of wireless networks: interference shaping and interference exploitation. Both approaches offer better performance in interference-limited communication regimes than traditionally thought possible. This article provides a high-level overview of several different interference shaping and exploitation techniques for single-hop, multi-hop, and multi-way network architectures. Graphical illustrations that explain the intuition behind each strategy are provided. The article concludes with a discussion of practical challenges associated with adopting sophisticated interference management strategies in the future.

I. INTRODUCTION

Interference is a fundamental phenomenon in wireless communication networks. It is a result of the superposition and broadcast nature of wireless communication along with spectrum shared among multiple users. Uncoordinated interference reduces wireless network throughput. As a result, it is essential to understand and manage interference to achieve the highest network performance.

Conventional approaches to deal with interference are 1) avoiding interference through orthogonalization of the shared time/frequency resource, 2) treating other transmitters’ signals as noise, or 3) decoding interference. These strategies have been studied extensively and adapted to contemporary wireless systems such as cellular and wireless local area networks (WLANs). Although these approaches control interference without system overhead, it turns out that they are not the optimal in most network configurations, except in certain special cases. For example consider the $K$-user interference channel where $K$ transmitters send data to their corresponding receivers in a shared wireless medium. When the interference power is of the order of the power of the signal of interest, the traditional interference management approaches have resulted in (at best) achieving the same data rate order as the rate of a single communication link because of their inefficient usage of the spectrum.

Recently, new paradigms for interference management strategies have emerged: interference shaping and interference exploitation. Both techniques have opened possibilities for significantly better performance in the interference-limited communication regime than traditionally thought possible. The key concept of interference shaping is the creation of a certain interference shape when transmitters propagate signals so that the aggregated interference effect is minimized or eliminated at each receiver. Interference alignment [1], [2] and interference neutralization [3] are representative interference shaping techniques. The key idea of interference exploitation is to harness interference as a useful signal (or side-information) to increase data rates. Network coding [3], [4] is a representative technique for exploiting interference. A conceptual figure for interference alignment and physical-layer network coding is illustrated in Fig. 1.

In this article, we provide an overview of recent interference management strategies that leverage the ideas of interference shaping and exploitation from single-hop interference networks to multi-hop and multi-way interference networks with increasing levels of network complexity. We provide intuitive explanations for each strategy including figures to illustrate the main ideas without relying on the sophisticated mathematical expositions found in the original papers. Compared with our previous overview paper [5], we provide a more comprehensive overview of interference management techniques including interference alignment as well as other interference management techniques. We also consider applications to single-hop, multi-hop, and multi-way networks. We conclude the article with a discussion about practical limitations faced by cutting edge interference management techniques in wireless systems and possible directions towards interference management research.

II. SINGLE-HOP INTERFERENCE NETWORKS

Single-hop interference networks are good models for communication in cellular networks, wireless local area networks, and ad-hoc networks. The term single-hop means that the source delivers its message directly to the destination using other nodes as a relay. Further, every source has data for only one destination (otherwise known as single-way communication). Interference management in single-hop interference networks becomes convoluted, especially when the number of transmit and receive user pairs increases.

Interference alignment was among the first of the new class of interference management techniques [1], [2] (please also refer to the references in [1] for further background). As depicted in Fig. 1(a), the idea of interference alignment is to align multiple interfering signals at each receiver to minimize the signal dimension occupied by the interference signals. As a result of this alignment, each user is able to decode its desired signal with no interference by projecting a received signal onto...
of mean square errors were proposed for the multiple-input-signal to interference plus noise ratio or minimizes the sum produced by multiple antenna systems [1], [5], [6]. For exam-
algorithms using multiple signal dimensions inherently in-
the finite SNR regime is to apply interference alignment due to high delays and buffer constraints in hardware.
architecture of interference alignment algorithm called ergodic interference alignment has been proven to achieve the best possible sum of degrees of freedom (sum-DoF), also known as multiplexing gain, in a wide class of single-hop interference networks such as the interference channel and the X channel [1], [2].
the null space of the interference signal space. Interference The sum-DoF is a coarse approximation of the sum-capacity of the networks, which describes how the sum of the rates scales with the log of SNR. Interference alignment makes it possible to linearly increase sum rates with a number of communication pairs in the idealistic case of an interference channel with time-varying channel coefficients [1].
Although interference alignment opens new possibilities to provide optimal throughput scaling in interference networks, it faces a number of challenges to be a practical interference management solution for many wireless systems. One problem is that the algorithms for implementing interference alignment over time-varying channels (also known as asymptotic interference alignment algorithms) may provide poor sum rate performance in the finite SNR regime [1]. This comes from the fact that transmitters need to code over many independent channel realizations (i.e., needs for large channel diversity), which essentially sacrifices the desired signal power over multiple channel uses at the cost of interference alignment. To overcome this issue, in time-varying channels, a near-optimal interference alignment algorithm called ergodic interference alignment was proposed to characterize an approximate er-
godic capacity to within a constant number of bits/sec/Hz, regardless of SNR in certain interference networks (see the references in [1]). The main drawback of ergodic interference alignment lies in the impracticality in current wireless systems due to high delays and buffer constraints in hardware.
Another direction for overcoming the performance loss in the finite SNR regime is to apply interference alignment algorithms using multiple signal dimensions inherently in-
duced by multiple antenna systems [1], [3], [4]. For example, iterative interference alignment algorithm that maximizes signal to interference plus noise ratio or minimizes the sum of mean square errors were proposed for the multiple-input-
multiple-output (MIMO) interference channels in [1], [5]. By aligning interference signals distributively while maximizing the desired signal’s strength, iterative interference alignment was found to achieve a higher total throughput compared to that of conventional interference management methods in the finite SNR regime. One drawback of conventional interference alignment algorithms is that they do not scale the total throughput linearly with the number of communicating pairs due to limited channel diversity provided by the MIMO channels. For example, for the symmetric K-user MIMO channel, each transmitter and receiver with M antennas, it turned out that the maximum sum-DoF is at most 2M [6]. This result reveals a fundamental performance limitation of interference alignment for multiantenna based wireless systems - the rates only scale with the number of antennas not the number of user pairs as in the time-varying case.

Another limitation for the interference alignment algorithms is that they require global and instantaneous channel state information at transmitter (CSIT), or overhead intensive over-
the-air iterative design. To resolve this, recently, interference alignment has moved in the direction of using limited channel knowledge to translate theoretical results into practical wireless systems [1], [7]. Blind interference alignment (see the references therein [1]) is a class of interference alignment techniques that use knowledge about autocorrelation functions of channels instead of channel values themselves, thereby requiring less CSIT. The idea is that a transmitter carefully and repeatedly sends symbols based on knowledge of the autocorrelation function of channels so that each receiver can see the same aggregated interference. This algorithm leads a receiver to simply subtract the aggregated interference and then resolve the multiple desired signals free from interference. The essence of blind interference alignment was extended in a case where channels independently vary over time or frequency (wherein autocorrelation functions do not help to predict channel patterns). In particular, in the context of the vector broadcast channel, an innovative transmission strategy was proposed. The core idea was that a transmitter sagaciously

Fig. 1. (a) An interference shaping strategy known as interference alignment at each receiver, three interferers collapse to appear at two. This enables interference free decoding in a desired signal subspace [1]. (b) An interference exploitation technique known as physical-layer network coding in a two-way relay channel. The two users exchange two packets within two time slots by using self-interference signal as side-information.
uses completely-delayed CSIT (i.e., CSI feedback delay larger than the channel coherence time) to align inter-user interference between the past and the currently observed signals. This method, surprisingly, revealed that completely delayed CSIT is still useful in providing substantial DoF gains in the channels compared to no CSIT \[1, 7\].

Blind alignment techniques were extended to different limited CSIT models, including moderately delayed CSIT (feedback delay is less than the channel coherence time) \[8\], mixed (perfect delayed and partial instantaneous) CSIT, and alternating CSIT \[9\]. In particular, under the moderately delayed CSIT model, space-time interference alignment in \[8\] was found to achieve the optimal sum-DoF for a certain class of interference channels even if the feedback delay exists, provided that the feedback delay is less than a certain fraction of the channel coherence time. The idea of space-time interference alignment is illustrated in Fig. 2 for a two-cell multi-user uplink communication scenario where two users placed at the cell-edge area wish to communicate with their respective base station (BS) by sharing the same time-frequency resource. Under the premise of the moderately-delayed CSIT model, each user employs (perfect) outdated CSIT for the two-thirds of the channel coherence time, while it exploits (perfect) current CSIT for the remaining fraction of it. In such a setting, it is possible to show that the four users are able to send four independent information symbols \(a_1, a_2, b_1,\) and \(b_2\) to the two BSs by spanning three time slots \(t_1, t_2,\) and \(t_3\) that are belong to different channel blocks. In time slot one, the two users in cell 1 send their information symbols \(a_1\) and \(a_2.\) Then, BS 1 and BS 2 obtain a linear combination of the two symbols where the linear coefficients are chosen from the channel values between the transmitter and receiver. In the second time slot, the two users in cell 2 transmit information symbols \(b_1\) and \(b_2.\) Then, similar to the first time slot, each BS receives a linear combination of \(b_1\) and \(b_2.\) In the third time slot, the users exploit the current and delayed CSIT jointly so that the two BSs receive the same interference equations that previously received. To accomplish this, each user applies a precoding coefficient that inverts the current channel response from the user to the interfering BS and, then multiplies the same channel coefficients that the interfering BS observed previously. This interference alignment in the third time slot allows for each BS to perform successive interference cancellation with the overheard interference equation during the first and second time slots; thereby, the desired information symbols are reliably decodable at each BS.

Following upon the success of the interference alignment techniques with limited CSIT, more recent and emerging work has considered developing interference management techniques using extremely less knowledge of CSIT. Topological interference management in \[10\] is an ingenious approach in that direction. The idea is to smartly schedule multiple transmissions based on network connectivity information at transmitter. This approach was shown to achieve considerable DoF gains for a certain class of partially connected interference channels only with network connectivity information. Remarkably, topological interference management has also received attention because of its connections to index coding as well as its practicality. As illustrated in Fig. 3 a partially connected interference channel can be represented by a direct graph \(G\) where each vertex corresponds to a transmit-and-receive pair and the direct edges represent the connectivity of interfering links. By taking the complement of the direct graph, \(\overline{G}\), it was shown \[10\] that topological interference management can be converted into an index coding problem with side-information graph \(G\).

Finding the optimal solution for the topological interference management problem is challenging for the \(K\)-user interference channel with an arbitrary network connectivity. Using the strong relation to index coding, however, one can find the upper and lower bound on the symmetric DoF for the topological interference management problem with an arbitrary network connectivity. This is because, for the given direct side-information graph \(G\), the optimal index code length, \(L\), is lower and upper bounded by the maximum independent set number of the corresponding graph, \(\overline{G}\), and the chromatic number of its complement, \(\overline{G}\). These graph-theoretical approaches also can be used to characterize the bounds on the symmetric DoF, \(\frac{K}{L}\) for the corresponding topological interference management problem. Algebraic approaches can also be effective methods to solve topological interference management problems. Using the fact that the
Fig. 3. Diagrams illustrating the connection among a topological interference management problem, the equivalent index coding problem, and the matrix completion problem.

optimal linear index code length equals to the minimum rank of a matrix that fits the side-information graph $G$, it is possible to solve topological interference management problems by equivalently solving a matrix completion problem over a finite field as illustrated in Fig. 3. Despite the strong relation to index coding, finding the optimal solutions for the topological interference management problems via index coding is NP-hard for a general network connectivity. It would be a good direction to design an algorithm that solves any topological interference management problems with polynomial time complexity, while providing a solution close to the optimal symmetric DoF.

III. MULTI-HOP INTERFERENCE NETWORKS

Multi-hop communication, in this article, refers to the case where a source and destination communicate through one or more other nodes that act as a relay. As in the single-hop case, we consider single-way configurations where a source only talks with a single destination. Interference management in multi-hop networks is convoluted as relay nodes between the source-destination pairs propagate not only the desired signals but also interference signals on the network. This makes it difficult to design relay strategies because it is ambiguous as to what extent a relay should forward, remove, align, or otherwise manage interference.

Interference neutralization was proposed in [3] to overcome the interference barrier for multi-hop interference networks. The main idea of interference neutralization is a careful selection forwarding strategies at relays that results in the cancellation of interference signals through multiple channel paths. As a result of neutralization, each destination node is capable of decoding the desired signal without interference. By employing interference neutralization, it was demonstrated that interference-free communication is possible for a certain class of two-hop interference networks, provided that the number of relays is sufficiently larger than the number of source and designation pairs $K$. Fig. 4(a) illustrates an example of interference neutralization in a two-pair two-hop interference channel. Interference going through multiple paths can be cancelled via cooperation of three relays; thereby each destination can perform interference-free decoding.

The idea of interference neutralization was generalized by leveraging the idea of interference alignment. Considering precoding techniques over multiple symbols, aligned interference at relays can be neutralized through multiple paths; this is referred to as aligned interference neutralization [1], [11]. Using this idea, it was demonstrated that the optimal sum DoF of the two-pair two-hop interference network is achievable with two cooperative relays (see the reference therein [1]). The core idea of aligned interference neutralization in [11] is illustrated in Fig. 4(b). In this channel, a cognitive relay has global channel knowledge while two dumb relays simply amplify and forward their received signals with no knowledge of channel conditions. In the first hop, source 1 sends two signals $A$ and $B$ while source 2 transmits signal $C$ over two time slots so that the cognitive relay sees the aligned signal $B + C$ in a signal dimension while observing $A$ in a separate signal dimension. By carefully choosing the relaying coefficients over the two signal dimensions, it is possible to neutralize the aggregated interference propagated from the dumb relays and the cognitive relay at both destinations, which allows for the two destinations to extract their desired signals. Recent work [12] for two-hop interference networks with $K$ sources, $K$ relays, and $K$ destinations showed that the cut-set bound (i.e., $\text{sum-DoF}=K$) is achievable by asymptotically canceling the interference between all source-destination pairs using a variant of aligned interference neutralization.

Although the interference neutralization techniques show that considerable DoF gains can be attainable in multi-hop interference networks, they often require complicated relaying strategies with demanding CSIT knowledge and have a poor sum rate performance in the finite SNR regime.
A general communication scenario where multiple users exchange information with the help of multiple relay nodes. This wireless network architecture has received attention because of its broad applications to cellular networks, sensor networks, and device-to-device (D2D) communication. The most distinctive feature of multi-way relay networks are that source and destination nodes are inseparable. This feature introduces a new potential of exploiting interference signals as an efficient interference management approach.

Network coding is a representative technique of exploiting interference. For multi-hop wired networks, [4] originally introduced the idea of network coding to boost network throughput. The crucial principle underlying network coding is that intermediate nodes in networks forward functions (a linear combination) of their received packets, instead of independent packets. The same spirit of exploiting interference was extended into wireless networks. In the two-way relay channel in which two nodes exchange information with each other via a shared relay node, the concept of physical layer (analog) network coding [3] was introduced. As illustrated in Fig. 1(a), physical-layer network coding allows the exchange of packets A and B within two communication phases by canceling the known self-interference signal a prior. Drawing upon this idea, [3] showed that the rates of information exchange are double of these achieved by traditional interference management strategies.

The concept of interference exploitation was extended by combining the ideas of interference alignment and network coding; this is referred to signal space alignment for network coding [13]. Consider a three user multi-way communication scenario where a user with two antennas wants to exchange two independent messages each via a relay with three antennas; this is referred to a MIMO Y channel [13]. As illustrated in Figure 5, when each user sends two independent messages to the relay in the multiple access phase, the relay observes a total of six incoming signal streams. Since a relay is able to use a three dimensional signal space, the users cooperatively send the signals so that a pair of two signals for network coding can each be aligned as a signal dimension. In the broadcast phase, the relay applies the multi-user beam forming technique that cancels unmanageable interference to the users. At the user end, each user is able to first subtract its own transmit signal, the so-called self-interference, and then extract the desired signal from its partner, in a process that is analogous to network coding. This idea achieved the optimal sum DoF in the MIMO Y channel and in a broad class of multi-way communication networks with relays.

Recently, the interference exploitation idea also was applied to fully-connected multi-way relay channels. Unlike the prior physical-layer network coding approaches that only exploit the self-interference signal as the main source of side-information, a new physical-layer network coding strategy called space-time physical layer network coding was proposed in [14]. The essence is the exploitation of overheard interference signals as side-information in addition to self-interference signals for fully-connected multi-way relay networks. As illustrated in Fig. 5 consider a fully-connected multi-way information exchange scenario where two pairs (user 1-3 and user 2-4) exchange packets with their partners via a relay with two antennas. This scenario can model the case where two D2D user pairs cooperatively exchange video files by sharing a WiFi access point. In time slot 1, user 1 and user 3 send two packet A and C. Then, since user 2 and user 4 have a single antenna, the both cannot decode the desired packet reliably due to mutual interference. Instead, they just store the overheard linear combination of two packets A and C to exploit it later as side information. Whereas, the access point with two antennas is able to decode the two packets reliably by applying a zero-forcing decoder. In time slot 2, user 2 and 4 send packets B and D. Then, similarly, user 1 and user 3 store the linear combination of B and D, while the access point decodes the two packets thanks to the multiple antennas. Recall that during the previous two time slots, the access point

![Fig. 4](attachment:image.png)

(a) Interference neutralization (b) Aligned interference neutralization
has decoded all the packets, A, B, C, and D. Furthermore, each user has obtained two different types of side-information: 1) what it sent and 2) what it overheard. In time slot 3, the access point sends out a linear combination of the four packets using space-time precoding so that every users exploits both different types of side-information simultaneously. For example, the precoding vector carrying packet B is selected so that the packet B does not propagate to user 1 who does not have knowledge of packet B as side information. By carefully choosing precoding vectors with the same principle, every users is able to decode the desired packets successfully from the received signal in time slot 3 using the two types of side information obtained in the prior time slots.

V. RESEARCH CHALLENGES

Despite the theoretical performance gains of the advanced interference management techniques described in the previous sections, there are many research challenges that remain to transform theory to practice.

A. Out-of-Cell Interference

Most of the interference management techniques reviewed in this article were developed in idealized interference network settings. These settings consider a particular number of cooperative transmit-and-receiver pairs, ignoring the potential interference from outside of the cooperative set and often deemphasizing noise effects. There exists apparent limitations in translating the performance gains obtained from the advanced interference management techniques into practical wireless systems due to their simplified natures.

To realize the advanced interference management methods in future wireless systems, they should be reevaluated using models that accurately capture the impact of the irregular spatial structure of wireless node locations and channel characteristics depending on operating frequency bands (e.g., low frequency or mmWave bands). One possible direction is to use analytical models for large-scale interference networks via stochastic geometry, which facilitates compact expressions of coverage probability and spatially averaged spectral efficiency of in networks. For example, by adopting the downlink cellular network model via stochastic geometry [15], it would be interesting in future work to analyze the system-level performance of the advanced interference management techniques.

B. Partial CSIT

A major problem found in most of the advanced strategies is that they substantially increase transmission rate only when ample knowledge of instantaneous and global CSIT is available. For example, interference alignment and neutralization need global and perfect knowledge of CSIT across networks. In practice, however, the acquisition of such instantaneous and global CSIT as a means toward cooperation is highly challenging due to the distributed nature of transmitters and dynamic wireless propagation environments. In many limited CSIT scenarios, the promising gains from interference management strategies using instantaneous and global CSIT disappear, often providing the same result as cases where there is no CSIT.
To achieve potential gains in practical wireless systems, an interesting direction for future study is to explore the effects of using only statistics of the CSIT. For example, one may devise an efficient interference management technique that only requires the mean or covariance of the channel at the transmitter, i.e., the first-order or second-order statistics of the channel. This approach could possibly reduces the amount of channel feedback significantly and increases the robustness for the CSIT uncertainty by delay and CSI quantization, at the expense of reduced performance compared with perfect and complete CSIT.

C. Link Scheduling through Index Coding

Designing link scheduling algorithms based on index coding are promising as they only require to know information about network connectivity, causing the minimal CSIT acquisition overhead in wireless systems. A natural extension for future study is to explore the link scheduling algorithms using index coding where each wireless device has multiple antennas. This would bring the additional performance improvements through multiplexing gains in MIMO systems. Furthermore, by leveraging the idea of index coding, it would be interesting to devise the joint scheduling algorithms among source and relay nodes in multi-hop interference channels. This approach possibly opens a new approach that manages interference with channel connectivity knowledge in multi-hop interference networks. In addition, it would be interesting to investigate the performance of link scheduling algorithms from an ergodic perspective, considering time-varying network connectivity.

D. Interference Shaping in mmWave Systems

Millimeter wave (mmWave) carrier frequencies promising candidate for next-generation cellular and WLAN wireless. MmWave offers the potential to support gigabit-per-second data rates due to both the vast bandwidth available in mmWave bands and the use of the large number of antenna arrays packed in a small area. Despite the gains, there are many practical challenges in the realization of mmWave wireless systems especially in terms of dealing with interference. It would an interesting direction for future study to gauge the potential gains of interference shaping algorithms in irregularly and densely deployed mmWave wireless networks in which interference possibly provides a huge impact on the data rates. For example, it would be interesting to explore interference alignment algorithms for multiuser transmission that use a hybrid MIMO processor consisting of a radio frequency chain (analog) beamformer and a baseband MIMO (digital) beamformer for mmWave communications.

VI. Conclusion

Interference management is important for every wireless network. This article provided a high level introduction to several recently developed interference management strategies. These strategies use the principles of interference shaping and interference exploitation to achieve better performance compared with systems that neglect interference. The potential gains and limitations for the new interference management techniques were discussed in a various interference network scenarios including single-hop, multi-hop, and multi-way. The article concluded with a discussion of some relevant research directions that make interference management more practical. The frontier for practical interference management techniques remains vast.

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