Interference Alignment in Multi-user MIMO Systems

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Abstract

Interference alignment (IA) has been studied extensively as an advanced technology to obtain the maximum degree of freedom (DoF) of multi-user wireless communication systems. This letter provides a brief review of recent works on IA. The most effective approach of IA is to deploy optimal linear transceivers by exploiting spatial characteristics of wireless channels. It is evaluated in measured multi-input multi-output (MIMO) interference channels. The implementation of IA depends on the characteristics of channel state information (CSI) feedback to the transmitters, such as imperfect, noisy, localized, delayed nature, and so on. In this work, we present a review of existing techniques for IA in typical multi-user MIMO systems. Moreover, we also consider some future research issues related to implementation. The study covers IA’s feasibility conditions, solution algorithms in MIMO interference channel and MIMO multi-cell networks, with emphasis on the CSI feedback technology which remains as the major challenge of IA.

Index Terms: MIMO, Interference Channel, Multi-cell Networks, Limited Feedback

1. Introduction

Recently, the Internet and data telecommunication services have developed rapidly and create a demand for higher communication capacity and data rate. Interference is the major challenges faced by designers of next generation wireless networks, as it will significantly restrict the reusability of the spectral resource and, therefore, may decrease the throughput of multi-user wireless communication systems. Various orthogonalizing techniques are the main interference management methods in current wireless communication networks. However, they are the “cake-cutting” approaches which avoid interference between coexisting wireless systems by dividing spectrum resource. Obviously, with orthogonal access schemes, each mobile user only gets a fraction of spectrum resource, which decreases with the increase of the number of users, and the sum of these fractions is equal to one.

The capacity of wireless networks is a “holy-grail” of network information theory. Some optimum transmit strategies are introduced in [1] for the multi-user multi-input multi-output (MIMO) systems. However, except some specific networks, the capacity characterization of most communication networks remains a long standing open problem. IA is a novel idea that has recently emerged out of the capacity analysis of wireless networks. IA was proposed as a general principle to get the optimal degree of free (DoF) of K-user interference channel by Cadambe and Jafar in [2]. It is shown to achieve almost surely a throughput multiplexing gain of K/2 per time, frequency and antenna dimension for K-user interference channels [3], which means that wireless networks are not essentially interference limited [4]. To make the scheme a reality, various schemes have been designed to implement IA by aligning interference using signal levels, time or frequency channel extensions, and multiple antennas at interfering users. Among these schemes, aligning the interference over spatial dimension is the most practical approach. Therefore,
most literatures about IA focus on the multi-user MIMO systems.

In this work, we provide a brief review of available literatures on IA in multi-user MIMO systems. Moreover, we discuss some under-explored open issues based on the existing works. In section II, we review the works of IA for MIMO interference channels. In section III, we provide a discussion on IA for multi-cell networks. IA with limited feedback is discussed in section IV. Finally, we conclude the paper in section V.

**2. IA for the MIMO interference channel**

Information researchers have pursued capacity characterizations of interference channels for over three decades, and proposed extensive interesting results. The key to achieving near-optimal capacity is IA. With IA, multi-interfering users communicate simultaneously and keep the desired signals separable from interference, which is consolidated to span a space at each receiver with a small number of dimensions

**2.1 Principle**

The diversity of channels is the key premise for IA, it enables independence between desired signal and interference signal for each receiver. Therefore, interference signal from different transmitters can be overlapped each other by designing transmit signal in ingenious ways. The achievable rate of IA depends on the characteristics of CSI feedback to the transmitters, such as the imperfect, noisy, localized and possibly delayed. While beamforming approaches are common in existing MIMO wireless communication systems, IA based on linear precoding (beamforming), i.e. linear IA, is easily implement from a practical perspective, and it is also the main focus of this paper.

**2.2 Feasibility conditions**

We denote the interference channel with K users where the transmitter k, equipped with Mk antennas, transmit dk independent streams of information symbols to receiver k which is equipped with Nk antennas as \((M1\times N1, d1)\), \((M2\times N2, d2)\), \(\ldots, (MK\times NK, dK)\). In the symmetric setting, \(Mk=M\), \(Nk=M\), \(dk=d\) for all k, mathematically, The linear IA problem is equivalent to the design of transmit precoding matrices \(Vk\) and receive combining matrices \(Uk\). There are two conditions must be satisfied, one is the condition that existence of a separately desired space with \(dk\) dimensions, the other is the condition that ensures that the desired signal is not interfered by the signal transmitted by other users. However, for a general channel, they are proved to be NP-hard for finding the optimal IA solutions and checking the achievability of a given tuple of DoF. We can find the analytical IA solutions only in some special cases, for example, three-user MIMO interference channel in which each node equipped with two antennas.

The existence of linear IA solutions for MIMO interference channel is equivalent to the feasibility of the polynomial equations. But the solvability of a generic system of polynomial equations is also an open problem. An IA problem as improper or proper is defined based on the intuition that a general polynomial equation is solvable if and only if the number of variables does not less than the number of variables. In most cases, proper systems are likely to be feasible and improper systems are likely to be infeasible. For a symmetric system \((M\times N,d)K\), it is proved that the linear IA problem is proper if and only if \(d\leq(M+N)/(K+1)\). For some special cases, the proper systems are feasible, but it is incorrect for generic systems. However, improper systems are indeed infeasible in general [4].

**2.3 Solutions**

To solve the linear IA problems, more studies have focused on iterative algorithm. By iteratively minimizing leakage interference and maximizing signal-to-interference-plus-noise ratio (SINR), two distributed IA algorithms are proposed that require only local CSI at each node [5]. Inspired by these works, with different optimization goals, extensive iterative algorithms to numerically find the alignment solutions are proposed. Such as interference minimization, MSE minimization, sum-rate maximization, and so on. These solutions try to achieve the optimal tradeoff balance between performance and complexity for IA in MIMO interference channels. However, most of IA algorithms aim to find the best solution only in terms of users’ selfish performance, that neglected the interference relationship between users and limited the system performance. By revisiting the problem of IA on MIMO interference channel through the prism of game-theory, a new IA algorithm that aimed at throughput maximization is proposed in [6] based on balancing the egoistic and the altruistic behavior of each user.

Although some progress is being made, algorithms remain a hot topic for IA research. Novel IA algorithm needs to be developed for practical application with further improvement, such as less complexity, distributed computation, and insensitivity to imperfect CSI.
3. IA for the MIMO multi-cell networks

While most of works on IA focus on interference channel, IA was first used to improve the user throughput in a multi-cell network in [7]. A new IA based scheme for multi-cell networks is proposed, namely subspace IA, it approaches to interference-free DoF as the number of users in each cell increases. This result is surprising because the maximum DoF is achievable by MIMO cellular networks without data sharing among the base stations. Motivated by such a promising performance of IA, many recent works strived to design more practical schemes based on IA for multi-cell networks.

3.1 Solutions

In view of the challenges in implementation of subspace IA, an IA algorithm aim at aligning interference only from one neighboring BS is proposed for downlink cellular networks in [8]. Compared to a standard multi-user MIMO precoding technique, simulation results show that the proposed scheme achieves better performance. That IA solution achieves good performance especially when the interference from a dominant interferer base station is significantly stronger than the remaining interference.

Furthermore, to reduce feedback and computation complexity, for a two-cell MIMO interference broadcast channel (IFBC), W. Shin et al. in [9] proposed a novel grouping IA technique by jointly designing the transceiver beamforming vectors using a closed-form expression without a need for iterative computation. It was shown both analytically and numerically that the proposed scheme achieves the optimal DoF. It is extended to multi-cell networks by novel design of transceiver beamformer design [10,11].

3.2 Feasibility conditions

For the multi-cell MIMO networks, to achieve the optimal DoF with linear IA, it is crucial to decrease number of transceiver antennas while guaranteeing feasibility of linear IA. Yet the feasibility of linear IA for general MIMO multi-cell networks is still an open problem. The feasibility conditions of linear IA include the necessary and sufficient conditions. As the same as interference channel, the proper condition is one of the necessary conditions for the IA feasibility of general MIMO cellular networks. T.Liu et al. provided a comprehensive and descriptive view of the feasibility of linear interference for the MIMO multi-cell networks in [12]. The necessary conditions of the IA feasibility for general MIMO multi-cell networks are provided and proved. Except for the proper condition, another kind of necessary condition is found.

3.3 Challenges

Of course, to make IA technology available for modern cellular networks, there exist some problems in IA research, such as scheduling, resource allocation, and backhaul signaling delay, and these problems have to be paid attention to and settled urgently. Moreover, IA algorithms should be re-evaluated using models that more accurately resemble modern cellular systems, such as macrocells, picocells, small cells, relay networks, and so on. In these aforementioned works, globally perfect CSI is assumed at the transmitters. However, in practical networks, acquiring perfect CSI at the transmitter (CSIT) is difficult due to the low-rate feedback links.

4. CSI feedback for IA

Despite being a promising technique for interference management, IA is far from being practical. A key challenge in implementing IA approaches is that each transmitter requires global and perfect CSI at transmitters of all interference links, incurring potentially unacceptable CSI feedback overhead. Extensive works about limited feedback focus on point to point MIMO communications.

Consequently, some works addressed this issue of the IA with limited feedback.

4.1 Effect of limited feedback

Grassmannian codebook is near optimal for CSI quantization, but it is challenging to be designed. The minimum number of feedback bits to achieve the maximum DoF of interference channel is analyzed for a frequency selective single-input single-output (SISO) system in [13]. And this work was extended to MIMO case [14], where a limited feedback scheme has been proposed. However, a large amount of feedback bits is required to attain reasonable throughput, and some problems are brought on.

For moderate-size systems, random vector quantization (RVQ) codebook performs close to the optimum codebook. An IA scheme with RVQ codebooks for the constant MIMO interference channel was investigated in [15]. By considering the cost of both training and limited feedback, Xie et.al discuss the effective DoF achieved by IA to evaluate the performance fairly, and investigate both lower and upper bounds of throughput for block-fading interference channels [16].

When the transmit SNR is high, the number of feedback
bits increases sharply, resulting in less practical of limited feedback. To reduce overhead of limited feedback and improve CSI quality, some works were proposed by exploiting the characteristics of system channel.

4.2 Solutions

A new channel quantization algorithm for the MIMO IA with limited feedback was proposed in [17] by introducing an additional receive filter at each receiver before quantizing the channel and the imperfect CSI error is reduced. Based on the closed form IA solution for a single stream per user, Cho et.al proposed an efficient feedback topology for IA in [18], which allows significant reduction of CSI feedback compared with the full-feedback topology. However, as the number of iterations increases, the full DoF in the K-user interference channel cannot be achieved since it causes the time delay of transmission that results in significant interference misalignment for fast fading channel. In [18, 19], dynamic quantization schemes are proposed via bit allocations for different interference links by exploiting heterogeneous path loss to improve the efficiency of limited feedback.

When the interference is insignificant, it is also important to note that IA may be outperformed by spatial multiplexing because of some additional spatial dimensions are sacrificed for accommodating interference rather than transmitting desired signal. This effect induces a partially connected interference topology, which may contribute to not only limiting the aggregate interference but also decreasing the number of required antennas. The feasibility condition and solution algorithms of partially connectivity are investigated for MIMO interference channels [20] and cellular networks [21], separately.

4.3 Challenges

In point to point MIMO systems, the imperfect CSI causes only an SNR offset in the capacity vs. SNR curve. However, the accuracy of the CSI decreases the slope of the curve, i.e., DoF, in the multi-user MIMO systems. The overhead of feedback is a key challenge of system design. Channel characteristics such as temporal correlation, spatial correlation, and heterogeneous path loss, can be used to improve the performance of feedback. Feedback schemes must be designed carefully to balance the system performance against feedback overhead.

5. Conclusion

IA is a promising interference management technology for multi-user wireless communication systems. The survey has provided a brief review of techniques for multi-user MIMO systems evolved during the recent years and future direction of research issues related to system implements and performance. There has been huge research space in the emerging areas of wireless communication. The idea has to be focused in the view of performance and compatibility that the key challenge faced by most researchers. The IA solutions and feasibility conditions are introduced for MIMO interference channel and MIMO multi-cell networks, separately. Moreover, CSI quantization and feedback schemes are investigated for IA scheme. Some works are introduced to improve the efficient performance by fully exploiting the characteristic of the interference topology.

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