Opportunistic Communications in Interference Alignment Networks with Wireless Power Transfer

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Abstract

Interference alignment (IA) is a promising technology for interference management in wireless networks, however, there are still some practical challenges. Signal to interference plus noise ratio (SINR) decrease is one of the key challenging issues due to the inherent property of IA and channel fading. Recent advances in opportunistic communications (OC), including multiuser diversity and antenna selection, can be applied in IA wireless networks to improve the SINR performance. In this article, we review some existing research works on OC-based IA wireless networks. In addition, we propose a novel simultaneous wireless information and power transfer scheme based on OC in IA wireless networks. Simulation results are presented to show the performance comparison of these schemes. The methods for reducing the complexity of the OC-based IA algorithms are finally summarized.

Index Terms

Interference alignment, opportunistic communications, multiuser diversity, antenna selection, simultaneous wireless information and power transfer.

I. INTRODUCTION

Interference is a fundamental nature of wireless communication systems, in which multiple transmissions often occur simultaneously over a common wireless medium. In future wireless
systems, hyper-dense heterogeneous networks will be deployed to accommodate the tremendous growth of mobile data traffic [1]. Thus, interference management is one of the key issues in next generation wireless systems. Recently, as a promising solution to the interference problem, *interference alignment* (IA) has been proposed in wireless networks [2]. In IA wireless networks, all the interferences are cooperatively constrained into certain subspaces at the unintended receivers through precoding matrices at the transmitters, and thus the desired signal can be recovered in the remaining interference-free subspaces at each receiver [3]. Due to its promising performance, IA has been successfully applied to cognitive radio, heterogeneous network, multi-cell OFDMA networks, etc.

Despite the potential vision of IA, there are still some significant challenges when applying IA to practical networks [4]. One of the most challenging issues is the signal to interference plus noise ratio (SINR) decrease, in which the power of the desired signal may decrease greatly when the desired signal and interference are aligned in the similar directions. This SINR decrease problem will significantly affect the quality of service (QoS) and throughput of the network [5], [6].

Recent advances in *opportunistic communications* (OC) can be applied in IA wireless networks to improve the SINR performance [6]–[11]. In the past, researchers used to deem the channel fading as one of the fundamental aspects of wireless communications that makes the problem challenging, however, the channel fluctuations may be turned from foe to friend according to the idea of OC [12]. In a wireless network with multiple users that want to utilize the same wireless resource, the basic idea of OC is that only the user under the best channel condition can access the spectrum at each time slot, which is known as multiuser diversity. The performance gain of multiuser diversity comes from exploiting the fluctuations of the fading channel, i.e., making full use of the fading property of the channel to improve the performance of the network.

The existing research works on OC-based IA can be mainly categorized into two groups,
multiuser diversity and antenna selection. In multiuser diversity based IA wireless networks, the 
users with optimal performance of the network can be selected to form an IA networks at each 
time slot [7]–[9], and thus the average throughput of the network can be optimized. When antenna 
selection is adopted in IA wireless networks [10], [11], only some of the antennas equipped at the 
receivers or transmitters are selected to form the IA network, and the performance of IA can be 
improved. A special kind of antenna selection is antenna switching [6], in which reconfigurable 
antennas are equipped at each receiver, and the best modes of the antennas are selected according 
to the sum rate of the network.

In this article, we review some existing research works on OC-based IA wireless networks. 
Then, we propose a novel simultaneous wireless information and power transfer (SWIPT) scheme 
based on OC in IA wireless networks. As radio-frequency (RF) signals are commonly used as a 
vehicle for transmitting information, SWIPT has become an emerging technique attracting great 
attention for green communications and energy harvesting (EH) [13]. Nevertheless, SWIPT has 
largely ignored in existing IA studies [14], where the interferences are usually leveraged to 
separate out the desired signal instead of re-utilizing the interferences, which is a great waste of 
energy in wireless networks. In this work, both OC-based user selection and antenna selection 
are exploited to achieve SWIPT in IA wireless networks. Furthermore, we also summarize the 
methods for reducing the complexity of the OC-based IA algorithms.

The rest of this article is organized as follows. In Section II, we describe IA techniques and the 
SINR decrease issue. Then we present OC-based IA wireless networks with multiuser diversity 
and antenna selection to improve the performance of IA in Section III. The proposed OC-based 
IA algorithms for SWIPT are presented in Section IV. In Section V, the methods for reducing 
the complexity of the OC-based IA algorithms are summarized. Finally, we conclude the article 
in Section VI.
Fig. 1. A linear interference alignment wireless network with \( K \) MIMO users (Background noise is omitted for simplicity).

II. LINEAR INTERFERENCE ALIGNMENT AND SINR DECREASE

IA can be performed in time, frequency or spatial dimensions [3]. In this article, we concentrate on the linear IA in the spatial dimension, i.e., IA in multiuser MIMO systems. Fig. 1 shows a linear IA wireless network with \( K \) users.

Assume that \( d \) data streams are transmitted at each transmitter, and the signal vector of user \( k \), \( \mathbf{x}^{[k]} \), is precoded through using a unitary matrix \( \mathbf{V}^{[k]} \). The precoded signal \( \mathbf{V}^{[k]} \mathbf{x}^{[k]} \) is transmitted by the antennas from transmitter \( k \) to receiver \( k \), and it will also cause interference at other unintended receivers. At receiver \( k \), the interferences from other transmitters, \( \mathbf{H}^{[kj]} \mathbf{V}^{[j]} \mathbf{x}^{[j]} \), \( \forall j \neq k \), are aligned into the same subspace through the coordination of the precoding matrices, which is orthogonal to \( \mathbf{U}^{[k]} \). Thus the interferences at receiver \( k \) can be eliminated through the decoding matrix \( \mathbf{U}^{[k]} \), and the desired signal of user \( k \) can be recovered in the remaining
interference-free subspace as $U[k]H[kk]V[k]_k x[k]$. In essence, the linear IA can be deemed as an effective method to solve a system of linear equations when there are more variables than equations. Through the precoding matrices, IA can reduce the number of variables through aligning the undesired variables, and the system of equations becomes solvable.

When perfect IA can be achieved with $U[k]H[kj]V[j]_j x[j] = 0, \forall j \neq k$, the recovered signal at receiver $k$ can be expressed as $U[k]H[kk]V[k]_k x[k]$, without considering the background noise. $V[k]$ and $U[k]$ are i.i.d. and independent of $H[kk]$, and thus the desired signal of user $k$ can be regarded to be transmitted through the effective channel $\tilde{H}[kk] \triangleq U[k]H[kk]V[k]$. In other words, the $K$-user MIMO interference network is decomposed into $K$ equivalent and independent $d \times d$ MIMO Rayleigh fading channels ($\tilde{H}[kk], k = 1, 2, \ldots, K$) through IA. $d$ is much smaller than the number of antennas equipped at each transceiver of the network when IA is feasible. Thus the SINR performance of the desired signal in IA networks will be definitely decreased compared to that of the single-user MIMO systems with the same number of antennas at each transceiver, because better performance will be achieved with more antennas in MIMO systems. The detailed analysis of SINR decrease in IA can be found in [6].

III. OPPORTUNISTIC COMMUNICATIONS IN INTERFERENCE ALIGNMENT NETWORKS

In this section, we review some existing research works on OC-based IA networks. We first introduce multiuser diversity based IA networks. Then, antenna selection combined with IA is presented. Finally, the performance of IA networks with multiuser diversity and antenna selection is analyzed.

A. Interference Alignment with Multiuser Diversity

In the past, researchers used to believed that the throughput in multiuser channel can be maximized by the optimal power control. However, recently it is shown that even higher throughput can be achieved by multiuser diversity when opportunistic communication is adopted. An initial
kind of OC is multiuser diversity, which is a form of inherent diversity in wireless networks, and it can be achieved by tracking the channel fluctuations of the users and scheduling transmissions only to the ones when their instantaneous channel quality is near its peak [12].

Multiuser diversity has already been applied to IA to improve its SINR or throughput performance, and several multiuser diversity based IA schemes have emerged [7]–[9]. Although they seem different, the basic ideas are similar, i.e., to form the IA network through selecting a number of users among the candidates at each time slot to optimize the network’s throughput. Thus a common multiuser diversity based IA wireless system is presented in this section.

In a symmetric multiuser diversity based IA network, assume that all the users have the same parameters, i.e., $M$ and $N$ antennas at each transmitter and receiver, respectively, and $d$ data streams for each user. According to the feasibility of IA [3], the largest number of users that the IA network can accommodate when the interferences can be perfectly eliminated, $K$, is equal to $\frac{M+N}{d} - 1$. When there exist $Q$ users (candidates) wishing to access the spectrum, i.e., $Q > K$, only $K$ out of $Q$ users can be selected to form an instantaneous IA network at each time slot.

A simple idea of user selection is to select $K$ users in a round-robin principle, and the users can access the spectrum during successive time slots in a circular order regardless of the channel conditions, which is fair but not efficient. When the idea of multiuser diversity is introduced, the $K$ users adopted in the IA network are selected according to the throughput of the network. Thus at each time slot, only the $K$ users, through which the maximum throughput of the interference-free IA network can be achieved, should be selected in the multiuser diversity based IA network. The remaining inactive users can turn into sleep mode at this time slot to save energy.

To find the optimal $K$ users out of $Q$ candidates, the number of all the possible solutions for the problem can be calculated as $\binom{Q}{K}$. If $K$ is fixed for a certain IA network, when $Q$ is larger, the computational complexity of the IA network with user selection increases rapidly. Thus combinatorial optimization algorithms should be utilized to find the optimal solution in
large-scale IA networks with multiuser diversity.

Fairness is one of the key issues in OC, and it should also be considered in IA networks with multiuser diversity. In the ideal symmetric network, the fading statistics of users are the same, and the network’s throughput can be maximized due to multiuser diversity combined with IA, with the long-term throughput of each user guaranteed. However the short-term throughput of each user can not be guaranteed, especially when $Q$ is much larger than $K$. Besides, in reality the statistics are not symmetric and the fading may be slow, so the users with better channels may be always scheduled to transmit, while the ones with worse channels may have little chance to access the spectrum. Consequently the fairness among users should be considered, and the well-known proportional fair scheduling can be simply leveraged in the user selection based IA network [12].

When the number of users wishing to access the spectrum is less than the largest number of users that the IA network can accommodate, i.e., $Q \leq K$, user selection can also be exploited. This scenario can happen during the low SU traffic period, when there exist only a small number of SU-candidates. In this scenario, when the channel condition is poor, PU’s performance may not be guaranteed because there are no enough SUs for PU to collaborate with to satisfy its QoS. To solve this problem, only a portion of SUs can be selected to form the IA network with the PU using the Max-SINR algorithm [5]. The performance of PU can be improved due to the multiuser diversity and receive diversity from the user selection and Max-SINR algorithm.

B. Interference Alignment with Antenna Selection

Antenna selection is an emerging kind of OC, and it was first used in the MIMO system to improve its throughput or reliability [15]. Recently, antenna selection has also been applied to IA to solve its SINR-decrease problem [10], [11]. In IA networks, the channel state information (CSI) is usually estimated at receivers, and then fed back to the transmitters. Thus it is more
suitable to perform antenna selection at the receivers according to the estimated CSI. The diagram of a certain receiver in the antenna selection based IA networks is shown in Fig. 2(a).

At each receiver in the antenna selection based IA network, assume that $N_1$ antennas are equipped, and according to the feasible condition of IA, only $N_2$ antennas are needed to form the IA network, $N_1 > N_2$. Based on the CSI estimated and shared among the transceivers at the current time slot, $N_2$ antennas are selected out of all of the $N_1$ antennas at all the receivers, to maximize the throughput of the network.

In searching the optimal $N_2$ antennas at each receiver in the IA network, the number of all the available antenna combinations of the $K$ users is $\binom{N_1}{N_2}^K$, and the antenna combination with the best performance is selected to form the IA network. Thus the computational complexity of antenna selection in IA increases dramatically when the number of users $K$ and the number
of available receive antennas $N_1$, become larger. In [11], discrete stochastic optimization (DSO) based antenna selection algorithm is designed for IA, and it can fast converge to the optimum with low computational complexity. Furthermore, it can also reduce the influence of the imperfect CSI and track the time-varying channel environment.

Antenna selection can be combined with IA to improve its QoS, however, its size is large because additional antennas should be equipped. In [6], antenna switching based on reconfigurable antennas is introduced to IA to reduce the size of receivers in the antenna selection scheme, as depicted in Fig. 2(b). In the antenna switching IA scheme, some of the receive antennas are replaced by reconfigurable antennas. Each reconfigurable antenna can switch among $S$ preset modes, and the channel coefficients are different when working in these modes. Thus, the optimal modes of all the reconfigurable antennas can be selected at each time slot to improve the performance of the IA network. In a $K$-user IA network with $N_c$ configurable antennas at each receiver, its computational complexity is proportional to $S^{N_c}K$.

C. Performance Analysis of the OC-based IA Networks

The user selection (or multiuser diversity) based IA (US-IA), antenna selection based IA (ASe-IA) and antenna switching based IA (ASw-IA) schemes can all be deemed as a unified version of OC in IA networks. The performance gain of IA coming from OC depends on the number of possible combinations of the users, receive antennas, or switching modes of reconfigurable antennas. If the network is symmetric and the fading statistics of all the channels are i.i.d., the performance gain of IA is the same when the number of possible solutions is the same, no matter which scheme of OC is applied. When the number of possible solutions is larger, the performance of the IA network becomes better too.

The performance of the US-IA, ASe-IA, ASw-IA, and linear IA without OC is compared in Fig. 3. In the US-IA scheme, 2 antennas are equipped at each transceiver, and $K = 3$ users are
selected from $Q = 6$ users to form an IA network with 20 possible solutions. In the ASe-IA scheme, 2 and 3 antennas are equipped at each transmitter and receiver in a 3-user IA network, respectively, and 2 antennas are selected at each receiver with 27 possible solutions. In the ASw-IA scheme, 2 antennas are equipped at each transceiver, and one of the antennas at each receiver is reconfigurable with two preset modes. Thus 8 available solutions are in the ASw-IA scheme. In the 3-user linear IA scheme without OC, 2 antennas are equipped at each transceiver.

From the results in Fig. 3, we can see that the performance of OC-based IA networks becomes better with a larger number of possible solutions. However, we can also observe that, when the number of possible solutions grows (e.g., from 20 to 27) in OC-based IA networks, the performance gain due to the increase of the number of possible solutions is not significant. Therefore, there is no need to provide a very large number of possible solutions in practical
OC-based IA networks, and a trade-off can be made between the number of possible solutions and the performance of IA networks.

IV. OC-BASED IA ALGORITHMS FOR SIMULTANEOUS WIRELESS INFORMATION AND POWER TRANSFER

RF signals carry energy and information simultaneously, however, RF signals are usually adopted to only transmit information in the conventional wireless communications. In the emerging trends of green communications and energy harvesting, the energy carried by RF signals can also be a new source for energy harvesting. Due to the different fading statistics in IA networks, it is better to harvest power than transmit information in some of the channels, and vice versa. Thus opportunistic communications can be applied to IA networks to improve the performance of both information and power transfer. In this section, an OC-based IA algorithm for SWIPT is proposed by exploiting multiuser diversity, as shown in Fig. 4.

A. OC-based IA User Selection Algorithm for SWIPT

In the conventional IA network based on multiuser diversity, assume that $Q$ users want to access the spectrum simultaneously, however, according to the feasibility of IA, only $K$ ($K < Q$) of them can be allowed to form an IA network at each time slot. Thus the $K$ users that have the optimal performance are selected to form the instantaneous IA network, and the other $Q - K$ users are remaining idle at this time slot. However, the idle receivers can collect the wireless energy from the active transmitters, and SWIPT can be performed in this system. Assume that the harvested energy due to the background noise is negligible and can be ignored. In the OC-based IA (OIA) network with one data stream for each user, the harvested power by a certain unselected user $u$ in the network can be expressed as

$$
E^{[u]} = \zeta P_t \sum_{j \in S} \| \mathbf{H}^{[uj]} \mathbf{v}^{[j]} \|_2^2, \quad u \notin S,
$$

(1)
where $\mathcal{S}$ is the set containing the selected $K$ users of the OIA network at the time slot, and $\tilde{H}^{[u,j]}$ denotes the channel gain from the selected user $j$ to the unselected user $u$. $P_t$ is the transmitted power of each active transmitter in the network. $\zeta \in (0, 1)$ is a constant representing the loss in the energy transducer for converting the harvested energy to electrical energy to be stored [13].

The OIA user selection (OIAUS) algorithm for SWIPT should be performed according to some objective function to jointly optimize the performance of the information transmission (IT) and EH. According to the specific requirements and the IT and EH capability of each user, the objective function can be defined as

$$
\mathcal{F} = \sum_{s \in \mathcal{S}} \alpha^{[s]} R^{[s]} + \sum_{u \notin \mathcal{S}} (1 - \alpha^{[u]}) \beta E^{[u]},
$$

where $R^{[s]}$ is the transmission rate of user $s \in \mathcal{S}$, when the IA network is formed by the selected users in $\mathcal{S}$. $0 \leq \alpha^{[k]} \leq 1$ represents the weight given to the requirement of transmission rate
of user $k$, and $1 - \alpha^{[k]}$ is the corresponding weight to its harvested power. For a certain user in the network, its value of $\alpha$ means the relationship between the requirements of IT and EH. $\beta$ is a constant to balance the rate and power with unit bit/s/Hz/W. When $\alpha$ becomes larger, it represents that the battery power of this receiver is sufficient and the required rate of this user is high; when $\alpha$ becomes smaller, it means low-power status of the battery of the receiver, and the rate of this user is not so high.

Thus the performance of SWIPT can be optimized by selecting the IT and EH users in the OC-based IA network to maximize $\mathcal{F}$ in the objective function of (2), in which the IT and EH capacity of the users is considered, as well as the specific requirements of each user. The performance of the proposed OIAUS algorithm for SWIPT is also analyzed. In the simulation, $K = 3$, and 2 antennas are equipped at each transceiver. Rayleigh block fading is adopted, and perfect CSI is assumed to be available at each node. The signal attenuation due to the path loss $a_p$ is equal to 0.05. $\zeta = 0.2$, $\beta = 100$, and the transmit SNR is set to 30dB, which is the ratio between transmit power and the background noise.

The average throughput and harvested power with different number of $Q$ and different values of $\alpha$ in the OC-based IA network for SWIPT are compared in Fig. 5. From the results, we can see that both of the average throughput and harvested power will increase with larger $Q$ when the proposed OIAUS algorithm is performed, and the performance of the proposed algorithm is much better than that when the users are randomly selected. When $\alpha = 1$, the throughput of the OIA network is optimized; when $\alpha = 0$, the harvested power is optimized; when $\alpha = 0.5$, the throughput and power are jointly optimized. Thus a tradeoff can be made between rate and power with different values of $\alpha$. When $\alpha = 0.5$ and $Q$ is larger than 6, the throughput of the OC-based IA network is almost unchanged with different $Q$, this is because optimizing power is becoming more important when $Q$ is large, and increasing $Q$ will no longer achieve better rate performance in this situation.
Fig. 5. Comparison of the average throughput and harvested power of the OC-based IA algorithm for SWIPT through user selection with different numbers of $Q$ and different values of $\alpha$.

B. Antenna Selection Based IA Algorithm for SWIPT

Similar to the OC-based IA algorithm for SWIPT with multiuser diversity, antenna selection can also be used for the SWIPT in IA networks. In conventional antenna selection based IA networks, more antennas than needed are equipped at each receiver, and only some of them are selected to recover the desired signal at each time slot, which can optimize the performance of the network. However the unselected antennas are idle at the time slot, thus it is a waste of the wireless resource. In the OC-based IA algorithm for SWIPT with antenna selection, some of the antennas at each IA receiver are selected to recover the information according to the EH and IT capability of all the antenna combinations, and the other antennas are dedicated to EH. Thus the extra antenna resource of the system will be fully exploited through the antenna selection scheme for energy harvesting in IA networks.
V. METHODS FOR REDUCING THE COMPLEXITY OF THE OC-BASED IA ALGORITHMS

In this section, the methods for reducing the complexity of the OC-based IA algorithms are summarized, and the random complexity-reduced algorithm is studied as a concrete example.

A. Low-Complexity Methods for the OC-based IA Algorithms

In the above OC-based IA algorithms, when the number of available solutions to be searched is larger, its computational complexity becomes higher. Thus the complexity of the OC-based IA algorithms should be effectively reduced when applied to practical systems, and some of the methods are summarized as follows.

- **Random complexity-reduced algorithm:** Only a portion of the available solutions is randomly chosen in the random complexity-reduced algorithm to find the optimal solutions. This is a simple method that is suitable for different kinds of OC-based IA networks.

- **Sequential selection algorithm:** In the sequential selection algorithm [6], only one solution of OC is performed at each time slot in a frame, and the communication among users still performs by distributed IA algorithm during each time slot. The selection stops when the threshold is met or it has already performed $I_{th}$ times in a frame, and thus the complexity can be reduced effectively.

- **DSO algorithm:** The DSO algorithm uses a stochastic approximation approach with less computational complexity compared to that of the exhaustive search, and it can converge fast [11]. In addition, it can be used when the available CSI is imperfect.

- **Evolutionary algorithms:** Since the problem to be solved in OC-based IA networks is a combinatorial optimization problem, evolutionary algorithms can be adopted to solve it, e.g., genetic algorithm and ant colony optimization algorithm.

Among these low-complexity methods, the random complexity-reduced algorithm is simple but effective. In the following, we use it in the proposed OIAUS algorithm for SWIPT as a
concrete example.

B. Random Complexity-Reduced OIAUS Algorithm for SWIPT

The OIAUS algorithm for SWIPT aiming at optimizing (2) is a combinatorial optimization problem. When brute-force search is adopted to enumerate all the possible combinations of the selected users to obtain the optimal solution, the computational complexity of the OIAUS algorithm increases dramatically with larger $Q$ and smaller value of $|K/Q - 0.5|$. The computational complexity of the OIAUS algorithm should be reduced when it is applied to practical systems. Besides, as the number of available solutions is larger, the performance enhancement is becoming slower. Therefore, we propose a random complexity-reduced OIAUS (RCR-OIAUS) algorithm for SWIPT to reduce the computational complexity of the OIAUS algorithm.

In the proposed RCR-OIAUS algorithm, only a portion of the available solutions is randomly chosen to be searched. Define $T_r$ as a positive integer that is smaller than the number of all the available solutions $T$, and $T_r$ solutions are randomly selected from all the candidates to form the reduced set of solutions to be used in the RCR-OIAUS algorithm. The computational complexity of the RCR-OIAUS algorithm is only $\frac{T_r}{T}$ of that in the OIAUS algorithm, and its IT and EH performance is close to that of the OIAUS algorithm when $T_r$ is large enough. Thus $T_r$ should be set with a tradeoff between the computational complexity and performance.

The average throughput and harvested power performance of the RCR-OIAUS algorithm when $Q = 10$ and $K = 3$ is compared in Fig. 6 with different values of $T_r$. The parameters are set similar to those in Subsection IV-A, and $\alpha = 0.5$. From the results, it is shown that the performance of RCR-OIAUS algorithm is becoming better with larger $T_r$, and the performance enhancement is becoming slower with larger $K$. When $T_r$ gets close to $T$ in the OIAUS algorithm, the performance of the RCR-OIAUS algorithm is getting to that of the OIAUS algorithm.
VI. CONCLUSIONS

Interference alignment is an emerging technology for interference management. One of the key challenges in interference alignment is SINR decrease, which will affect the QoS of users. Opportunistic communications, including multiuser diversity and antenna selection, can be applied to IA to improve its performance. In this article, the concept of linear IA was introduced, and the reason of SINR decrease was analyzed. Then, recent advances in OC-based IA (i.e., multiuser diversity based IA and antenna selection based IA) were reviewed, and the performance of these OC schemes for IA was compared. Finally, we proposed a novel simultaneous wireless information and power transfer scheme based on OC in IA networks, where both user selection and antenna selection are considered. Simulation results were presented to show the performance comparison of these schemes.
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