Interference Alignment Using *Shadow* Channel

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***Abstract*—The time variance of a channel is exploited in interference alignment techniques. However, in the case of static channels, these interference alignment techniques do not hold, specifically for single-antenna systems. In this paper, we introduce simple data processing techniques that enable us to create the effect of a time varying channel from the underlying static channel. We call this channel the shadow channel. We exploit the time-varying nature of the relative channels introduced by the shadow channel for interference alignment. We demonstrate the throughput benefits of this interference alignment technique for different topologies. This technique can be thought of as operating over the two dimensions of the complex space of typical communication systems. In this paper, we present the feasibility of interference alignment techniques for single antenna nodes in static channel. We establish bound on the throughput gain due to this technique. Finally, we implement interference alignment over the shadow channel on the NI PXIe 1082 based software defined radio. We achieve throughput gains of upto 1.44X over TDMA systems using this interference alignment technique and upto 1.61X when this technique is coupled with interference cancellation.**

I. Introduction

Interference alignment systems have been analyzed, studied and implemented extensively in recent years. Interference alignment results in a linear increase in the total network throughput with increasing number of nodes. When every node has only one antenna, interference alignment techniques exploit the time varying nature of wireless channels to align interference. These techniques assume that the wireless channel between nodes varies over time. However, the *coherence time* of these channels is in the order of 10s to 100s of milliseconds in relatively stationary indoor environments [7]. For a WiFi system, for example, this *coherence time* is comparable to multiple packet durations: a 1500 byte packet sent at 54Mbps takes only 0.2ms. Since interference alignment can decode a packet only after multiple independent channel realizations, there can be a significant and often, intolerable latency. On the other hand, these techniques cannot align the interference when the channel is stationary (details explained in Section II). This paper enables interference alignment under stationary channel conditions. This significantly reduces implementation latency while still realizing throughput gains of interference alignment systems. We achieve it using a concept called *shadow channel*.

Figure 1 shows the instantiation of a *shadow channel*. Figure 1(a) shows a transmitter and two receivers with channels h_{AB} and h_{AC}[1]. For the transmitter to align its interference at one of the receivers, the ratio $\frac{h_{AB}}{h_{AC}}$ should change over time (Section II). Using a precoding vector [2] in this case (within channel coherence time) is not useful since while each channel changes by a factor of the precoding vector, the channels remain the same relative to each other i.e $\frac{h_{AB}}{h_{AC}}$ remains static. Figure 1(b) shows this case.

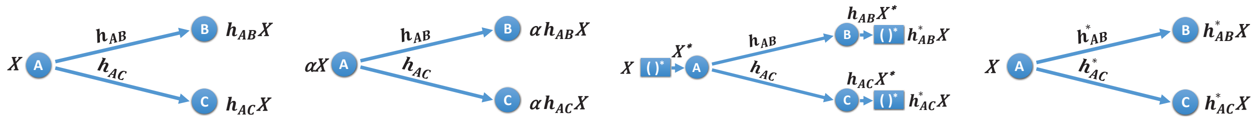
Figure 1(c) shows the realization of the shadow channel. The transmitter transmits x^* and the receivers receive $h_{AB}x^*$ and $h_{AC}x^*$. Now, the receivers use a conjugate function to get $h^*_{AB}x$ and $h^*_{AC}x$. This is equivalent to having transmitted symbol x through the channels h^*_{AB} and h^*_{AC} as shown in Figure 1(d). The channel ratio is now $\frac{h^*_{AB}}{h^*_{AC}} \neq \frac{h_{AB}}{h_{AC}}$ (under most circumstances). Thus, just a conjugate operation carried out at both the transmitter and the receivers has transformed the static channel into a seemingly time-varying channel usable from an interference alignment perspective. We call the channel enabled using the conjugate operation as the *shadow channel* throughout this paper.

But, how does shadow channel achieve interference alignment? Figure 2 shows a cross (X-) channel in which clients 1 and 2 have packets to send to access points, AP1 and AP2. The APs are connected via a backbone wired network and are allowed to exchange decoded packets with each other. This is typical in an enterprise wireless network. Clients 1 and 2 transmit x_2 and y in slot 1, respectively. In slot 2, they send the conjugates of $(x_1 + x_2)$ and y, respectively, with the scaling factors as shown on the left corner table in Figure 2. The right corner table shows what AP1 receives in the two slots. AP1 applies the conjugate to the received symbols in the second slot. Thus, AP1 gets $h_{11}x_2 + h_{21}y + h_{11}x_1$. It subtracts the symbols from slot 1 to get $h_{11}x_1$. This was possible only because both x_2 and y were both aligned in the two slots. Thus, AP1 can decode x_1. AP1 shares x_1 with AP2. AP2 cancels x_1 from its received symbols from the two slots and decodes x_2 and y. Shadow channel realization in the second slot ensures that the resulting two equations in x_2 and y are linearly *independent*. Thus, the shadow channel has allowed us to decode 3 packets (x_1, x_2 and y) in two slots. Note that, without the shadow channel, the only alternative would have been for the clients to take turns in the two slots and send one packet in each slot. Thus, such a time division multiple access (TDMA) scheme would enable only 2 packets in two slots. This gives a throughput gain of $1.5X$.

Contributions: First, we show how the shadow channel presented above enables interference alignment in static channel

[1] h_{ij} is the channel between node i and node j

[2] Precoding vector without specification throughout the paper is in time domain. This differs from most typical interference alignment system work applied on the antenna domain.



(a) A static channel (b) A static channel with precoding (c) Shadow channel using conjugates (d) An equivalent channel

Fig. 1. Shadow Channel: (a) shows a network with channel gains. (b) shows that the transmitter uses a precoding vector α before transmitting. The received symbols are equivalent to transmitting symbol x through channels αh_{AB} and αh_{AC}. (c) shows the same channel but the transmitter and the receivers apply conjugates to their symbols. (d) shows the channels equivalent to (c). (d) shows the channel gains that are conjugates of the static channel gains in (a). Thus, (d) shows the *shadow channels*.

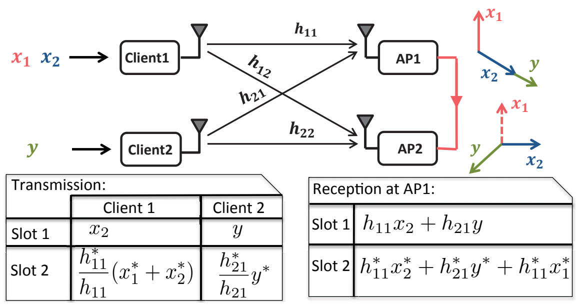


Fig. 2. Shadow channel usage for a two client two AP network. APs are connected using a backbone connection. Clients transmit over two slots as shown. AP1 takes a conjugate of what it receives in slot 2 and subtracts what received in slot 1 from it. AP1 can decode x_1. It exchanges x_1 with AP2 over the backbone. AP2 decodes x_2 and y.

conditions. Second, we present applications that benefit in throughput using the shadow channel for interference alignment. Third, we theoretically show the maximum achievable throughput gain for all the topologies as the number of users increases. Fourth, we present a fully working implementation of the proposed system and verify throughput gains expected in theory (4/3, discussed in Section IV).

We compare the throughput of our implementation of interference alignment using shadow channel with that of an omniscient TDMA system in the X-channel scenario. We report an average throughput gain of 1.29X and a maximum throughput gain of 1.44X. The maximum throughput gain observed is higher than the theoretical maximum because of diversity gain of transmitting the symbol over multiple slots. When combined with interference cancellation techniques, we observe a throughput gain of upto 1.61X.

II. Background and Motivation

A. Understanding Interference Alignment

Recently, interference alignment theory has been developed analytically and empirically. A recent work shows that for k single-antenna node pairs in one collision domain, it is possible to enable k/2 simultaneous data transmissions [6]. The result implies that every pair of nodes access *half* the channel. However, this technique assumes that the channel between these node pairs is time-varying. In reality, however, channel coherence time can be much larger than a data packet. Thus to implement interference alignment, proposed in [6], decoding a single symbol can introduce significant delay. The delay performance is greatly sacrificed.

Why is interference alignment not possible under static channel conditions? Let us try invoking the interference alignment method presented in [6] in a static channel scenario as shown in Figure 3.

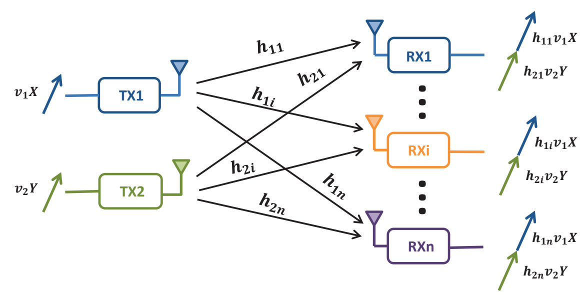


Fig. 3. For static channel condition, alignment in one receiver results in the alignment of data at all the receivers.

Generally, aligning a vector in the direction of another vector implies that these two vectors are related by a scalar.In the case of alignment at receiver 1 in Figure. 3,

$$h_{11}\boldsymbol{v_1}X = \alpha h_{21}\boldsymbol{v_2}Y$$

where symbol vector X from transmitter TX1 and symbol vector Y from TX2 align at receiver RX1. $\boldsymbol{v_1}$ and $\boldsymbol{v_2}$[3] are the precoding vectors at TX1 and TX2 respectively. α is a scalar. In a static channel, the direction of the received vectors of X and Y are only determined by the precoding vectors $\boldsymbol{v_1}$ and $\boldsymbol{v_2}$. Therefore, $\boldsymbol{v_1} = (\frac{\alpha h_{21}Y}{h_{11}X})\boldsymbol{v_2}$ implies that the vectors, $\boldsymbol{v_1}$ and $\boldsymbol{v_2}$ are aligned (as $\frac{\alpha h_{21}Y}{h_{11}X}$ is a scalar). This further implies that, X and Y are aligned at all the receivers (i.e. at receiver i, $h_{1i}\boldsymbol{v_1}X = (\frac{h_{1i}}{h_{2i}}\frac{\alpha h_{21}}{h_{11}})h_{2i}\boldsymbol{v_2}Y$). This implies that X and Y cannot be differentiated at any of the receivers. Data decoding will automatically fail. From this example, we can tell that *time-varying* channels are crucial for interference alignment as they naturally yield different sets of channels over time.

In the past few years, most of interference alignment system works focused on multiple-antenna system or MIMO applications, [8] for instance. With multiple antennas, data could be transmitted from different antennas. From the receivers' perspective, the data coming through different antennas have different channels. Thus, although channels are static over

[3]Explicitly, each time slot adds a vector dimension. Since, the channel is static, we denote the channel vector using just h_{ij}

time, multiple antennas present an opportunity to carry out interference alignment over antennas (not time). In this paper, we only look at single-antenna nodes. Thus, time is the only source of available dimensions.

B. Shadow Channel

From the above analysis, we can see that the existence of different sets of channels is the fundamental requirement for interference alignment. This subsection will show that, for any set of static channels, a differentiable set of hidden channels exists. As there is a one-to-one and onto mapping between the original channel and the hidden channel, we refer to this channel as **Shadow Channel** in the rest of the paper. This channel can be achieved by simple signal processing.

Let us consider a simple illustrative example. Assume there are two transmitters TX1, TX2 and two receivers RX1 and RX2 in a network. All the four radios are in one collision domain. The channels between TXi and RXj are h_{ij}, where $i \in \{1,2\}$ and $j \in \{1,2\}$ as presented in Figure. 4(a). Thus with $\begin{pmatrix} x \\ y \end{pmatrix}$ as the transmitter vector, the receiver vector W can be represented by the following equation:

$$W = \begin{pmatrix} w_1 \\ w_2 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + n_0, \quad (1)$$

where n_0 is the noise introduced to the system.

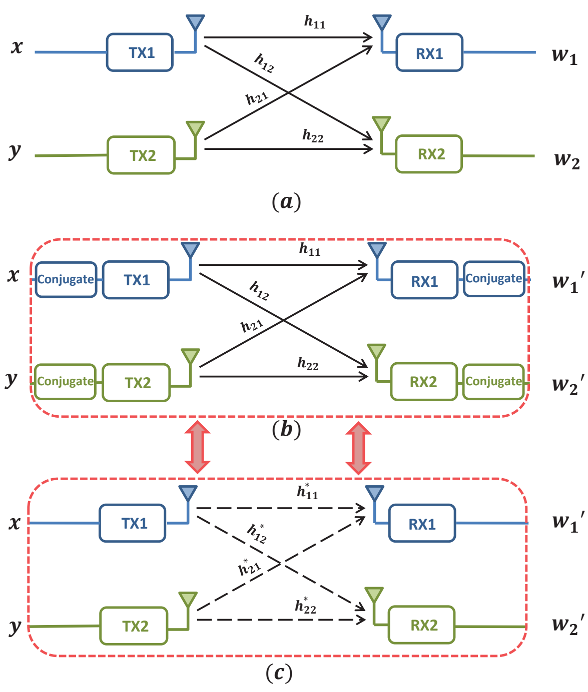


Fig. 4. An illustrating example for shadow channel. (a) A regular 2 by 2 interference channel. (b) Conjugate module added to both transmit and receive radios to create the shadow channel. (c) Equivalent network of Figure (b).

Next, we add a signal processing module – conjugate module – to all the transmitter and receiver radios. At the transmitter side, the signal transmitted by the antennas are x^* and y^*. At the receivers, the receiver signals also go through a conjugate process as shown in Figure. 4(b). Thus, the receiver vector can be presented as:

$$\begin{aligned} W = \begin{pmatrix} w_1' \\ w_2' \end{pmatrix} &= \left[\begin{pmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{pmatrix} \begin{pmatrix} x^* \\ y^* \end{pmatrix} + n_0 \right]^* \\ &= \begin{pmatrix} h^*_{11} & h^*_{21} \\ h^*_{12} & h^*_{22} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + n^*_0 \end{aligned} \quad (2)$$

Comparing Equation 2 with Equation 1, the signals act as if they went through a new channel set $\begin{pmatrix} h^*_{11} & h^*_{21} \\ h^*_{12} & h^*_{22} \end{pmatrix}$ as illustrated in Figure. 4(c) with the real existing channel $\begin{pmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{pmatrix}$. As the conjugate processing is not a linear operation, the new channel can be judged as a channel different from the underlying static channel. Thus, it has the potential to be utilized for interference alignment.

Implications of the Shadow Channel:

(i) The fact that two different sets of channels can be generated from one static channel condition is quite surprising. It challenges the stereotype of lack of suitability of *static channel* for interference alignment. Meanwhile, *finding* the shadow channel is trivial; it can be easily achieved in any wireless system by using conjugates.

(ii) Another way to understand the existence of shadow channel is that communication system is a complex system. Therefore, every communication occupies a two dimensional space. The function of shadow channel is to exploit this two dimensional space to produce a differentiable set of channels.

(iii) As the shadow channel gives us a new way to exploit interference alignment, it can be combined with the existing interference alignment techniques. This will introduce either network-level throughput gain or relaxation of physical layer requirements to achieve similar performance.

III. Exploiting Shadow Channel with Interference Alignment

Here we show interference alignment using the shadow channel. With simple examples we illustrate the consequent significant achievable throughput gains.

A. X-channel

Consider two single-antenna transmitters $TX1$, $TX2$ and two-single antenna receivers $RX1$, $RX2$ placed in one collision domain as shown in Figure. 5. The channel matrix is $\begin{pmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{pmatrix}$. Say both the transmitters have messages for $RX1$ and $RX2$. Thus, there are four independent data streams. Assume $TX1$ has message x_1 for $RX1$ and message x_2 for $RX2$, while $TX2$ has y_1 for $RX1$ and y_2 for $RX2$. This setup is commonly referred to as the X-channel [9].

Using TDMA, following 802.11 protocol, the X-channel supports only one message at a time. We show how interference alignment can be achieved using shadow channel such that x_2, y_2 are aligned at $RX1$, and x_1, y_1 are aligned at $RX2$. Transmitters follow the precoding vector according to Table I.

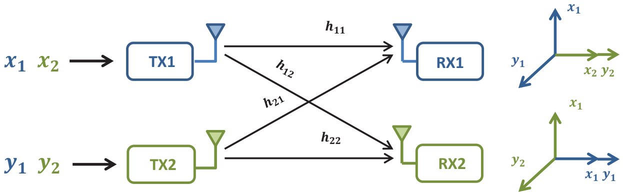


Fig. 5. Example for interference alignment using shadow channel in X-channel topology. Messages X_2, y_2 align at RX1 so that it can decode the messages x_1 and y_1 from TX1/TX2 respectively. Messages x_1 and y_1 align at RX2 so that messages x_2, y_2 from TX1/TX2 can be recovered at RX2.

Time Slot	1	2	3
TX1	x_1	x_2	$\frac{h_{12}^*}{h_{12}}x_1^* + \frac{h_{11}^*}{h_{11}}x_2^*$
TX2	y_1	y_2	$\frac{h_{22}^*}{h_{22}}y_1^* + \frac{h_{21}^*}{h_{21}}y_2^*$

TABLE I
THREE SLOT PRECODING SCHEDULING FOR X-CHANNEL.

RX_1 receives signals $w_1(1)$, $w_1(2)$, and $w_1(3)$ in three slots[4]:

$$\begin{aligned} w_1(1) &= h_{11}x_1 + h_{21}y_1, \\ w_1(2) &= h_{11}x_2 + h_{21}y_2, \\ w_1(3) &= h_{11}\left(\frac{h_{12}^*}{h_{12}}x_1^* + \frac{h_{11}^*}{h_{11}}x_2^*\right) + h_{21}\left(\frac{h_{22}^*}{h_{22}}y_1^* + \frac{h_{21}^*}{h_{21}}y_2^*\right) \\ &= h_{11}^*x_2^* + h_{21}^*y_2^* + \frac{h_{11}h_{12}^*}{h_{12}}x_1^* + \frac{h_{21}h_{22}^*}{h_{22}}y_1^*, \end{aligned}$$

We can see that x_2 and y_2 are aligned, only one dimension of information will be sacrificed to remove these two messages:

$$\begin{pmatrix} w_1(1) \\ w_1^*(3) - w_1(2) \end{pmatrix} = \begin{pmatrix} h_{11} & h_{21} \\ h_{11}^*h_{12}/h_{12}^* & h_{21}^*h_{22}/h_{22}^* \end{pmatrix} \begin{pmatrix} x_1 \\ y_1 \end{pmatrix}$$

x_1 and y_1 can be recovered in 3 slots. Similarly at $RX2$, x_2 and y_2 are recovered.

Performance analysis: Interference alignment using shadow channel in X-channel scenario provides 4/3 multiplexing throughput gain. This throughput improvement is same as the system introduced in [13], which requires an additional antenna at each receiver.

B. Uplink Transmission in Enterprise Wireless Local Area Network

In an Enterprise Wireless Local Area Network (EWLAN), APs are connected through a backbone Ethernet. Thus, they can share packets between APs. [8] applies interference alignment in the antenna domain to improve the uplink performance for multiple-antenna systems. [4] considers the throughput improvement opportunity for uplink transmission in multi-collision domain. However, for static single antenna one collision domain setting, it seems that existing techniques in literature cannot improve uplink performance. The example shown in this subsection will show that interference alignment using shadow channel enhances performance in this scenario.

Consider two clients (Client1 and Client2) and two APs (AP1 and AP2) in one collision domain as shown in Figure. 6. The channel matrix is $\begin{pmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{pmatrix}$. Both the clients have some uplink flow requests.

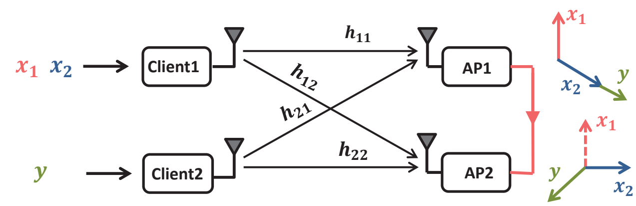


Fig. 6. Example for interference alignment using shadow channel in EWLAN uplink traffic case. Messages x_2 and y align at AP1 so that AP1 decodes message x_1 and sends it to AP2 over Ethernet. AP2 subtracts x_1 through interference cancellation. As a result, AP2 decodes messages x_2 and y.

Using TDMA, following 802.11 protocol, a single flow is enabled each time slot. However, using shadow channel, 3 messages can be delivered in 2 slots. Clients follow the precoding vector according to Table II;

Time Slot	1	2
Client1	x_2	$\frac{h_{11}^*}{h_{11}}(x_1^* + x_2^*)$
Client2	y	$\frac{h_{21}^*}{h_{21}}y^*$

TABLE II
TWO SLOTS PRECODING SCHEDULING FOR EWLAN UPLINK TRAFFIC.

AP1 receives signal $w_1(1)$ and $w_1(2)$ in the two slots respectively:

$$\begin{aligned} w_1(1) &= h_{11}x_2 + h_{21}y, \\ w_1(2) &= h_{11}\frac{h_{11}^*}{h_{11}}(x_1^* + x_2^*) + h_{21}\frac{h_{21}^*}{h_{21}}y^* \\ &= h_{11}^*x_2^* + h_{21}^*y^* + h_{11}^*x_1^* \end{aligned}$$

x_2 and y are aligned at AP1. Therefore, x_1 can be recovered through $w_1^*(2) - w_1$. Then, the recovered message, x_1 is exchanged with AP2 over the backbone. After cancellation as introduced in [8], x_2 and y can be recovered at AP2 since they are not aligned.

Performance analysis: Applying interference alignment using shadow channel, single antenna uplink traffic could experience a 1.5X throughput gain. In the example shown here, throughput for client 1 is twice as much as it is for client 2. Alternatively, the case in which client 2 sends 2 messages while client 1 sends one is possible too. Balancing these two transmission settings, for a wide range of the traffic requests, we can achieve the throughput gain. Recall that from the table above, the only channel information needed is the channel to AP1. AP2 can be seen as a helping AP.

[4]For illustration purpose, the noise components are not shown in the equations. It is the same for all the example in this section.

C. Pair transmission interference alignment

Now, consider a network with three transmitter-receiver pairs with transmission flows TX1-RX1, TX2-RX2 and TX3-RX3, in a single collision domain network as shown in Figure. 7. The channel matrix is $\begin{pmatrix} h_{11} & h_{21} & h_{31} \\ h_{12} & h_{22} & h_{32} \\ h_{13} & h_{23} & h_{33} \end{pmatrix}$. Contrary to the X-channel scenario, in this example, each transmitter is only associated with a unique receiver. This is the most common traffic demand in wireless networks.

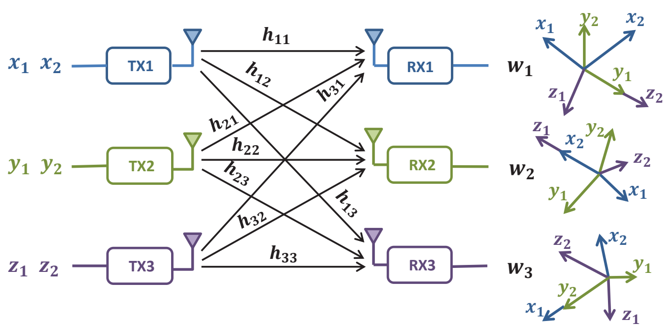


Fig. 7. Example for interference alignment using shadow channel in pair traffic demand scenarios. Messages x_1 and y_2 align at RX3, which decodes z_1 and z_2. Messages y_1 and z_2 align at RX1, which decodes x_1 and x_2. Messages z_1 and x_2 align at RX2, which decodes y_1 and y_2

Similar to previous cases, the best TDMA scheduling is simply enabling one flow at one time. We show that Interference alignment using shadow channel lets 6 messages be delivered in 5 slots: x_1 and x_2 are delivered on link TX1-RX1, y_1,y_2 on link TX2-RX2 and z_1,z_2 on link TX3-RX3. The transmitters use the precoding vector in Table. III;

Time slot	1	2	3	4	5
TX1	x_1	x_2	–	$\frac{h_{13}^*}{h_{13}}x_1^* + \frac{h_{12}^*}{h_{12}}x_2^*$	$\frac{h_{13}^*}{h_{13}}x_1^* + e^{j2/3\pi}\frac{h_{12}^*}{h_{12}}x_2^*$
TX2	y_2	–	y_1	$\frac{h_{21}^*}{h_{21}}y_1^* + \frac{h_{23}^*}{h_{23}}y_2^*$	$e^{-j2/3\pi}\frac{h_{21}^*}{h_{21}}y_1^* + \frac{h_{23}^*}{h_{23}}y_2^*$
TX3	–	z_1	z_2	$\frac{h_{32}^*}{h_{32}}z_1^* + \frac{h_{31}^*}{h_{31}}z_2^*$	$e^{j2/3\pi}\frac{h_{32}^*}{h_{32}}z_1^* + e^{-j2/3\pi}\frac{h_{31}^*}{h_{31}}z_2^*$

TABLE III
FIVE SLOTS PRECODING SCHEDULING FOR THREE PAIRS OF TRANSMISSIONS.

RX1 receives signals $w_1(1)$, $w_1(2)$, $w_1(3)$, $w_1(4)$ and $w_1(5)$ in five slots, respectively. Messages y_1 and z_2 are aligned at RX1. Removing these 2 messages, we get 4 variables in 4 equations as shown in Equation 3. Therefore, x_1 and x_2 can be recovered at RX1. Similarly, y_1, y_2, z_1, z_2 can be decoded at RX2 and RX3 respectively.

Performance analysis: Six messages in five slots give a multiplexing gain of 20%. Although the throughput improvement is not significant, a significant contribution of this design is that it enables static channel interference alignment without changing the radio design.

IV. Analysis Of Shadow Channel Interference Alignment

Interference Alignment using shadow channel exploits the complex signalling dimension. It can be combined with antenna domain interference alignment. However, the technology itself has a limitation.It provides just one additional set of channels. This limits the generalization of shadow channel interference alignment. This feature gives two properties for interference alignment using shadow channel:

(i) It can always be achieved through **half-blind** construction. Half-blind construction depicts the case where the transmitter does not need the entire channel matrix, but just the channel coefficients associated with the transmitter itself. For instance, for certain transmitter TXi, it only needs the channel information from TXi to the receivers. The precoding vectors for examples in section III reinforce this point. We generalize half-blind construction sufficiency.

(ii) The improvement shown in section III-A and section III-C already achieves its **upper-bound** of the possible throughput gain.

Rest of the section consolidates these two observations. First, let us look at the alignment process to understand the constraint imposed by two sets of distinct channels. The proof for the results presented in the following Lemmas are presented in a technical report [18], given space constraints.

Lemma IV.1. ***Consider interference alignment at one receiver where m interference flows align in an n-dimensional subspace where $n < m$. If interference is aligned using shadow channel and the intended message flows can be decoded at at least one receiver, then (m, n) satisfies the relationship $2n \geqslant m$.***

Thus, say a receiver requires m interference flows to align in an n-dimensional. We achieve interference alignment by choosing $2(m-n)$ from the m flows and divide them into $m-n$ pairs. The flows belonging to each such pair align with each other. From Lemma IV.1, we know $2(m-n) \leqslant m$. Thus, this interference alignment construction is always feasible. Next, we argue that any flow can only be aligned with one other flow in one receiver (Lemma.IV.2).

Lemma IV.2. ***If the network interference is aligned to a single dimensional subspace at each receiver using shadow channel, then to make sure the system decodes all the message flows, each message flow can only be aligned at just one receiver.***

a) ***Half-blind alignment scheduling:*** Lemma IV.2 implies interference alignment at each receiver can be constructed independently. With this property, the alignment can be done

$$\begin{pmatrix} w_1(1) \\ w_1(2) \\ w_1^*(4) - w_1(3) \\ w_1^*(5) - e^{j2/3\pi} w_1(3) \end{pmatrix} = \begin{pmatrix} h_{11} & 0 & h_{21} & 0 \\ 0 & h_{11} & 0 & h_{31} \\ h_{11}^* h_{13}/h_{13}^* & h_{11}^* h_{12}/h_{12}^* & h_{21}^* h_{23}/h_{23}^* & h_{31}^* h_{32}/h_{32}^* \\ h_{11}^* h_{13}/h_{13}^* & e^{-j2/3\pi} h_{11}^* h_{12}/h_{12}^* & h_{21}^* h_{23}/h_{23}^* & e^{-j2/3\pi} h_{31}^* h_{32}/h_{32}^* \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ y_2 \\ z_1 \end{pmatrix} \quad (3)$$

half-blind: on the original channel transmission slots, precoding vector is independent of the channel matrix; on the shadow channel transmission slots, the precoding vector is a vector multiplied by $\frac{h^*}{h}$, where h is the channel coefficient from that transmitter to the receivers.

For instance, message flow x and y from transmitter TX1 and TX2 align at receiver R. The channel from TX1 to R is h_1, channel from TX2 to R is h_2. In slot i, assuming the receiver independent precoding value is $\boldsymbol{v_i}$.

1) Transmission on original channel: TX1 transmits $\boldsymbol{v_i}x$ while TX2 transmits $\boldsymbol{v_i}y$. Then at the receiver R, the ratio between x,y is $\frac{h_1\boldsymbol{v_i}}{h_2\boldsymbol{v_i}} = \frac{h_1}{h_2}$.

2) Transmission on shadow channel: TX1 transmits $\boldsymbol{v_i}\frac{h_1^*}{h_1}x^*$ while TX2 transmits $\boldsymbol{v_i}\frac{h_2^*}{h_2}y^*$. Then at the receiver R, the ratio is $\frac{[h_1\boldsymbol{v_i}\frac{h_1^*}{h_1}]^*}{[h_2\boldsymbol{v_i}\frac{h_2^*}{h_2}]^*} = \frac{h_1}{h_2}$.

As the ratio is a constant along all the transmission slots, interference alignment is achieved.

*b) **Upper-bound of capacity improvement using shadow channel for single-antenna system:**:* Assume K message flows injected into the network. Let all messages be decoded by at least one receiver in L slots. Thus, the capacity gain is K/L. Given M receivers, we can show that K/L is bounded by $\frac{\boldsymbol{M}}{\boldsymbol{M-0.5}}$ (refer technical report [18] for proof.) This results in gains of 4/3 in the two-receiver case and 1.2 in three-receiver case.

V. Practical Issues

Prior single antenna interference alignment work is of theoretic nature. In this section we discuss the practical issues in implementing our interference alignment scheme.

A. Synchronization

This technique requires symbol level synchronization. Recent work, SourceSync [15], demonstrated distributed synchronization across multiple concurrent transmissions within 10s of nanoseconds. Since then, several multi-user beamforming and interference alignment techniques based on the SourceSync [3], [11], [16]have been proposed.

B. Measuring and Sharing Channel State Information

Channels are traditionally measured at the receiver and fedback to the transmitter through ACK like packets. Every receiver needs to broadcast the channel coefficients to each transmitter and for every subcarrier. Assume m transmitters and n receivers with k subcarriers in the network, then, we need mn time slots to share mnk channel coefficients between the receivers and the transmitters. We reduce the cost of estimating and sharing channel information between all the nodes using a suite of techniques described below:

(a) Channel Reciprocity: Channel reciprocity says that the channel from radio i to radio j and the reverse channel from j to i, h_{ij} and h_{ji} has the following relationship:

$$h_{ij} = C_{i,tx} h_{ji} C_{j,rx}$$

where $C_{i,tx}$ depends on the hardware of i while $C_{j,rx}$ depends on the hardware of j. According to [8], those hardware related parameters can be determined by one time measurement.

This implies that each transmitter only needs to measure the channel between the receivers and itself, in order to estimate the channel between itself and the receiver. This eliminates the need for explicit feedback. We make use of channel reciprocity to gather the channel information at the transmitters. This information is used for computing the precoding vectors (discussed in (c)).

(b) Concurrent Channel Estimation at Transmitters: To apply channel reciprocity, receivers need to send reference tones for the transmitter to measure the channel. In these symbols, the only information transmitted is reference signals. OFDM usually allocates subcarriers called pilot tones for channel estimation. As no data is transmitted, in our implementation we use the data subcarriers also for channel estimation. Thus, the receivers share the subcarriers to send the reference signals concurrently in an OFDMA-like fashion. This enables each transmitter to measure the channels to all the receivers simultaneously over an OFDM symbol duration. Of course, the reference signals sent from all the receivers need to be synchronized. SourceSync can be used for the desired synchronization between these distributed receivers. We discuss the effect of lack of synchronization in (d).

(c) Calculating Precoding Vector at the Receiver: With the concurrent channel estimation at transmitters, the precoding vector at the transmitter can be determined directly. This is because the precoding vector is only a function of the channel between the transmitter and its receivers. However, at a particular receiver, the channel coefficients between the transmitter to the other receivers are still unknown but required. For instance, for the example shown in the section III-B, if AP2 does not know h_{11} and h_{21}, it cannot decode x_2 and y. To resolve this issue, we multiply reference pilot tones of each transmitted message with the precoding vector. Thus, the channel measured at the receivers will directly provide the unknown channel coefficients for a particular message.

In the X-channel case, when more than one message needs to be precoded in the same slot, alternate reference pilot tones are used to include the respective precoding vectors. For instance, in the example above, in time slot 3 at TX1, the odd pilot tones are multiplied with $\frac{h_{11}^*}{h_{11}}$ while the even tones are multiplied with $\frac{h_{12}^*}{h_{12}}$.

(d) Dealing with Packet Detection Delay: Channel reciprocity works well for narrow band transmissions. However, for wideband signals, channel measurement based on channel reciprocity introduces errors because of packet detection delay. Packet detection delay refers to the difference in arrival time of a packet among multiple receivers, illustrated in Figure. 8(a). Delay in OFDM transmission results in a phase shift in the frequency domain, [15]. Since the channel estimation is done concurrently, the packet detection delay observed due to difference in propagation delay affects the channel estimation at each transmitter. Packet detection delay exists because of two main reasons: (a) *limitation of achievable synchronization between distributed nodes*. (b) *Presence of multiple receivers*. Propagation delay from transmitter to the receivers depends on the distance from the transmitters to the receivers . This distance can be calibrated at one receiver. However, with multiple receivers, it is impossible to synchronize at all the receivers simultaneously.

To understand the effect of packet detection delay, consider OFDM symbols, with N_s subcarriers over W bandwidth and d packet detection delay at subcarrier i. The equivalent rotated phase $\Delta\theta$ follows the formula:

$$\Delta\theta = \frac{2\pi i d W}{N_s}$$

For a typical WiFi transmission of 20MHz bandwidth, the phase rotation on the edge would be around $\pi d \times 20M$. For a 10 nanosecond synchronization error, the phase shift is $\pi/5$. This is significant especially as the interference alignment achieved through the shadow channel is based on the precise knowledge of the phase of the channel [5]. Thus, this phase shift negates the advantage of interference alignment using shadow channel.

To overcome this problem, in the calibration period, we measure the packet detection delay from each transmitter to a receiver at the receiver and feed it back to the transmitters. The delay for each link is just one real number. We assign m subcarriers at each of the n receivers to share the calculated delays at the receivers among all the transmitters over the duration of one OFDM symbol. The transmitters use this information to adjust its estimated channel coefficients in its transmitted precoding vectors. Figure. 8(b) illustrates this process. Combined with the packet detection delay measured at the receiver, we can have an accurate estimation of the channel as shown in Figure. 8(c) and apply principles of channel reciprocity. The calibration process of duration of around three OFDM symbols is done once per frame.

In the above discussion, we assumed the receivers estimate the delay. We use the fact that time delay of an OFDM transmission results in phase rotation in the frequency domain. We indirectly estimate delay in the frequency domain. Although channel across frequency domain is not exactly the same, we use a linear fitting of the phase at different reference subcarriers to obtain an accurate estimate of the packet detection delay (using Eq. 4).

[5]The term $\frac{h^*}{h}$ which used in the previous sections is equivalent to the rotation of the phase of the channel twice

VI. Performance Evaluation

Setup: We implement interference alignment using shadow channel on a four-node system on the PXIe-1082 platform. This platform houses four Virtex-5 based FPGAs. The platform provides a communication backplane between the FPGAs for the purpose of control, data transfer and synchronization. Each FPGA itself is connected to an RF front end, NI-5791. Each radio has a single antenna. We let each transmitter send an OFDM symbol at 2.412 GHz on a 5 MHz bandwidth using QPSK modulation with a transmission power of 0 dBm. A (1/2)-convolutional coding scheme is used to encode and decode the packets. We perform these experiments in our office space, a multipath rich environment, with stationary to semi-stationary nodes.

Synchronization: We achieve time synchronization between the transmitters by making use of the communication backplane shared by the radios. We assign a lead transmitter to trigger the start of each transmission. The transmitters synchronize in frequency by locking their RF oscillators to a common reference clock, also accessible through the backplane. It must be noted that while we have used an additional channel (the backplane) to synchronize for convenience, recent works such as SourceSync [15], MegaMIMO [16], have demonstrated the feasibility of time and frequency synchronization among distributed transmitters.

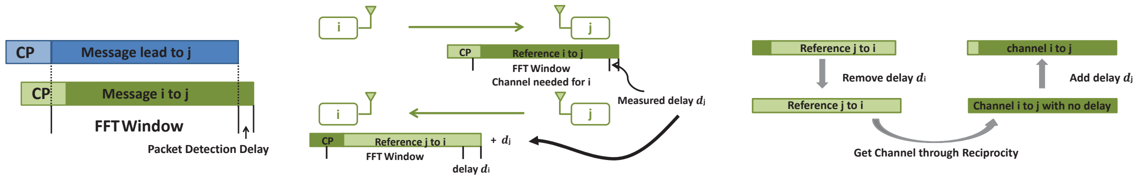
Comparison: We compare our proposed scheme with an omniscient TDMA scheme. Other interference alignment schemes cannot be applied to our system. While distributed MIMO can potentially achieve higher gains, it requires sharing large *volume* data samples between the distributed APs which can overwhelm the backbone as the network scales. Hence, we do not compare our work with a distributed MIMO implementation.

Implementation: Channel estimation and sharing channel state information between the receivers and transmitters is implemented as discussed in the previous Section. All the transmitters send a preamble to enable all the receivers to detect the start of data payload. Following the preamble, we club three successive OFDM symbols together as a virtual "super-symbol". The receiver sends back the estimated channel to the transmitter every 200ms (within an average channel coherence time of 250ms measured in our environment).

For omniscient TDMA, we let each transmitter send data in alternate time-slots since each transmitter has data for each receiver in the X-channel scenario. Thus, there is no loss in efficiency of the TDMA implementation due to backoff. For all experiments, each transmitter sends a 1500B data packet to assist with measuring throughput at the receiver. We do not utilize any rate-adaptation techniques in our implementation.

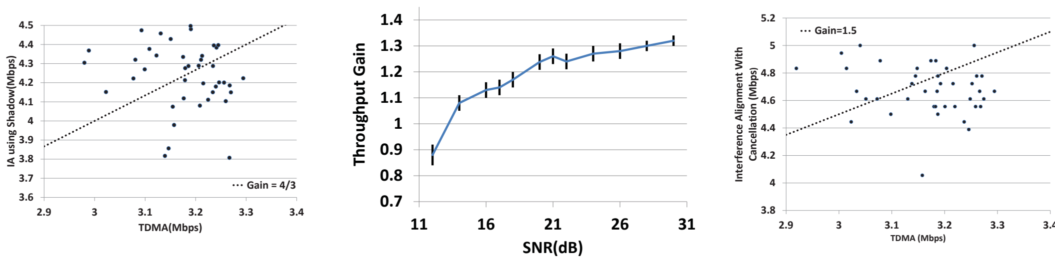
A. X-Channel Scenario

Methodology: We place the four radios (antennas) at random locations as illustrated in Figure 9 such that each node can



(a) Packet Detection Delay (b) Channel Measuring Transmission Process (c) Channel Estimation at Transmitter

Fig. 8. (a) shows the packet detection delay. Because of the synchronization process, the delay mismatch are within the CP(cyclic prefix) [15]. (b) shows that receivers receivers send reference signal the measured packet detection delay for the transmitter channel measurement. (C) illustrate the process of channel estimation at the transmitter end.



(a) (b) (c)

Fig. 10. (a)Throughput comparison in X-Channel scenario; (b)Throughput Gain vs SNR; (C)Throughput comparison in X-Channel scenario with interference cancellation

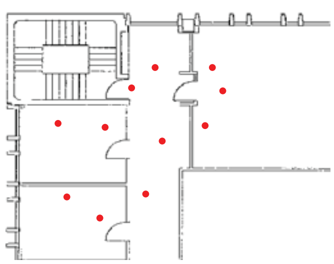


Fig. 9. Testbed for evaluating Interference Alignment using Shadow Channel. Four random points from the testbed were selected for each run of the experiment

listen to every other node (to form an X-channel). For each of these locations, we compare the performance of interference alignment using shadow channel with omniscient TDMA. We measure the throughput at each receiver for each location using both methods. We repeat the experiment across 40 locations. We precode each slot of this super-symbol as indicated in Table I.

Results: Figure 10(a) illustrates the throughput of our scheme against the throughput of the TDMA implementation. We achieve an average throughput gain of 1.29x - i.e. on average we achieve almost the entire multiplexing gain presented by our scheme. The gain itself varies from 1.12x to 1.44x depending on the relative location of the nodes and the channel conditions between the nodes. The throughput measurements do not account for the difference in the MAC overhead between interference alignment using shadow channel technique and TDMA. However, the MAC overhead for our implementation is amortized by the relatively large period (relative to packet duration) between channel feedback from the receivers to the transmitter.

Discussion: Some of the node locations result in a throughput gain higher than the theoretically predicted 4/3. The reason for this observation is the following: The TDMA technique is limited by a poor channel between one of the transmitters and the receivers. Since, the X-channel has data from each transmitter to each receiver and our implementation does not have any rate adaptation techniques, the TDMA throughput is limited by this channel. However, interference alignment using shadow channel, in effect, transmits three data packets over two slots using distinct channel uses and hence benefits from *diversity gain*, and appreciably when one of the channels is poor.

Also, at few of the observed locations the throughput gain drops below 1.2x. The throughput gain in these channels is limited by the relatively lower SNR of more than one of the channels in the X-channel. To evaluate the SNR we fix the location of the nodes such that the SNR at each receiver is approximately the same. We then lower the transmission power at each transmitter and compare the throughput of our scheme with TDMA. We lower the transmission power in steps of 1dB and repeat the experiment ten times at each transmission power. Figure 10(b) illustrates the throughput gain of our scheme across SNR. The throughput gain is relatively steady until the SNR drops to approximately 18dB.

It must be noted that our scheme requires $\frac{h_{11}^*}{h_{11}}$ to be different from $\frac{h_{12}^*}{h_{12}}$. Similarly, with $\frac{h_{21}^*}{h_{21}}$ and $\frac{h_{22}^*}{h_{22}}$. When these phases are equal, interference alignment will not work resulting in one equation with two unknowns. While, it is possible to realize an X-channel that closely approximates to these conditions, we did not come across such channel conditions while running our experiment.

B. With Interference Cancellation

Interference alignment using shadow channel can be coupled with interference cancellation techniques whenever possible to achieve higher performance gains. We repeat the experiment performed for the X-channel scenario but now we let the receivers share data between them. We implement the interference cancellation operation itself offline. In this case, we have the transmitters send three packets over two slots as listed in Table II. We perform the experiment over the same set of locations we used for the X-channel scenario. Figure 10(c) lists the throughput of this technique against TDMA implementation. We observe an average throughput gain of approximately 1.5X and a maximum throughput gain of approximately 1.61X.

VII. Related Work

A. Interference Alignment

On the theoretic side, many researchers have explored interference alignment. For single antenna nodes, using time-varying channels interference is aligned [6], enabling every transmission pair access to half the channel. Ergodic interference alignment [14] waits for right channel conditions to implement alignment techniques. Both techniques introduce formidable latency.Moreover, both schemes require time-varying channels. In its absence, either interference alignment completely fails (for a perfectly stationary case) or would induce larger delays (for the case when coherence time is reasonably large). Our proposed work enables interference alignment in both scenarios.

Interference alignment in networks with multiple antenna nodes has been explored [1], [8], [12], [13]. Here, even under static channel conditions, the antennas provide additional dimensions for interference alignment. Our work looks at single antenna systems. Robinhood [5] considers using additional APs to help with the alignment. We don't need any additional helper devices. Further, as our scheme introduces interference alignment from a new dimension, it can be combined with existing interference alignment techniques.

B. Conjugate-based Space Time Coding

The Alamouti scheme [2] is seminal work based on conjugate operation. The authors considered a two antenna transmitter sending to a single antenna receiver. Our work differs from Alamouti and its extensions [10], [17] in the following ways. Alamouti's goal was to propose a technique that would maximize the received signal strength of two transmitted symbols at the receiver. He showed that by sharing data between the transmitting antennas and using conjugate and conjugate negative, he could orthogonalize the channels between the first transmit antenna and the second transmit antenna to the receive antenna. By doing this he demonstrated transmit diversity in the low SNR regime even without knowing the channel at the transmitter. On the other hand, our scheme works in the high SNR regime where Alamouti's scheme doesn't provide much improvement. Secondly,our work creates independent channel realizations, not orthogonal channel realizations.

VIII. Conclusion

In this paper, we presented the feasibility of achieving interference alignment in static channel conditions. We present a technique that requires no modification to the radio architecture. The notion of a shadow channel is defined to create the effect of time variance between the relative channels required for interference alignment. We utilize this relative time variance for interference alignment. The throughput gains of this interference alignment technique is studied theoretically and empirically over the X-channel network. Interference alignment using shadow channel can be interpreted as interference alignment along one dimension of the two dimensional complex communication space. Thus, this technique can be cascaded with other interference alignment techniques.

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