Interference Alignment for MISO Broadcast Channels under Jamming attacks

SaiDhiraj Amuru, Ravi Tandon, R. Michael Buehrer and T. Charles Clancy
Bradley Department of Electrical and Computer Engineering
Virginia Tech, Blacksburg, VA USA
Email: {adhiraj, tandonr, rbuehrer, tcc}@vt.edu

Abstract—Jamming attacks can significantly impact the performance of wireless communication systems, and lead to insurmountable overhead in terms of re-transmissions and increased power consumption. In this paper, we consider the two-user multiple-input single-output (MISO) broadcast channel (BC) in the presence of a jamming attack in which either one, or both or none of the users can be jammed or interfered at any given time. We present countermeasures for mitigating the effects of such jamming attacks. The effectiveness of anti-jamming countermeasures is quantified in terms of the degrees-of-freedom (DoF) of the MISO BC under various assumptions regarding the availability of the channel state information (CSIT) and the jammer state information at the transmitter (JSIT).

I. INTRODUCTION

The inherent openness of the wireless medium makes it susceptible to eavesdropping and jamming attacks. The study of information theoretic security (or communication) in presence of eavesdropping attacks was initiated by Wyner [1], Csiszár and Körner [2]. We refer the reader to a comprehensive tutorial [3] on this topic and the references therein. Jamming attacks are ones in which the jammer can transmit information in order to disrupt reliable data transmission or reception. While there has been some work in studying the impact of jamming on the capacity of point-to-point channels (such as [4]–[6]), the literature on the study of jamming attacks (and associated countermeasures) for multi-user channels is relatively sparse in comparison to the case of eavesdropping attacks.

In this paper, we focus on a class of time varying jamming attacks over a fast-fading two-user MISO BC, in which a transmitter equipped with 2 transmit antennas intends to send independent messages to two single antenna receivers. In particular, we consider a jammer equipped with 2 transmit antennas and at any given time instant, the jammer has the capability of randomly jamming either one or both or none of the receivers. In addition, we assume that the jammer’s signal is additive white Gaussian noise (AWGN), with power as high as the transmit signal. Such a time-varying jamming attack may be inflicted either intentionally (by an adversary); or unintentionally due to interference from neighboring cells in a cellular system; which can be particularly harmful for cell edge users. Interference power in such scenarios can be time varying depending on whether the interfering cells are transmitting on the same frequency or not (which can change with time); and the spatial separation of the users from the interfering cells.

We study the impact of such jamming attacks on the DoF region of the MISO BC. The DoF of a channel can be regarded as an approximation of the channel capacity at high signal-to-noise ratio (SNR); and is also referred to as the pre-log of capacity. For fast fading channels, even in the absence of a jammer, the achievable DoF is crucially dependent [7] on the availability of channel state information at the transmitter (CSIT). In order to take this dependence into account, we denote CSIT availability through a variable $I_{CSIT}$, which can take values either P, D or N: where the state $I_{CSIT} = P$ indicates that the transmitter has perfect and instantaneous channel state information at time $t$, the state $I_{CSIT} = D$ indicates that the transmitter has perfect but delayed channel state information (i.e., it has channel matrices of time $\{1,2,\ldots,t-1\}$ at time $t$), and the state $I_{CSIT} = N$ indicates that the transmitter has no channel state information.

The impact of CSIT on the DoF of MISO broadcast channels has been explored for scenarios in which there is no adversarial interference. The novelty of this work is two fold: a) incorporating un-intentional interference (resulting from neighboring cells) or intentional interference (due to jamming), and b) studying the joint impact of CSIT and the knowledge about the absence/presence of such interference at the transmitter.

In this paper, we show that in the presence of a time-varying jamming attack (adversarial interference), not only the CSIT availability but also the transmitter’s knowledge about the jammer’s strategy (in other words, presence or absence of external interference) significantly impacts the DoF. Observe that if the transmitter is non-causally aware of the jamming strategy at time $t$, i.e., if it knows which receiver (or receivers) is going to be disrupted at time $t$, it can accordingly adapt by either: a) sending information to the receiver which is not jammed; or b) sending information to both receivers simultaneously (if none is jammed); or c) conserve energy by temporarily shutting off and not transmitting any information (if both are jammed). However, such adaptation may not be feasible if there is significant delay in learning the jammer’s strategy.

Feedback delays could arise in practice as the detection of a jamming signal would be done at the receiver (via a binary
Jammer’s signal

\[ Y_k(t) = H_k(t)X(t) + S_k(t)G_k(t)J(t) + N_k(t), \]

where \( X(t) \) is the 2 \times 1 channel input vector at time \( t \) with \( E(\|X(t)\|^2) \leq P_T \), where \( P_T \) is the power constraint on \( X(t) \). In (1), \( H_k(t) \) is the 1 \times 2 channel vector from the transmitter to receiver at time \( t \), \( G_k(t) \) is the 1 \times 2 channel response from the jammer to receiver at time \( t \) and \( J(t) \) is the 2 \times 1 jammer’s channel input at time \( t \). Without loss of generality, the channel vectors \( H_k(t) \) and \( G_k(t) \) are assumed to be sampled from any continuous distribution (for instance Rayleigh) with an identity covariance matrix, and are i.i.d. across time. This models a fast-fading scenario in which the channel coherence time is equal to the symbol duration. The additive noise \( N_k(t) \) is distributed according to \( \mathcal{CN}(0, 1) \) for \( k = 1, 2 \) and are assumed to be independent of all other random variables. The random variable \( S(t) = (S_1(t), S_2(t)) \) is a quaternary-valued i.i.d. random variable; taking values \( \{(0, 0), (0, 1), (1, 0), (1, 1)\} \) with probabilities \( \\{\lambda_{00}, \lambda_{01}, \lambda_{10}, \lambda_{11}\} \) for arbitrary \( \lambda_{ij} \geq 0 \) such that \( \sum_{i,j} \lambda_{ij} = 1 \). The jammer state (or the state of interference) \( S(t) \) at time \( t \) can be interpreted as follows:

- \( S(t) = (0, 0) \) – none of the receivers are jammed.
- \( S(t) = (0, 1) \) – only receiver 2 is jammed.
- \( S(t) = (1, 0) \) – only receiver 1 is jammed.
- \( S(t) = (1, 1) \) – both receivers are jammed.

Using these, we can write the marginal probabilities

\[ \lambda_i = \lambda_{00} + \lambda_{01}, \quad \lambda_j = \lambda_{00} + \lambda_{10}, \]

where \( \lambda_k \in [0, 1] \) denotes the total probability with which receiver \( k \) is not jammed.

Furthermore, it is assumed that the elements of \( J(t) \) are distributed i.i.d. as \( \mathcal{CN}(0, P_T) \), i.e., the jammer transmits i.i.d. AWGN signal at each time instant with power \( P_T \). This model attempts to capture a time-varying interference (here jammer) limited scenario, where the interference power can be as high as the transmit signal power \( P_T \). We denote the global channel state information at time \( t \) by \( \mathbf{H}(t) = \{H_1(t), H_2(t)\} \).

Throughout the paper, we assume that both the receivers have complete knowledge of global channel vectors \( \{\mathbf{H}(t)\}_{t=1}^T \) and also of the jammer’s strategy, i.e., \( \{S(t)\}_{t=1}^T \), i.e., full CSIT and full JSIR (similar assumptions were made in earlier works, see [7], [9] and references therein). As mentioned earlier, the receivers do not require the knowledge of the channel between jammer and the receivers i.e., \( G_k(t) \). A rate pair \( (R_1, R_2) \), with \( R_k = \log(\|W_k\|)/n \), where \( n \) is the number of channel uses, is achievable if the probability of decoding error for message \( W_k \), for \( k = 1, 2 \) can be made arbitrarily small for sufficiently large \( n \). We are interested in the degrees of freedom region, which is defined as the set of all achievable pairs \( (d_1, d_2) \) with \( d_k = \lim_{P_T \to \infty} \frac{\log(P_T)}{R_k} \).
III. MAIN RESULTS AND DISCUSSION

In this section, we present the DoF regions for the following \(\text{(CSIT, JSIT)}\) configurations: \(\text{NN, PP, PD, PN and DD}\).

**Theorem 1:** The DoF region for the (CSIT, JSIT) configuration \(\text{NN}\) is given as
\[
\frac{d_1 + d_2}{\lambda_1 + \lambda_2} \leq 1. \tag{3}
\]

**Theorem 2:** The DoF regions for each of the (CSIT, JSIT) configurations \(\text{PP, PD and PN}\) are same and given by the set of non-negative pairs \((d_1, d_2)\) that satisfy
\[
d_1 \leq \lambda_1, \quad d_2 \leq \lambda_2. \tag{4}
\]

**Theorem 3:** The DoF region for the (CSIT, JSIT) configuration \(\text{DD}\), is given by the set of non-negative pairs \((d_1, d_2)\) that satisfy
\[
\frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} \leq 1
\]
\[
\frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} \leq 1. \tag{5}
\]

**Remark 1:** The coding schemes that achieve the corresponding DoF regions (see Figure 2) are detailed in Section IV. Due to space limitations, converse proofs are not presented here and can be found in [12].

**Remark 2:** It is interesting to note that the DoF regions in Theorems 1-3 only depend on the marginal probabilities \((\lambda_1, \lambda_2)\) for which each of the receivers is not jammed. This implies that two different jamming strategies with statistics, \(\{\lambda_{00}, \lambda_{01}, \lambda_{10}, \lambda_{11}\}\) and \(\{\lambda'_{00}, \lambda'_{01}, \lambda'_{10}, \lambda'_{11}\}\) result in the same DoF regions as long as \(\lambda'_{00} + \lambda'_{01} = \lambda_{00} + \lambda_{01} = \lambda_1\) and \(\lambda'_{00} + \lambda'_{10} = \lambda'_{00} + \lambda'_{10} = \lambda_2\).

**Remark 3:** We note from Theorem 2 that when perfect CSIT is available, DoF region remains the same regardless of availability/unavailability of the jammer state information at the transmitter. This implies that with perfect CSIT, no jammer state information is necessary in order to achieve the optimal DoF region.

**Remark 4:** The achievability of Theorem 3 is based on synergistic usage of delayed CSIT (d-CSIT) and delayed JSIT (d-JSIT) by exploiting side-information created at the un-jammed receiver in the past and transmitting linear combinations of such side-information symbols in the future. This scheme is similar to retrospective interference alignment (see [7], [9], [10] and references therein).

IV. ACHIEVABILITY PROOFS

A. Achievability for Theorem 1: NN configuration

In this section we explain the achievability of the DoF pair: \((d_1, d_2) = (\lambda_1, 0)\). To this end, first note that receiver 1 is jammed in an i.i.d. manner with probability \((1 - \lambda_1)\). This implies that for a scheme of sufficiently large duration \(n\), it will receive \(\lambda_1 n\) jamming free information symbols (corresponding to those instants in which \(S_1(t) = 0\)). However, in the NN configuration (no CSIT and no JSIT), the transmitter is not aware of the symbols which are received without being jammed. In order to compensate for the lack of this knowledge, it sends random linear combinations (LCs)\(^1\) of \(\lambda_1 n\) symbols over \(n\) time slots. For sufficiently large \(n\), receiver 1 obtains \(\lambda_1 n\) jamming free LCs and hence it can decode these symbols. Thus the DoF pair \((\lambda_1, 0)\) is achievable. Similarly, by switching the role of the receivers, the pair \((0, \lambda_2)\) is also achievable. Finally, the entire region in Theorem 1 is achievable by time sharing between these two strategies.

B. Achievability for Theorem 2: PN configuration

In this section we sketch the achievability of the pair \((d_1, d_2) = (\lambda_1, \lambda_2)\) for the PN configuration. Clearly, if this pair is achievable with perfect CSIT and no JSIT (i.e., PN configuration), then it is also achievable for PP and PD configurations.

The goal of the transmitter is to simultaneously send \(\lambda_{1n}\) symbols to receiver 1 and \(\lambda_{2n}\) symbols to receiver 2 in \(n\) time instants (for sufficiently large \(n\)). Let \(\{a_j\}_{j=1}^{\lambda_{1n}}\) and \(\{b_j\}_{j=1}^{\lambda_{2n}}\) denote the information symbols intended to be sent to receiver 1 and 2 respectively. In contrast to the NN configuration, the transmitter has the knowledge of \(\{H_1(t), H_2(t)\}\) (perfect CSIT) in the PN configuration. At time \(t\), the transmitter sends the following input:

\[
X(t) = B_1(t)f_1(a_1, \ldots, a_{\lambda_{1n}}) + B_2(t)g_1(b_1, \ldots, b_{\lambda_{2n}}), \tag{7}
\]

where \(B_1(t)\) and \(B_2(t)\) are \(2 \times 1\) precoding vectors satisfying \(H_1(t)B_1(t) = 0\) and \(H_2(t)B_1(t) = 0\) and \(f_1(\cdot), g_1(\cdot)\) are linear combinations of the respective \(\lambda_{1n}\) and \(\lambda_{2n}\) symbols. Thus, the received signals at time \(t\) are given as

\[
Y_1(t) = H_1(t)B_1(t)f_1(a_1, \ldots, a_{\lambda_{1n}}) + S_1(t)G_1(t)J(t) + N_1(t)
\]
\[
Y_2(t) = H_2(t)B_2(t)g_1(b_1, \ldots, b_{\lambda_{2n}}) + S_2(t)G_2(t)J(t) + N_2(t).
\]

The \(k\)th receiver can decode the intended symbols upon successfully receiving un-jammed and interference free \(\lambda_{1n}\) linearly independent combinations transmitted using the zero-forcing strategy. Hence \((d_1, d_2) = (\lambda_1, \lambda_2)\) is achievable.

\(^1\)The random coefficients are assumed to be known at the receivers [11].
C. Achievability for Theorem 3: DD configuration

In this subsection, we present a scheme that achieves the following \((d_1, d_2)\) pair (which corresponds to intersection of (5) and (6)):

\[
(d_1, d_2) = \left( \frac{\lambda_1}{\lambda_1 + \lambda_2}, \frac{\lambda_2}{\lambda_1 + \lambda_2} \right).
\] (8)

To this end, we present a three-stage scheme. In stage 1, the transmitter sends symbols intended only for receiver 1 and keeps re-transmitting them until they are received within noise distortion (or uncorrupted by the jamming signal) at least one receiver. In stage 2, the transmitter sends symbols intended only for receiver 2 in the same manner. Stage 3 consists of transmitting the undelivered symbols to the intended receiver. The specific LCs to be transmitted in stage 3 are determined by the feedback (i.e., d-CSIT and d-JSIT) received from the stages 1 and 2. The eventual goal of the scheme is to deliver \(n_1\) symbols to receiver 1 and \(n_2\) symbols to receiver 2.

Below we explain the 3-stages involved in the proposed transmission scheme.

Stage 1—In this stage, the transmitter intends to deliver \(n_1\) symbols, in a manner such that each symbol is received at least one of the receivers. At every time instant the transmitter sends two symbols on two transmit antennas. A pair of symbols are re-transmitted until they are received at least one receiver. Any one of the following four scenarios can arise:

**Event 00:** none of the receivers are jammed (which happens with probability \(\lambda_{00}\)). Without loss of generality, suppose that at time \(t\), if the transmitter sends \((a_1, a_2)\); then receiver 1 gets \(f_1(a_1, a_2)\) and receiver 2 gets \(f_2(a_1, a_2)\). The fact that the event \(00\) occurred at time \(t\) is known at time \(t + 1\) via d-CSIT; and the LC \(f_1(a_1, a_2)\) can be obtained at the transmitter at time \(t + 1\) via d-CSIT. The goal of stage 3 would be to deliver \(f_2(a_1, a_2)\) to receiver 1 by exploiting the fact that it is already received at receiver 2. Thus, at time \(t + 1\), the transmitter sends two new symbols \((a_3, a_4)\).

**Event 01:** receiver 1 is not jammed, whereas receiver 2 is jammed (which happens with probability \(\lambda_{01}\)). Suppose that at time \(t\), if the transmitter sends \((a_1, a_2)\); then receiver 1 gets \(f_1(a_1, a_2)\) and receiver 2’s signal is drowned in the jamming signal. The fact that the event \(01\) occurred at time \(t\) is known at time \(t + 1\) via d-CSIT; and the LC \(f_1(a_1, a_2)\) can be obtained at the transmitter at time \(t + 1\) via d-CSIT. Thus, at time \(t + 1\), the transmitter sends a fresh symbol \(a_3\) on one antenna; and a LC of \((a_1, a_2)\); say \(f_1(a_1, a_2)\); such that \(f_1(a_1, a_2)\) and \(f_1(a_1, a_2)\) constitute two linearly independent combinations of \((a_1, a_2)\). In summary, at time \(t + 1\), the transmitter sends \((a_3, f_1(a_1, a_2))\).

**Event 10:** receiver 2 is not jammed, whereas receiver 1 is jammed (which happens with probability \(\lambda_{10}\)). If at time \(t\), the transmitter sends \((a_1, a_2)\); then receiver 1 is jammed, whereas receiver 2 gets \(f_2(a_1, a_2)\) cleanly. The fact that the event \(10\) occurred at time \(t\) is known at time \(t + 1\) via d-CSIT; and the LC \(f_2(a_1, a_2)\) can be obtained at the transmitter at time \(t + 1\) via d-CSIT. By the nature of stage 3, it would be to deliver \(f_2(a_1, a_2)\) to receiver 1 by exploiting the fact that it is already received at receiver 2. Thus, at time \(t + 1\), the transmitter sends a fresh symbol \(a_3\) on one antenna; and a LC of \((a_1, a_2)\); say \(f_2(a_1, a_2)\); such that \(f_2(a_1, a_2)\) and \(f_2(a_1, a_2)\) constitute two linearly independent combinations of \((a_1, a_2)\). In summary, at time \(t + 1\), the transmitter sends \((a_3, f_2(a_1, a_2))\).

**Event 11:** both receivers are jammed (which happens with probability \(\lambda_{11}\)). Using d-CSIT, the transmitter knows at time \(t + 1\) that the event 11 occurred and hence at time \(t + 1\), it re-transmits \((a_1, a_2)\) on the two transmit antennas.

The above events are disjoint, so in one time slot, the average number of useful LCs delivered to at least one receiver is given by

\[
E[\# \text{ of LCs delivered}] = 2\lambda_{00} + \lambda_{01} + \lambda_{10} \triangleq \phi.
\] (9)

The time spent in this stage to deliver \(n_1\) LCs is \(N_1 = \frac{n_1}{\lambda_1 + \lambda_2}\). Since receiver 1 is not jammed in events 00 and 01, i.e., for \(\lambda_1\) fraction of the time, it receives only \(\lambda_1 N_1\) LCs. The number of undelivered LCs is \(n_1 - \lambda_1 N_1 = \frac{\lambda_2 n_1}{\lambda_1 + \lambda_2}\). These LCs are available at receiver 2 (corresponding to events 00 and 10) and are known to the transmitter via d-CSIT. This side information created at receiver 2 is not discarded, instead it is used in Stage 3 of the transmission scheme.

Stage 2—In this stage, the transmitter intends to deliver \(n_2\) symbols, in a manner such that each symbol is received at least one of the receivers. Stage 1 is repeated here with the roles of the receivers 1 and 2 interchanged. On similar lines to Stage 1, the time spent in this stage is \(N_2 = \frac{n_2}{\lambda_1 + \lambda_2}\). The number of LCs received at receiver 2 is \(\lambda_2 N_2\) and the number of LCs not delivered to receiver 2 but are available as side information at receiver 1 is \(n_2 - \lambda_2 N_2 = \frac{\lambda_1 n_2}{\lambda_1 + \lambda_2}\).

**Remark 5:** At the end of these 2 stages, following typical situation arises: \(f(a_1, a_2)\) (resp. \(g(b_1, b_2)\)) is a LC intended for receiver 1 (resp. 2) but is available as side information at receiver 2 (resp. 1). Notice that these LCs are transmitted to the complementary receivers so that the desired symbols can be decoded. In Stage 3, the transmitter sends a random LC of these symbols, say \(L = h_1 f(a_1, a_2) + h_2 g(b_1, b_2)\) where \(h_1, h_2\) that form the new LC are known to the transmitter and receivers a priori. Now, assuming that only receiver 2 (resp. 1) is jammed, \(L\) is received at receiver 1 (resp. 2) within noise distortion. Using this LC, it can recover \(f(a_1, a_2)\) (resp. \(g(b_1, b_2)\)) from \(L\) since it already has \(g(b_1, b_2)\) (resp. \(f(a_1, a_2)\)) as side information. When no receiver is jammed, both the receivers are capable of recovering \(f(a_1, a_2), g(b_1, b_2)\) simultaneously.

\(^2\)These symbols are received along with additive noises, which have unit variance and do not impact the DoF calculation. Henceforth, we ignore the additive noise in describing the scheme.

\(^3\)Corresponding to events 00, 01 in Stage 1; and events 00, 10 in Stage 2.
Stage 3—In this stage, the undelivered LCs to each receiver are transmitted using the technique mentioned above. Let us assume that $f_1(a_1, a_2)$ and $g_1(b_1, b_2)$ are LCs available as side information at receivers 2 and 1 respectively. The transmitter sends $\mathcal{L}(f_1, g_1)$, a LC of these symbols on one transmit antenna, with the eventual goal of multicasting this LC (i.e., send it to both receivers). Following events (as in Stages 1, 2) are possible:

Event 00: Suppose at time $t$, if the transmitter sends $\mathcal{L}(f_1, g_1)$, then both the receivers get this LC within noise distortion. With the capability to recover $\mathcal{L}(f_1, g_1)$ within a scaling factor, the receivers 1 and 2 decode their intended LCs $f_1$ and $g_1$ respectively using the side informations $g_1$ and $f_1$ that are available with them. Since the intended LCs are delivered at the intended receivers, the transmitter, at time $t + 1$, sends a new LC of two new symbols $\tilde{\mathcal{L}}(f_1, g_1)$.

Event 01: Since receiver 2 is jammed, its signal is drowned in the jamming signal while receiver 1 gets $\mathcal{L}(f_1, g_1)$ and is capable of recovering $f_1$ using $g_1$ available as side information. The fact that event 01 occurred is known to the transmitter at time $t + 1$ via d-CSIT. Thus, at time $t + 1$, the transmitter sends a new LC $\tilde{\mathcal{L}}(f_1, g_1)$ since $f_1$ has not yet been delivered to receiver 2.

Event 10: This event is similar to event 01, with the roles of the receivers 1 and 2 interchanged. Hence, receiver 2 is capable of recovering $g_1$ from $\mathcal{L}(f_1, g_1)$ while receiver 1’s signal is drowned in the jamming signal. Thus at time $t + 1$, the transmitter sends a new LC $\tilde{\mathcal{L}}(f_1, g_1)$ since $f_1$ has not yet been delivered to receiver 1.

Event 11: Using d-CSIT, the transmitter knows at time $t + 1$ that the event 11 occurred and hence at time $t + 1$, it retransmits $\mathcal{L}(f_1, g_1)$ on one of its transmit antennas.

Since, all the events are disjoint, in one time slot, the average number of LCs delivered to receiver 1 is given by

$$E[\# \text{ of LC’s delivered to user } 1] = \lambda_{00} + \lambda_{01} = \lambda_1.$$  

Hence, the expected time to deliver one LC to receiver 1 in this stage is $\frac{1}{\lambda_1}$. Given that $\frac{\lambda_2 n_1}{\lambda_1 + \lambda_2}$ LCs are to be delivered to receiver 1 in this stage, the time taken to achieve this is $\frac{\lambda_2 n_1}{\lambda_1 (\lambda_1 + \lambda_2)}$. Interchanging the roles of the users, the time taken to deliver $\frac{\lambda_1 n_2}{\lambda_1 + \lambda_2}$ LCs to receiver 2 is $\frac{\lambda_1 n_2}{\lambda_2 (\lambda_1 + \lambda_2)}$. Thus the total time required to satisfy the requirements of both the receivers in Stage 3 is given by

$$N_3 = \max \left( \frac{\lambda_2 n_1}{\lambda_1 (\lambda_1 + \lambda_2)}, \frac{\lambda_1 n_2}{\lambda_2 (\lambda_1 + \lambda_2)} \right).$$  

The optimal DoF achieved in the DD configuration is readily evaluated as $d_k = \frac{\eta}{n_1 + n_2 + N_3}$, for $k = 1, 2$. Substituting $\{N_3\}_{i=1,2,3}$, we have,

$$d_1 = \frac{1}{\lambda_1 + \lambda_2} + \max \left( \frac{\lambda_2 \eta}{\lambda_1 (\lambda_1 + \lambda_2)}, \frac{\lambda_1 (1-\eta)}{\lambda_2 (\lambda_1 + \lambda_2)} \right)$$  

$$d_2 = \frac{1 - \eta}{\lambda_1 + \lambda_2} + \max \left( \frac{\lambda_2 \eta}{\lambda_1 (\lambda_1 + \lambda_2)}, \frac{\lambda_1 (1-\eta)}{\lambda_2 (\lambda_1 + \lambda_2)} \right).$$

where $\eta = \frac{\alpha_1}{n_1 + n_2}$. Eliminating $\eta$ from the above two equations, yields the $(d_1, d_2)$ pair given in (8).

Remark 6: It is worth noting that in Stage 3, only delayed JSIT is necessary and no CSIT is required. The DoF region described by Theorem 3 (for a given $\lambda_1, \lambda_2$) can be obtained from (11) and (12) by varying $\eta \in [0, 1]$. Furthermore, if $\lambda_1 = \lambda_2 = 1$, (i.e., $\lambda_{00} = 1$), the optimal sum DoF is $\frac{2}{7}$ which is the optimum DoF achieved in a d-CSIT scenario without jamming attack as shown in [7].

V. CONCLUSIONS

In this paper, the DoF region of a MISO broadcast channel has been characterized in the presence of a time-varying jammer (interference). From our results, the interplay between CSIT and JSIT and associated impact on the DoF regions are illuminated. For the case in which there is perfect CSIT, by employing a randomized zero-forcing precoding scheme, the DoF region remains the same irrespective of the availability/availability of JSIT. On the other hand, for the case of delayed CSIT and JSIT, our results show that both the jammer and channel state information must be synergistically used in order to provide DoF gains. The result for the NN configuration quantifies the DoF loss in case of unavailability of JSIT and CSIT. Investigating the remaining DP, DN, NP and ND configurations is part of our planned future work.

REFERENCES