Exploiting Channel Correlations - Simple Interference Alignment Schemes with no CSIT

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Abstract—We explore a few selected multiuser communication problems where the possibility of interference alignment, and consequently the total number of degrees of freedom (DoF) with channel uncertainty at the transmitters are unknown. These problems share the common property that in each case the best known outer bounds are essentially robust to channel uncertainty and represent the outcome with interference alignment, but the best inner bounds—in some cases conjectured to be optimal—predict a total collapse of DoF, thus indicating the infeasibility of interference alignment under channel uncertainty at transmitters. Our main contribution is to show that even with no knowledge of channel coefficient values at the transmitters, the knowledge of the channels’ correlation structure can be exploited to achieve interference alignment.

I. INTRODUCTION

There is much recent research activity aimed at characterizing the degrees of freedom of wireless networks. The topic is of interest due to the novel insights—in particular those related to interference alignment—that have emerged out of this perspective. While the capacity benefits of interference alignment schemes have been shown to be substantial, the caveat behind most of these results has been the assumption of perfect, and sometimes global, channel state information at the transmitters (CSIT). Indeed, in the absence of channel knowledge it is well known that the degrees of freedom of many networks collapse entirely to what is achievable simply by orthogonal time-division among users [1], [2]. With partial channel knowledge the possibility of interference alignment becomes very intriguing and very little is known about the network degrees of freedom. A common trend is discernible in the diverging inner and outer bounds for various networks under partial CSIT [3], [4], [5]. While the best known inner bounds predict a total collapse of degrees of freedom, the best known outer bounds remain fairly robust to channel uncertainty. A few representative examples extracted from prior work, that illustrate this trend, are listed below.

1) MISO BC with no CSIT for One User: Consider the multiple input single output (MISO) broadcast channel (BC) with 2 antennas at the transmitter and 2 receivers (users), each equipped with a single antenna. The channel state of one user is known perfectly to the transmitter while the other users’ channel state is unknown. Assuming that the channel states are generic and fixed throughout the duration of communication, the best known outer bound on the total DoF, obtained in [4], is equal to $\frac{3}{2}$. However, the best known inner bound on the total DoF if user 2’s channel state is drawn from some continuous distribution, is only 1 - which is trivially achieved by orthogonal time-division between users. The inner bound is conjectured to be optimal.

2) MISO BC with no CSIT for Both Users: For the same 2 user MISO BC setting, if the channel states of both users are unknown to the transmitter, and held fixed, then the best known outer bound on the total DoF, also found in [4] is $\frac{3}{2}$. If the channel states are time-varying, the best known outerbound on the total DoF, derived in [3] is still equal to $\frac{3}{2}$. In both cases the best inner bound is only 1. In both cases, the inner bound is conjectured to be tight.

3) X Channel: The best known outer bound on the total DoF of the X channel with 2 transmitters and 2 receivers — whether the channel is time-varying or held constant—follows from the arguments as presented in [6] and is equal to $\frac{3}{4}$—same as with perfect channel knowledge. The best known inner bound in this case is also only 1.

4) MIMO Interference Channel: A similar open problem is pointed out in the context of the 2 user time-varying MIMO interference channel studied in [5]. Consider the setting with 1, 3 antennas at transmitters 1, 2 and 2, 4 antennas at receivers 1, 2 respectively. If user 1 achieves 1 DoF (his maximum possible DoF), then what is the maximum DoF simultaneously achievable by user 2? The outer bound for the DoF achieved by user 2 found in [5] is $\frac{3}{2}$ but the best known achievable DoF for user 2 is only equal to 1, which is achieved by simple zero forcing at the receivers and no interference alignment.

This paper is motivated by the need to find robust alignment schemes with the understanding that an interference alignment scheme is robust if the alignment is achieved even with the transmitters remaining oblivious of the values of channel coefficients which may be drawn from a continuum. The main contribution of the paper is summarized in the following new insight.

Key New Insight - Even if the transmitters have no knowledge of channel coefficient values, they can still align interference based on the knowledge of only the channel autocorrelation structures of different users.

The result of this work shows that the autocorrelation structure plays a very important role in a network—especially in terms of how it varies from user to user—because the difference in channel autocorrelation structures of different
users creates opportunities for interference alignment. For example, consider a MISO BC where all channels are i.i.d. Rayleigh fading across users and antennas, with perfect CSIR and no CSIT. On the one extreme we have the case where all users follow the same autocorrelation model. In this case all receivers are statistically equivalent, and it is well known that the DoF of this channel collapses to unity [1]. In fact time division is capacity optimal at any SNR and the capacity does not depend on the correlation structure at all. Now, contrast this with a setting where the users have different autocorrelation structures, e.g. block fading where one user has a larger coherence time and the other user has a larger coherence bandwidth. In this paper we find that based on just this statistical knowledge, without any knowledge of the values of the channel coefficients, the transmitters are able to design their signals such that interference is aligned, so much so that even the outer bounds considered unachievable in the benchmark scenarios outlined above, are achievable. Moreover, the coding scheme proposed in this paper to achieve this alignment with no CSIT has several desirable features as highlighted below.

- No knowledge of the values of channel coefficients is required at the transmitters. This in contrast to the infinite precision channel knowledge needed at transmitters to achieve the DoF outer bounds, for almost all interference alignment schemes proposed so far.
- The encoding is a simple linear beamforming scheme. This is in contrast to sophisticated lattice alignment schemes used in [7], [8], [9], [10], [11].
- The size of supersymbols and the number of independently encoded streams over which beamforming takes place is small. This is in contrast to the long symbol extensions needed for the alignment scheme in [12].

II. CHANNEL MODEL - STAGGERED BLOCK FADING

Our purpose in this paper is not to exhaustively consider all settings, but rather to highlight the possibility of blind interference alignment through simple examples that illustrate the key concept. For our analysis we will assume a staggered block fading model with a coherence interval \( T = 2 \). In this model each users’ channel state is constant for 2 channel uses and then switches to a different generic (i.e. drawn from a continuous distribution but not necessarily independent) value. What makes the model staggered is that the coherence blocks of the users are not aligned. Unless explicitly mentioned otherwise, the channel states are assumed to be known perfectly to the receivers and not known to the transmitters.

A. Physical Justification

Before proceeding further, we discuss the physical justification for the staggered block fading model. While the staggered block fading model appears to be artificial, we explain below how it corresponds to certain natural settings. Specifically, we rely on two kinds of supersymbol structures in this work.

The first is a 2-symbol block where the channel of one user changes while the channel of the other user stays constant. This is shown in Fig. 1. The same supersymbol structure can be seen to arise from either the artificial staggered block fading model assumed in this paper (shown at the bottom of Fig. 1) or the much more natural setting (shown at the top of Fig. 1) where user 2 has a much longer coherence time than user 1. Indeed, in a geographically distributed network, users in more mobile local environments may have smaller channel coherence times than other users who are in relatively stationary local environments. Through an interleaving of symbols this difference in coherence times can be converted into the 2-symbol supersymbol structure needed in this paper.

The other supersymbol structure we use in this work is a 3-symbol block where the channel of one user changes after the first symbol while the channel of the other user changes after the second symbol. Fig. 2 shows how this supersymbol arises out of the staggered block fading model. However, this supersymbol structure also arises in the much more natural setting where – User 1 has a much larger coherence time than user 2, while user 2 has a much larger coherence bandwidth than user 1. Since coherence time is determined by mobility and coherence bandwidth is determined by delay spread, the two assumptions are not mutually exclusive. Now consider two time slots \( T_1, T_2 \) that are well within user 1’s channel coherence time so that his channel does not vary in time across these time slots, but are far enough apart to exceed user 2’s channel coherence time so that user 2’s channel varies in time
across these time slots. Further, consider these time slots over two frequency slots $F_1, F_2$ that are well within user 2’s channel coherence bandwidth but exceed user 1’s channel coherence bandwidth, so that user 1’s channel changes in the frequency dimension but user 2’s channel remains unchanged across these two frequency slots. Now consider 3 transmissions over time-frequency slots $(T_1, F_1), (T_1, F_2), (T_2, F_2)$. Clearly, now we have three channel uses where user 1’s channel changes after the first slot but remains fixed over the second and third slots, while user 2’s channel remains fixed over the first two slots and changes in the third slot. This gives rise to the 3-symbol supersymbol shown in Fig. 2.

Our goal in the next few sections is to consider each of the representative problems highlighted in the introduction and to show, in each case that, contrary to the conventional wisdom formalized by the pessimistic conjectures, the degrees of freedom do not collapse to unity due to channel uncertainty at the transmitters. In fact, the achievable degrees of freedom in each of the cases presented below coincide with the outer bounds found for similar settings in prior work.

We expect the reader to be very familiar with the Shannon-theoretic definitions of achievable rates, capacity, degrees of freedom etc. which are used in this work only in the standard sense. Therefore, we will proceed directly to the technical content.

III. MISO BC WITH NO CSIT FOR ONE USER

Consider the MISO BC, as shown in Figure 3, with two antennas at the transmitter and two users with single antenna each, under a staggered block fading model with coherence time $T = 2$ and generic channel states. The channel state of user 1, $h[1] = [h_1^{[1]} h_2^{[1]}]$, is known perfectly to the transmitter while the channel state of user 2, defined similarly, is unknown to the transmitter. Perfect CSIR is assumed at both receivers. We do not distinguish between real or complex settings here, while the channel state of user 2, defined similarly, is unknown across these time slots. Further, consider these time slots over two frequency slots $F_1, F_2$ that are well within user 2’s channel coherence bandwidth but exceed user 1’s channel coherence bandwidth, so that user 1’s channel changes in the frequency dimension but user 2’s channel remains unchanged across these two frequency slots. Now consider 3 transmissions over time-frequency slots $(T_1, F_1), (T_1, F_2), (T_2, F_2)$. Clearly, now we have three channel uses where user 1’s channel changes after the first slot but remains fixed over the second and third slots, while user 2’s channel remains fixed over the first two slots and changes in the third slot. This gives rise to the 3-symbol supersymbol shown in Fig. 2.

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**Theorem 1:** For the 2 user MISO BC as defined in this section a total of $\frac{3}{2}$ DoF are achievable, almost surely. Note that $\frac{3}{2}$ is the DoF outer bound found for the corresponding scenario in the finite state compound network setting in [4]. A constructive proof is presented next.

**Proof:** We define a supersymbol as comprising of two symbols in the manner shown in Figure 3. Thus, user 1’s channel state changes over the supersymbol while user 2’s channel state maintains a fixed value over a supersymbol.

The received signals of the two users are expressed as follows. To keep the equations contained within the column space, we occasionally omit the additive white Gaussian noise terms. See full paper [13] for detailed expressions.

$$
\begin{bmatrix}
y^{[1]}(1) \\
y^{[1]}(2) \\
y^{[2]}(1) \\
y^{[2]}(2)
\end{bmatrix} =
\begin{bmatrix}
h_1^{[1]}(1) & h_2^{[1]}(1) & 0 & 0 \\
0 & 0 & h_1^{[2]}(2) & h_2^{[2]}(2) \\
h_1^{[2]}(1) & h_2^{[2]}(1) & 0 & 0 \\
0 & 0 & h_1^{[1]}(2) & h_2^{[1]}(2)
\end{bmatrix}
\begin{bmatrix}
x_1^{(1)} \\
x_2^{(1)} \\
x_1^{(2)} \\
x_2^{(2)}
\end{bmatrix}
$$

$$
\begin{bmatrix}
y^{[2]}(1) \\
y^{[2]}(2)
\end{bmatrix} =
\begin{bmatrix}
h_1^{[2]}(1) & h_2^{[2]}(1) & 0 & 0 \\
0 & 0 & h_1^{[1]}(2) & h_2^{[1]}(2)
\end{bmatrix}
\begin{bmatrix}
x_1^{(1)} \\
x_2^{(1)} \\
x_1^{(2)} \\
x_2^{(2)}
\end{bmatrix}
$$

The symbol $y$ is used for received signals, $h$ for channel coefficients, $x$ for input signals. The superscript within square parentheses indicates the user index, the subscript is the antenna index and the index within the round parentheses is the time index within the supersymbol. In compact notation we write equivalently (note the AWGN terms $Z[k]$ that were previously omitted due to lack of space):

$$
\begin{align}
Y^{[1]} &= H^{[1]}X + Z^{[1]} \\
Y^{[2]} &= H^{[2]}X + Z^{[2]}
\end{align}
$$

Our goal is to send 2 DoF to user 1 and 1 DoF to user 2, for a total of 3 DoF. Since this is accomplished over two symbols, the normalized total DoF value is $\frac{3}{2}$. The achievable scheme is based on simple linear beamforming. The transmitted signal is constructed as:

$$
X =
\begin{bmatrix}
1 & 0 \\
0 & 1 \\
1 & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
u_1^{[1]} \\
u_2^{[1]}
\end{bmatrix} +
\begin{bmatrix}
h_2^{[1]}(1) \\
h_1^{[2]}(1)
\end{bmatrix}
\begin{bmatrix}
u_1^{[2]} \\
u_2^{[2]}
\end{bmatrix}
$$

The achievable scheme is constructed as:

$$
\begin{bmatrix}
y^{[1]}(1) \\
y^{[1]}(2) \\
y^{[2]}(1) \\
y^{[2]}(2)
\end{bmatrix} =
\begin{bmatrix}
h_1^{[1]}(1) & h_2^{[1]}(1) & 0 & 0 \\
0 & 0 & h_1^{[2]}(2) & h_2^{[2]}(2) \\
h_1^{[2]}(1) & h_2^{[2]}(1) & 0 & 0 \\
0 & 0 & h_1^{[1]}(2) & h_2^{[1]}(2)
\end{bmatrix}
\begin{bmatrix}
u_1^{[1]} \\
u_2^{[1]} \\
u_1^{[2]} \\
u_2^{[2]}
\end{bmatrix} +
\begin{bmatrix}
z_1^{[1]}(1) \\
z_1^{[1]}(2)
\end{bmatrix}
$$

Thus user 1 sees no interference from user 2, and accesses a full rank $2 \times 2$ MIMO channel through which he is able to achieve 2 DoF. Now consider the received signal of user 2.

$$
\begin{bmatrix}
y^{[1]}(1) \\
y^{[1]}(2) \\
y^{[2]}(1) \\
y^{[2]}(2)
\end{bmatrix} =
\begin{bmatrix}
h_1^{[2]}(1) & h_2^{[2]}(1) & 0 & 0 \\
h_1^{[1]}(2) & h_2^{[1]}(2) & 0 & 0 \\
h_1^{[1]}(1) & h_2^{[1]}(1) & 0 & 0 \\
h_1^{[2]}(2) & h_2^{[2]}(2) & 0 & 0
\end{bmatrix}
\begin{bmatrix}
u_1^{[1]} \\
u_2^{[1]} \\
u_1^{[2]} \\
u_2^{[2]}
\end{bmatrix} +
\begin{bmatrix}
z_1^{[2]}(1) \\
z_1^{[2]}(2)
\end{bmatrix}
$$

where $\alpha = h_1^{[2]}(1)h_2^{[2]}(1) - h_1^{[1]}(1)h_2^{[1]}(1) \neq 0$, almost surely.

Thus, the two streams carrying user 1’s signal align into one dimension at user 2’s receiver, leaving the remaining dimension to achieve 1 DoF for his desired signal. In this case, a simple projection of the received signal along the vector.
[1 − 1] provides the interference free signal needed to achieve the desired 1 DoF.
\[ y_1^{[2]} = y_1^{[2]}(1) - y_2^{[2]}(2) = \alpha u_1^{[2]} + z_1^{[2]}(1) - z_2^{[2]}(2) \]
Thus, user 1 achieves 2 DoF and user 2 achieves 1 DoF as desired. Note that the transmitter does not know user 2’s channel coefficients at all. Moreover, even for user 1, whose channel is known to the transmitter perfectly, note that only the knowledge of the channel coefficient values over the first coherence interval is used. In other words, the transmitter does not need to know even user 1’s channel coefficients over the second coherence interval.

IV. MISO BC WITH NO CSIT FOR BOTH USERS

Consider the same 2 user MISO BC channel as in the previous section, with one exception — now we assume that the channel states of both users are unknown to the transmitter.

The main result for this model is stated in the following theorem.

**Theorem 2:** For the 2 user MISO BC as defined in this section a total of \( \frac{4}{3} \) DoF are achievable, almost surely. Note that \( \frac{4}{3} \) is the DoF outer bound found for the corresponding scenario in the finite state compound network setting in [4]. A constructive proof is presented next.

**Proof:** While our coherence model is the same as the previous section, i.e. staggered block fading with coherence time \( T = 2 \) for both users, in this case we define the supersymbol as comprised of three symbols. As shown in Figure 4 the 3 symbols are chosen such that the channel state of user 1 changes after the first symbol and remains fixed for the last 2 symbols, while the channel state of user 2 is fixed for the first 2 symbols and changes in the last symbol. The received signals over one supersymbol defined in this manner, are expressed in equations (4-5).

Our goal is to achieve two DoF for each user over this supersymbol consisting of 3 symbols, to achieve an overall normalized DoF equal to \( \frac{4}{3} \), consistent with the outer bounds in [3], [4] for similar settings. To accomplish this objective, we construct the input vector \( \mathbf{X} \) as follows.

\[
\mathbf{X} = \begin{bmatrix}
1 & 0 \\
0 & 1 \\
1 & 0 \\
0 & 1 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
u_1^{[1]} \\
u_2^{[1]}
\end{bmatrix}
+ \begin{bmatrix}
0 & 0 \\
1 & 0 \\
0 & 1 \\
1 & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
u_1^{[2]} \\
u_2^{[2]}
\end{bmatrix}
\]

where \( u_1^{[k]} \) and \( u_2^{[k]} \) are the independently encoded scalar Gaussian codeword symbols for user \( k = 1, 2 \) respectively, each carrying one DoF. Note that the beamforming vectors do not depend on the values of channel coefficients. With this scheme the signal at receiver 1 is shown in equation (7).

Thus in the 3 dimensional received signal space of receiver 1, the interference from user 2’s signal aligns within 1 dimension, while the desired signals, carrying 2 DoF, occupy two linear independent dimensions. It remains to check that the two desired signal dimensions do not overlap with the one interference dimension. The details of this calculation are presented in the full paper [13]. By symmetry the same arguments can be used to show that user 2 achieves 2 DoF as well, so that the desired \( \frac{4}{3} \) (normalized) DoF are achieved.

V. THE X CHANNEL

The X channel that we consider in this section, consists of two transmitters and two receivers, each equipped with a single antenna and 4 independent messages, one for each transmitter-receiver pair. Note that if we separate the two antennas at the transmitter of the MISO BC considered in the previous section to form two separate transmitters, i.e., if we do not allow joint processing of signals or common knowledge of messages at the two transmit antennas of the MISO BC, then we obtain the X channel. The remaining assumptions – no CSIT, perfect CSIR – and staggered block fading with coherence time \( T = 2 \), are the same as the MISO BC in the previous section. The channel input output relationships are also the same as the previous section. The DoF result for the X channel is stated in the following theorem.

**Theorem 3:** For the X channel as defined in this section a total of \( \frac{4}{3} \) DoF are achievable, almost surely.

Note that \( \frac{4}{3} \) is the DoF outer bound found even with perfect CSIT. Therefore it is also an outer bound with no CSIT.

**Proof:** The proof of Theorem 3 follows trivially from the proof of Theorem 2. Note that no cooperation between the two transmit antennas is needed for the achievable scheme of the 2 user MISO BC with no CSIT described in the previous section. Thus, the same achievable scheme can be applied directly for the 2 user X channel as well. In both cases \( \frac{4}{3} \) DoF are achieved. Note that this insight is consistent with the result from the finite state compound setting found in [11], where also it is found that with enough channel uncertainty, the MISO BC devolves into the X channel as the DoF benefits of joint processing across transmit antennas are lost.
Transmitter 1 maximum DoF achievable by user 2 simultaneously as user fading block structure at Receiver 1 is of significance. At Receiver 1 — Receiver 2 has enough antennas to separate Receiver 2, the channels may have any coherence time, and the temporal correlation is seen by Receiver 2. As seen by Receiver 2, the channels may have any coherence time, and the fading blocks may be aligned or staggered. The key to this problem is the possibility of interference alignment only at Receiver 1 — Receiver 2 has enough antennas to separate all signal and interference — it is not surprising that only the fading block structure at Receiver 1 is of significance.

The question posed in [5] is the following — what is the maximum DoF achievable by user 2 simultaneously as user 1 achieves his maximum (one) DoF? The best outer bound found in [5] is $\frac{1}{2}$ but the best inner bound is only able to achieve 1 DoF for user 2.

The DoF result for this channel is presented in the following theorem.

Theorem 4: For the 2 user MIMO interference channel defined in this section, users 1 and 2 can simultaneously achieve 1 and $\frac{3}{2}$ DoF, respectively, almost surely. Note that this result also matches the outer bound found in [5].

The key to this achievability, as suggested in [5] is interference alignment at Receiver 1. A constructive proof follows next.

Proof: Our goal is for user 1 to achieve 2 DoF and for user 2 to achieve 3 DoF over this two symbol extension, which corresponds to normalized values of 1 and $\frac{3}{2}$, respectively. Interference alignment is needed to accomplish this objective along with all previous examples we rely on linear beamforming techniques.

For this example, we define a supersymbol as comprised of two symbols, which leads to the structure shown in Figure 6. Within a supersymbol, the signal at Receiver 1 is expressed as shown in equation (9). Equivalently, in compact notation

$$Y^{[1]} = H^{[12]}X^{[2]} + H^{[11]}X^{[1]} + Z^{[1]}$$

The key to the alignment is to design user 2’s signal as follows.

$$X^{[2]} = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1 \\
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}$$

VI. THE 2 USER MIMO INTERFERENCE CHANNEL

Fig. 6. MIMO Interference Channel and the Supersymbol Structure

This example is based on the open problem in [5]. We have a two user MIMO interference channel with 1 and 3 antennas at the transmitters and 2 and 4 antennas at their corresponding receivers, respectively. As in all preceding sections we assume no CSIT, perfect CSIR, and a staggered block fading model with coherence time $T = 2$, with one subtle difference. The coherence times are staggered as seen by the receiver, rather than the transmitter, i.e., from Receiver 1’s perspective, the block fading channels from transmitter 1 and 2 are staggered. For the problem we are interested in, it does not matter what temporal correlation is seen by Receiver 2. As seen by Receiver 2, the channels may have any coherence time, and the fading blocks may be aligned or staggered. Since the key to this problem is the possibility of interference alignment only at Receiver 1 — Receiver 2 has enough antennas to separate all signal and interference — it is not surprising that only the fading block structure at Receiver 1 is of significance.

The question posed in [5] is the following — what is the maximum DoF achievable by user 2 simultaneously as user
where \( u_1^{[1]} \) is the \( i^{th} \) independently coded scalar stream sent from transmitter 2. Each stream carries 1 DoF. With this coding scheme, the signal at Receiver 1 is shown in equation (12).

The interference alignment is manifested in the rank deficiency of the \( 4 \times 3 \) effective channel matrix between transmitter 1 and receiver 2. Note that the first and third rows are identical, as are the second and fourth rows. Thus this matrix has rank only 2. Equivalently, the interference space seen by Receiver 1 is spanned by the first two columns of this matrix. In a 4 dimensional received space at Receiver 1, since interference spans only two dimensions, the remaining 2 dimensions are available to achieve its desired 2 DoF. We must ensure that the desired signals arrive along linearly independent directions from the interference. The details of this calculation are presented in the full paper [13]. The achievability of user 2's three DoF is straightforward, because with 4 receive antennas, receiver 2 is able to invert the channel from both transmitters simultaneously, which allows it to separate the two users' signals, regardless of the coherence times.

VII. CONCLUSION

The main contribution of this work is the idea that channel autocorrelation structure can be exploited to achieve interference alignment, even when the transmitter has no information about the precise values taken by the channel coefficients, which may be drawn from a continuum of values. The result is surprising because conventional wisdom, formalized in various conjectures mentioned in the introduction, holds that no multiplexing of signals is possible in the MISO broadcast channel without the knowledge of channel coefficients at the transmitter. Through simple examples we show how statistical knowledge of channel autocorrelation structure creates the possibility of interference alignment. The results open the door to further investigations of blind signal multiplexing schemes under much more elaborate channel autocorrelation models.

REFERENCES