Experimental Evaluation of Interference Alignment for Broadband WLAN Systems

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Abstract

In this paper we present an experimental study on the performance of spatial Interference Alignment (IA) in indoor wireless local area network scenarios that use Orthogonal Frequency Division Multiplexing (OFDM) according to the physical-layer specifications of the IEEE 802.11a standard. Experiments have been carried out using a wireless network testbed made up of six nodes equipped with Multiple-Input Multiple-Output (MIMO) radio interfaces. This setup allows the recreation of a 3-user MIMO interference channel. We have implemented different IA decoding schemes that operate either before or after the fast Fourier transform block, and that can be designed according to different criteria (e.g. zero-forcing or MaxSINR). For all these schemes, IA has been experimentally evaluated analyzing practical issues such as the number of OFDM training symbols used for channel state information estimation, the feedback time or the collinearity between the signal and the interference subspaces. We also evaluated the performance of IA in terms of average throughput in comparison to different time-division multiple access transmission schemes. Our results indicate that spatial IA performs satisfactorily in practical indoor scenarios in which wireless channels often exhibit relatively large coherence times.

Index Terms

Interference alignment, WLAN systems, OFDM, interference channel, MIMO testbed.

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I. INTRODUCTION

Interference management is a key issue in the design of wireless systems. When several users transmit over the same wireless resources, orthogonal access techniques such as Frequency-Division or Time-Division Multiple Access (FDMA and TDMA, respectively) are traditionally applied to avoid interference among them. In orthogonal multiple access schemes the system bandwidth and/or time resources are divided among users and the individual data rates decrease with the network size. Interference Alignment (IA) has been recently proposed as an alternative interference management method that confines interference signals within half of the signal space at each receiver, hence allowing each user to transmit over the interference-free subspace [1].

Although a large number of theoretical results have shown IA to be a very promising technique, there is still lack of experimental Over-The-Air (OTA) results evaluating its actual performance in real wireless scenarios. This scarcity of experimental results is mainly due to the high costs and effort required to conduct OTA measurements in IA scenarios. For example, to evaluate the practical performance of spatial IA methods, at least six nodes (three transmitters and three receivers) with two antennas each are needed to recreate the simplest Multiple-Input Multiple-Output (MIMO) interference channel. To put our work in context, in the following we briefly review some previous experimental works carried out to evaluate the performance of IA techniques.

A. Previous Experimental Work on IA

The first work that tackled a real-world implementation of IA was presented in [2]. This work considered the implementation of IA techniques combined with cancellation methods over a wireless network testbed comprised of 20 Universal Software Radio Peripheral (USRP) nodes equipped with two antennas each. The implemented technique does not correspond to pure IA because it requires certain amount of cooperation among access points in such a way that all the network interference can be nulled out. Several practical issues were addressed in this work, showing that IA is unaffected by frequency offsets or by the use of different modulations. Imperfect time synchronization, however, affects IA but this issue can be overcome by performing IA at the sample level, i.e. before demodulation and synchronization takes place. Finally, this work posed the interesting question of how to perform sample level alignment in Orthogonal Frequency-Division Multiplexing (OFDM) systems over frequency-selective channels.
IA was further evaluated in [3], where the authors conducted an experimental study over measured indoor and outdoor MIMO-OFDM channels. By modifying the distance among network nodes and antennas, they characterized the effect of spatial correlation and subspace distance, and showed that IA is able to achieve the maximum available Degrees of Freedom (DoF) over realistic channels. However, although the channels were obtained from measurements, no OTA transmissions of aligned signals were actually measured. Therefore, many practical issues such as time/frequency synchronization, imperfect Channel State Information (CSI), and dirty Radio-Frequency (RF) effects such as phase noise, non-linearities, IQ imbalance, or clipping and quantization in the Digital-to-Analog and Analog-to-Digital converter (DAC/ADC) were not taken into account. In [4], different IA schemes are evaluated in the 3-user Single-Input Single-Output (SISO) interference channel using frequency extensions. As in [3], the results in [4] were obtained using urban macro-cell measured channels but without actually transmitting aligned signals.

In [5]–[7] the first aligned real transmissions were conducted to evaluate spatial-domain IA in a 3-user interference channel, thus providing more precise results about the actual performance of IA in realistic scenarios. In [5], the feasibility of spatial IA over indoor channels and single-carrier transmissions was studied, identifying also some practical issues that affect IA performance already pointed out in [2] and [3]. In addition, CSI errors were also described as an important issue which was further analyzed in [6]. The 3-user MIMO interference channel with OFDM transmissions is also studied in [7], along with coordinated multi-point transmission methods. In this work RF impairments are identified as an important source of mismatch between practical and theoretical performance of IA. However, the work in [7] focuses on verifying simulation models and no analysis of the inherent limitations of IA is performed.

More recently, the work in [8] described two real-time implementations of IA in a 3-user MIMO-OFDM scenario showing that the computational power of current embedded platforms makes software-defined implementations of IA feasible. Another approach was followed by the authors of [9], where blind IA was implemented with the aim of avoiding the intense global CSI requirements of spatial-domain IA.
B. Summary of Key Practical Issues Arising when Implementing IA Techniques

Despite the promising theoretical results on IA, several practical impairments come up in real scenarios that might degrade the overall system performance. In the following we will summarize the main issues affecting practical IA transmissions:

- IA is usually studied assuming perfect CSI is available at every node of the network, which never happens in practice. Moreover, since the computation of the precoders and decoders involves all the pairwise interference channels, even a slight time variation of a single channel would ideally result in a change of all IA precoders and decoders. In practice, this may cause two problems. First, the presence of channel estimation errors or time variations makes it impossible to perfectly suppress interference [5], [6]. Second, nodes must exchange its local CSI to compute the IA solution and this introduces additional overhead and delay between channel estimation and data transmission. During this elapsed time, the channel may vary, hence out-dating the CSI estimates especially when there are moving scatterers in the surroundings. Besides CSI estimation errors, dirty RF effects [10] are also responsible for a great portion of the gap between ideal and practical setups. Major contributors to distortion in OFDM systems are nonlinear amplifiers, clipping, ADC effects and phase-noise. Some of these effects have been modeled in [7].

- Even under the unrealistic assumption that perfect CSI is available, in order to null interfer-
ences once they are aligned, the received signal is projected into the subspace orthogonal to the interference. In this process, part of the energy of the desired signal is lost due to spatial collinearity between signal and interference subspaces. In the presence of high spatial collinearity, the desired signal power is severely reduced. To overcome this problem, recent works have suggested the use of antenna switching strategies [11], [12].

- In theoretical works it is also assumed that the IA precoders and decoders operate at symbol-level, i.e. after frame detection and time/frequency synchronization tasks have been successfully carried out. In practical systems, however, detection and synchronization have to be performed at the sample-level, right after the RF demodulation stages and hence they are affected by interference. As a consequence, depending on the level of coordination among the users participating in the alignment, two different scenarios arise for the application of IA techniques under OFDM packet-based transmissions. In the first scenario, which we
denote as synchronous, all users transmit their packets synchronously using the obtained IA precoders. In this case, each receiver can use conventional frame detectors and synchronizers and, consequently, the IA decoder can be applied after the Fast Fourier Transform (FFT) block on a carrier-by-carrier basis. In a second scenario, denoted asynchronous, each user transmits the IA precoded packets at arbitrary time instants. In this situation, if the delays among the received packets are larger than the cyclic prefix of the OFDM signal, conventional synchronizers fail to work due to the high level of interference at the input of the receiver. In this case, the IA decoder must be applied at sample-level before the FFT (i.e. in the time domain) to get rid of the interference before synchronization takes place. In other words, IA decoding in asynchronous scenarios must be the first task in the RX signal processing chain. In this paper, we have implemented both synchronous (post-FFT IA decoding) and asynchronous (pre-FFT IA decoding) schemes, and their pros and cons have been analyzed.

C. Contributions

In this paper, we extend our work in [5], [6] to broadband OFDM wireless transmissions. Specifically, we use the IEEE 802.11a Wireless Local Area Network (WLAN) physical-layer standard [13] as a benchmark to evaluate the performance of spatial IA in an illustrative indoor scenario. The measurement setup can be thought of as an indoor WLAN system in which three access points —with two antennas each— communicate simultaneously over the same frequency (channel) with three static devices (e.g. laptops), also equipped with two antennas each. This is opposed to conventional WLAN systems that would assign different channels to each communication link (i.e. FDMA). The goal of this paper is to evaluate experimentally several spatial IA schemes in indoor WLAN applications, identifying and analyzing the main issues that degrade their performance in broadband OFDM transmissions, and comparing their end-to-end measurements with those of TDMA-based schemes. In this work, we only consider systems in which each user transmits a single stream of data to its intended receiver. More specifically, the main contributions of this work are the following:

- With respect to our previous work in [5] and [6], in which only single-carrier transmissions over flat-fading channels were considered, here the experimental work focuses on OFDM transmissions based on the 802.11a standard. Broadband transmissions pose new difficulties
but also permit the implementation of more complex IA schemes. Additionally, we have improved our measurement methodology by reducing the time elapsed between channel estimation and IA transmission from 5 seconds in [5] and [6] to less than 1 second\(^1\).

- As discussed previously, we consider and compare the performances of spatial IA decoding schemes that operate either in time domain (pre-FFT) [14], [15], or in a more conventional per-subcarrier basis (post-FFT). For pre-FFT schemes the impact of the decoder length on the final performance has been thoughtfully investigated. Furthermore, we have implemented and evaluated with OTA measurements the actual performance of IA and MaxSINR schemes [16] for post-FFT schemes.

- Additionally, we analyze the main issues that might affect IA performance in practice such as the number of training symbols used for channel estimation, the feedback time elapsed between training and payload transmissions in relation to the channel coherence time or the collinearity between signal and interference subspaces.

- Finally, we present Error Vector Magnitude (EVM) and Bit Error Rate (BER) measurement-based results for different data rates. We also compare them to those obtained when TDMA-based transmissions are employed. The comparison includes SISO and MIMO systems transmitting over the dominant mode of the MIMO channel (referred to as Dominant Eigenmode Transmission or DET [17]).

The rest of the paper is organized as follows. Section II describes spatial IA in a 3-user 2 × 2 MIMO-OFDM channel considering in particular post-FFT and pre-FFT IA decoding schemes. In Section III, the wireless network testbed utilized for the measurements is briefly described. Measurement set-up and methodology are both explained in Section IV and Section V, respectively. The obtained results are presented and discussed in Section VI. Finally, Section VII concludes the paper.

II. SPATIAL INTERFERENCE ALIGNMENT

IA is able to exploit the multiple time, frequency and spatial dimensions available in a wireless system. However, when aligning over the frequency or time domain, the number of dimensions

\(^1\)Note that the low mobility of the chosen scenario facilitates CSI estimation and, as a consequence, the implementation of IA. This is in contrast to cellular networks where the high mobility among terminals demands for fast CSI updates
Fig. 1. Scheme of the $(2 \times 2, 1)^3$ interference network. Direct channel links are shown in black solid lines whereas interference channels are plotted in gray dashed lines.

to achieve the maximum DoF promised by IA grows exponentially with the number of users. The number of required dimensions, on the contrary, is considerably less when aligning interference over the spatial dimension [18] which facilitates its practical implementation. For instance, for a 3-user channel, $3n + 1$ symbols can be transmitted using $2n + 1$ extensions, where $n$ is an integer, yielding a total of $(3n + 1)/(2n + 1)$ DoF [1]. This would require a theoretically infinite number of frequency domain extensions to achieve the maximum number of DoF in the 3-user interference channel, while spatial domain IA is able to achieve the maximum number of 3 DoF with constant channels and two antennas. Another advantage of spatial IA is that it can be readily applied while being compliant with any OFDM signalling format such as the 802.11a WLAN standard, as shown in this paper. On the contrary, any alignment scheme over time or frequency would require major changes on the physical layer format. Further, we focus on the $2 \times 2$ MIMO 3-user interference channel because it can be easily recreated with the multiuser MIMO testbed described in Section III.

This section reviews the concept of IA in the spatial domain and discusses the application and design of post-FFT and pre-FFT IA decoders. Let us note, however, that in all experiments the IA precoders were always applied at the transmitters before the IFFT on a per-subcarrier basis, whereas at the receivers the decoders are applied either in the time domain (pre-FFT) or in the frequency domain (post-FFT).
A. Interference Alignment with Post-FFT Decoding

Let us consider a 3-user MIMO interference channel comprised of three transmitter-receiver pairs (links) that interfere with each other as shown in Fig. 1. Each user is equipped with two antennas at both sides of the link and it sends a single stream of data. Following the convention introduced in [19], this interference network is denoted as \((2 \times 2, 1)^3\). Assuming a fully coordinated scenario in which all users transmit their OFDM symbols exactly at the same time instants, or when the possible delays among users can be accommodated by the Cyclic Prefix (CP), each receiver can use a conventional synchronizer and, consequently, the IA decoder can be applied after the FFT block on a carrier-by-carrier basis (see Fig. 2(a)).

Assuming that the CP is sufficiently long to accommodate the delay spread of the channel, the discrete-time signal \(y_i\) at the \(i\)-th receiver for a given subcarrier\(^2\) is the superposition of the signals transmitted by the three users, weighted by their respective channel matrices and affected by noise, i.e.

\[
y_i = H_{ii}x_i + \sum_{j \neq i} H_{ij}x_j + n_i, \tag{1}
\]

where \(x_i \in \mathbb{C}^{2 \times 1}\) is the signal transmitted by the \(i\)-th user, \(H_{ij}\) is the \(2 \times 2\) flat-fading MIMO channel from transmitter \(j\) to receiver \(i\), and \(n_i \in \mathbb{C}^{2 \times 1}\) is the additive noise at receiver \(i\).

Spatial IA uses a set of beamforming vectors (precoders) \(\{v_i \in \mathbb{C}^{2 \times 1}\}\) and interference-suppression vectors (decoders) \(\{u_i \in \mathbb{C}^{2 \times 1}\}\) that must satisfy the following zero-forcing conditions for all transmitter-receiver pairs \(i = 1, 2, 3\),

\[
\begin{cases}
    u_i^H H_{ii} v_i \neq 0 \\
    u_i^H H_{ij} v_j = 0, \quad \forall j \neq i.
\end{cases} \tag{2}
\]

There exists a three-step analytical procedure to obtain precoders and decoders for the \((2 \times 2, 1)^3\) case [1]:

1) The precoder for user 1, \(v_1\), is any eigenvector of the following \(2 \times 2\) matrix \(E\) (each eigenvector yields a different IA solution):

\[
E = (H_{31})^{-1} H_{32}(H_{12})^{-1} H_{13}(H_{23})^{-1} H_{21}. \tag{3}
\]

\(^{2}\)To not overload the notation unnecessarily, the index denoting the subcarrier is omitted in this section.
2) The precoders for users 2 and 3, $v_2$ and $v_3$, are respectively obtained as

$$v_2 = (H_{32})^{-1}H_{31}v_1,$$  \hspace{1cm} (4)

and

$$v_3 = (H_{23})^{-1}H_{21}v_1. \hspace{1cm} (5)$$

Since $E$ is a full-rank $2 \times 2$ matrix with probability one for generic MIMO channels, it has two eigenvectors that can be chosen as the precoder for the first user, hence yielding two distinct IA solutions. An interesting fact of the 3-user interference channel is that it induces a permutation structure which makes that starting the procedure described above with a different user leads to exactly the same set of IA solutions. In summary, there are only two different IA solutions per subcarrier.

3) Finally, the interference-suppression filters (decoders) are designed to lie in the orthogonal subspace of the received interference signal, i.e., the decoder of user 1 is the eigenvector of $[H_{12}v_2, H_{13}v_3]$ associated with the zero eigenvalue. The decoders for users 2 and 3 are obtained in an analogous way.

When zero-forcing IA linear precoders and decoders are applied at both sides of the link, the signal received by the $i$-th user is given by

$$z_i = u_i^H H_{ii} v_i s_i + \sum_{j \neq i} u_i^H H_{ij} v_j s_j + u_i^H n_i$$

$$= u_i^H H_{ii} v_i s_i + u_i^H n_i, \hspace{1cm} (6)$$

where $s_i$ is the transmitted signal corresponding to the $i$-th user. Notice that the signal from the $i$-th transmitter to the $i$-th receiver travels over the equivalent SISO channel $u_i^H H_{ii} v_i$. The interference terms are totally suppressed when projecting the received signal onto the subspace whose basis is $u_i$.

Similarly to channel equalization, zero-forcing IA suffers from noise amplification when MIMO channels are close to singular. Other approaches can be used to mitigate this limitation, and perform better in the medium and low Signal-to-Noise Ratio (SNR) regimes. One such example is the MaxSINR algorithm [16], which has also been adopted in the measurements of this work for comparison purposes.
B. Interference Alignment with Pre-FFT Decoding

In asynchronous scenarios, the existence of symbol timing offsets between the desired and the interfering OFDM symbols impairs the synchronization procedure. Therefore, interference must be eliminated (or at least sufficiently reduced) before the synchronization step. To this end, pre-FFT IA decoders must be applied at the receiver side. Let $v_j[n] \in \mathbb{C}^{2 \times 1}$ be the impulse response of the linear precoder of transmitter $j$ and let $u_i[n] \in \mathbb{C}^{2 \times 1}$ be the impulse response of the pre-FFT linear decoder of receiver $i$. The output signal at receiver $i$ is given by

$$z_i[n] = u_i^H[-n] * H_{ii}[n] * v_i[n] * s_i[n - \mu_{ii}] + \sum_{j \neq i} u_i^H[-n] * H_{ij}[n] * v_j[n] * s_j[n - \mu_{ij}] + u_i^H[-n] * n_i[n],$$

where $s_j[n]$ is the discrete-time OFDM signal transmitted by user $j$, $H_{ij}[n]$ is the matrix impulse response of the frequency-selective MIMO channel between transmitter $j$ and receiver $i$, and $*$ denotes convolution. The received signal at user $i$ is also affected by an additive, spatially and temporally-white Gaussian noise $n_i[n] \sim \mathcal{N}(0, \sigma^2 I)$. Notice that we are now considering an asynchronous wireless system and, for this reason, a delay $\mu_{ij}$ between transmitter $j$ and receiver $i$ is explicitly introduced in the signal model given by Eq. (7).

The design of pre-FFT IA precoders and decoders is a more challenging problem than that of post-FFT ones [14]. Note that for the interference to be mitigated before time synchronization,
only pre-FFT decoders are strictly necessary, while precoders can be applied either in the time or in the frequency domain. Therefore, and for simplicity, we will consider that precoders operate in the frequency domain whereas the decoders are applied in the time domain (pre-FFT). A schematic of the pre-FFT IA decoding scheme is shown in Fig. 2(b). Using this approach, the signal at the input of the synchronization block is (ideally) free of interference. In the ensuing lines we propose a simple method to compute the pre-FFT decoders that mitigate the interference before time synchronization. Nevertheless, the design of pre-FFT IA algorithms is not the aim of this work and the proposed technique is just a simple method that allows us to assess the performance degradation of pre-FFT decoding with respect to its post-FFT counterpart. Assuming again perfect CSI knowledge, we propose the following method for computing the pre-FFT IA decoders:

- First, the IA precoders and decoders are computed on a per-subcarrier basis applying the closed-form solution described in Section II-A.
- Next, a $N_{\text{FFT}}$-point IFFT is applied to the set of post-FFT decoders in order to obtain their impulse response.
- Finally, the pre-FFT filters are truncated to a given length, $L$, so as to reduce the Inter-Symbol and Inter-Carrier Interference (ISI and ICI, respectively).
Note that the shorter the impulse response of the equivalent channel —consisting of the actual wireless channel convolved with the pre-FFT filters— the lower the ISI/ICI but the higher the residual Multi-User Interference (MUI), and vice versa. Thus, pre-FFT filtering involves a trade-off between both sources of interference \[14\].

It is important to notice that the OFDM \((2 \times 2, 1)^3\) interference channel is being interpreted as \(N_{\text{FFT}}\) parallel single-carrier \((2 \times 2, 1)^3\) interference channels and that there exists two IA solutions per subcarrier. Thus, there is a total of \(2^{N_{\text{FFT}}}\) solutions in the OFDM case, as each of the \(N_{\text{FFT}}\) subcarriers can use a different solution without altering the alignment conditions. However, as we are interested in pre-FFT filters with an impulse response as short as possible (and, consequently, pre-FFT filters with a frequency response as smooth as possible in the frequency domain) it is important to select those solutions that provide the smoothest frequency response for the equivalent channel. Simulations have shown that there are only two sets of smooth solutions out of \(2^{N_{\text{FFT}}}\). Fig. 3 plots the magnitude of the frequency responses of one of the SISO equivalent channels obtained after calculating the IA precoders and decoders using one of these sets (empty circles) and the other one (full circles), respectively. Note that any other combination of this two sets leads to more abrupt changes in the frequency response. Obviously, this method is not necessarily optimal and other approaches such as those proposed in \[14\], \[15\] can be applied. Nevertheless, the design of such algorithms is beyond the scope of this paper.

### III. Multiuser MIMO Testbed

This section describes the MIMO wireless network testbed that has been used to assess in a realistic scenario the IA techniques presented in the previous section. Both transmit and receive testbed nodes (see Fig. 4) have a Quad Dual-Band front-end from Lyrtech, Inc. \[20\]. This RF front-end can use up to eight antennas that are connected to four direct-conversion transceivers by means of an antenna switch. Each transceiver is based on Maxim \[21\] MAX2829 chip, which supports both up and down conversion operations from either 2.4 to 2.5 GHz or 4.9 to 5.875 GHz. The front-end also incorporates a programmable variable attenuator to control the transmit power value. The attenuation ranges from 0 to 31 dB in 1 dB steps, while the maximum transmit power declared by Lyrtech is 25 dBm per transceiver.

The baseband hardware is also from Lyrtech. More specifically, each node is equipped with a VHS-DAC module and a VHS-ADC module, respectively, containing eight DACs and eight
ADCs. Each pair of DAC/ADC is connected to a single transceiver of the RF front-end and the signals are passed in I/Q format.

Both transmit and receive nodes employ real-time buffers that are dedicated to store the signals to be sent to the DACs as well as the signals acquired by the ADCs. The utilization of such buffers allows for the transmission and acquisition of signals in real-time, while the signal generation and processing is carried out off-line. Additionally, both baseband hardware and RF front-ends of the transmit nodes are synchronized in time and in frequency by means of two mechanisms:

- Transmit nodes implement a hardware trigger attached to the real-time buffers, and to the DACs and ADCs. When one of the nodes fires the trigger (usually the node corresponding to user 1) all buffers, DACs and ADCs receive the signal and start transmission and acquisition simultaneously (the timing between nodes is precise up to 2 samples, hence resulting in an error upper bound of ± 50 ns).

- The same common external 40 MHz reference oscillator is distributed to the DACs, ADCs and RF front-ends of all nodes, hence guaranteeing high-quality frequency synchronization.

The core component of each node is a host PC which allocates the baseband hardware, and configures and controls the baseband hardware as well as the RF front-end. Furthermore, the host PC provides remote control functionalities that allow the node to be externally controlled through socket connections. This flexible design has been found very useful for the integration...
of all nodes because each node can be transparently controlled without taking into account its particular technical differences. Also, it allows a so-called control PC with standard TCP/IP connections to use Matlab to interact with the whole testbed, which considerably enhances the development of multiuser experiments. Moreover, this control PC acts as a feedback channel to share CSI among nodes and carries out all signal processing operations. The web page of the COMONSENS project [22] contains detailed information about the technical features of the testbed.

**IV. MEASUREMENT SETUP**

Figure 5 shows the measurement scenario set up at the University of Cantabria to recreate a typical 3-user indoor interference channel. The access to the room was carefully controlled during the measurements to ensure that there were no moving objects in the surroundings. Additionally, we also checked that the frequency bands measured at 5 GHz were not in use by other wireless systems. All nodes were equipped with monopole antennas at both transmitter and receiver sides [23], [24], while the antenna spacing was set to approximately seven centimeters (forced by the separation of the antenna ports at the RF front-end).

We followed the IEEE 802.11a WLAN standard with the conventional frame structure and synchronization headers. Figure 6 shows the 802.11a physical-layer frame. The header comprises the Short Training Sequence (STS), the Long Training Sequence (LTS), and the Signal Field (SF).
The STS is used for frame detection, while the LTS is utilized for frequency offset correction and channel equalization. The SF contains information about the data rate and the frame length. During our experiments, the frame length remained constant and there was no rate adaptation. Therefore, we made no use of the information conveyed by the SF.

Each OFDM symbol contains 48 data symbols and 4 pilots, which were OFDM-modulated using a 64-point IFFT. The CP length is 16 samples (800 ns).

Figure 7 shows the general block diagram of a transmitter chain which differs from that of a conventional 802.11a in the IA precoding block and in the utilization of two transmit antennas. Both software and hardware elements perform the following steps:

- The source bits are encoded (convolutional code, scrambling and interleaving) and mapped to a BPSK, QPSK, 16-QAM, or 64-QAM constellation depending on the transmission rate according to the 802.11a standard (cf. [13]). The data frame length is set to a reasonable length for a WLAN frame (1250 bytes) which depending on the transmission rate translates into a different number of OFDM data symbols. In Table I the number of OFDM data
An IA precoder is applied to each subcarrier and two OFDM symbols (one for each antenna) are generated.

- At each antenna, the OFDM-sampled symbols are encapsulated into 802.11a standard-compliant frames and afterwards they are interpolated by a factor of two.
- The resulting signals are scaled so as to have a mean transmit power of 5 dBm per antenna, quantized according to the 12-bit resolution of the DACs, and finally stored in the real-time buffers available at the transmit nodes of the testbed.
- At this point, the transmitters are ready to receive the trigger signal and start transmitting simultaneously. Once the transmit nodes are triggered, the buffers containing the OFDM signal are read by the corresponding DACs at a rate of 40 Msample/s. Next, the analog signals are sent to the RF front-end in order to be transmitted at the center frequency of 5610 MHz. Simultaneously, the three receivers start to acquire the transmitted frames.

Figure 8 shows the hardware and software elements corresponding to a receiver implementing pre-FFT decoding. Notice the position of the IA decoder block, which is applied in time domain before synchronization takes place, as explained in Section II. The pre-FFT IA decoder generates one stream of data that is subsequently processed following a typical 802.11a receiver structure. The block diagram corresponding to post-FFT decoding is analogous to the transmitter shown in Fig. 7 and does not require an additional description.

The trigger signal is received by both transmitters and receivers simultaneously. When triggered, the receive nodes carry out the following operations:

- The RF front-end down-converts the signals received by the selected antennas to the base-
band, generating the corresponding I and Q analog signals.

- All I and Q signals (four in total) are then digitized by the ADCs at a sample rate of 40 Msample/s and they are stored in the real-time buffers.
- The signals are properly scaled according to the 12 bits ADC resolution. Notice that this factor is constant during the course of the whole measurement, thus not affecting the properties of the wireless channel.
- (Only for pre-FFT decoding) The acquired signals are processed by the pre-FFT IA decoder which generates a single data stream to be subsequently processed by a standard 802.11a receiver.
- Frame detection and time synchronization takes place.
- The frame is properly disassembled and the OFDM symbols are parallelized and synchronized in frequency.
- The 64-point FFT is applied. Only once for pre-FFT decoded frames and twice for post-FFT decoded frames.
- (Only for post-FFT decoding) Frequency-domain symbols are processed by the post-FFT IA decoder which generates a single data stream for the next processing blocks.
- The next step is least squares channel estimation and zero-forcing equalization.
- Finally, a symbol-by-symbol hard decision decoder is performed followed by a channel decoder which outputs the estimated transmitted bits.

V. MEASUREMENT METHODOLOGY

Success in the experimental evaluation of wireless communication systems relies mainly on the measurement methodology utilized, which depends on the scenario and the methods to be assessed. Given the complexity of the setup (see Fig. 1) the correct design of the measurement methodology is even more critical. In order to perform a fair comparison, it is necessary that the measurement methodology supports the assessment of several figures of merit, with and without interference, while guaranteeing that in both cases the signals experience the same channel realization. The methodology should also allow us to measure the amount of interference created by each user as well as the interference leakage.

The proposed measurement methodology consists of two stages that require two different signal transmissions through the testbed for the assessment of a single frame. The first one is
Fig. 9. Training frame for MIMO channel estimation. For each transmit antenna, we use a training sequence comprised of $M$ long training symbols.

The training stage because its objective is to obtain an estimate of the nine $2 \times 2$ MIMO channels of the 3-user interference channel. Once all channel estimates are available, the precoders and decoders of the different adopted schemes are computed and the second stage takes place. Aligned signals as well as signals from other schemes are sent—in a single transmission cycle—during this second stage in order to evaluate the performance of the IA approach and to compare such performance to that exhibited by other alternative approaches, all of them experiencing the same channel realization.

To conduct the training stage, we have introduced the training frame shown in Fig. 9 whose format differs from that of the IEEE 802.11a standard. In the following, we detail the measurement procedures performed at each stage.

- **Training stage**: all users sequentially transmit over each transmit antenna training frames comprised of $M$ OFDM long training symbols, while the three receivers are simultaneously acquiring. Once the receivers have acquired all the training signals, the nine pairwise MIMO channels are estimated and the precoders and decoders for each transmission scheme are computed.

- **Data transmission stage**: users transmit data frames comprised of $N$ OFDM symbols according to different transmission schemes. These schemes are as follows:
  1) **IA transmission**: all users transmit simultaneously, hence creating a 3-user interference channel. The IA precoders are applied at the transmitter, and both IA pre-FFT and post-FFT decoding are performed at the receiver. The pre-FFT decoder length is set

\[^3\text{Notice that the wireless channel can be estimated free of interference and in an independent way for each scheme transmitted in order to verify that all schemes experienced the same channel realization.}\]
to $L$ samples.

2) **Perfect IA transmission**: each user applies the same set of precoders and decoders of the previous scheme but transmitting in a sequential fashion. This transmission scheme enables us to measure the residual interference level created by each transmitter at each receiver. In other words, we are able to evaluate the impact of the residual interference by comparing the actual performance during the IA stage with that in the absence of interference.

3) **MaxSINR transmission**: all users transmit simultaneously, creating again a 3-user interference channel. The IA precoders and decoders are computed with the MaxSINR algorithm, as explained in Section I. The noise variance has been obtained according to Table I. This transmission scheme allows us to analyze the impact of collinearity between the signal and the interference subspaces, which may appear in IA and Perfect IA transmissions. While IA focuses exclusively in canceling the interference, without paying attention at the quality of the resulting equivalent channel, MaxSINR trades interference mitigation and desired signal enhancement.

4) **DET-TDMA transmission**: users transmit sequentially through the principal eigenvectors of the channel. This scheme is sometimes denoted as Dominant Eigenmode Transmission (DET) [17] and provides the best equivalent channel response. Therefore, it allows us to evaluate what the degradation of the desired links is when all available antennas are solely employed for interference mitigation.

5) **SISO-TDMA transmission**: users transmit sequentially using a single antenna for transmission and reception, hence creating a standard-compliant 802.11a link. In the experiments, each transmitter uses the first antenna while both antennas are sequentially used for reception. This strategy provides data transmitted over two different SISO channel realizations and more accurate results after averaging.

For each channel realization, the foregoing procedure is repeated for all individual data rates specified by the IEEE 802.11a standard. Therefore, a training stage followed by a data transmission stage is conducted for each data rate. Notice that in 802.11a the Medium Access Control (MAC) layer adapts the data rate according to the quality of the received signal. In our experiments, however, we fix the rate regardless of the reception quality.
TABLE I
FORMULAS APPLIED TO TRAINING OR DATA FRAMES FOR OBTAINING THE DIFFERENT PARAMETERS.

| Channel | Signal power | Noise power | Noise variance | EVM |
|---------|--------------|-------------|----------------|-----|
| $h_s = \frac{\sum_n z_{s,n}}{M \bar{z}_s}$ | $S_s = \left| \frac{\sum_n \bar{z}_{s,n}}{M} \right|^2$ | $N_s = \frac{\sum_n |z_{s,n} - h_s \tilde{z}_s|^2}{M}$ | $\sigma_s^2 = \frac{N_s}{|h_s|^2}$ | $\text{EVM}_s = \frac{\sum_n |\bar{z}_{s,n} - \tilde{z}_{s,n}|^2}{N}$ |

$z_{s,n}$: received symbol  \hspace{1cm} \bar{z}_{s,n}$: equalized received symbol  \hspace{1cm} \tilde{z}_{s,n}$: transmitted symbol
$s$: subcarrier index \hspace{1cm} n$: OFDM symbol index
$M$: number of training symbols \hspace{1cm} N$: number of data symbols

VI. RESULTS

A. Characterization of the Channel Realizations

In order to ensure statistically representative results, we conducted a sufficiently large number of executions of the aforementioned procedure over different wireless channels. Without changing the position of the nodes, we are able to obtain up to 4096 different channel realizations\(^4\) by choosing four different antenna sets attached to each front-end and controlled by two binary switches.

First of all, we characterized the quality of the channels in our setup. To this end, we plot in

\(^4\)All channel measurements are available for download in http://www.comonsens.org/index.php?name=demonstrators
Fig. 11. Example of one of the $2 \times 2$ MIMO channels obtained in the measurement scenario, as well as the four noise estimates that can be obtained using the four SISO links. Notice that the noise power is not flat over frequency and varies according to the amplitude of the corresponding channel coefficient.

Fig. 10 the estimated Probability Density Function (PDF) of the SNR for both the desired and the interfering links at each receiver. The SNR for each subcarrier has been obtained with the expressions indicated in Table I. As shown in the figure, the SNRs range from approximately 15 to 30 dB, with significant differences among receivers: interference is slightly stronger than signal at receivers 1 and 3, whereas receiver 2 experiences higher signal strength. These measurements show that all desired and interfering signals are of comparable strength, hence demonstrating the suitability of the scenario for the evaluation of IA methods.

As an example, we provide in Fig. 11 the magnitude of the frequency response of one of the measured $2 \times 2$ MIMO channels normalized by the average of the channel amplitudes. Fig. 11 also plots the estimated noise power at each receive antenna obtained as indicated in Table I. Notice that we can obtain four noise variance estimates, one for each transmit-receive antenna pair. It can be observed that the noise level is not flat over frequency and follows the quality of the corresponding channel coefficient, i.e. it is proportional to the channel gain. This behavior is explained by the signal distortion at the transmitter, also referred to as transmitter noise [25], and it will be further discussed in the following sections.
B. Comparison of Pre-FFT and Post-FFT IA Decoding

In this section we evaluate the performance of the pre-FFT IA decoding scheme proposed in Section II-B in comparison to post-FFT decoding. All data transmissions are done at 24 Mbit/s and the EVM of the received signal constellation (calculated as in Table I) is used as the performance metric.

We start by studying the impact of the pre-FFT decoder length on the performance of IA which, as mentioned in Section II-B, involves a trade-off between ISI and residual MUI. To this end, we evaluate the EVM of the received signal constellation when MUI is suppressed with both post- and pre-FFT decoders. Training frames consist of $M = 30$ training OFDM symbols per transmit antenna. Fig. 12 shows the median EVM degradation of the pre-FFT technique for different decoder lengths, $L \in [1, 64]$, with respect to the post-FFT decoder which obviously provides the best performance. In order to demonstrate the ISI vs. residual MUI trade-off, the comparison has been carried out for both IA and Perfect IA transmissions. For Perfect IA the degradation is only due to ISI and, as expected, it increases with the decoder length. On the other hand, for IA a short decoder cannot properly suppress the MUI leading to a high degradation of the constellation EVM. As the decoder length increases, however, the amount of MUI is greatly...
reduced whereas the degradation due to ISI grows at the rate seen in the Perfect IA curve. This analysis illustrates the existing ISI-MUI trade-off from which it turns out that a good choice for the decoder length would be 30 taps. This decoder length will be used in the remaining experiments since it provides slightly less than 1 dB of EVM degradation (whereof around 0.3 dB are due to ISI) with the advantage of a reduced receiver complexity and the possibility to perform frame synchronization in totally unsynchronized scenarios.

Secondly, we evaluate the effect that the quality of the CSI has on the performance of aligned transmissions. In Fig. 13 we show the evolution of the EVM for different number of OFDM training symbols. From the two upper curves (corresponding to IA transmissions) it can be observed that a small number of training symbols, below 20 or 30, does not provide an accurate CSI and leads to a significant degradation of the EVM due to interference. On the other hand, a number of training symbols above 30 does not improve the EVM anymore, which leads to a constant degradation between Perfect IA and IA of around 4 dB. The gap between post-FFT decoding and pre-FFT decoding for Perfect IA is due to ISI whereas for IA it is due to ISI and residual interference. The fact that the EVM does not improve when increasing the number of training symbols suggests that the performance of IA is not only limited by imperfect CSI but also by other spurious effects.

Another source of error occurs if the channel varies between the training stage and the data transmission stage so that the channel estimates used to compute the IA precoders and decoders are outdated by the time the aligned precoded transmission is actually performed. To evaluate the impact of such error, we conducted an additional experiment where a deliberate feedback time has been introduced. The results in Fig. 14 show that increasing feedback time does not cause additional degradation of the received signal EVM, hence proving the channel remains static for at least 10 seconds. This is consistent with the special care taken to guarantee that our measurement scenario is completely static (see Section IV).

Once the hypotheses of having inaccurate and/or outdated CSI estimates have been ruled out, there are still other reasonable effects which may jointly limit the quality of the IA scheme:

- Signal distortion caused by non-linearities in power amplifiers (whose effect on IA was empirically evaluated in [7]).
- RF oscillator phase noise (also considered in [7]).
- Random power fluctuations at the transmitter over time which are different for every antenna
and transmitted frame.

- ADC, DAC quantization and clipping effects.

When the signal distortion occurs at the transmitter it is referred to as transmitter noise which leads to spatially colored noise at the receiver. Transmitter noise, also referred to as dirty RF, is specially important when the transmitter and the receiver are close to each other since its effect is directly proportional to the channel power gain. Section VI-A shows that transmitter noise is present in our measurement campaign. Its detrimental impact on the performance of MIMO systems is already well-known and has been empirically studied in [25]–[27].

Finally, in view of the results in Figs. 12 and 13, we have chosen the parameters which provide a nearly optimal performance with a reasonable complexity, that is, $M = 30$ training symbols and a decoder length of $L = 30$ samples. The Cumulative Distribution Function (CDF) of the received constellation EVM obtained with this parameter setup is shown in Fig. 15. It is shown that the performance loss caused by moving from a post-FFT to a pre-FFT decoder is always below 1 dB for IA and below 0.5 dB for Perfect IA. As a counterpart, pre-FFT decoding has the advantage that no interuser time synchronization is required.

Additionally, these differences are negligible compared to the roughly 4 dB difference between
Perfect IA and IA schemes. We recall that, as a consequence of the spurious hardware effects mentioned before, it is not possible to reduce the gap by estimating the CSI using a higher number of training symbols.

C. Comparison of the Adopted Schemes

In this subsection we compare the performance of the five adopted schemes using two different metrics. First, we show in Fig. 16 the CDF of the received signal constellation EVM. As expected, DET-TDMA provides the lowest EVM and guarantees an EVM better than -15 dB in all channels, whereas IA ensures the same signal quality in 60% of the realizations. On the other hand, Fig. 16 also shows a noticeable degradation of IA with respect to Perfect IA where the latter is able to achieve the same EVM value of -15 dB in a 20% more of channel realizations. This effect was already observed in Fig. 15 and is due not only to channel estimation errors, which avoid the interference to be perfectly nulled out, but also to transmitter noise coming from the interfering users, as already explained in Sections VI-A and VI-B. Alternatively, the MaxSINR scheme provides little EVM improvement over IA, increasing the percentage in only 4% at -15 dB. This suggests that the operating SNRs are sufficiently high for IA to achieve good performance, and
therefore MaxSINR algorithm converges to the zero-forcing IA solution in most subcarriers. However, when there exists high collinearity between the signal and the interference subspaces, MaxSINR enhances the desired channel, thus providing an improvement in the average EVM performance. Finally, it is worth mentioning that the quality of the equivalent channels after applying the IA precoders and decoders, which is represented by the EVM performance of Perfect IA, is more spread than that of SISO channels. This is a reasonable result since the IA precoders and decoders are independent of the desired links, hence yielding collinearity as well as orthogonality between the signal and the interference subspaces with the same probability.

Now we show BER results for the five adopted schemes, which are plotted in Fig. 17. This figure represents the average achievable sum-rate that guarantees a BER equal or lower than a given value. For each channel, the achievable sum-rate is obtained assuming an optimal MAC layer which selects for each user the maximum rate that satisfies the required BER. It is important to notice that results in Fig. 17 do not take additional overhead or higher-level issues into account and they only suggest how the optimum performance of such schemes would be. We observe that IA schemes achieve higher throughput than TDMA schemes for all BER requirements. For instance, IA provides an average rate of 73 Mbit/s with a maximum BER of $10^{-4}$, whereas SISO
and DET achieve 32 and 53 Mbit/s, respectively. On the other hand, although MaxSINR does not provide a significant improvement in terms of EVM (see Fig. 16) it does provide substantially higher data rates than IA. More specifically, it achieves 7 Mbit/s more than IA at the same operating point of BER $\leq 10^{-4}$. This is due to the fact that the channel decoder is very sensitive to changes in the received EVM, and thus a small improvement in the signal quality may yield a significant BER decrease, hence showing the importance of enhancing the signal quality when collinearity between the signal and the interference subspaces occurs. Following these lines, we also observe that Perfect IA provides a large throughput improvement over IA, which evidences once again the significant impact of practical impairments such as channel estimation errors and transmitter noise. Such impairments, along with collinearity issues, significantly limit the performance of IA schemes (specially as the number of users increases) and should be considered in future IA designs.

VII. CONCLUSION

In this paper we have presented an experimental performance evaluation of spatial IA in the 3-user MIMO-OFDM interference channel. We have carefully analyzed the main practical impairments that may degrade the end-to-end performance, namely imperfect CSI, collinearity
between signal and interference subspaces, frame detection in asynchronous scenarios, and dirty RF effects. To this end, we have deployed a suitable experimental setup made up of three MIMO transmitters and receivers, and measured received constellation EVM and BER for a set of indoor channels following the conventional frame structure and synchronization strategies of the IEEE 802.11a WLAN standard. We have firstly pointed out that pre-FFT (time-domain) IA decoding must be applied in totally asynchronous scenarios to cancel out the interference before time synchronization, and we have proposed a simple design for such decoders. Our results indicate that the EVM degradation due to pre-FFT IA decoding is less than 1 dB when choosing an appropriate decoder length. Secondly, an analysis of imperfect CSI has been carried out, and we have observed that the received EVM is dominated by transmitter noise (dirty RF) when the channel estimates are sufficiently accurate, which significantly limits the end-to-end performance of IA. The performance of IA has also been compared with that of different TDMA schemes, and we have shown that IA may achieve a significantly higher throughput for a given BER requirement under real settings. Finally, this work highlights the relevance of experiments where signals are actually transmitted over the air and all practical impairments are taken into account. This experimental research is not only useful to evaluate theoretical results in real-world...
scenarios but also to uncover new research lines.

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**REFERENCES**

[1] V. R. Cadambe and S. A. Jafar, “Interference alignment and degrees of freedom region of the $k$-user interference channel,” *IEEE Transactions on Information Theory*, vol. 54, pp. 3425–3441, August 2008.

[2] S. Gollakota, S. D. Perli, and D. Katabi, “Interference alignment and cancellation,” *SIGCOMM Comput. Commun. Rev.*, vol. 39, pp. 159–170, August 2009.

[3] O. El Ayach, S. Peters, and R. Heath, “The feasibility of interference alignment over measured MIMO-OFDM channels,” *IEEE Transactions on Vehicular Technology*, vol. 59, pp. 4309 –4321, November 2010.

[4] R. Brandt, H. Asplund, and M. Bengtsson, “Interference alignment in frequency - a measurement based performance analysis,” in *Proceedings of the 19th Internation Conference on Systems, Signals and Image Processing (IWSSIP 2012)*, (Vienna, Austria), April 2012.

[5] Ó. González, D. Ramírez, I. Santamaría, J. A. García-Naya, and L. Castedo, “Experimental validation of interference alignment techniques using a multiuser MIMO testbed,” in *Proceedings of the International ITG Workshop on Smart Antennas (WSA 2011)*, (Aachen, Germany), February 2011.

[6] J. A. García-Naya, L. Castedo, Ó. González, D. Ramírez, and I. Santamaría, “Experimental Evaluation of Interference Alignment Under Imperfect Channel State Information,” in *Proceedings of the 19th European Signal Processing Conference (EUSIPCO 2011)*, (Barcelona, Spain), August 2011.

[7] P. Zetterberg and N. Moghadam, “An experimental investigation of SIMO, MIMO, interference-alignment (IA) and coordinated multi-point (CoMP),” in *Proceedings of 19th International Conference on Systems, Signals and Image Processing (IWSSIP 2012)*, pp. 211–216, IEEE, 2012.

[8] J. Massey, J. Starr, S. Lee, D. Lee, A. Gerstlauer, and R. Heath, “Implementation of a real-time wireless interference alignment network,” in *2012 Conference Record of the Forty Sixth Asilomar Conference on Signals, Systems and Computers (ASILOMAR)*, pp. 104–108, 2012.

[9] H. V. Balan, R. Rogalin, A. Michaloliakos, K. Psounis, and G. Caire, “Achieving high data rates in a distributed MIMO system,” in *Proceedings of the 18th annual international conference on Mobile computing and networking*, pp. 41–52, ACM, 2012.

[10] G. F. et. al., “Dirty RF: A new paradigm,” in *Proceedings of the International Symposium on Personal, Indoor and Mobile Radio Communications, (PIMRC 2005)*, (Berlin, Germany), September 2005.

[11] M. El-Hadidy, M. El-Absi, L. Sit, M. Kock, T. Zwick, H. Blume, and T. Kaiser, “Improved interference alignment performance for MIMO OFDM systems by multimode MIMO antennas,” in *Proceedings of the 17th International OFDM Workshop 2012 (InOWo’12)*, pp. 1–5, 2012.
[12] R. Bahl, N. Gulati, K. R. Dandekar, and D. Jaggard, “Impact of pattern reconfigurable antennas on interference alignment over measured channels,” in 2012 IEEE Globecom Workshops (GC Wkshps), (Anaheim, CA, USA), pp. 557–562, December 2012.

[13] IEEE, “IEEE Standard for Information technology–Telecommunications and information exchange between systems–Local and metropolitan area networks–Specific requirements IEEE Std 802.11™-2007 (Revision of IEEE Std 802.11-1999).”

[14] C. Lameiro, Ó. González, J. Vía, I. Santamaría, and R. W. Heath, “Pre- and post-FFT interference leakage minimization for MIMO OFDM networks,” in Proceedings of the IEEE 9th International Symposium on Wireless Communication Systems (ISWCS 2012), (Paris, France), August 2012.

[15] Ó. González, C. Lameiro, J. Vía, I. Santamaría, and R. W. Heath, “Interference leakage minimization for convolutive MIMO channels,” in Proceedings of the IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP 2012), (Kyoto, Japan), March 2012.

[16] K. Gomadam, V. Cadambe, and S. Jafar, “A distributed numerical approach to interference alignment and applications to wireless interference networks,” IEEE Transactions on Information Theory, vol. 57, pp. 3309–3322, June 2011.

[17] J. B. Andersen, “Array gain and capacity for known random channels with multiple element arrays at both ends,” IEEE Journal on Selected Areas in Communications, vol. 11, pp. 2172–2178, November 2000.

[18] M. Razaviyayn, G. Lyubeznik, and Z.-Q. Luo, “On the degrees of freedom achievable through interference alignment in a MIMO interference channel,” IEEE Transactions on Signal Processing, vol. 60, pp. 812–821, February 2012.

[19] C. M. Yetis, , T. Gou, S. A. Jafar, and A. H. Kayran, “On feasibility of interference alignment in MIMO interference networks,” IEEE Transactions on Signal Processing, vol. 58, pp. 4771–4782, September 2010.

[20] “Lyrtech, Inc.” 2011.

[21] “Maxim Integrated Products, Inc.;” 2011.

[22] “COMONSENS: Foundations and Methodologies for Future Communication and Sensor Networks;” 2012.

[23] “Mobile Mark No. PSKN3-24/55S;” 2012.

[24] “L-Com Antenna No. HG2458RD-SM;” 2010.

[25] P. Castro, J. Gonzalez-Coma, J. Garcia-Naya, and L. Castedo, “Performance of MIMO systems in measured indoor channels with transmitter noise,” EURASIP Journal on Wireless Communications and Networking, vol. 2012, no. 1, p. 109, 2012.

[26] H. Suzuki, T. V. A. Tran, I. B. Collings, G. Daniels, and M. Hedley, “Transmitter noise effect on the performance of a MIMO-OFDM hardware implementation achieving improved coverage,” IEEE Journal on Selected Areas in Communications, vol. 26, no. 6, pp. 867–876, 2008.

[27] C. Studer, M. Wenk, and A. Burg, “MIMO transmission with residual transmit-RF impairments,” in 2010 International ITG Workshop on Smart Antennas (WSA), pp. 189–196, 2010.