Software Implementation of Spatial Interweave Cognitive Radio Communication using OpenAirInterface Platform

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***Abstract*—We present in this paper a software implementation of a cognitive radio (CR) communication based on long term evolution-time division duplex (LTE-TDD) channel reciprocity. We study the problem of calibration and beamforming design for a CR system in which a multiple-input single-output (MISO) secondary link, wants to opportunistically communicate without harming the primary SISO system. Specifically, we evaluate the CR communication through the EURECOM's experimental OpenAirInterface (OAI) software platform. We will show that it is feasible to restore the reciprocity after calibration in a non reciprocal channel, and provide an overview of challenges in the channel estimation for real conditions.**

***Index Terms*—Channel reciprocity, precoding, calibration techniques, cognitive radio, LTE-TDD, experimental platform.**

I. Introduction

Channel reciprocity is an advantageous hypothesis in radio communication. However, miscellaneous discrepancies such as the radio frequency (RF) impairments make it inexploitable in real situations. Specifically, a persistent problem in cognitive radio (CR) is to find best ways for secondary users (SUs) to transmit without disturbing primary users (PUs). In this respect, the beamforming (BF) is an interesting technique, since it uses an antenna array to steer a signal towards a specific receiver (Rx) then maximizes the signal to noise ratio (SNR) for the considered Rx [1].

Moreover, till now, feedback techniques are commonly used to perform BF at the transmitter (Tx), but a feedback is impossible between PUs and SUs. Consequently, some studies proposed calibration procedures to solve the RF impairments. This procedure consists in exchanging the channel state information (CSI) between terminals, and derive parameters using the relation between the CSI and/or through adequate algorithms.

Although the importance of reciprocity calibration for wireless communications, only few algorithms exist in the literature. Authors in [2] proposed to solve the calibration problem in using several version of uplink (UL) and downlink (DL) channels over the time. With the hypothesis of invariant calibration parameters, they derive the calibration parameters through a total least squares (TLS) formulation. In [3], [4], different calibration methods are presented, they assume no antenna coupling effects and solve the calibration problem by the Tx/Rx exchange of coefficients from antenna. Furthermore in [5], authors, after comparing different reciprocity calibration approaches, they have shown that even with antenna coupling effects, it is possible to find reliable calibration parameters. The same authors illustrated in [6] the implementation of calibration algorithms in an experimental platform.

In this paper, we adopt the same framework as presented in [5], [6]. Specifically, we chose the less complex calibration method described in [5], which consists in subdividing the multi-input multi-output (MIMO) channel into single channels, and find the calibration factors for each single channel, helped by TLS technique [7], [8]. To this end, we introduced a CR scenario including two SUs and two PUs in a system based on long term evolution-time division duplex (LTE-TDD) specifications [9]. Then we determine the calibration parameters in the secondary system and exploit these parameters to define a precoder allowing to avoid interferences towards the primary system. To achieve the secondary system calibration, the DL channel is estimated by the SU, then is feedback to the secondary BS which compute the calibration using the selected algorithm. However, the considered LTE system is limited by several elements like the transmission mode and the payload in the UL. Throughout the paper, we propose innovative solutions to overcome these drawbacks such as quantized feedback, channel decimation and modified pilot location.

The final goal is to implement a real time reciprocity-based TDD CR communication and the scenario in an experimental platform based on LTE specifications provide by the OpenAirInterface (OAI) platform [10], [11]. OAI platform is composed of simulation, emulation and real time experiment part which tests the validity of concepts in radio networks. The calibration technique will be firstly performed in the OAI CR simulator to test performances before real time experiments.

The rest of this paper is structured as follows. Section II describes the reciprocity-based scenario and the TLS-based calibration that will be exploited. In Section III we detail the LTE-TDD specifications implemented in OAI platform. The implementation procedures are described in Section IV while performance evaluation using OAI is presented in Section V. Finally, conclusions are summarized in Section VI.

II. RECIPROCITY-BASED COGNITIVE RADIO SCENARIO

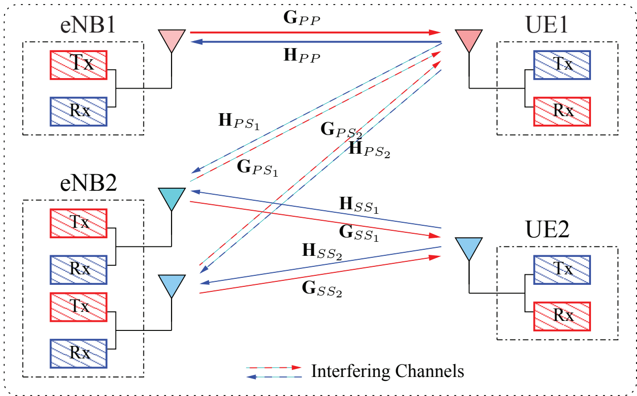

Fig. 1. Illustration of the primary system including eNB1 and UE1, and the secondary system, eNB2 and UE2, with interfering channels between systems.

Fig. 1 presents the implemented CR scenario consisting of a primary system including the licensed users, eNB1 and UE1 designed with one antenna, and a secondary system composed of opportunistic users, eNB2 and UE2 with two antennas and one antenna respectively, which are not licensed to transmit in the radio environment. The denomination eNodeB (eNB) and User Equipment (UE) is conform to LTE, and depicts a communication including one node and an attached LTE equipment. Orthogonal frequency division multiplexing (OFDM) is the modulation of choice for the proposed scenario over a time division duplex (TDD) mode. The radio frequency circuitry (RF) is represented on Fig. 1 by the transmission and reception filters Tx and Rx for each antenna. Throughout the paper, we will use the following notation:

- $\mathbf{G}_{SS_i}$ is the estimated downlink (DL) channel gain between i-th Tx antenna at eNB2 and Rx antenna at UE2;
- $\mathbf{H}_{SS_i}$ is the estimated uplink (UL) channel gain between Tx antenna at UE2 and i-th Rx antenna at eNB2;
- $\mathbf{G}_{PP}$ is the estimated DL channel gain between UE1 Rx and eNB1 Tx;
- $\mathbf{H}_{PP}$ is the estimated UL channel gain between UE1 Tx and eNB1 Rx;
- $\mathbf{G}_{PS_i}$ is the estimated DL channel gain between i-th Tx antenna at eNB2 and Rx antenna at UE1;
- $\mathbf{H}_{PS_i}$ is the estimated UL channel gain between Tx antenna at UE1 and i-th Rx antenna at eNB2;
- $\mathbf{C}_{S_i}$ is the calibration factor between i-th eNB2 antenna and UE2 antenna.

The CR system structure is based on an interference avoidance at the secondary transmitter (eNB2) and the primary receiver (UE1). The proposed interference avoidance technique is a simple zero forcing beamforming technique implemented in secondary base station eNB2. The per-subcarrier received signal at the primary user $\mathbf{y}_p \in \mathbb{C}^N$ UE1 in DL configuration is expressed by:

$$\mathbf{y}_p = \mathbf{G}_{pp}\mathbf{x}_p + \mathbf{G}_{ps}\mathbf{x}_s + \mathbf{n}, \tag{1}$$

we aim at send a null interference in the direction to UE1, leading to:

$$\mathbf{G}_{ps}\mathbf{x}_s = \begin{bmatrix} g_{ps1} & g_{ps2} \end{bmatrix} \begin{bmatrix} x_{s1} \\ x_{s2} \end{bmatrix} = 0. \tag{2}$$

A solution is to design a precoder $\mathbf{p}$ at eNB2 such as:

$$\mathbf{G}_{ps}\mathbf{p}\mathbf{s}_x = \begin{bmatrix} g_{ps1} & g_{ps2} \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \end{bmatrix} \begin{bmatrix} s_{x1} & s_{x2} \end{bmatrix} = 0, \tag{3}$$

where $\mathbf{x}_s = \mathbf{p}\mathbf{s}_x$, and $\mathbf{s}_x$ the transmitted symbol at eNB2. In order to fulfill this condition, we propose to design $\mathbf{p}$ such:

$$g_{ps1}p_1 + g_{ps2}p_2 = 0; \;\; p_1 = g_{ps2}, p_2 = -g_{ps1}. \tag{4}$$

The efficiency of the precoder $\mathbf{p}$ will be linked to the reliability of the crosslink channel estimation ($\hat{\mathbf{G}}_{ps} = [\hat{g}_{ps1}\ \hat{g}_{ps2}]$). Due to the non cooperation between primary and secondary, this channel cannot be estimated directly by secondary eNB2. we propose to deduce it using channel reciprocity assumption that occur in TDD systems. Though in such a system the radio frequency front-ends perturb the reciprocity, this reciprocity can be restored based on previous reciprocity-calibration investigations illustrated in [5], [6]. Finally, using the complex coefficients of the crosslink channel estimation $\hat{\mathbf{G}}_{ps}$, and taking into account the transmission power constraint at eNB2, the normalized precoder is expressed as:

$$\mathbf{p} = \begin{bmatrix} \frac{\hat{g}_{ps2}}{\beta} \\ \\ \frac{-\hat{g}_{ps1}}{\beta} \end{bmatrix}, \beta = \sqrt{||\hat{g}_{ps1}||_2 + ||\hat{g}_{ps2}||_2}, \tag{5}$$

In [12], a technique to avoid crosslink calibration was presented, the authors do not require a priori knowledge of the crosslink CSI at the secondary transmitters, but they are able to obtain information required for Tx beamforming through smart exploitation of received signal during a TDD time slot. The same framework will be adapted in this paper, nevertheless we suppose here that the required DL crosslink channel (from eNB2 to UE1) estimations are known to the secondary transmitter. In the proposed solution, the calibration parameters at the secondary transmitters allow to estimate the crosslink DL channel without a feedback from the primary system, as can be shown in Fig. 1.

In this study, the calibration is achieve in exploiting the information contained in the DL ($\mathbf{G}_{SS} = [\mathbf{G}_{SS_1}, \mathbf{G}_{SS_2}]$) and the UL channels ($\mathbf{H}_{SS} = [\mathbf{H}_{SS_1}, \mathbf{H}_{SS_2}]$). The objective is to firstly collected several versions of both channel over the time, and to infer the calibration parameters $\mathbf{C}_{S_1}$ and $\mathbf{C}_{S_2}$. These parameters will be used to find automatically the DL channel, without any feedback. Finally, the information provided by the determined channel $\mathbf{G}_{SS}$ will be exploited to design the beamformer based on the channel reciprocity.

We will adopt the calibration technique described in [7] and evaluated in [5] and [6]. This technique simplifies the calibration problem in subdividing the multi-input single-output (MISO) secondary user channel into several single channels and then uses a TLS technique to solve the calibration. More concretely, the algorithm restores the reciprocity assumption by finding the calibration parameters $\mathbf{C}_S = [\mathbf{C}_{S_1}, \mathbf{C}_{S_2}]$ consisting of RF parameters.

$$\mathbf{G}_{SS} = \mathbf{C}_S\mathbf{H}_{SS}^T \tag{6}$$

In order to improve the estimation of calibration parameters in noisy channel, we consider K versions of the channel across the time assuming that calibration factors vary slowly in time. Let's write $\underline{\mathbf{G}}_{SS}$ and $\underline{\mathbf{H}}_{SS}$ respectively the DL and UL concatenated channel between the two antennas at eNB2 and antenna at UE2. The equation is finally reformulated into TLS problem such:

$$\arg\min_{\mathbf{C}_S} \left(||\tilde{\mathbf{H}}_{SS}||^2 + ||\tilde{\mathbf{G}}_{SS}||^2 \right)$$
$$\text{s.t} \quad \left(\underline{\mathbf{H}}_{SS} + \tilde{\mathbf{H}}_{SS} \right) \mathbf{C}_S = \left(\underline{\mathbf{G}}_{SS} + \tilde{\mathbf{G}}_{SS} \right), \qquad (7)$$

where $\tilde{\mathbf{H}}_{SS}$ and $\tilde{\mathbf{G}}_{SS}$ are the estimation error correction. Throughout this paper, we will focus on the singular value decomposition (SVD) solution presented in [8].

III. OAI-LTE Frame Description

Although the long term evolution (LTE) is a complex standard, it is flexible and improves the compatibility between product from different equipment suppliers. These benefits (just to mention a few) explain our interest for a LTE compliant platform namely the OpenAirInterface. In this study, we assume an orthogonal frequency division multiplexing (OFDM) in downlink. Subsequently, the implementation on the OAI platform is performed using the 10 ms periodic TDD frame structure type 2, with the configuration number 3 which is composed of 10 subframes as described in Fig. 2. Each

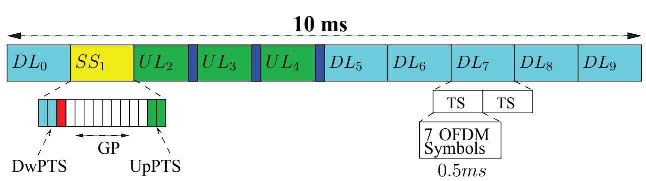

Fig. 2. OAI Frame specifications time

subframe is divided into 2 time slots (TS). A TS is consisting of 7 OFDM symbols (in the UL and the DL) and a normal cyclic prefix is set to avoid inter symbol interferences (ISI). The selected OFDM model assumes 512 subcarriers (SC) on 5 MHz (in DL), where 300 are really used. This TDD frame structure will be exploited in the secondary transmissions, assuming that the secondary system knows the primary frame type, it will modify its frame structure in order to listen the primary frame and exploit primary reference signals (RS, pilots). The system uses OFDMA for the UL and the DL transmissions, but the subframe structure is different. OAI implements a slightly modified version of signal mapping to resource elements. A brief description of the three subframe structures (downlink, uplink and special subframe) is given in the following subsections.

In the frequency domain, the RSs are located in specific OFDM symbols. In these symbols, for a 2 antennas case at the eNB, there is one RS from different antennas every 3 SC (total 300 SC, see Fig. 4). The first half of first TS of each subframe is consisting of the control signals (CS). Data associated CSs are carried by physical DL control channel which transport the DL control information (DCI). The DCI indicates several information including: resource block assignment, spatial layers information, modulation and coding scheme, power control command. Note that the location of pilots in RB are not used for data transmission.

In the UL, the CSs fill the edge of the bandwidth in the RB, the remaining bandwidth is used for RSs and transmission data. The UL control signaling is different with that in DL phase, all the relevant information associated with the data is already known and are centralized at eNB, due to multiple users in the same cell. In the UL, a special RS denoted demodulation RS (DRS) is associated with transmission of UL data on physical UL shared channel (PUSCH) and control signaling. Another RS denoted sounding RS (SRS) is used for channel quality estimation to enable frequency selective fading on the UL [9]. In the configuration used for the system developed in our work, the SRS is transmitted on the last symbol of every subframe in order to provide channel quality after every subframe.

The special subframe (SS) is an important part of our implementation. It includes the guard period (GP) denotes the switching point between DL and UL transmission (see Fig. 2), its length determines the maximum supportable cell size. The DL pilot time slot (DwPTS) always contains reference signals and control information like a regular DL subframe, and may carry data transmission. It also contains the primary synchronization signal (PSS) used for DL synchronization. The UL pilot time slot (UpPTS) have two values (1 or 2 OFDM symbols) it is used by the UE to either sounding RSs or random access transmission.

IV. Software Implementation

This section describes the software implementation based on the selected frame structure described previously. The simulation is designed to fit the real implementation conditions and requirements. We introduce *decalibration* filters and a frequency offset in order to simulate the effects of RF impairments at both side. Fig. 1 describes the channel and the decalibration for one eNB↔UE link. This architecture is repeated on all eNBs and UEs. The final goal is to restore the channel reciprocity (despite these perturbations) and improve the transmission using precoding at eNB2 Tx. $\mathbf{H}$ and $\mathbf{G}$ are generated following different channel models.

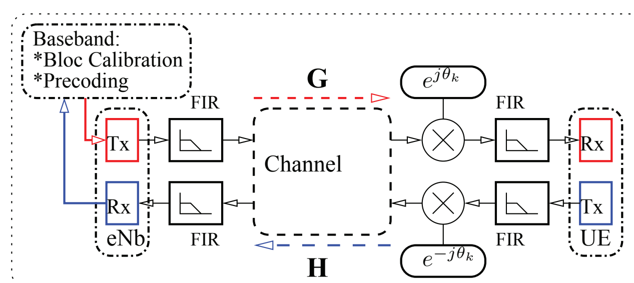

Fig. 3. Illustration of simulation chain and software implementation.

For the sake of simplicity and a quick hardware implementation, our study uses LTE transmission mode 1 which implies no diversity techniques and one antenna transmission. The calibration algorithm requires the channel estimations from two antennas of eNB2. To solve this problem, we modified the special subframe (SS) structure which is therefore not anymore LTE standard compliant. Fig. 4 shows the positioning of the RS (cell-specific RS) in SS, the considered location of the REs is designed to allow channel estimation for 2 antennas at eNB2 in transmission mode 1.

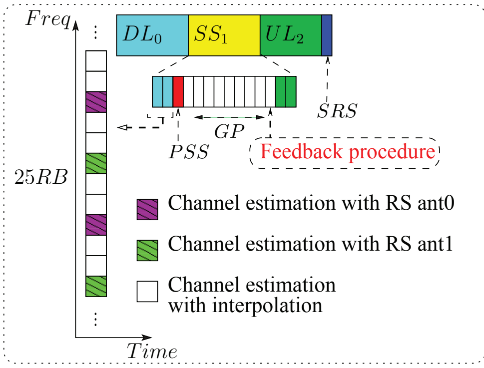

Fig. 4. Illustration of the special subframe (SS) structure with the selected transmission strategy and the exploitation of SS for feedback process.

The new layout of RS occupies 1 or 2 OFDM symbol, so it can hold in the SS. Notice that the RS of ant0 and ant1 (see Fig. 4) are spread in frequency and are delay by 2 SC, in 2 RS case, they will be spread also in time. Upon reception the overall channel estimates are obtained by frequency (and eventually time) interpolation. The interpolation in SS at UE2 will be adapted to the new positioning in SS at eNB2, see [9] for details about interpolation procedure in LTE.

V. Performance Evaluating

A. Transmission Parameters

This section describes the physical transmission parameters for the simulation, as illustrated in Table I the bandwidth is divided into Resource Blocks (RB) of 12 SC each. The OFDMA configuration in DL uses a 15 kHz SC spacing ($12 \times 15kHz = 180kHz$ in each RB). The number of RBs gives the total covered bandwidth. The lowest supported bandwidth is $1.08Mhz$, because the initial synchronization signals covers 6 RBs. We have shown in our previous study [5]

Parameters	Values
Sample duration T_s	$\frac{1}{7.68MHz}\mu s$, $130.2ns$
OFDM Symbol duration	$548T_s$, $71.35\mu s$
Cyclic prefix length	$36T_s$, $4.69\mu s$
1 Slot component	7 OFDM symbols, $500\mu s$
Subframe length	2 slots, $1ms$
Radio frame length	10 subframes, $10ms$
Bandwidth allocated, RB number	$5MHz$, 25 RB
Number of subcarriers	512 (300 useful)
Subcarrier spacing	$\Delta 15kHz$
Max Tx bandwidth	$4.5MHz$
Central carrier frequency	$1.9GHz$

TABLE I
Transmission Specifications

that $K \in [10, 15]$ (K channel estimations) for 2 antennas allow to find a valuable calibration parameters, accordingly we fixed the number of required channel estimation for calibration to $K = 10$ in our simulation. Then, assuming that the channel is coherent at least for one frame duration ($10ms$), we store at each side (eNB and UE) one UL/DL channel estimate by frame. Consequently, we need K frames to determine the calibration factors. The K UL/DL channels estimates are firstly supposed transmitted and stored perfectly at each side. This first step corresponds to relative calibration training phase [2]. In the proposed model, we take into account the pathloss in free space expressed by: $P_{ls} = 20log_{10}\left(\frac{4\pi d}{\lambda}\right)$, where d is the distance between the Tx and Rx antennas, and λ the wavelength. In the simulation, the results are obtained in varying several parameters (the pathloss, the SNR, the transmit power, the number of frame). In order to estimate the calibration parameters for all the 300 SC, the training phase is performed using 25 RB. The required rate to feedback the signal from UE2 to eNB2 depends on the selected modulation and coding scheme (MCS), the number of antenna port that have to be estimated at UE2 ($2ant$), the quantization bit of DL channel estimation at UE2 ($8bits$), and the number of considered SC ($300SC$).

The DL channel is estimated by UE2 in one subframe and this estimation is feedback to the eNB2, using the PUSCH. The transmission of all the SC complex coefficients using the PUSCH required $8bits \times 300SC \times 2ant \times 2 = 9600bits$ (the real and imaginary part of complex coefficients are transmitted separately) that have to be transmitted in 1 frame duration ($10ms$) $9600bits/10ms$. Based on the LTE-TDD specification [13], we observe that for 25 RB, we can chose to transmit the channel coefficients only in one subframe which implies a $MCS = 18$ at UE and a rate around $\approx 968Kb/s$. Nevertheless, under the strong assumption that the channel is coherent for at least one TDD frame ($10ms$), we can improve the reliability of the transmission in sending the channel coefficients in 3 UL subframes (TDD frame configuration 3) for $MCS = 8$ and a rate $\approx 1Mb/s$.

In order to reduce the length of the transmitted feedback signal, the first solution consist in retransmitting only the pilot receive by UE2 (close to analog feedback techniques). However, the solution adopt in this paper consist in decimating the channel estimation at UE2 before the retransmission, thus the higher the decimation factor, the lower the required payload in PUSCH. This latest solution selected for our implementation will not be discuss here, due to the lack of space.

B. Results

In order to evaluate the impact of the proposed interference avoidance technique on the coexistence between the primary and the secondary, we compare the constellation of the primary systems before and after the activation of the precoder at the secondary system. Nonetheless, it is important to observe the capabilities of the propose reciprocity-calibration, therefore, we compare the normalized mean squares error (MSE) expressed by: $\frac{||\mathbf{G}_{ss}-\hat{\mathbf{G}}_{ss}||}{||\mathbf{G}_{ss}||}$ between the reconstructed downlink channel at eNB2 $\hat{\mathbf{G}}_{ss}$ and the estimated downlink channel $\mathbf{G}_{ss}$ from both antennas of eNB2 at UE2. We firstly assume that the channel is perfectly reciprocal (see perfect case Fig. 5) and then we observe the case when we active the decalibration filters in Fig. 3. Fig. 5 shows that even if the MSE of the perfect reciprocity case slightly outperforms the decalibration case, the error generated by the filters can be easily compensated by the calibration procedure, and the reconstruction MSE of the downlink channel using only the calibration parameters and the uplink channel is close to the perfect case. Then, we run the simulation with 500 frames, $K = 10$ and different MIMO channel models, using our calibration

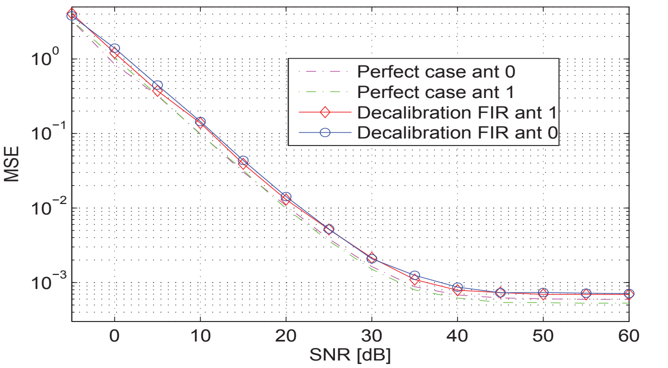

Fig. 5. MSE comparison of downlink channel reconstruction in the perfect case, then assuming the decalibration filters.

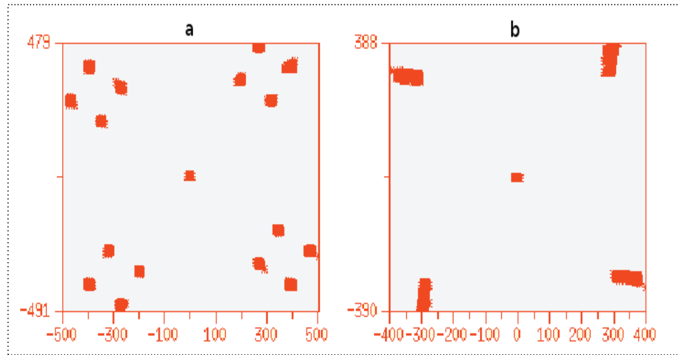

Fig. 6. The QPSK Constellation of primary receive signal at UE1, with interference from secondary eNB2 $P_{ls} = -5dB$, $SNR = 25dB$ in perfect reciprocity case, Fig. a: without ZFB, and Fig. b: with ZFB activated.

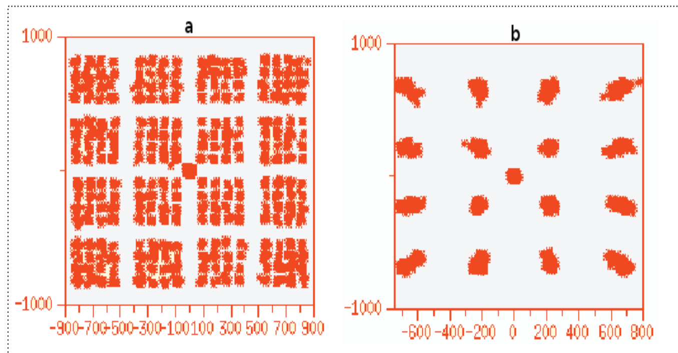

Fig. 7. The 16QAM Constellation of primary receive signal at UE1, with interference from secondary eNB2 $P_{ls} = -5dB$, $SNR = 25dB$ in perfect reciprocity case, Fig. a: without ZFB, and Fig. b: with ZFB activated.

procedure and the precoder defined in the secondary system, we observe in Fig. 6 and Fig. 7 constellation diagrams of the receive signal at the primary receiver UE1 respectively with a QPSK modulation and a 16QAM mapping. Considering a low pathloss ($P_{ls} = 5dB$) (which mean that primary and secondary are close i.e. in the same room), and a frequency selective Ricean channel model (at least one line of sight and 8 taps), we see that without a precoder at secondary, the interference from secondary lead to a bad constellation at UE1 mainly due to the lack of interference avoidance techniques. Subsequently, The precoder expressed in Section II is applied at eNB2. We observe the result assuming the same set of parameters and we see that with the precoding scheme at secondary transmitter, the primary signal is not anymore disturbed by interference generate from eNB2, and the complex points of the constellation for QPSK in Fig. 6 and for 16QAM in Fig. 7 are well located in the diagram, which suggest a better decoding of the primary signal from eNB1. It is so clear that the precoder improves the UE1 signal reception in presence of interference from secondary. Eventually, using the BF, all systems are able to transmit, under the strong assumption that the determined calibration factors are constant during the simulation process (≥ 500 frames).

VI. Conclusion

This paper studied a realistic software implementation of a reciprocity based CR scenario. We proposed innovative solutions to avoid interferences towards the primary system. Specifically, we designed a TLS-based calibration technique and a beamforming strategy based on the channel reciprocity. The proposed CR communication was evaluated through the EURECOM's OAI software platform. The OAI simulator reveals an improvement in terms of throughput, brought by the selected MIMO calibration method and the beamforming procedure. To conclude, we mention that the channel reciprocity restored through the calibration achievement opens the door to several applications in channel estimation theory, precoding and feedback techniques.

Acknowledgment

This work was carried out from a cooperation between EURECOM, Intel Mobile Communications and I3S Laboratory. It is supported by the European projects ACROPOLIS, CROWN and SACRA.

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