Auto-Calibrated MIMO-OFDM Channel Sounder for 3D Spatial Channel Characterization

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***Abstract*— This paper presents an improved test-bed designed for analyzing the spatial behaviour of wideband indoor channels using MIMO-OFDM systems. A 3D antenna positioning system (3-DAPS) is specifically designed for obtaining 3D spatial data. Also, it allows carrying out some measurements in the range of correlation distance where fading of the radio channel link is significant for indoor scenarios. Special emphasize is made on the RF calibration module, which is designed to track the frequency response of all RF chain of transmitter and receiver and apply those responses to the channel measurements. The average of the pseudo-spectrum MUSIC over all frequencies improves the resolution of the spatial spectrum giving clear peaks where a signal source is and smoothing fake peaks coming from scatters.**

I. Introduction

The knowledge of spatial behaviour of propagation channels can improve the performance of communication systems. A lot of research in multiple antennas field like Multiple-Input Multiple Output (MIMO) systems has been made in last years for estimating channel parameters like Angle-of-Arrival (AoA), Angle-of-Departure (AoD) and Delay-of-Arrival (DoA). Spatial channel characterization of different scenarios using frequency modulation techniques, like Orthogonal Frequency Division Multiplexing (OFDM), is very interesting; especially in indoor environments since fading caused by multipath can be combated with OFDM to improve quality of signal.

Several previous works have been published trying to explain the spatial behaviour of channels, like in [1]. However, there are some gaps to be filled to get a better understanding of the MIMO-OFDM directional channels, specially there is missing more measurement campaigns that validated the theoretic models [2].

A complete understanding of the spatial behaviour of the MIMO-OFDM channel implies exploring both the azimuth and elevation planes. For that purpose, an upgrading of the planar scanner presented in [3] has been carried out for collecting some measurement in the range of correlation distance where fading of the radio channel link is significant for indoor scenarios.

A new 3D antenna positioning system (3DAPS) is specifically designed for obtaining 3D spatial data for direction-of-arrival (DoA) estimation. It is based on a three orthogonal branches located along the x-, y- and z-axes of the Cartesian coordinate system. The 3D scanner is controlled by a user-friendly graphical interface and allows configuring several virtual array geometries.

At the receiver and transmitter, the amplitude phase calibration of each RF chain is fundamental for analysing the directional characteristics of the channel since the phase difference between each branch should only reflect the effect of the propagation channel. Otherwise, any of those RF chains cannot be taken into account to be a phase reference point for DoA estimation.

The paper is organized as follows. After introduction of section I, a description of the measurement equipment is made specially focusing in the calibration module and its characterization in frequency domain where s-parameters are measured. Section III describes and explains the 3D antenna positioning system and how it is controlled. In section IV, measurement setup is presented and some results of the spatial characteristics in terms of DoA are given especially focusing the frequency diversity improvements for DoA estimation.

II. Measurement Equipment

A. Calibration Setup

The design of the calibration module is based on a switching network fabricated with Printed Circuit Boards (PCB) technology shown in Fig. 1. The same circuit design works well for transmitter and receiver. There are four input/output paths which are digitally controlled by four integrated circuits (IC). All ICs are configured to be in two states: bypass and calibration state. In the bypass state, the four ICs interconnect directly the inputs with the outputs where inputs are RF signals are sent them directly to the antennas to be transmitted. In the calibration state, one IF/RF input signal is forward to a fifth IC while all other inputs are loaded to ground.

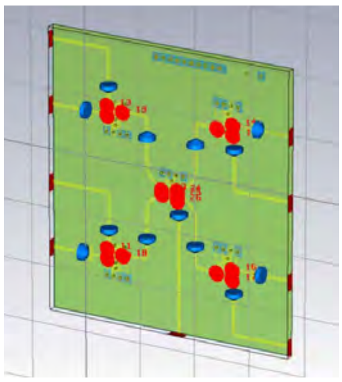

Fig. 1 Switching network of the calibration module.

The fifth IC switch to connect one of its four inputs to its calibration output whose signal is used for measuring variations on amplitude and phase of the complete RF chain at the transmitter/receiver. The stored frequency response is used for calibrating the received signal in order to eliminate the phases errors derived from the RF components.

The reflection losses are 2 dB in both bypass and calibration state while the insertion losses are 1.7dB in both states. The measured losses are very similar values having 3.7 dB and 4 dB of insertion losses in bypass and calibration state respectively. The measured S-parameters of the PCB can be seen in Fig. 2a and Fig. 2b.

The switching network presents a linear behaviour in phase within the operation frequency as is illustrated in Fig. 3.

At both transmitter and receiver RF chains is necessary to interconnect one additional Tx/Rx RF chain for receiving and transmitting the signal of the calibration output given by the calibration module. This extra receive/transmit RF chain translates the frequency spectrum to IF/RF frequency band. The calibration modules are connected to the RF chains at both sides of the radio link, which are shown in Fig. 4a and Fig. 4b.

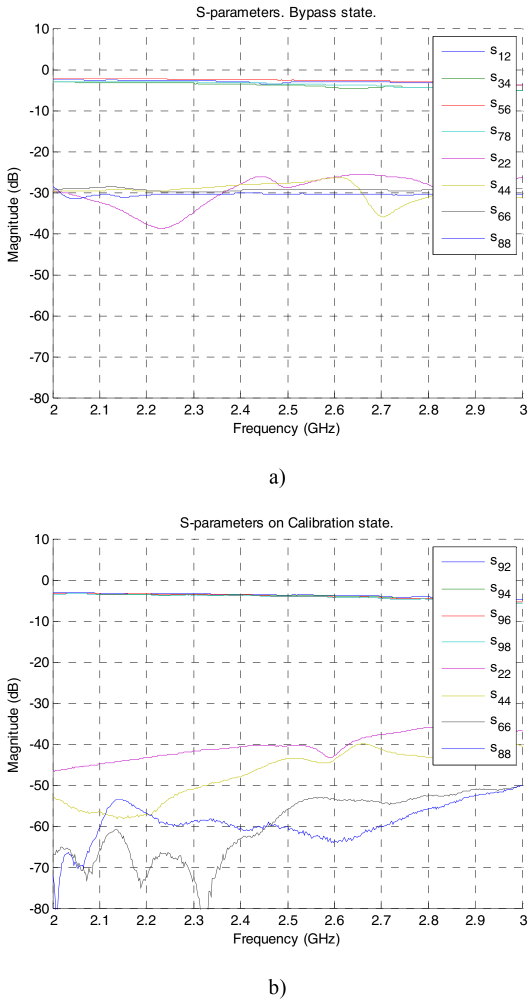

Fig. 2. Measured s-parameters of switching network in a) bypass and b) calibration state.

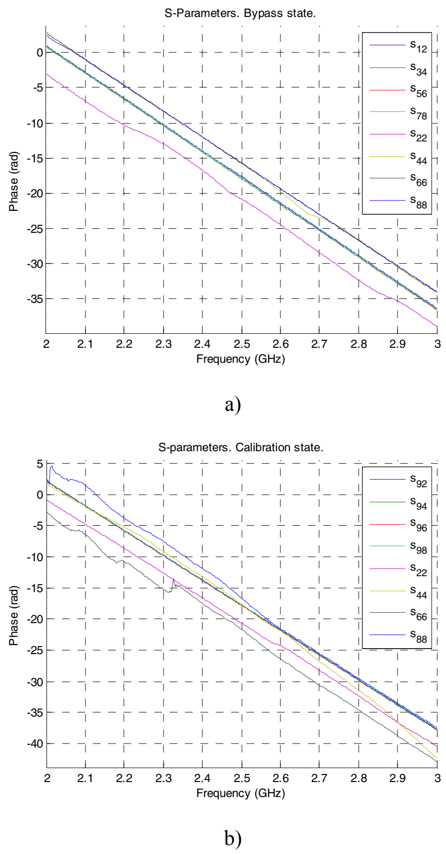

Fig. 3. Measured phase response of switching network in a) bypass and b) calibration state.

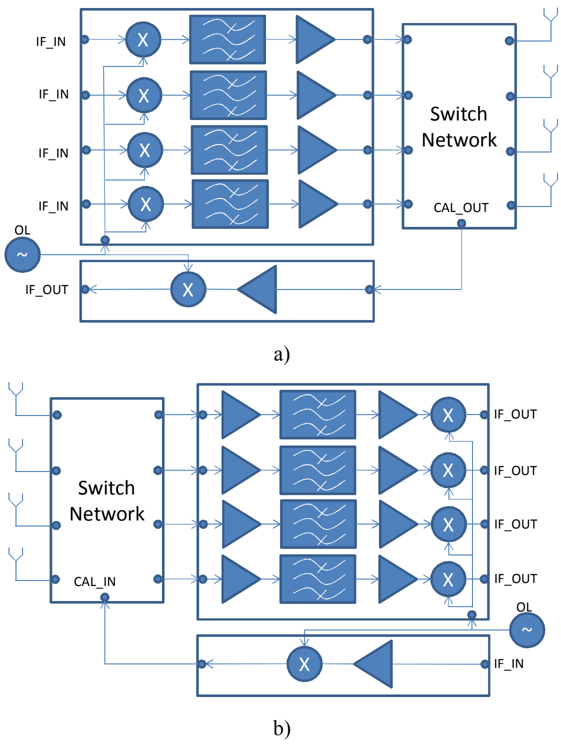

Fig. 4. RF chains with the calibration module at a) transmitter and b) receiver.

The calibration process consists of two steps. The first one compensate the amplitude and phase variations of the RF circuits at transmitter and receiver side by multiplying the received signals with the complex components Hr_k y Ht_k of the frequency response of all RF chains. The compensated received signal is given by

$$x_k = Hr_k \cdot Ht_k \cdot rx_k, \quad \text{with } k = 1 \cdots 4 \qquad (1)$$

where rx_k is the signal received at the k-th antenna. In the second step, once the signals have been compensated, the complex responses of the four channels are normalized in order to have the same amplitude and phase reference in all receive/transmit RF chains. Then, the compensation factor is

$$c_k = \frac{|x_k|}{|x_1|} e^{-j(\measuredangle x_k - \measuredangle x_1)}, \quad \text{with } k = 1 \cdots 4 \qquad (2)$$

leading to build the normalized and compensated received signal as

$$X_k = x_k \cdot c_k, \quad \text{with } k = 1 \cdots 4 \qquad (3)$$

The frequency responses Ht_k and Hr_k are measured just before a measurement process is launched. Finally, the X_k signals are used in different spatial algorithms to analyse the spatial characteristics of channels and to construct the MIMO-OFDM channel matrix.

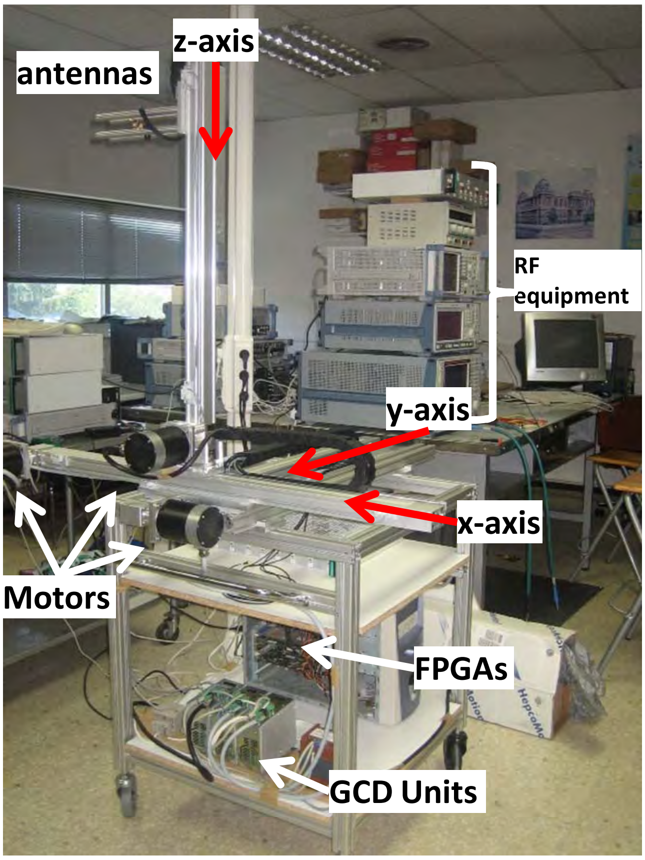

Fig. 5. 3D antenna positioning system for spatial exploring.

III. 3D Antenna Positioning Systems

The 3D antenna positioning system is based on a scanner controlled by a unit control (GCD) which receives commands from a PC connected through a serial port. The structure of the scanner is built of three orthogonal branches that can be moved independently to each other. The antenna support can be moved until 6λ along each axis for a WLAN operation frequency.

The improvement of the scanner consists of adding one more branch along the z-axis (vertical). Thus, the spatial behaviour of the channel in the elevation plane can be studied by collecting samples along the vertical axis. Fig. 5 shows the scanner.

Jointly, a software platform was developed for configuring several parameters like number of antenna positions, array geometries, axes to be explored, algorithm testing for DoA estimation and channel capacity.

IV. Spatial Channel Characterization

The understanding of channel propagation involves the description of the spatial behaviour of channel. In this section, the spatial characterization is carried out through the estimation of DoA in both azimuth and elevation planes by exploiting the frequency diversity.

A. Measurement setup

The new physical configuration of the scanner allows to have a measurement grid up to 10x10x10 points spaced half a wave length (at 2.45 GHz operation frequency). This spatial diversity leads to build a virtual array of three dimensions. Under this configuration, the spatial sensitivity for estimating elevation angles is increased because the broadside of virtual z-axis array steers its main beam toward the area where the density power of incident signals is expected to be maximum.

Instead mounting a single antenna to collect measurements, a MIMO antenna was mounted at the antenna support in order to measure some system parameters like MIMO capacity. Then, at each measurement point of the grid, a total of 128 snapshots are collected at each measurement trial where each snapshot is composed of 1024 OFDM carriers.

The measurement scenario is indoor-to-indoor like a PC lab where transmitter and receiver are in line-of-sight (LOS) and the channel conditions are quasi-static. Thus a time-invariant channel can be observed by the receiver antenna at different time/position of the measurement grid.

B. Estimated Pseudo-spectrum MUSIC

Spatial channel characterization is carried out by analysing the direction of arrivals. The DoA estimation techniques based on subspaces, like MUSIC [4], perform well in the case of uncorrelated signal sources. In the case of partially correlated signals, like in indoor environments, these techniques loss resolution and their performance is degraded. In order to overcome this drawback, the preprocessing scheme called spatial smoothing [5] is applied in order to maintain the non-singularity property of the input covariance matrix.

The DoA estimation is evaluated considering two cases: transmitting one single-frequency signal and transmitting one OFDM signal. In both cases, the multipath is characterized by four specular paths with its own DoA, power and frequencies. For the first case, one spatial spectrum is estimated for each carrier of the OFDM spectrum. The DoA estimated shows that all multipaths are resolved by the algorithm where peaks are at the azimuth and elevation angles of incident sources, as shown Fig. 6.

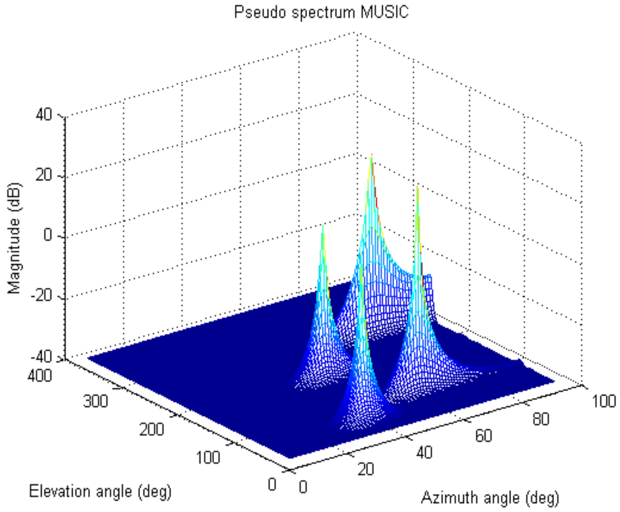

Fig. 6. Pseudo-Spectrum MUSIC without frequency diversity.

In the case of OFDM sources, the scatters cause that some carriers loss its orthogonal property at the receiver where the effect of that frequency correlation can shadow the peaks of the spatial spectrum. The final spatial spectrum is an averaged-spectrum over all frequencies. In Fig. 7 it can be seen the final frequency-averaged spatial spectrum with three multipath components resolved. It is clear that a technique to diminish the frequency correlation is needed to reduce the false peaks in the spatial spectrums.

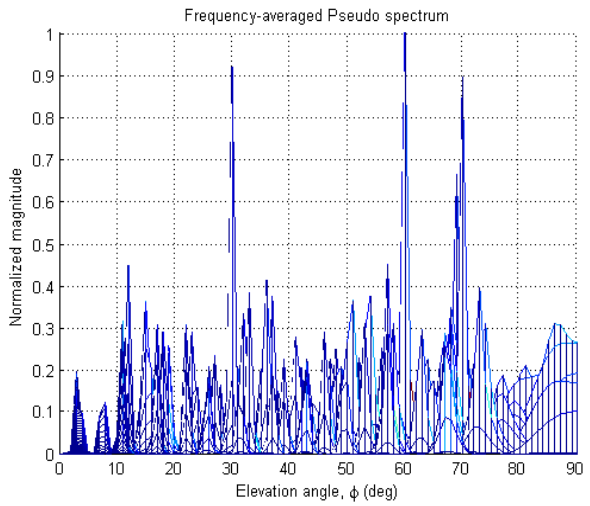

Fig. 7. Elevation angle of arrival of OFDM signal.

The positioning errors of the antenna support can degraded the performance of the applied algorithm for DOA estimation.

A significant improvement in the estimation of the number of incident sources is achieved by using all carrier frequencies of the OFDM spectrum. The eigenvalues associated to the incident signals and those associated to the noise are illustrated in Fig. 8.

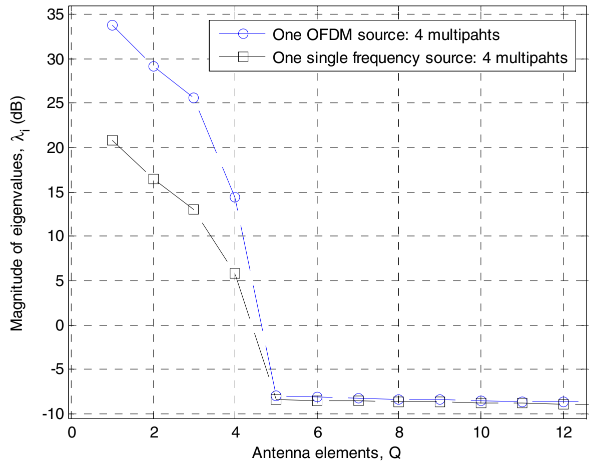

Fig. 8. Eigenvalues calculation using OFDM and single-frequency transmited signals.

More results regarding DoA estimation and MIMO channel capacity will be presented at the EuCAP2010 Conference.

V. Conclusions

In this paper an auto-calibration MIMO-OFDM testbed is presented for spatially characterizing of wideband channels in terms of DoA. A calibration module with linear phase behaviour in the WLAN operation frequency is designed to eliminate the phase error introduced by the RF components at the transmitter and receiver side. The average of the pseudo-spectrum MUSIC over all frequencies improves the resolution of the spatial spectrum giving clear peaks where a signal source is and smoothing fake peaks coming from scatters.

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