Antenna Array Design for Full Duplex Applications

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***Abstract*—This contribution aims to introduce the design, implementation and validation (measurement) of a two-element antenna array for full-duplex relay applications. The antenna array is designed to provide a large isolation between transmission and reception links which is obtained by changing the polarization of the channels and by designing a suitable radiation pattern of the transmission antennas. The design of the antenna array is developed using the characteristic S-parameters of the antenna elements.**

***Index Terms*—Full Duplex, Antenna Array, Antenna Cancellation, Self-interference.**

I. Introduction

Full-duplex transmission using the same time and frequency slot suffers a performance degradation due to the self-interference (SI) problem. The isolation between transmission (Tx) and reception (Rx) channels is the most important limitation to develop full-duplex communications at present.

Several methods have been proposed to maximize the isolation between TX-RX channels [1]. In a full-duplex scenario, the received signal is composed by the signal of interest and the interference generated by the signal from the transmitted antenna (self-interference, SI). Due to the short distance between TX and RX antennas, the SI is stronger than the useful signal and its cancellation/reduction is mandatory.

Self-interference can be reduced by using a combination of antenna isolation techniques (passive), and active methods implemented at the RF analog domain [3], [4] and baseband digital domain. A compilation of these techniques is needed to reduce successfully the self-interference effects. There are two factors that define the required amount of cancellation: a) the dynamic range of the analog-to-digital converter (ADC) placed after the down-converter, and b) the range of the desired signal at the receiver. The dynamic range of the ADC determines the ratio between the powers of the strongest and the weakest received signal power. The SI must be reduced in order to accommodate the received signal at the ADC dynamic range, avoiding saturation. After processing the signal at digital baseband, the reduction of SI at the analog domain is mandatory in order to avoid large quantization noise levels and clipping noise [2].

Combination of passive and active SI cancellation techniques are required to provide an isolation to reduce the SI to the receiver error floor. Considering a WiFi radio system, the receiver error floor is -90 dBm and the maximum transmitted power is 20 dBm. SI cancelers are required to provide 110 dB of attenuation. To accommodate the combined signal (signal of interest and self-interference) on the ADC dynamic range, the passive cancelers need to provide large isolation. In that case, the level of SI is reduced and the quantization noise from the ADC converter can be managed.

This work addresses the design of a full-duplex antenna cancellation technique that obtain large isolation, > 50 dB, to be applied in WiFi frequency band. The performance of the antenna cancellation block is essential to allow a good operation of the digital signal processing (DSP) cancellation techniques applied after down-conversion and ADC converter. It is worth to mention, that the combination of antenna cancellation and DSP techniques is a requisite to obtain the desired performance.

In this work the focus is addressed to the antenna front-end. In that context it is presented the design and implementation of a spatial canceler, shaping the transmission radiating pattern with good results. The reception antennas are treated as independent elements and the signals they received can be further processed by analog and DSP methods to improve the isolation and obtain the requirements aimed for full-duplex implementation [5]. The antenna array final design obtained is of reduced size and fits in the back of a modern laptop (14 inch display).

The paper is organized as follows. The antenna architecture and design are presented in Section 2. Section 3 introduces the architecture and design of the transmission - reception array. In Section 4, array simulations results are presented and discussed. Section 5 introduces the implementation and validation (measurements), followed by conclusions in Section 6.

Note: It is important to note that the WiFi band goes from 2.4 to 2.48 GHz, and our design operates in a slightly upper frequency (2.5 GHz). This operation frequency allow us to done the measurements of the device at conventional laboratory where WiFi signals from several sources cannot be avoided.

II. Antenna architecture and design

Patch Antenna: The proposed antenna is depicted in Fig. 1. The reason to choose this type of antenna is mainly due to its implementation simplicity, low cost and low profile, which makes it as good candidate for our goal. In case that a wider bandwidth is required, another type of antenna can be used (ie., an elevated patch or a slot patch antenna). For the specific design and optimization of the antenna, the CST Microwave Studio computer-aided design tool has been used[6].

In particular, an RF35 substrate from *Taconic* is used, with thickness of 1.52 millimeters, dielectric constant of ϵ= 3.5

and a loss tangent of δ= 0.0018. The final dimensions of the antenna are shown in Fig. 1, values of S_{11} parameter of the antenna are illustrated in Fig. 2.

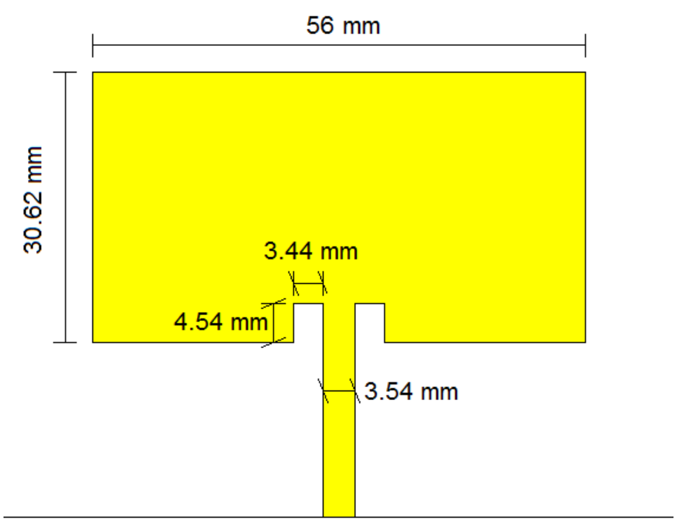

Fig. 1. Dimensions of the patch antenna.

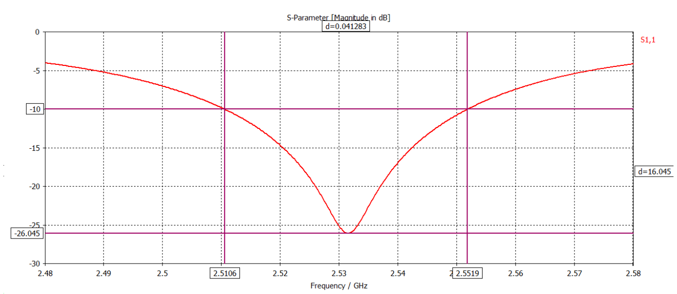

Fig. 2. Simulated S_{11} parameter of the patch antenna.

The center frequency is 2.5315 GHz and the final bandwidth obtained is about 41 MHz.

III. Array Architecture and Design

A. Transmission array

As stated previously, a key objective is to maximize the isolation between the Tx and Rx array. For that reason, Tx radiation pattern is designed to have a null in the direction of the reception antennas. A similar approach is used in [7], but without using the benefits of low profile and cross - polarization isolation. Since the constraint of the dimensions of the screen size of a laptop is used to design the array, it is decided to implement it with a separation of 1.5λ in the central frequency. This selection gives 3 lobes in far-field and allows to feed them with a 180 degrees of phase difference. Unlike [8], both arrays (Tx and Rx) are located in the same side and pointing in the same direction. Starting with the theoretical value of separation, an optimization of the design is made taking as the optimization variable the distance between the transmission antennas. The final dimensions of the transmission array are depicted in Fig. 3.

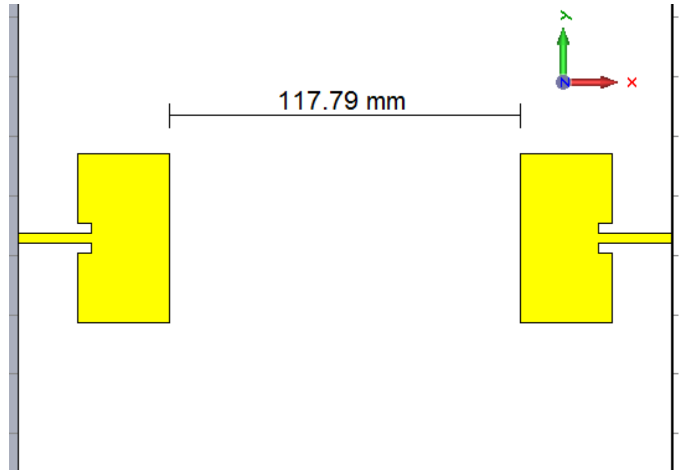

Fig. 3. Dimensions of the transmission array.

The feeding circuit for the transmission antennas is a *rat race coupler* used to make a 180^o phase change between the outputs; two cables of the same length are used to connect the coupler to the antennas. A view of the rat race design is shown in Fig. 4.

The main parameters of the coupler are illustrated in Fig. 5 and 6. As shown in these figures, the isolated port is approximately below -41 dB in the band of interest and the output ports are almost equal with a maximum difference of 0.06 dB in the upper frequency, and a difference of 0.05 dB in the central frequency. In Fig. 6 the phase difference between the output ports is depicted. The design is optimized and a phase difference of 179.908^o in the center of the bandwidth is obtained. With a shift from the bandwidth center a slight deviation from this value is expected (simulations show a deviation from the optimal value (180^o) of -0.604^o in the upper frequency and +0.433^o in the lower).

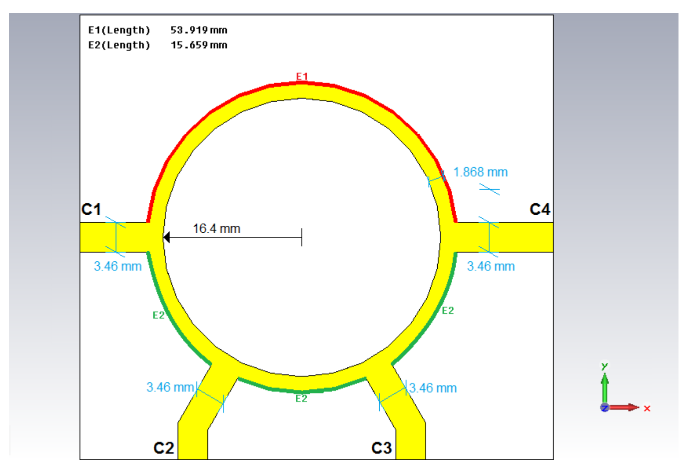

Fig. 4. Dimensions of the coupler.

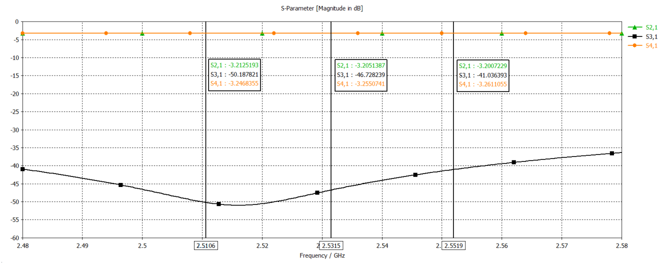

Fig. 5. Simulated S parameters of the coupler.

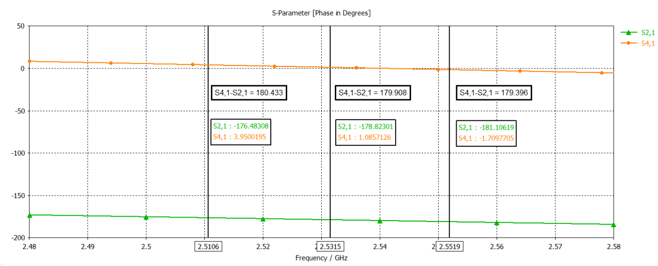

Fig. 6. Simulated phase difference between outputs.

B. Separation between Tx and Rx antennas

To analyze the position of the reception array several simulations were made for different coupling factors. Firstly, a simple simulation was made between one transmission antenna and one reception antenna. The axis position of the reception antenna starts in the middle of the transmission antenna axis. One parameter that can be used to improve the isolation is the polarization of the antennas, as it can be seen in [9]. In this first implementation, a simple patch is used to test the concepts of the design. Further exploitation of this resource can be made by changing the antenna patch used in this paper. With this simulation the cross polarization coupling between transmission and reception antennas is evaluated. In Fig. 7 the setup of the simulation is described and the results are depicted in Fig. 8.

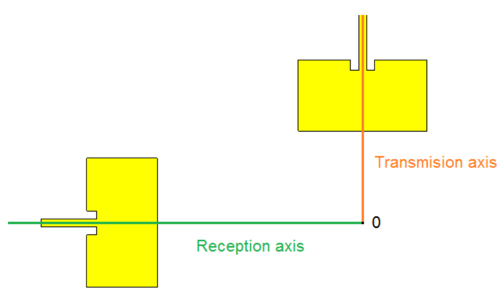

Fig. 7. Polarization coupling simulation setup.

By design, an isolation of at least 30 dB can be observed in Fig. 8, where two regions can be identified. These zones can be exploited in order to maximize the antennas cross-polarization coupling. One is near the axis of the transmission array up to 14,33 mm and the other starts at 102,84 mm

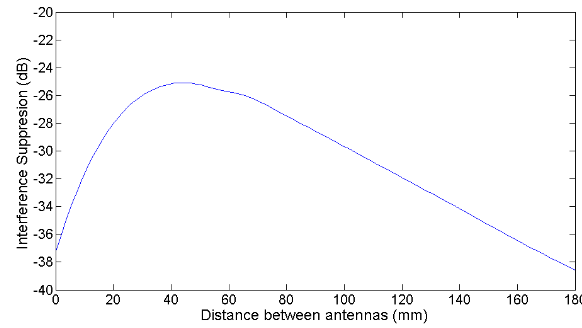

Fig. 8. Cross-polarization coupling versus distance.

(measured from the center of the patch). For our application, the second zone is the optimal because two antennas for the reception array are employed and the transmission array sets a null in that direction. Another limitation arises because of the expected size for the total array, so the maximum possible value for our application is taken, which is 106.26 mm of separation, measured from the center of the reception patch to the transmission axis. This results in a separation between the internal borders of the receptions antennas of 179,88 mm.

IV. Array Simulation Results

A. Array only simulation

The results of the array without the coupler connected are discussed first. That results in a 4 port network with 4 antennas. The isolation between the antennas taking into account only the separation and cross-polarization coupling without the pattern shaping is evaluated. The simulated S parameters are illustrated in Fig. 9, where ports 3 and 4 correspond to the transmission antennas, and ports 1 and 2 correspond to the reception antennas.

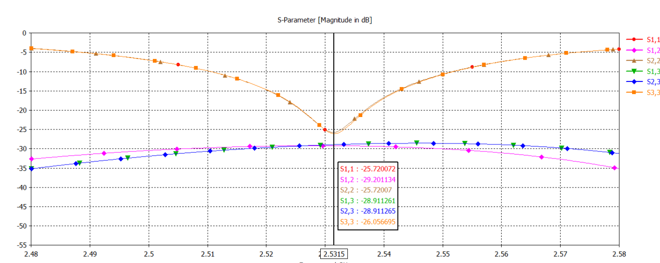

Fig. 9. Simulated S parameters of the array without the pattern shaping.

Fig. 9 illustrates the relation between ports 1, 2 and 3 (the relation between port 4 with 1 and 2 is identical because ports 3 and 4 are symmetrical), where it can be concluded that isolation between Tx and Rx antennas is about 28.51 dB in the band of interest and the isolation between the Rx antennas is about 29.18 dB (worst cases). In spite of that, these isolation levels between Tx and Rx antennas are not still suitable for full-duplex applications. This result motivates the implementation of radiation pattern shaping to tackle this limitation.

B. Complete design simulation

The setup used for this analysis is illustrated in Fig. 10. For this evaluation, it is used the schematic tool of CST Studio [6] connecting both pre-evaluated circuits and performing an S-parameter analysis. In order to allow a fair comparison with the array without shaping obtained previously, the numbering of the ports is the following: ports 1 and 2 are the reception ports, and port 3 now feeds the two transmission antennas going through the coupler.

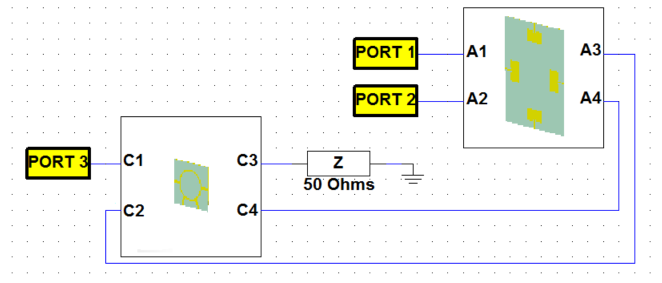

Fig. 10. Design setup for S parameters analysis.

The results (Fig. 11) show a very good improvement in the isolation between Tx and Rx antennas without any modification in the isolation between the Rx antennas. The improvement in the central frequency is about 50 dB and the worst case is located in the upper frequency (40.5 dB). In the band of interest the isolation is higher than 70 dB, which makes this kind of design a good candidate for implementation of a full-duplex antenna array [5].

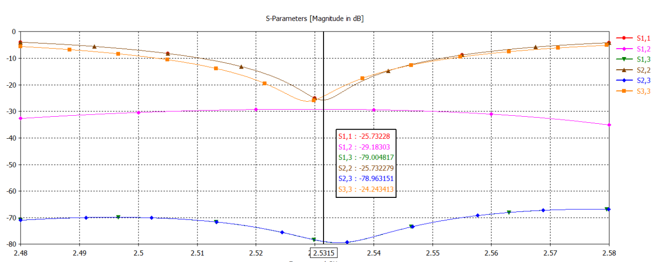

Fig. 11. Design S parameters simulation results.

The radiation pattern of the transmission array was also simulated, as illustrated in Fig. 12, where a perspective of the 3D pattern is presented with the array. It can be appreciated that in the axis of the Rx antennas there are nulls. To visualize in detail the effect of the shaping of the patterns, two cuts are made and illustrated in Fig. 13.

In both cuts it is possible to appreciate that the array design generates a null in the axis of the reception antennas.

V. Implementation and Measurements

The full array implemented is illustrated in Fig. 14. S parameters for the coupler and the antenna array were obtained by using a *Rohde & Schwarz ZVA 24 Vector Network Analyzer* and the results are presented in Fig. 15 and Fig. 16. The

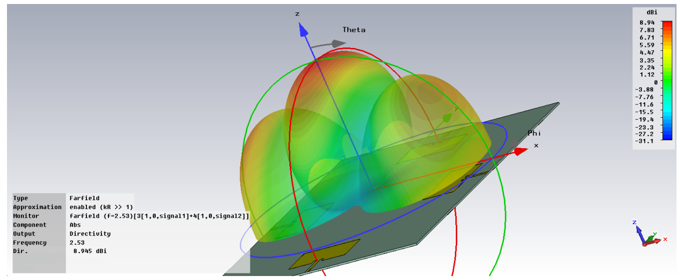

Fig. 12. Design 3D simulated radiation pattern.

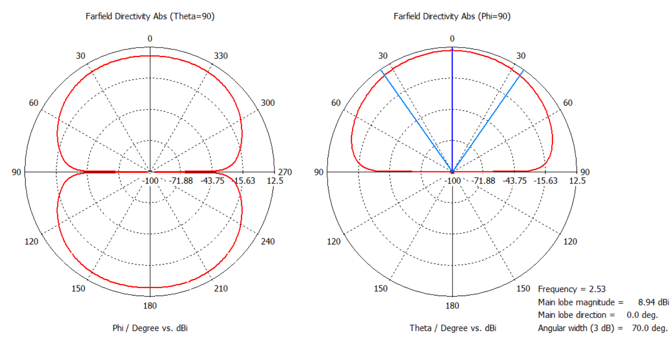

Fig. 13. Design simulated radiation pattern cuts.

results were obtained in a real scenario instead of an anechoic chamber. Therefore, different results between the simulated parameters and the measured ones are expected due to channel reflection effects.

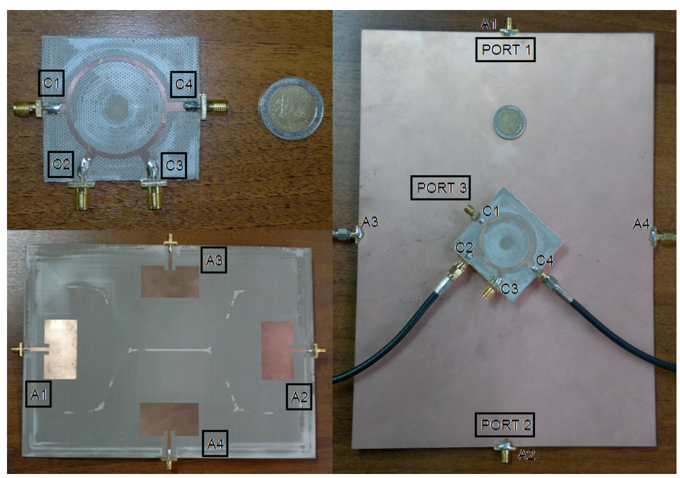

Fig. 14. Implemented array.

As it can be seen in Fig. 15, the parameters found in the measurement are well aligned with the ones obtained in the simulation (Fig. 9). Since S_{13} parameter is a little higher than expected, it is analyzed this result making another measurement and verifying that the difference is produced mostly by the scattering in the room setup. The results of the complete design presented in Fig. 16 show very good improvement in the isolation between Tx and Rx antennas, having more than 50 dB of isolation in the band of interest.

However, it was not possible to obtain the values simulated and presented in Fig. 11 in a real scenario. The worst case of improvement is found in the lower frequency of the band of interest (17.9 dB for one of the reception antennas). In the center frequency the improvement is as high as 31.26 dB for one of the reception antennas and 23.91 dB for the other. The room scattering is the main contributor to this difference between both reception antennas.

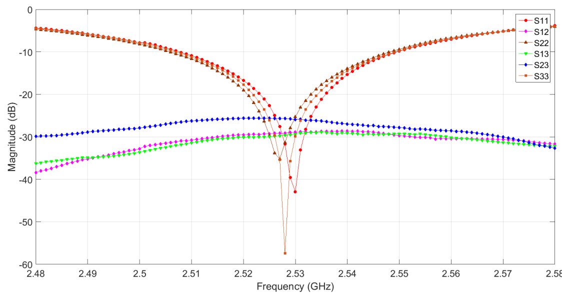

Fig. 15. Measured S parameters of the array without pattern shaping.

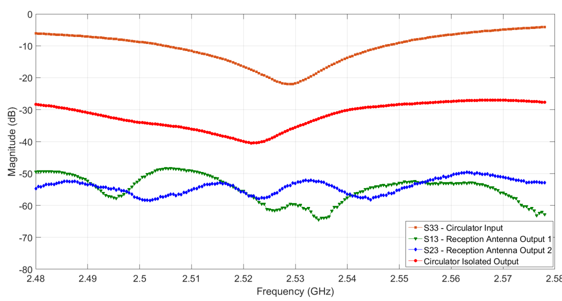

Fig. 16. Complete design S parameters results.

VI. Conclusions

In this paper the design, simulation and implementation of an antenna array for full-duplex transceivers was presented. Measurements in a real scenario were made to validate the true behavior of the complete design. The next steps to be taken to complete the full characterization of the complete design are the measurement of the radiation pattern and the S parameters in an anechoic chamber.

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