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A 2-order MIMO Full-Duplex Antenna System

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***Abstract*—The paper presents an antenna system with combined full-duplex and 2-order multiple-input-multiple-output (MIMO) functionalities, i.e., a system capable of spatially multiplexing and spatially demultiplexing 2 datastreams in the same frequency and in the same time. By exploiting symmetries in the construct and the feed, simple corrective beamforming weights can be applied at the transmitter (Tx) ports in order to selectively cancel the Tx signal at the receiver (Rx) ports, thus guaranteeing a large amount of isolation necessary for full-duplex (i.e., simultaneous and in-band Tx and Rx) operation. On the other hand, the 2 MIMO ports (either at the Tx or at the Rx) are sufficiently decoupled thanks to polarization diversity. The proposed antenna system exhibits a remarkable level of full-duplex isolation over a wide bandwidth while maintaining low coupling between its MIMO ports and can serve as a concrete implementation of an antenna system equipped with both MIMO as well as full-duplex capabilities.**

***Index Terms*—Full-duplex systems, MIMO arrays, antenna isolation.**

I. INTRODUCTION

MIMO systems have been proposed for enhanced spectral efficiency by transmitting and receiving multiple datastreams over the same frequency and time utilizing multiple antennas at the Tx and / or the Rx terminal. While MIMO is becoming a well-established technology in existing and emerging wireless standards [1], [2], future development of wireless communications networks will require additional radical improvements over the current radio transmission and network solutions to support the tremendous growth of data traffic [3]. To this end, full-duplex radio has attracted significant research attention by introducing a new communication paradigm where the same carrier frequency is used for concurrent transmission and reception at the same device. The approach holds the potential to significantly improve the radio network performance, e.g., by effectively doubling the single-link throughput through the utilization of the channel for simultaneous collision-free transmissions and receptions with full data capacity in both directions, by activating the concurrent source-relay and relay-destination links in multi-hop configurations and by facilitating wireless networking [4], [5]. Therefore, transceivers with combined full-duplex and MIMO technologies can significantly boost the capacity of wireless networks and help to meet the ever-increasing datarate demands.

So far, the immense difference between the Tx power level (between $0-30$ dBm, e.g., in WiFi systems) and the sensing radio sensitivity (around -100 dBm) has prohibited practical deployment of full-duplex systems [6]. Hence, the feasibility of full-duplexing depends solely on the ability of isolating the Tx path from the Rx path to a level which ensures that the Tx signal acting as a local self-interference does not affect the Rx sensitivity. Such immense level of required Tx-Rx isolation or *full-duplex isolation* (in the order of 100 dB) is much larger than the isolation level needed to decouple two Tx or two Rx antennas for MIMO capabilities (MIMO isolation).

In order to provide Tx-Rx isolation, active filters have been proposed [5], [7]-[10]. Such digital or analogue filters utilize the knowledge of the local Tx signal to produce a signal that is added at the Rx signal to cancel the self-interference. The addition happens in the Rx baseband after the analogue-to-digital (ADC) conversion (baseband cleaning) [7], [8], or in the Rx radio-frequency (RF) stage (power cancellation) [5], [9], [10], respectively. To generate the cancellation signal, the Tx signal is properly digitally or RF modulated in both amplitude and phase so as to emulate the coupling channel responsible for interference in the Rx. However, when the self-interference is much stronger than the desired signal, the baseband cleaning approach suffers from saturation of the ADC of the Rx, whereas the power cancellation is inherently narrowband and may impact the Tx radiation efficiency [6]. Moreover, the total isolation of $\sim$60 dB obtained by combing active analogue and digital filtering is still not enough to provide full duplexing.

Another approach, a focus of this work, can be found in [6], [11]-[14]. Therein, Tx-Rx isolation for a single-input-single-output (SISO) system is gained by reducing or canceling the coupling trans-impedance between the Tx and Rx ports, thus, unlike power cancellation or baseband cleaning, the approach selectively cancels the Tx power in the Rx direction before arriving at the Rx port. First, this is partially achieved by allocating separate antennas for the Tx and the Rx. Secondly, by equipping the Tx with redundant antenna elements or ports, the Tx signal can be properly weighted (either in baseband or the RF) and nulled in the Rx direction. Such a technique, herein referred to as corrective beamforming, reportedly provided $\sim$73 dB of wideband isolation in a SISO configuration which can be further enhanced by subsequent active digital or analogue filtering stages [6].

In this work, we take a step further to propose an antenna system with combined full-duplex and MIMO capabilities. Unlike [6], [11]-[14], the full-duplex MIMO system must be thoughtfully designed to achieve the required large isolation for full-duplexing (full-duplex isolation) within a MIMO setup. Therefore, with more than a single Tx and Rx communication ports for MIMO, the challenge here is to maintain significantly high isolation among all possible

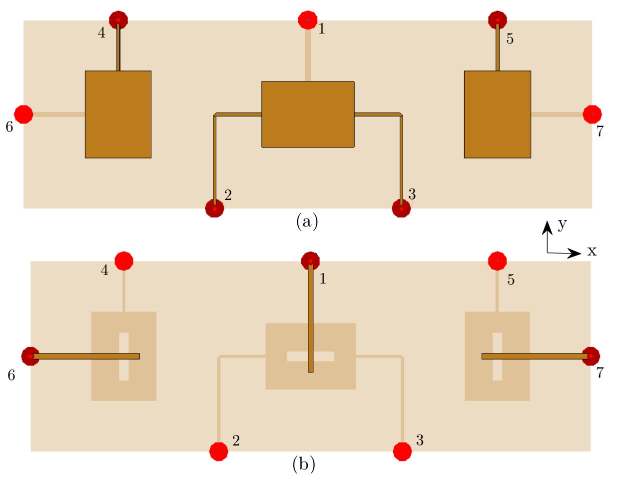


Fig. 1. Symmetric topology of three side-by-side patch antennas: (a) top view and (b) bottom view. On the two outer patches the Tx feeds are deployed whereas the Rx ports are deployed on the central patch.

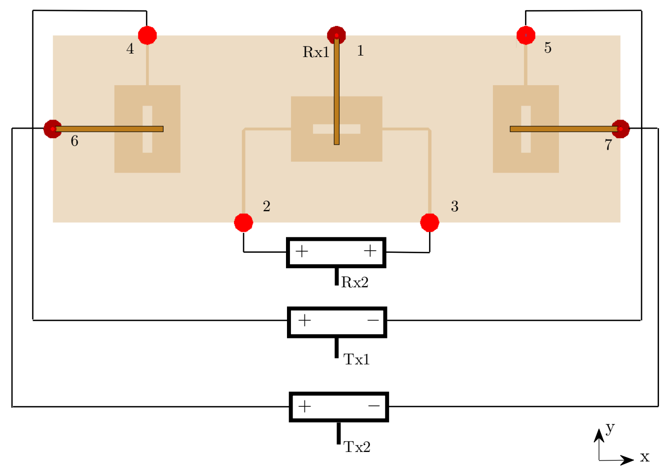


Fig. 2. Symmetric topology of three side-by-side patch antennas (bottom view) showing the out-phasing and the in-phasing of the Tx and the Rx signals for Tx signal cancellation at the Rx.

Tx-Rx pairs. In the same time, low coupling should exist among the system's communication ports both at the Tx as well as at the Rx in order to permit space-time processing (MIMO isolation). Specifically, we propose an antenna system of 2 Tx and 2 Rx ports intented for spatial multiplexing and demultiplexing of 2 datastreams in the same frequency and in the same time. This is made possible by applying the corrective beamforming scheme properly extended for the full-duplex MIMO setup within a symmetric system topology. The proposed system achieves ∼70 dB of full-duplex isolation which is not compromised with Tx efficiency or bandwidth. The isolation will be evaluated in an environment with minimal reflections from the scattering channel back to the Rx ports which can be assumed deterministic. If this condition is not met then adaptive full-duplexing can be enabled by adapting the corrective beamforming weights in a dynamic manner. Moreover, the 2 MIMO ports during both at transmission and at reception are isolated thanks to more than 21 dB of wideband decoupling coming from polarization diversity. It is noted since the MIMO isolation comes from such a dual-polarization configuration, the MIMO ports will generally remain sufficiently decorrelated under both line-of-sight (LOS) and non LOS scattering channels [15]. The proposed design can serve as a concrete implementation of an antenna system offering combined full-duplex and 2-order MIMO capabilities.

The rest of the paper is organized as follows. Section II describes the proposed full-duplex MIMO antenna system and explains the corrective beamforming technique for selectively canceling the signal coming from the 2 Tx ports in the direction of the 2 Rx ports. Certain practical aspects of the proposed approach are also discussed. Section III evaluates the full-duplex as well as the MIMO isolation performance of the proposed antenna system. Finally, Section IV concludes the paper.

II. Proposed Full-duplex MIMO Antenna Topology

We consider a symmetric antenna topology where three patch antennas are located on the top layer of a three-layer substrate and ground plane configuration shown in the top and bottom views of the system in Fig. 1. The three layers comprising each patch are as follows from top to bottom: a) a substrate layer with the radiation patch and coplanar-fed microstrip line(s) on its upper surface, b) the ground plane layer with a rectangular coupling slot, and c) a second substrate layer with an aperture-coupled feeding line on its lower surface. At each patch element, the coplanar-fed microstrip line and the aperture-coupled feeding line(s) excite two orthogonal polarizations. A rectangular microstrip patch is chosen as the radiation element because of its simple structure and good radiation characteristics of the orthogonal polarization.

Since the corrective beamforming approach generally uses redundant and properly weighted Tx ports for nulling the self-interference of the device in the direction of its Rx ports [6], the Rx ports are considered only on the central patch of the proposed antenna system, whereas the Tx ports are placed on the two outer patches. Specifically, a total number of 7 ports employed in the three-patch antenna system of Fig. 1 shall be properly grouped and weighted in order to provide the desired self-interference cancellation in a MIMO setup as explained in the following.

A. *Self-interference Cancellation in a 2-order MIMO setup via Corrective Beamforming*

Let $\mathbf{S}_\mathrm{A}$ denote the $7{\times}7$ standard scattering matrix of the 7-port antenna system in Fig. 1, with entries S_{ij}, $\{i,j\} \in \{1,2,\ldots,7\}$, where $S_{ij}{=}S_{ji}$, $i \neq j$ by reciprocity in a linear medium. Moreover, due to the symmetries of the topology in Fig. 1, the matrix can be assumed to have

$$S_{61} \cong S_{71}, \; S_{41} \cong S_{51}, \; S_{62} \cong S_{73},$$

$$S_{63} \cong S_{72},\ S_{42} \cong S_{53},\ S_{43} \cong S_{52}. \tag{1}$$

With reference to Fig. 2, the first MIMO Rx port, namely Rx1 is assigned to port 1, whereas the second MIMO Rx port, namely Rx2 is the result of the combination of ports 2 and 3. On the other hand, the first MIMO Tx port, namely Tx1, is obtained by grouping ports 4 and 5. Similarly, Tx2 is the result of grouping the ports 6 and 7. In this way, the Rx ports Rx1 and Rx2 are dual-polarized and so is the case for the Tx ports Tx1 and Tx2. Such orthogonal polarization will provide us with the *MIMO isolation* for both reception and transmission. Moreover, ports Rx1, Rx2, Tx1 and Tx2 are pair-wise symmetric. Such symmetry permits as to apply simple corrective beamforming weights on the Tx ports in order to cancel the Tx signal toward the Rx ports. To explain, we assume that the Tx1 ports 4 and 5 are weighted with $1/\sqrt{2}$ and $-1/\sqrt{2}$, i.e., the power is simply equally split across the two ports which are out-phased by π radians. The same weights are applied to the Tx2 ports 6 and 7. The digital operation of such corrective beamforming on the Tx ports 4 and 5 as well as on the ports 6 and 7, together with port combining of ports 2 and 3 to construct Rx2 can be written with the 7×4 transfer matrix $\mathbf{W}$ in an analogue representation as follows

$$\mathbf{W}^{\mathrm{T}} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & +\frac{1}{\sqrt{2}} & +\frac{1}{\sqrt{2}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & +\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & +\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{bmatrix}, \tag{2}$$

where superscript T denotes the transpose operator. By cascading $\mathbf{W}$ with $\mathbf{S}_{\mathrm{A}}$ the resulting 4×4 scattering matrix $\mathbf{S}_{\mathrm{C}}$ of the 2-order full-duplex MIMO system becomes

$$\begin{aligned} \mathbf{S}_{\mathrm{C}} &= \mathbf{W}^{\mathrm{T}}\mathbf{S}_{\mathrm{A}}\mathbf{W} \\ &:= \begin{bmatrix} S_{\mathrm{Rx1Rx1}} & S_{\mathrm{Rx1Rx2}} & S_{\mathrm{Rx1Tx1}} & S_{\mathrm{Rx1Tx2}} \\ S_{\mathrm{Rx2Rx1}} & S_{\mathrm{Rx2Rx2}} & S_{\mathrm{Rx2Rx1}} & S_{\mathrm{Rx2Tx2}} \\ S_{\mathrm{Tx1Rx1}} & S_{\mathrm{Tx1Rx2}} & S_{\mathrm{Tx1Tx1}} & S_{\mathrm{Tx1Rx2}} \\ S_{\mathrm{Tx2Rx1}} & S_{\mathrm{Tx2Rx2}} & S_{\mathrm{Tx2Tx1}} & S_{\mathrm{Tx2Tx2}} \end{bmatrix}, \end{aligned} \tag{3}$$

representing the equivalent transfer function of the digital feeding $\mathbf{W}$ in (2). The above operation results in the following expressions for the cross-coupling channels between the two Tx's and the two Rx's

$$\begin{aligned} S_{\mathrm{Rx1Tx1}} &= S_{\mathrm{Tx1Rx1}} = (S_{41} - S_{51})/\sqrt{2} \cong 0 \\ S_{\mathrm{Rx1Tx2}} &= S_{\mathrm{Tx2Rx1}} = (S_{61} - S_{71})/\sqrt{2} \cong 0, \end{aligned} \tag{4}$$

due to the symmetries in (1). Similarly,

$$\begin{aligned} S_{\mathrm{Rx2Tx1}} &= S_{\mathrm{Tx1Rx2}} = [(S_{42} - S_{52}) + (S_{43} - S_{53})]/\sqrt{2} \cong 0 \\ S_{\mathrm{Rx2Tx2}} &= S_{\mathrm{Tx2Rx2}} = [(S_{62} - S_{72}) + (S_{63} - S_{73})]/\sqrt{2} \cong 0. \end{aligned} \tag{5}$$

From (4) and (5), the cross-coupling between all possible Tx and Rx pairs in this antenna system has been designed to be almost zero to provide the desired *full-duplex isolation*.

B. Remarks

Certain observations should be made:

- The approximate inequality symbol $\cong$ has been used instead of the equality symbol in (1), since in practice the antenna elements and ports may not be manufactured with infinite accuracy (i.e., perfectly identical and exactly symmetrical) [13]. Consequently the obtained full-duplex isolations in (4) and (5) will depend on the level up to which the scattering coefficients in (1) are equal in both amplitude and phase.
- Viewing the cross-coupling channels between the two Tx's and the two Rx's as the scattering parameters of the final 4-port full-duplex MIMO antenna system in (4) and (5), assumes near-field LOS conditions between the local Tx's and Rx's, i.e., other reflections from the surrounding environment affecting the Tx-Rx channel (such as far-field scatterers) are minimal or can be assumed deterministic. This is due to the vicinity of Tx and Rx antennas, causing the near-field effects to be significant and dominate the system behavior [16]. Nonetheless, in the case where the far-field surrounding environment varies substantially, then adaptive digital weights could be applied in the ports comprising Tx1 and Tx2 [6].
- The MIMO isolation expressed via S_{Tx1Tx2} and S_{Rx1Rx2} is provided due the dual-polarized configurations among Tx1 and Tx2 as well as among Rx1 and Rx2. The antenna decorrelation coming from such isolation is generally robust to variations in the far-field scattering channel conditions as explained in [15].
- In case of near-field disturbances, such as those incurred by the user proximity, then the full-duplex isolation (as well as the MIMO isolation to a smaller extent) may need to be adaptively compensated for. In this case, adaptive weights should be applied before combining the ports. However, the proposed system can be generally deployed on small base stations / access points being unaffected by near-field disturbances.

III. Performance Evaluation

In this part, the computer simulation results of the proposed antenna system are provided. The detailed dimensions for each patch antenna are shown in Fig. 3 whereas the total area of the three-patch antenna system is 180 x 60 mm^2. Moreover, the thickness of each of the three layers is 1 mm. The top substrate and bottom layers of each patch are made of FR-4 whereas the radiating patches are made of annealed copper. The simulated scattering parameters $\mathbf{S}_{\mathrm{A}}$ of the 7-port antenna system where obtained using the transient solver in frequency domain from CST MICROWAVE STUDIO.

Fig. 4 shows the simulation results for the return losses and the coupling levels of the resulting 4-port antenna system after applying the weighting matrix $\mathbf{W}$ to $\mathbf{S}_{\mathrm{A}}$ as in (3) and self-conjugate matching [17] at 2.45 GHz center frequency. It can be seen from the Fig. 4 that the minimum full-duplex isolation between the transmit and receive ports is in the order of 70

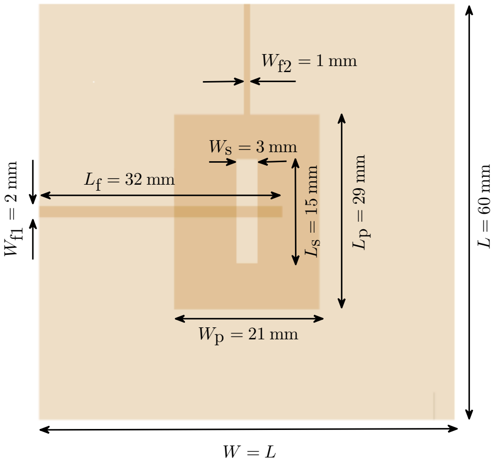


Fig. 3. Dimensions (in mm) of one of the 3 patches (bottom view) comprising the proposed full-duplex MIMO antenna system.

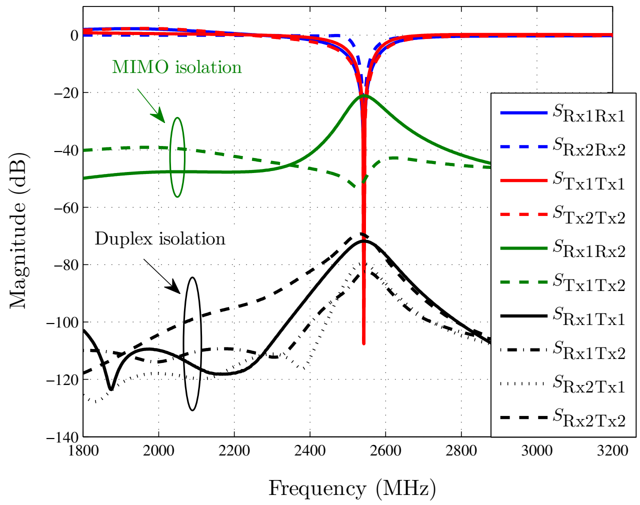
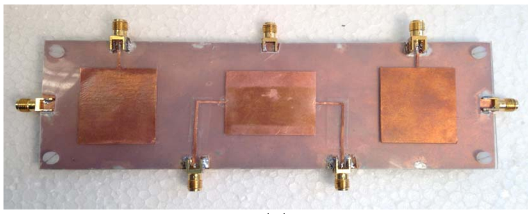


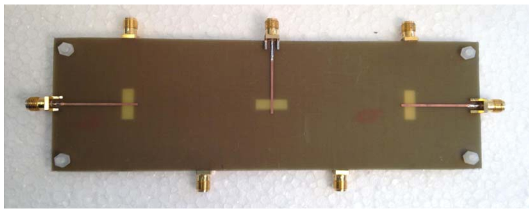
Fig. 4. Frequency response of the 4-port full-duplex MIMO antenna system after applying corrective beamforming on Tx1 and Tx2, port-combining on Rx2 and self-conjugate matching.

dB showing a significant amount of wideband self-interference cancellation. On the other hand, due to the orthogonal polarization between the two feeds on the rectangular patch we have obtained a considerable amount of MIMO isolation (21.5 dB between Tx1 and Tx2 and 50 dB between Rx1 and Rx2) which allows for MIMO processing. The fact that the pair Tx1-Tx2 presents higher MIMO isolation compared to the pair Rx1-Rx2 is due to the fact that the L-shaped coplanar-fed microstrip lines at ports 2 and 3 comprising Rx2 couple more strongly to the aperture-coupled feeding line at port 1 of Rx1, compared to the corresponding feeding lines of Tx1 and Tx2 which are purely cross-polarized.

An initial antenna prototype has been fabricated as shown in the photograph illustrated in Fig. 5. Future work will include the measurement results of the fabricated passive mockup (not included here due to time limitations) with the possibility of an active adaptive weight mechanism evaluated in both static and varying scattering conditions.



(a)



(b)

Fig. 5. A preliminary fabricated prototype of the proposed full-duplex MIMO antenna system: (a) top view and (b) bottom view.

IV. Conclusion

A 2-order MIMO full-duplex antenna system has been proposed in this work by utilizing symmetry in the shape and the feeding. The full-duplex functionality has been achieved by synthesizing a spatial filter where two outer patch antennas are out-phased with respect to a central one. Furthermore, the MIMO functionality is enabled by maintaining orthogonality among the MIMO modes utilizing inherent polarization properties of patch antenna elements.

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