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The performance of an antenna cancellation technique for a multiple-input–multiple-output (MIMO) full-duplex system that is based on null-steering beamforming and antenna polarisation diversity is investigated. A practical implementation of a symmetric antenna topology comprising three dual-polarised patch antennas operating at 2.4 GHz is described. The measurement results show an average of 60 dB self-interference cancellation over 200 MHz bandwidth. Moreover, a decoupling level of up to 22 dB is achieved for MIMO multiplexing using antenna polarisation diversity. The performance evaluation of the proposed technique was performed by simulation and measurement and the results have good agreement.

Introduction: Recently, full-duplex (FD) systems have attracted a lot of interest in the research community for their ability to allow a radio terminal to transmit and receive simultaneously on the same frequency band. FD systems can potentially double the rates that can be achieved in half-duplex systems. However, it is very difficult to achieve this in practice due to implementation challenges. Usually, the self-interference (SI) cancellation techniques that were proposed in earlier works use a combination of analogue-circuit, digital techniques or exploit propagation properties [1–4]. Most of these works consider the use of SI cancellation techniques mainly for a single-input–single-output system. Notably, there exist only a few experimental works that evaluated the FD-multiple-input–multiple-output (MIMO) system, such as the work presented in [5]. However, in [5] SI is attenuated mainly due to the propagation path loss over the SI channel.

In our previous work [6], we proposed an SI cancellation technique based on a combination of null-steering beamforming and antenna polarisation diversity. In this Letter, we follow up this work by providing the experimental results for the proposed technique in [6]. Our measurement results show that using the proposed technique, SI can be effectively mitigated up to 60 dB. Additionally, we show that the proposed technique can achieve a decoupling level of up to 22 dB to allow MIMO multiplexing.

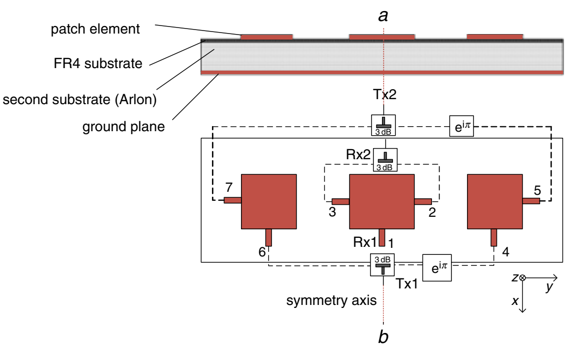

Fig. 1 *Symmetric antenna topology*

a Side view of structure with different layers
b Top view of antenna structure with feeding network

Antenna cancellation topology: We designed a symmetric antenna system consisting of three dual-polarised patch antennas. Side and top views of our proposed antenna topology are shown in Fig. 1. The antenna structure is composed of three layers: (i) a top layer of 0.5 mm thickness FR4 substrate ($\varepsilon_r = 4.1$, $\tan\delta = 0.025$ at $f = 2.4$ GHz) with the printed patch antenna elements, (ii) a middle layer substrate made of Arlon Cu 217Lx material ($\varepsilon_r = 2.1$, $\tan\delta = 0.0009$ at $f = 2.4$ GHz) with 6 mm thickness and (iii) a ground plane layer. We used extra transmit antennas (ports 4 and 5 in Fig. 1) to exploit the use of null-steering beamforming for an improvement of SI cancellation. As a result, the two outer patch antennas located symmetrically with respect to the centre patch act as null-steer beamformers. The first MIMO receive (Rx) port, namely Rx1 assigned to port 1 is placed symmetrically from the x-axis. To maintain the symmetry in the antenna topology from the x-axis, we introduced port Rx2 by combining ports 2 and 3. Principally, to achieve perfect SI cancellation in the direction of the receiver, the outer patch antenna (ports 4 and 5) is phase shifted by π. The input signal power at MIMO transmit (Tx) port Tx1 is equally split between ports 6 and 4, whereas the signal at port 4 is shifted by π. Similarly, we formed the second MIMO transmit port, Tx2 by grouping ports 5 and 7.

The mapping from the internal 7-port system to the external 4-port system is performed using the following weight matrix $\boldsymbol{B}$:

$$\boldsymbol{B}^{\mathrm{T}} = \begin{array}{c} \\ Rx_1 \\ Rx_2 \\ Tx_1 \\ Tx_2 \end{array} \begin{array}{c} \begin{array}{ccccccc} P_1 & P_2 & P_3 & P_4 & P_5 & P_6 & P_7 \end{array} \\ \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & +\frac{1}{\sqrt{2}} & +\frac{1}{\sqrt{2}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & +\frac{1}{\sqrt{2}} & 0 & -\frac{1}{\sqrt{2}} & 0 \\ 0 & 0 & 0 & 0 & +\frac{1}{\sqrt{2}} & 0 & -\frac{1}{\sqrt{2}} \end{bmatrix} \end{array} \qquad (1)$$

where $[.]^{\mathrm{T}}$ denotes a transpose of a matrix. As a result, a 4×4 S-parameter matrix of the FD-MIMO system can be obtained by multiplying matrix $\boldsymbol{S}_A$ by $\boldsymbol{B}$, as follows:

$$\boldsymbol{S}_C = \boldsymbol{B}^{\mathrm{T}} \boldsymbol{S}_A \boldsymbol{B} \qquad (2)$$

where $\boldsymbol{S}_A$ is the scattering matrix of the 7-port antenna system.

Performance evaluation: First, we simulated and optimised the performance of our proposed antenna system using a transient solver in time domain from CST Microwave Studio 2013 software. A prototype of the proposed FD-MIMO system was fabricated and measured using a 2-port vector network analyser. To avoid reflections from the surrounding environments, we measured our results in an anechoic chamber. For stability of the antenna prototype, we used eight nylon screws to attach the three substrates. The geometric dimensions of the antenna prototype are shown in Fig. 2.

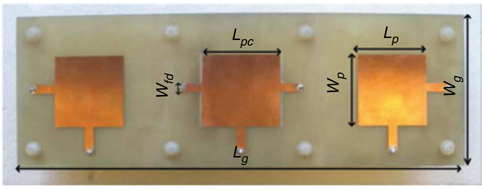

Fig. 2 *Fabricated antenna prototype*

Dimensions: $L_g = 240$ mm, $W_g = 80$ mm, $W_p = L_p = 37.5$ mm, $L_{pc} = 41$ mm and $W_{fd} = 4.5$ mm

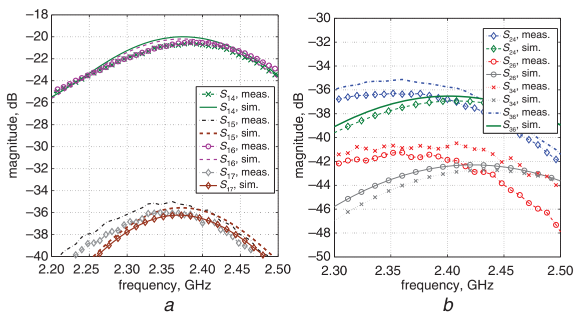

Fig. 3 *Isolation between selected ports*

a Coupling between transmitters and Rx1
b Coupling between cross-polarised transmitters and Rx2

The mutual coupling between ports was obtained by selecting two ports and terminating the other ports with a standard 50 Ω matching load. Although theoretically the coupling between each transmit–receive antenna pairs can be achieved with a perfect symmetry, in practice this is not the case. As a result of manufacturing tolerance, the S-parameter inequalities are introduced. Fig. 3 shows the measurement and simulation results of the isolation between different selected ports. The antenna is operating at 2.4 GHz with 8.5% bandwidth with a return loss of <−6 dB. Fig. 3*a* shows the isolation between the transmit ports and MIMO receiver port Rx1. It can be seen that the isolation level of 20 dB is obtained for the co-polarised antenna pairs. On the other hand, the isolation level for the cross-polarised antenna pairs is about −36 dB. Fig. 3*b* depicts the results for the isolation between MIMO port Rx2 (ports 2 and 3) and cross-polarised transmit ports, whereas the isolation level for these ports is in the range of 36–43 dB. Additionally, the results show an *S*-parameter imbalance variation of up to 1 dB between the transmit–receive antenna pairs. This variation results from the fabrication tolerance which can be also observed in the simulation results by shifting the centre patch element by 0.5 mm to one side.

The *S*-parameters for a 4-port FD-MIMO system are obtained according to (2). Fig. 4 shows the results for return losses and coupling levels of a 4-port MIMO system. On average, 60 dB SI cancellation can be observed from the measurement results and this complies with our simulation results. As indicated in Fig. 4*b*, the use of orthogonal polarisation between MIMO ports provides an 18 dB decoupling level at the centre frequency between ports Rx1 and Rx2, and 22 dB between ports Tx1 and Tx2. The total efficiency of MIMO port Rx1 was measured using Satimo Starlab [7]. The antenna has a high efficiency over the entire bandwidth with a maximum efficiency of −1.6 dB at the centre frequency.

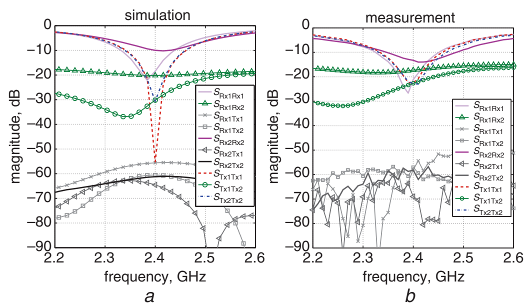

Fig. 4 *Frequency response of 4-port FD-MIMO system*

a Simulation results for scenario where centre patch is offset by 0.5 mm from centre
b Results from measured *S*-parameters

To investigate the impact of manufacturing inaccuracy on the isolation level, we considered three scenarios: (i) a scenario where the centre patch with the microstrip feed lines is shifted from the centre to one side; (ii) only the centre patch element shifted to one side; and (iii) the top layer substrate rotated to one direction. For the first and second scenarios, we considered the offset variations of 0.25, 0.5 and 0.75 mm from the centre and for the last scenario the rotation variations were 0.25°, 0.5° and 0.75°. Fig. 5 shows the simulation results of isolation variation between different ports at the centre frequency. The results indicate 10 dB isolation variations for the first and second scenarios. In addition, the scenario where the patch element is shifted from the centre has a higher impact on the isolation level compared with the first case. In the case of the third scenario, the isolation between co-polarised ports (S_{Rx1Tx1} and S_{Rx2Tx2}) is less affected by rotation compared with the isolation between cross-polarised ports (S_{Rx1Tx2} and S_{Rx2Tx1}). Overall, precision within 0.2 mm is necessary to achieve at least 60 dB SI cancellation.

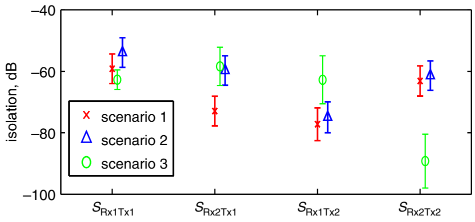

Fig. 5 *Impact of manufacturing inaccuracy on isolation level*

Conclusion: We have proposed an antenna cancellation technique for a FD-MIMO system. Based on simulation and measurement results, we have proved that the proposed technique is feasible. With the proposed technique, we obtained an average 60 dB SI cancellation level with a bandwidth of 8.5%. In addition, an up to 22 dB MIMO decoupling level is obtained due to the use of polarisation diversity. The proposed topology for SI cancellation can be achieved when the channel between the transmitter and the receiver is static with an LOS component. In the case of a dynamic channel, adaptive beamforming weight can be used to cancel the SI. The proposed technique can be employed in a wireless access point or a relay, where the influence of the surrounding objects is minimal. In future work, in order to completely suppress the SI, we will investigate concatenating different cancellation stages including the proposed technique.

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One or more of the Figures in this Letter are available in colour online.

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References

1 Jain, M., Choi, J.I., Kim, T., *et al.*: 'Practical, real-time, full duplex wireless'. Proc. 17th Annual Int. Conf. Mobile Computing Networking (Mobicom), Las Vegas, NV, USA, September 2011, pp. 301–312
2 Duarte, M., and Sabharwal, A.: 'Full-duplex wireless communications using off-the-shelf radios: feasibility and first results'. Proc. 44th Asilomar Conf. Signals, Systems and Computers, Pacific Grove, CA, USA, November 2011, pp. 1558–1562
3 Bharadia, D., McMilin, E., and Katti, S.: 'Full duplex radios'. Proc. ACM Sigcomm, Hong Kong, China, August 2013, pp. 375–386
4 Snow, T., Fulton, C., and Chappell, W.J.: 'Transmit-receive duplexing using digital beamforming system to cancel self-interference', *IEEE Trans. Microw. Theory Tech.*, 2011, **59**, (12), pp. 3494–3503
5 Duarte, M., Sabharwal, A., Aggarwal, V., *et al.*: 'Design and characterization of a full-duplex multiantenna system for WiFi networks', *IEEE Trans. Veh. Technol.*, 2014, **63**, (3), pp. 1160–1177
6 Tsakalaki, E., Foroozanfard, E., de Carvalho, E., and Pedersen, G.F.: 'A 2-order MIMO full-duplex antenna system'. Proc. 8th European Conf. Antennas Propagation (EuCAP), The Hague, The Netherlands, April 2014, accepted
7 Available at http://www.satimo.com/content/products/starlab