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Wideband Full-Duplex MIMO: A 5×5 Example Across 12.5-13.0 GHz with Baseband 100 MHz

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Abstract

Full-duplex wideband wireless radios with MIMO is a challenging open problem in communications. The adoption of a pair of arrays for physical symmetry-based passive cancellation of self-interference between antenna elements is demonstrated in the FR3 band. Up to 12 dB of additional self-interference cancellation (SIC) is observed. Further, machine learning-based DSP is used to mimic the nonidealities of each power amplifier in the MIMO system, thereby allowing additional 22 dB of digital SIC. A linear FIR MIMO filterbank is envisaged for cancelling environmental reflections across the MIMO interface. Work on both MIMO-RF and DSP-based cancellation is reported in the FR3 range of 12.5-13.0 GHz band with a DSP bandwidth of 100 MHz on Xilinx RF-SoC ZCU-111.

1 Introduction

The FR3 band (6-20 GHz) is receiving much attention due to favorable propagation characteristics for wireless links in dense urban settings. The band is usually assigned to multiple government applications, making spectrum expensive and highly sought-after by multiple entities. The ability to *listen while talk (LWT)* is a crucial capability, leading to real-time spectrum-sharing schemes, including dynamic spectrum sharing (DSA). Simultaneous transmit and receive (STAR) full-duplex radios in the FR3 band can support multiple-input multiple-output (MIMO) front-ends. STAR is applicable to a variety of high-capacity communications, DSA, spectrum sensing and other relevant applications spanning imaging, intelligence, and electronic warfare [1-2].

2 System Overview

Massive-MIMO allows for unbounded capacity that increases linearly with the number of independent spatial channels, i.e., transceivers and antennas. Massive MIMO is the dominant technology for scalable 6G wireless systems. We propose a MIMO-capable STAR front-end that cancels self-interference between every transmit antenna and every receive antenna in arrays [3,4].

The proposed approach is scalable due to its simple physical symmetry present in the near-field coupling of the antenna array. Key to this paper is the use of a second array, A_{CH}, that is physically and electrically identical to the communicating antenna, A_{COM}. This second array, A_{CH}, serves as a reference to acquire a more precise canceling signal that duplicates the one transmitted with all coupling effects and component non-idealities. A communication array A_{COM} is complemented by a second array A_{CH} that is designed to be physically and electrically identical. That is, array mutual coupling in A_{CH} is identical to that is A_{COM}. Notably, A_{COM} is open to the actual radio environment while A_{CH} is located inside an electromagnetically shielded (anechoic) chamber, shown in Fig. 1. Understandably, the mutual coupling between the elements of the transmitting array is replicated in the second array. Pairwise differential connections between array elements allows passive subtraction of self-interference, since received signals are not present inside the shielded chamber.

The proposed method is both simple and effective in solving the extremely challenging full-duplex MIMO STAR self-interference issue. In fact, use of the array pair $\{A_{COM}, A_{CH}\}$ solves the SIC challenges for MIMO when circulators are not used [3,4].

Despite not using circulators [3], the array-pair method is suitable for decoupling MIMO transmit waves from receive channels across an array of N elements. The SIC performance of the proposed array-pair MIMO canceller is ultimately limited by impedance mismatches and fabrication tolerances. As a result, additional multistage analog cancellations are required via analog tunable delay-line (ATDL) based SIC filters.

We assume the presence of both antenna array (stage-1) and ATDL-based analog cancellation (stage-2) stages within the MIMO radio RF front-end. We also proposed digital cancellation for the remaining self-interference cancellation. This is done using digital signal processing (DSP) within the software-defined radio (SDR) back-end. Specifically, we use a Xilinx RF-SoC evaluation board (ZCU-111) capable of 5x5 MIMO for wideband MIMO processing, including DSP-based SIC.

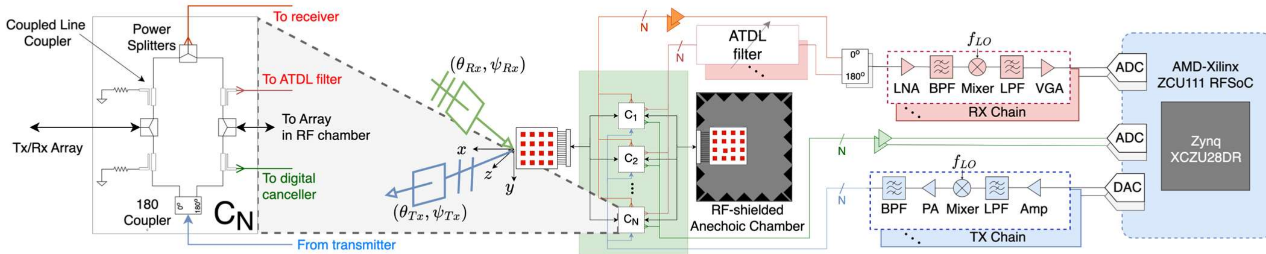

Figure 1. Wideband full-duplex radio with MIMO. Identical twin array is located inside a miniaturized radio frequency (RF) shielded anechoic chamber. The DSP backend operates on the AMD-Xilinx RF-SoC ZCU-111 FPGA platform.

The prototype consists of a uniform linear array (ULA) of antennas designed to provide 500 MHz of baseband bandwidth. The intent is for high-capacity wireless in the FR3 band (12.5-13.0 GHz). Although higher bandwidths are possible, the limitation is due to DSP algorithms for channel estimation, SIC, power amplifier (PA) linearization, modulation, and coding. These algorithms are difficult to operate in real-time for greater than 500 MHz of baseband bandwidth using RF-SoC technology, without resorting to multi-rate systolic processors. Thus, in this early work, we simplify requirements and focus on achieving 100 MHz of baseband MIMO processing in real-time on the RF-SoCs.

3 Electromagnetics of the Radio Interface

Following our early work in the sub-6 GHz band [3,4], we extend the array-pair cancellation-based front-end to the FR3 band. Notable, going from a 2.4 GHz system to a 12.5 GHz implies a 5x increase in RF frequency. Therefore, planar antennas would be 5x5=25 times smaller by area, and 125 times smaller in near-field volume. As such, they fit in the miniature RF-shielded anechoic (about the size of an iPhone box). Accordingly, we developed antenna arrays that operate within the 12.5-13.0 GHz band. Fig. 2 shows a photograph of a 5-element array with the measured S-parameters shown in Fig. 3. It is observed that the measured return losses are below -12 dB within the band of interest for all elements, implying excellent matching to the 50 Ω port. In addition, the mutual coupling of less than -25 dB across the FR3-range of interest of 12.5-13.0 GHz band.

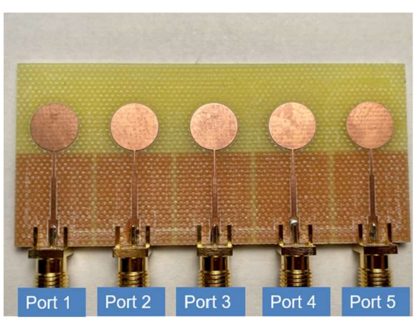

Figure 2. Photograph of 5-element ULA operating in the 12.5-13.0 GHz sub-band within the FR3 band.

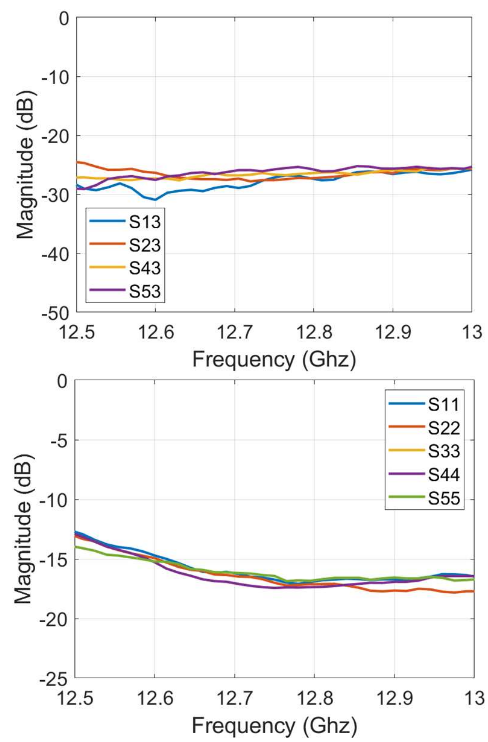

Figure 3. Measurements: (bottom) return loss, and (top) mutual coupling with reference to the middle element (#3).

Experiments: To explore the self-interference improvement using the proposed array pair $\{A_{COM}, A_{CH}\}$, we used two 5x1 arrays optimized for the 12-13 GHz band. This is done using a wideband microwave splitter (Model SCS-0131831215-SFSF-22) and subtractor (Model SCZ-1031831518-SFSF-43), as shown in Fig. 4.

It is noted that the splitter used to supply equal power to the array pair $\{A_{COM}, A_{CH}\}$ causes an inevitable ~3 dB loss in transmit power. To measure the self-interference using the array pair set-up, the S parameters were measured between two MIMO Rx/Tx ports, as depicted in Fig. 4. First, the RF mutual coupling between element 3 and its neighbor (element 2) of the array was measured and found to be about -25 dB in the 12.5-13.0 GHz band. Also, the mutual coupling between the Rx/Tx ports *a* and *b* was reduced to around -37 dB, as shown in Fig. 5.

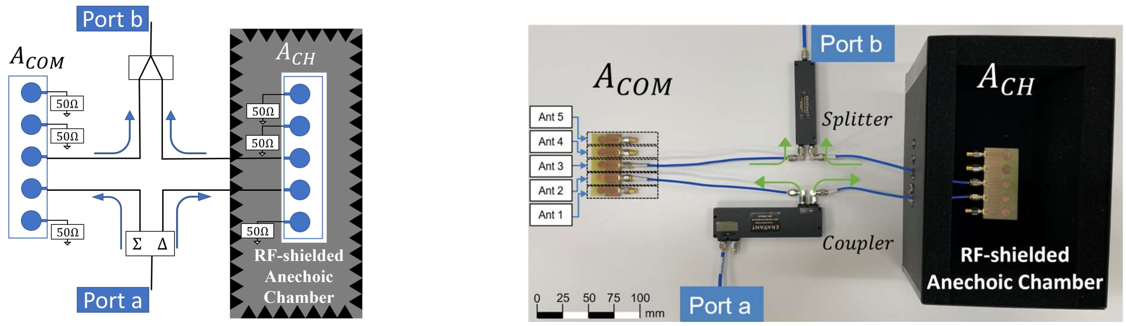

Figure 4. Test setup of the antennas pair with the proposed array pair shown within the small chamber at the right of the figure. A_{COM} is the communication array that receives the signal of interest. A_{CH} is a copy inside the RF-shielded anechoic chamber.

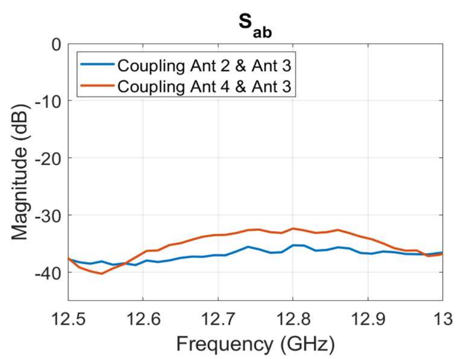

Figure 5. Measured isolation between the transmit port *a* and receive port *b* for the experiment in Fig. 4.

In Fig.5, the SIC is -37 dB, i.e., an additional ~12 dB reduction in coupling between Tx and Rx ports on the MIMO array is observed. Note that this improvement is achieved using only passive microwave circuits. Thus, the MIMO front-end is perfectly linear and extremely low-noise. As remarked, this improvement comes with a 3 dB loss in transmit power due the signal splitting needed to power arrays A_{COM} and A_{CH}.

4 Digital MIMO Interference Cancellation

An additional 22 dB of SIC across the 100 MHz baseband bandwidth was achieved using real-time DSP on a Xilinx RF-SoC ZCU-111. For simplicity, these tests were performed within the 2.1-2.6 GHz band. In future implementations, the FR3 radio unit will be down-converted to a low frequency baseband.

We used an augmented envelop neural network (AEN) based machine learning (ML) algorithm to model the nonlinear effects of the transceiver devices. The power amplifier used in this test (model ZHL-2W-63X-S+ from MiniCircuits) can deliver up to 100 mW of RF power in the 2.1-2.6 GHz band. The AEN is fed by an in-phase and quadrature (IQ) baseband signal, along with envelope information of the complex-valued IQ-baseband signal. AEN training is done with the PA in the loop, leading to a compact network that predicts the output signal. The transmit signal uses a 64-point quadrature amplitude modulation (64-QAM), operating at 64 MSym/s with a 0.5 roll-off pulse shaping filter. The training occurs in the host computer using MATLAB machine learning toolbox. The Tx and Rx samples are streamed to the host computer as packets with 2048 samples. Levenberg–Marquardt (LM) algorithm is used to train the TDNN using Tx samples as the input and Rx samples as the target [5-7].

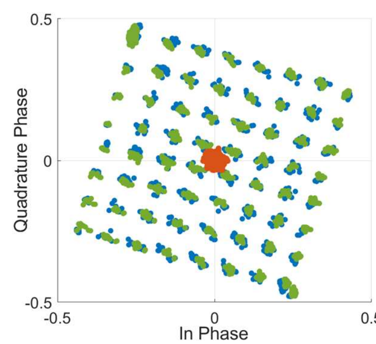

Figure 6. Measurement of digital cancellation in SISO configuration. The received SI, predicted SI, and residual SI are shown in blue, green and red, respectively.

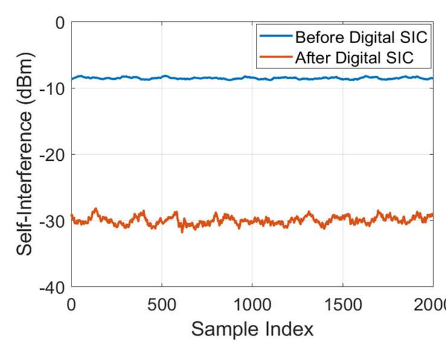

Figure7. Residual SI power with a PA in-the-loop for a 64-QAM transmission at 384 Mb/s datarate.

The measured results for digital SIC with the PA in-the-loop is shown in Fig. 6. It is clear that the predicted SI signal (green) overlaps the received SI signal (blue). The prediction error (red) is centered at zero. The variance in constellation represents the residual interference, which has an average value of -30 dBm as shown in Fig. 7.

MIMO FIR Filterbank Based Echo Canceller: The MIMO channel matrix is an N x N matrix of finite impulse response (FIR) filters that emulates the Tx signals in presence of reflections from the surrounding environment. The latter relates the N Tx-signals and N Rx-signals by generating N^2 unit impulse responses that fully characterize the MIMO channels for the external RF environment. To do so, the MIMO channel matrix must be measured at various times/instances and updated at a rate larger than the coherence time of the channel. Reflections from the surrounding environment follow linear time invariance, and as represented in the hardware-based DSP block using MIMO FIR filters. The FIR coefficients are not constant; they are updated regularly through channel sensing algorithms. Digital systolic array follows Fig. 8.

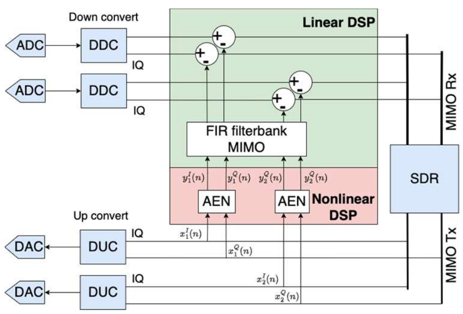

Figure 8. Digital SIC for MIMO radios, and by using a parallel set of augmented envelope neural networks to subtract the nonlinear distortion from the PAs.

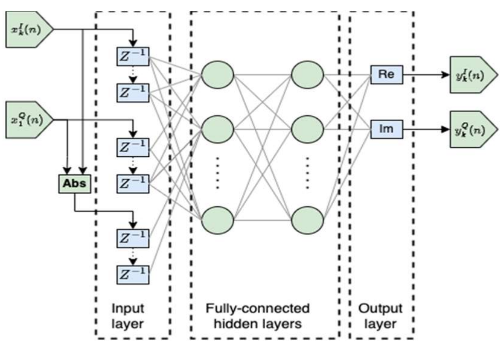

Figure 9. Augmented envelope neural network (AEN) architecture to model PA nonlinearities.

Augmented Envelope Network (AEN) based PA Model: As discussed in Section 4, the transmit signals from the power amplifiers (PAs) can have nonlinear distortion that corrupts the output of the transmitter. Any cancellation algorithm in the DSP must account for such distortion. In this work an AEN is used to model the PA nonlinearity.

The AEN is a low complexity fully connected neural network based on the time-delayed neural network (TDN) topology (see Fig. 9) [5-7]. The TDN weights are obtained by training against measured outputs from the PAs. PA chip nonlinearities are uniquely different. Every PA of the MIMO radio must have dedicated AEN.

5 Conclusion and Future Work

The FR3 band is especially attractive due its favorable electromagnetic propagation characteristics, and heavy utility of the frequencies within this band. Indeed, full-duplex 5G radios deployed in this band can achieve even higher spectrum utilization due to their simultaneous transmit and receive capability. In this paper, we proposed a multistage MIMO-FD radio architecture that employs an antenna pair based passive analog canceller in the RF domain and a neural network-based canceller in the digital domain. Our preliminary measurements showed a passive analog cancellation of about 35-37 dB across 500 MHz in 12.5-13.0 GHz range. Considering DSP-based digital cancellation at 2.1-2.6 GHz band of an additional 22 dB across a 100 MHz in the digital baseband bandwidth. Future work will integrate the stages 1,2 and 3 SIC cancellers and implement the proposed architecture to build MIMO-FD radios that operate in the FR3 band across at least of 500 MHz of digital baseband bandwidth. Our method becomes increasingly practical at mm-wave bands due to small size of the arrays and RF shielded chamber.

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