A Passive STAR Microwave Circuit for 1-3 GHz Self-Interference Cancellation

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Abstract-Simultaneous transmit and receive (STAR) allows full-duplex operation of a radio, which leads to doubled capacity for a given bandwidth. A circulator with high-isolation between transmit and receive ports, and low-loss from the antenna to receive port is typically required for achieving STAR. Conventional circulators do not offer wideband performance. Although wideband circulators have been proposed using parametric, switched delay-line/capacitor, and N-path filter techniques using custom integrated circuits, these magnet-free devices have non-linearity, noise, aliasing, and switching noise injection issues. In this paper, a STAR front-end based on passive linear microwave circuit is proposed. Here, a dummy antenna located inside a miniature RF-silent absorption chamber allows circulator-free STAR using simple COTS components. The proposed approach is highlylinear, free from noise, does not require switching or parametric modulation circuits, and has virtually unlimited bandwidth only set by the performance of COTS passive microwave components. The trade-off is relatively large size of the miniature RF-shielded chamber, making this suitable for base-station side applications. Preliminary results show the measured performance of Tx/Rx isolation between 25-60 dB in the 1.0-3.0 GHz range, and 50-60 dB for the 2.4-2.7 GHz range.

Index Terms—full duplex, simultaneous transmit and receive (STAR), self-inteference cancellation (SIC).

I. Introduction

The advent of 5G standard has galvanized the research on advanced radio systems in both sub 6 GHz frequencies [1] and millimeter wave frequencies [2], [3]. In this age of maxed-out spectrum in legacy frequency bands (<6 GHz), increasing demands for capacity on wireless networks has led to several potential solutions. Among the proposed approaches for capacity increase, notions of dynamic spectrum access in cognitive and full-duplex radios [4], in both the legacy and the mm-wave bands, are perhaps the most well developed. To achieve in-band full-duplex capability, the transceivers are required to achieve 90+ dB isolation between transmitter and receiver [5]. This can potentially be accomplished via multiple isolation stages, such as antenna isolation, RF isolation, and digital isolation [6], [7]. In this paper, we propose a novel passive RF isolation circuit that can be used in wideband fullduplex radios along with other antenna isolation and digital isolation techniques.

In full-duplex radios based on a single transmit (Tx)/receive (Rx) antenna, the usual approach is to use a circulator that provides isolation between the transmitter, being the output port of the power amplifier (PA), and the receiver, which is the input port of the low noise amplifier (LNA). The circulator is a non-reciprocal three-port device. The scattering

matrix of a mismatched circulator is shown in Eqn (1) where $|\gamma| \ll 1$ represents small imperfections like antenna mismatch and LNA/PA impedance variations. When all three ports are matched (i.e., reflection coefficient $\gamma=0$), it has perfect isolation from the transmitter to antenna making it suitable for STAR applications. However, when there is a mismatch, the circulator isolation is limited by γ [8]. Antenna tunning units (ATU) can somewhat mitigate this limitation [9].

$$S_{circulator} = \begin{bmatrix} \gamma & \gamma & 1 - \gamma^2 \\ 1 - \gamma^2 & \gamma & \gamma \\ \gamma & 1 - \gamma^2 & \gamma \end{bmatrix}, \ \gamma \in \mathbb{C} \quad (1)$$

An ideal wideband circulator ($\gamma=0$) isolates the Tx and Rx paths over a wide band of frequencies. Practical circulators are far from ideal in their characteristics, and cause a variety of problems: frequency-dependent responses and mismatch between the antenna, LNA and PA modules, leakage from the PA to the LNA which may cause undesirable self-interference and saturation of the receiver block or a non-linear response of the receiver chain. The circulator may be large in size and generally, also exhibit a narrowband performance when it uses traditional ferrite-based topology. Active integrated circuit based circulators have been proposed that offer relatively wide bandwidths and reasonable isolation, especially on mobile units/handsets.

II. WIDEBAND INTEGRATED CIRCULATORS

New types of magnetless circulators based on switched delay lines [10]-[12], parametric modulation [13]-[15] and Npath filtering [16]–[18] have been proposed and demonstrated. These circulators are compatible with microwave monolithic integrated circuit(MMIC) technology, which allows them to be integrated into transceiver chips. The experimental results have reported 20-50 dB Tx-Rx isolation and 1.7-8 dB Ant-Rx insertion loss, as reported in Table I. Magnet-free circulator approaches are indeed promising but nevertheless suffer several detriments; the performance in parametric circuits suffer from narrow bandwidth, high attenuation in the Tx-Ant path, nonlinear effects due to modulating of varactors, and poor noise figure due to addition of active components. Switched delay line based circuits have issues due to injection of switching noise, phase-mismatch between the delay lines, frequencydependent behavior, and relatively low band of operation within the primary Nyquist zone.

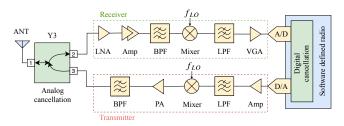


Fig. 1. A typical full duplex system architecture which shares the same antenna for transmit and receive, by introducing the RF block Y3.

The drive to create wideband circulators for STAR is based on the fact that the circulator is a classical microwave component and is an obviously good approach for achieving full-duplex STAR operation. However, circulation is sufficient but not necessary for full-duplex STAR operation. In fact, circulators are over-specified for this application. Unidirectional coupling from Tx-Ant ports is not necessary for STAR, nor is unidirectional coupling between the Rx-Tx ports. Therefore, we can find alternatives based on non-circulation approaches that lead to the desired STAR full-duplex functionality. One ideal example is a 3-dB splitter/combiner, where the antenna is connected to the sum port and transmitter and receiver on the remaining ports. If there is perfect isolation and perfect antenna matching over a wide band, a circulator can be replaced with a splitter at the cost of a 3-dB insertion loss to the received signal.

III. ACTIVE INTERFERENCE CANCELLER

Instead of relying on the standard circulators only, there were attempts to build analog interference canceller (AIC) circuits using active circuits [19]–[21]. In one approach, the self-interference signal is modeled by analog tapped delay line (ATDL) filters that have weights which are either trained by digital assistance [22] or optimized by analog feedback loops [23]. Another approach known as electrically balanced duplexing (EBD) tries to develop tunable LC circuits to imitate the impedance of the antenna [24]. Active analog interference canceller circuits can achieve over 50 dB Tx-Rx isolation [25]. While the small size and ability to fabricate on-chip makes AIC circuits more desirable for hand-held devices, they are limited by the bandwidth, complexity, noise/distortion, and power consumption. To support wide-bandwidth AIC circuits approaches yield high order filters that suffer from circuit complexity, power consumption, and long tuning/calibration times. We propose a passive self-interference canceller that trades physical size for very wideband performance, ultra low noise, zero distortion, zero power consumption (except for losses), while not requiring control circuits and/or calibration.

IV. PASSIVE INTERFERENCE CANCELLER: TWIN ANTENNA CIRCUITS

A STAR system is shown in Fig. 1, as is needed to utilize an antenna for both transmission and reception for full duplex radios. Therefore, to isolate the transmit and receive chains, a 3-port RF module Y3 (which is shown using a green box in Fig. 1) is required, such that a relatively large transmit signal

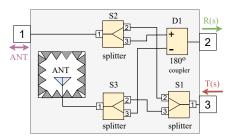


Fig. 2. Y3: The proposed full-duplex wideband linear isolator circuit.

does not present itself at the LNAs input. RF channel paths between the ports 2 to 1 and the ports 1 to 3 should exhibit small losses.

We propose a self-interference cancellation scheme where an identical antenna that resides in a miniature RF shielded box is used in a symmetrical parallel connection to the Tx/Rx communication antenna. The proposed twin-antenna system relies on creating a copy-of and then subtracting the coupled transmit signal from the received signal. Therefore, we refer to this scheme as twin-antenna wideband canceler. A schematic showing the proposed functionality of the Y3 block is shown in Fig. 2. All the cables in the design are phased matched to minimize the phase mismatches. Effectively, the proposed assembly of three splitters and a dummy antenna is used to create a copy of the signal, which could couple from Tx to Rx chain. The created copy is then subtracted from the received signal, using the difference block D_1 leaving only the desired received signal.

The copy of the coupled signal is created by performing the following operations. First, the transmit signal T(s) is split equally between topologically symmetric arms, using splitter S1, resulting in forward split transmit signal components $H_{s,f}(s)T(s)$ in each of the arms, where $H_{s,f}(s)$ is the forward transfer function of the splitter. We assume that the splitter is well balanced, and the isolation between the output ports 2 and 3 is high. The split transmit signal enters S2 and appears at the Tx/Rx communication antenna at the bidirectional port 1. The split transmit signal also enters S3 and appears at the Tx/Rx dummy antenna. Because the dummy antenna is identical to the communication antenna, the driving point impedance $Z_A(s)$ is the same as that of the communication antenna, given that both the antennas are fabricated with tightly controlled tolerances (that is, twin-antennas). The frequency-dependent transmit power coupling from ports 2 to 3 in S2 and S3 are identical. The dummy antenna should not receive any received signals from the air interface; therefore, it is placed inside a miniature RF shielded box to guarantee both reflection-free and RF-silent operation. Therefore, the residual leakage due to splitter non-ideality at port 3 of S2 and port 3 of S3 are both $T(s)H_{s,f}(s)H_{s,L}(s)$.

Under ideal conditions, desired component of the received RF signal could be obtained from subtraction to produce a zero self-interference. The interference-free received signal at the output port 3 of Y3 can be derived as follows. The communication antenna inserts the received signal R(s) on the S2, making the combined signal at port 3 to be

 $R(s)H_{s,f}(s) + T(s)H_{f,s}(s)H_{s,L}(s)$. Since dummy antenna is located in an RF-silent region, the signal received at the port 3 of the S3 is only the one coupled from the transmitter, i.e., $T(s)H_{s,f}H_{s,L}(s)$. Therefore, the output of the 180° coupler becomes $(R(s)H_{s,f}(s)+T(s)H_{f,s}(s)H_{s,L}(s) T(s)H_{s,f}H_{s,L}(s)H_{h,f}(s)$ where $H_{h,f}(s)$ is the forward function of the 180° coupler. The output is therefore, ideally, given by $R(s)H_{s,f}(s)H_{h,f}(s)$. Given, 180° coupler and splitter are sufficiently wideband and have approximate anticipated transfer function $H_{s,f}(s) = 0.707$ and $H_{h,f}(s) = 1$, the output signal is given by 0.707R(s). This implies a 3-dB loss in the proposed configuration, while the receiver does not experience the transmit signal T(s) at the input port of the LNA, as one desired in a full-duplex single antenna scheme. The proposed system also isolates the receiver chain from reflected power from port 2 of splitter S2, S3, and power amplifier due to the symmetry of the circuit.

The key idea is the use of an identical antenna inside the miniature RF-shielded box. In regular use, RF absorbers are used in the far-field, which is $\gg \lambda$, where λ is the wavelength of the lowest frequency radiated. However, in our experiments, we found out that a miniaturized RF-shielded box with dimensions of $\approx \lambda$ does not significantly alter the reflection coefficient of the antenna (S_{11}) . This observation leads to the implementation of twin-antenna cancellation systems with practical size for base stations. In our prototype design which operates in 1-3 GHz frequency range (i.e., $30 \ cm \ge \lambda \ge 10 \ cm$), the RF-shielded box has dimensions of $20 \times 24 \times 35$ cm³. For higher frequencies, the dimensions of the RF-shielded box is further reduced (volume scales as $V \approx \lambda_{Max}^3$ m³). The flat RF absorber sheets [26] used in the RF-shielded box provide 45 dB loss per one-inch thickness. Fig. 4 shows how the dummy antenna follows the wideband impedance curve of the communication antenna, while exactly modeling all the scattering present due to the communication antenna and the splitter S1. In effect, the dummy antenna acts like an analog computing block that models the coupling from Tx to Rx chain in the presence of the communications antenna. This modeling would be challenging to achieve using a finite order tapped delay-line finite impulse response filter (FIR) or other lumped circuit because of the necessary high order transfer functions make such a solution impractical. By using an exact copy of the communication antenna where the dummy antenna is needed, we avoid the difficult tapped-delay FIR filter requirement and obtain an exact solution "essentially for free", the trade-off being the size and the associated 3dB power loss.

V. EXAMPLE IMPLEMENTATION

To verify functionality of the Y3 block, experiments were conducted in the 1-3 GHz range. The Y3's realization is shown in Fig. 3. We designed Y3 using low-cost commercial off-the-shelf (COTS) components. The Minicircuits part ZX-2-25-S+ is used for the splitters and ZFSCJ-2-232-S+ for the subtractor D1. The splitters have 20 dB of isolation; we expect the performance of the Y3 to improve with better (and

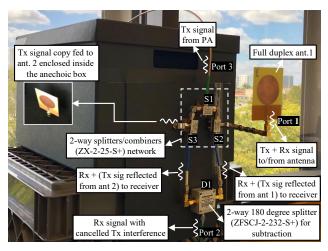


Fig. 3. Prototype for the proposed full duplex wideband linear isolator circuit.

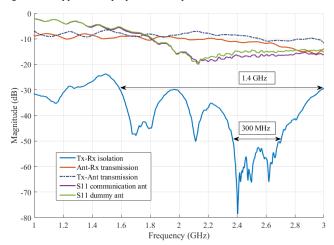


Fig. 4. VNA Measurements: Tx-Rx isolation (blue), Ant-Rx transmission (red), and Tx-Ant transmission (dotted blue) of the proposed full duplex circuit. The purple and green curves show the measured reflection coefficient of the communication antenna and the dummy antenna respectively.

likely a lot more expensive) power splitters and 180^{o} couplers having improved bandwidth and isolation, but the versions used in this paper are meant only as an initial proof of concept implementation.

The Tx/Rx port isolation (Port 2 to Port 3) is measured using a vector network analyzer (VNA) (Part number: NI PxIE 5632) and results are shown in Fig. 4. The measured isolation is the best-case performance of Y3 component in the case the loss from antenna to Rx is zero valued. However, we know that there is a 3 dB loss of the received signal due to the splitter at port 1 of Y3. Microwave components, such as the connectors, cables, and the 180° coupler contain their own losses. Losses reduce the received signal power available at the input of the LNA, and raise the noise temperature of the receiver. The absolute performance of Y3, measured using the VNA shows Tx/Rx isolation between 25-60 dB for the 1.0-3.0 GHz range, between 30-60 dB in the 1.6-3.0 GHz range, and better than 50 dB for the 2.4-2.7 GHz range. These measurements imply that Y3 has 6.5-33 dB improvement in Tx/Rx isolation when compared to the performance from using a splitter, which has a nominal performance of about 20 dB. The measured values are compared with previous work in Table I.

TABLE I

FULL-DUPLEX PERFORMANCE COMPARISON WITH PREVIOUS WORK. TA: TWIN ANTENNA, NPF: N-PATH FILTERING, SSDL: SEQUENTIALLY SWITCHED DELAY LINE, STCM: SPATIOTEMPORAL CONDUCTIVITY MODULATION, EBD: ELECTRICALLY BALANCED DUPLEXING.

Device	Bandwidth	Tx-Rx isolation	Ant-Rx IL	Technology
	(GHz)	(dB)	(dB)	
Proposed	1.0-3.0	25-60	8-15	TA
	1.6-3.0	30-60	8-15	
	2.4-2.7	50-60	11-13	
[17]	0.45-1	40-50	1.7-3	NPF
[27]	0.735-0.765	15-50	1.7	NPF
[12]	1-2	20-35	5-8	SSDL
[28]	1.15-1.2	22-25	3-6	SSDL
[29]	22.7-27.3	18-20	3.2-4	STCM
[25]	2.0-2.15	55-75	3.9	EBD

VI. CONCLUSION

A wideband passive self-interference canceller STAR circuit is proposed that can enable full-duplex radios. The experimental results of the prototype design showed over 25 dB Tx/Rx isolation in 1.0-3.0 GHz bandwidth and over 50 dB Tx/Rx isolation in 2.4-2.7 GHz bandwidth. The high insertion loss in the prototype design is due to the use of low-cost COTS components. The splitter and $180^{\rm o}$ coupler used in the experiment shows ≈ 4 dB and ≈ 5 dB insertion loss, respectively. The rated maximum frequency of the components is 2.5 GHz, which explains the high insertion loss near 3 GHz. These losses can be alleviated by using splitters and couplers that are optimized for the frequency band of interest. The canceller can be extended to build full-duplex wideband MIMO systems, which will be studied in future work.

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