A 700-950 MHz Tunable Frequency Division Duplex Transceiver Combining Passive and Active Self-interference Cancellation

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***Abstract*—This paper presents a novel tunable FDD transceiver architecture which uses an electrical balance duplexer (EBD) to isolate Tx noise in the Rx band, and combines this with active self-interference cancellation to suppress the Tx blocker. This overcomes the limited isolation bandwidth of EBDs, shifting complexity from the RF domain to the digital baseband domain in order to provide isolation in both bands. A discrete hardware prototype has shown promising results and demonstrated the viability of this architecture, achieving 6.0-7.4 dB antenna referred noise figure in a 20 MHz downlink bandwidth, in the presence of a +27 dBm Tx blocker, across a range of duplex configurations in the 700-950 MHz range.**

***Index Terms*—Duplexers, self-interference, FDD, IBFD**

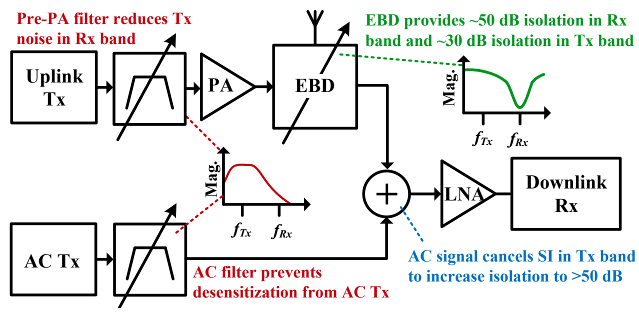


Fig. 1: Block diagram of the electrical balance and active cancellation FDD transceiver.

I. Introduction

Mobile devices currently rely on fixed-frequency surface acoustic wave (SAW) duplexing filters to implement frequency division duplexing (FDD), and require multiple off-chip duplexing components to support multi-band operation. Due to the cost, size, and losses of this architecture, today's devices typically do not support all of the 35 FDD bands defined in 3GPP long term evolution (LTE), requiring multiple device variants for different global regions, and restricting global roaming [1].

Various alternatives have been considered in the literature. In [2], tunable filters with (necessarily) lower rejection are combined with a passive feed-forward self-interference (SI) canceller to increase isolation, although the canceller was effective only in the Tx band, and thus the Rx band isolation is insufficient at just 30-40 dB. In [3], active cancellation (AC) only is used to cancel SI at the Rx input, however the Rx is desensitised to a noise figure of 15.4 dB at a Tx power of just +17 dBm, suggesting AC alone may be insufficient. Electrical balance duplexers (EBDs) implement a form of passive self-interference cancellation, and CMOS EBD prototypes have demonstrated the required power handling, insertion loss, and linearity for cellular handset applications [4], [5]. But, to date no EBD prototypes have demonstrated sufficiently wideband (>20 MHz) transmit-to-receive (Tx-Rx) isolation concurrently in the Tx *and* Rx bands [4]. However EBDs may be combined with additional filters to enhance isolation, e.g., [5], where an EBD provides Rx band isolation and is combined with a tunable SAW filter in the Rx path for Tx blocker rejection. Whilst achieving >50 dB isolation in both bands, this suffers from high complexity in the EBD balancing circuit, increases the Rx insertion loss, and still relies on off-chip components.

In this paper we propose a novel frequency division duplexer combining an EBD with an active SI canceller. A discrete proof-of-concept demonstrator has been built and tested, achieving comparable performance to SAW based FDD implementations, and demonstrating the system level feasibility of this approach. These cancellation techniques have previously been combined for in-band full-duplex (IBFD) applications [6], and thus this architecture supports both FDD and IBFD. This work also characterises the desensitisation in the presence of a +27 dBm Tx blocker, going beyond previous works which either did not characterise desensitisation noise [4], [5], or did not achieve full power operation [3]. Section II introduces the design and operation of the novel duplexing architecture, and Section III describes the hardware prototype. Section IV presents results and Section V concludes.

II. Design and Principle of Operation

Fig. 1 depicts the proposed electrical balance and active cancellation (EBAC) tunable FDD transceiver. A pre-PA filter is used to suppress the out-of-band (OOB) noise from the Tx chain, such that the Tx noise is due to PA thermal noise and spectral regrowth only, typically reducing the OOB noise by several dB. In this design, the EBD is tuned to maximize isolation in the Rx band, providing >50 dB of Tx-Rx isolation isolation across the Rx band. However due to the limited EBD isolation bandwidth (BW), the isolation in the Tx band may only be 20-40 dB (depending on the duplex separation). Active SI cancellation is applied to suppress the residual Tx band SI after the EBD to increase the Tx band isolation, as required to prevent receiver overloading.

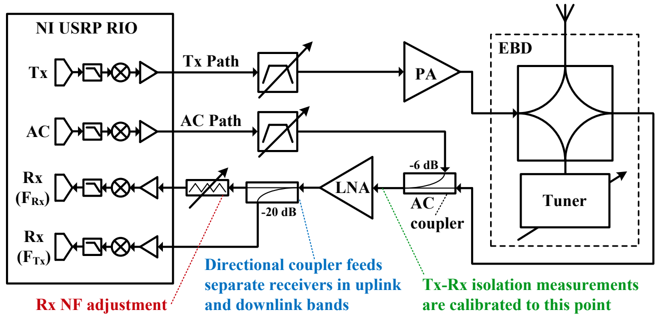


Fig. 2: Block diagram of the EBAC FDD prototype.

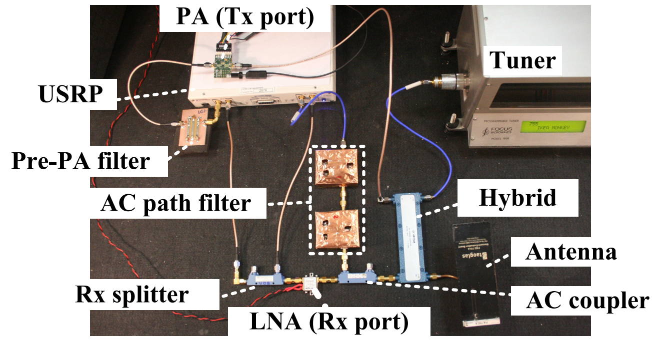


Fig. 3: Photograph of the EBAC FDD prototype.

A. AC path signal processing

The AC signal is generated in the digital baseband domain by filtering the baseband Tx signal. In orthogonal frequency division multiplexing (OFDM) systems, this can be conveniently performed using frequency domain equalization (FDE) on the Tx subcarriers [6]. The baseband cancellation signal is upconverted to RF using an additional Tx chain [3], [6], and the AC signal is injected prior to the LNA. The AC Tx chain will also generate noise in the Rx band, and therefore, to prevent receiver desensitisation from the AC path, a filter is required at the AC Tx output (see Fig. 1).

B. Subsystem design considerations

The additional Tx chain adds to the RF complexity, but this component (along with the EBD and tunable elements) can be implemented on-chip, which is favourable compared to off-chip components. Similarly, the cancellation signal processing complexity is in the baseband domain, reducing RF complexity compared to RF adaptive filters such as in [2]. Because there is substantial passive isolation prior to the AC stage, the AC Tx operates at low power compared to the main Tx: no AC PA is required, and therefore the power consumption is also comparatively low.

The AC path filter must suppress the AC Tx noise to below the LNA thermal noise floor to minimize desensitization. However, due to the low AC Tx power, the Rx band noise from this component is substantially lower. Pre-PA Rx band noise is typically -153 dBm/Hz for current front-end designs [7], and thus only 25 dB stopband rejection is required to reduce the desensitisation noise to -178 dBm/Hz. Furthermore, since the AC path power is low, the insertion loss of the AC path filter is not critical to the overall Tx efficiency. The specification of this filter is therefore substantially relaxed compared to fixed or tuned acoustic resonators, and, for example, may be implemented using microelectromechanical systems (MEMS) filters [7] and potentially integrated within the RFIC.

The AC signal may be injected using a directional coupler prior to the LNA, however the insertion loss of this device will degrade the Rx NF. To reduce component count and insertion loss the SI cancellation could be integrated with the LNA [8], or the AC and Rx signal could be combined within the EBD hybrid junction [6].

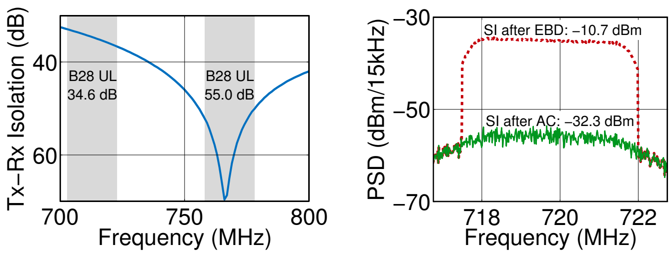
III. Hardware proof-of-concept

To demonstrate the viability of this novel duplexing scheme, a hardware proof-of-concept demonstrator was constructed using a National Instruments USRP-2942R software defined radio (SDR) platform and discrete RF components. The hardware configuration is shown in Fig. 2. The demonstrator has been designed to be broadly representative of a cellular handset RF front-end (RFFE); it uses typical values for the Tx power, LNA noise figure (NF), and includes a commercial off-the-shelf handset PA. The tunable filters are third-order microstrip interdigital filters, manually tuned using mechanically tunable capacitors, and fabricated on FR4. These achieve similar performance to the MEMS filters in [7] ($\sim$25 dB rejection). The Rx band noise at the USRP AC output is much higher than that in a handset RFIC (-145 dBm/Hz and -153 dBm/Hz respectively), and therefore an additional AC path filter is used to reduce the USRP noise to a representative -153 dBm/Hz. The PA is an RFMD RF7917, which delivers +27 dBm in LTE band 28, e.g., 703-748 MHz uplink (UL). This device can operate over wider frequency ranges with reduced output power and is also used in this work at 888 MHz, where it can deliver +23 dBm. The EBD subsystem comprises a Krytar 1831 symmetrical microstrip hybrid coupler and a focus 1808 impedance tuner. The antenna is a Taoglas PAD710 multiband cellular antenna.

The USRP NF is >7 dB - substantially higher than a handset RFIC (typically 2.0-2.5 dB at the LNA input). To mitigate this a Mini-Circuits ZX6083LNS+ LNA was included in the receiver path, along with an attenuator between the LNA and USRP, to achieve a cascaded receiver NF of 2.0 dB at the LNA input. For simplicity, a directional coupler (Mac Technology 3203-6) is used to inject the cancellation signal prior to the LNA. The insertion loss of the directional coupler (0.9 dB) and the hybrid junction (3.1 dB) add to give an Rx insertion loss of 4.0 dB, thus the antenna referred NF is 6.0 dB prior to desensitisation. The EBD is balanced by manually adjusting the impedance tuner to give high isolation in the Rx band. The system employs an OFDM physical layer with 15 kHz subcarrier spacing, and the AC signal is generated by applying FDE to the Tx subcarriers. The FDE coefficients are calculated using a zero forcing algorithm, as used in [6]. The

TABLE I
MEASURED VALUES FOR TX-RX ISOLATION AND ANTENNA REFERRED NOISE FIGURE FOR DIFFERENT DUPLEX CONFIGURATIONS.

	Config 1. f_u= 713.00 MHz f_d= 768.00 MHz DL BW= 5 MHz	**Config 2.** f_u= 719.75 MHz f_d= 768.00 MHz DL BW= 20 MHz	**Config 3.** f_u= 887.75 MHz f_d= 936.00 MHz DL BW= 20 MHz	**Config 4.** f_u= 719.75 MHz f_d= 832.00 MHz DL BW= 20 MHz
Rx band Isol. (EBD)	58.5 dB	55.9 dB	53.5 dB	56.2 dB
Tx band Isol. (EBD)	34.9 dB	37.7 dB	37.1 dB	29.7 dB
Tx band Isol. (EBAC)	57.8 dB	59.3 dB	59.0 dB	53.5 dB
Noise figure (Tx NC)	6.0 dB	6.1 dB	6.0 dB	6.0 dB
Noise figure (Tx idle)	6.5 dB	7.1 dB	6.8 dB	6.0 dB
Noise figure (Tx active)	6.9 dB	7.4 dB	6.9 dB	6.0 dB



(a) (b)

Fig. 4: (a): The Passive Tx-Rx isolation provided by the EBD, and (b): The Tx band SI before and after AC.

bandwidth of the USRP device is only 40 MHz, and thus is unable to simultaneously cover the Tx and Rx band. Therefore in this prototype, a second receiver is required to receive in the Tx band for the purpose of informing the AC algorithm. This is connected using a -20 dB directional coupler after the LNA. Tx-Rx isolation measurements are calibrated to the LNA input, this being analogous to the RFIC Rx input in a mobile device. Measured Rx band noise is calculated as the antenna referred NF.

IV. MEASURED PERFORMANCE

Fig. 4a shows the measured passive Tx-Rx isolation, with LTE band 28 (B28) frequency ranges indicated; the EBD provides sufficient isolation of 55.0 dB in the Rx band, but only 34.6 dB in the Tx band, as averaged across those 20 MHz bands. Fig. 4b show measured Tx band SI with and without AC, demonstrating 21.6 dB of further Tx band SI cancellation, reducing the Tx band SI to $<$-30 dBm, which is sufficient to prevent Rx overloading. The Tx signal used in this and in all measurements presented herein is a quadrature phase shift keying (QPSK) single carrier frequency division multiple access (SC-FDMA) signal occupying 25 LTE resource blocks (RBs) (i.e. a 4.5 MHz bandwidth) at the top of the uplink band, this being the uplink Tx blocker signal specified for all downlink (DL) Rx sensitivity testcases in the LTE specification in sub-1GHz bands [9, Section 7.3].

Table I presents the measured passive and active cancellation, and the measured NF with LNA thermal noise only (labelled Tx NC), the Tx connected but idle, and the Tx active, for four duplex configurations, with parameters as also given in Table I. Configurations 1 and 2 are the duplex configurations specified for LTE B28 sensitivity testcases for 5 MHz and 20 MHz respectively. Configuration 3 is the same duplex configuration shifted up in frequency to demonstrate tunability. Configuration 4 is the same as configuration 2 but with a much wider duplex separation.

The EBAC FDD architecture achieves satisfactory noise performance in all configurations. Configuration 2 exhibits the most desensitisation, showing 1.3 dB of desensitisation when the Tx is active, to achieve a 7.4 dB antenna referred NF. Desensitisation is also observed when the Tx is idle, indicating Tx path and AC path thermal noise are contributing factors in addition to OOB noise from spectral regrowth. Configuration 4 exhibits no desensitisation, achieving a 6.0 dB NF. This is due to the larger duplex separation - in this case the OOB noise power from the PA is lower and the AC path filter rejection is higher. Configuration 1 shows performance improves with a narrower DL BW due to better average isolation over the Rx band. Configuration 3 demonstrates the tunability of the design, and achieves reduced desensitisation compared to Config. 2 due to slightly better AC filter rejection.

This work does not consider bandwidths above 20 MHz, however this architecture may be suitable for wider bandwidths. Wider uplink bandwidths can readily be accommodated by the active canceller, as the cancellation bandwidth is limited only by the transceiver bandwidths. Increased EBD isolation bandwidth would be required to cover a wider downlink band, which may entail an increased number of tunable elements in the balancing network.

V. CONCLUSION

This paper has presented a novel FDD transceiver architecture based on passive and active SI cancellation techniques which are potentially suitable for integrated implementation. A discrete hardware prototype, tunable across 700-950 MHz, has achieved antenna referred Rx noise figures of 6.0-7.4 dB in the presence of a +27 dBm Tx signal. This demonstrates the viability of this design and is the first tunable duplexer prototype to demonstrate acceptable Rx noise figures at full Tx power. Further work is required characterize the performance of this design in an integrated implementation.

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