IN-BAND FULL-DUPLEX TECHNOLOGY FOR FUTURE GENERATIONS OF WIRELESS COMMUNICATIONS

Contact: Professor Xiaojing Huang, Distinguished Professor Jay Guo

Abstract

In-Band Full-Duplex (IBFD) technology has the potential of doubling the spectrum efficiency and data rates of existing and future wireless communications systems, and is currently being considered as part of the 6G standards. We have been pioneering the research and development of IBFD technology since 2016. Our IP covers system architecture, hardware implementation, and signal processing algorithms.

Introduction

For decades, wireless transceivers have been operating in the half-duplex mode, i.e., a pair of frequency bands is required for simultaneous two-way communications. As the demands for connectivity and data rates increase exponentially, there has been a shortage of frequency resources to support new systems, and this spectrum scarcity problem is becoming significantly more severe for 6G. In-band full-duplex (IBFD) technology, which allows transceivers to transmit and receive in the same frequency band simultaneously, is considered a key solution to the problem of spectrum scarcity. By enabling the full-duplex mode, a single radio can achieve double throughput compared to the conventional half-duplex counterpart. Moreover, combining this technology and multiple-input multiple-output (MIMO) systems is even more attractive to further enhance channel capacity and spectral efficiency.

A fundamental challenge to IBFD systems is self-interference (SI) which is the signal received by a receiver from a collocated transmitter. SI is typically much stronger than the signal received from an intended distant transmitter. Since the SI in an IBFD system occupies the same frequency band but has much higher power than the desired signal, it is very hard to be removed using conventional methods. To enable an IBFD operation, one would need to sufficiently reduce the SI, ideally to below the noise level. For example, if the transmit power level is +20 dBm and the thermal noise level of the receiver is -90 dBm, the SI should be suppressed by 110 dB.

Mitigating SI is challenging because it is unknown to the receiver even though the clean transmitted data is known. This is because when the baseband signal is up-converted to the radio frequency (RF) signal, it is distorted by the non-linearity of the power amplifier and the phase noise of the local oscillator. In addition, after being radiated, the SI arrives at the receive antenna over a multi-path dynamic channel. Therefore, to cancel the SI, a combination of different techniques is required.

Self-interference Mitigation

Self-interference is mitigated consecutively over three domains, namely, the propagation domain, the analog domain, and the digital domain. Figure 1 demonstrates the anatomy of a full-duplex system with three stages of SI cancellation [1].

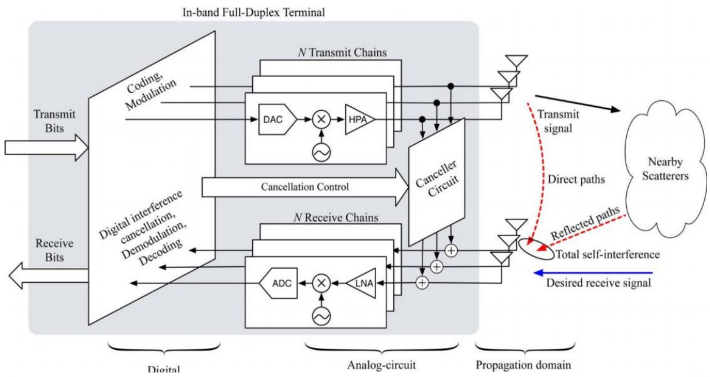

Figure 1. Block diagram of a full-duplex system with three stages of SI cancellation.

The propagation domain methods aim to isolate the transmitter and receiver to reduce the SI arriving at the receiver. This can be obtained by using orthogonal polarizations for transmit and receive antennas, advanced antenna decoupling methods or other IBFD antenna technologies. In MIMO systems, beamforming technique can be used to minimise the SI at the receiver.

Analog domain approaches intend to generate a signal, which mimics the SI, in order to cancel the SI at the receiver input. The cancellation signal can be produced by passing a copy of the transmitted signal through a multi-tap adaptive filter in which the signal is delayed, and its amplitude and phase are modified by weighting coefficients so that the output signal approximates the SI. The main problem here is how to calculate and generate the weighting coefficients of the adaptive filter. Conventional RF adaptive filters require an auxiliary receive chain to synthesize the weighting coefficients of the filters with the aid of digital signal processing.

Digital domain cancellation exploits the known transmitted data symbols and the estimated SI channel to cancel the residual SI in the digital baseband. The critical problem is to accurately estimate the residual self-interference channel, while ensuring the estimation time is as short as possible to avoid latency.

UTS Research Achievements on Self-interference Cancellation

The UTS team pioneered IBFD research on analogue domain SI cancellation with solutions in all three domains to achieve a sufficient level of SI suppression. The main research achievements can be classified into the following three categories.

- *Propagation Domain Solutions*
- *Analog Domain Cancellation*
- *Joint Analog and Digital cancellation*

Propagation Domain Solutions

In a single-input single-output full-duplex system, orthogonal polarizations can be used to transmit and receive antennae for SI suppression. The transmitter and receiver are matched with the corresponding antennae by a directional hybrid coupler. Conventional matching networks only work with narrow-band (< 10% fractional bandwidth) and low isolation (< 40 dB). UTS has developed a wideband hybrid coupler achieving at least 50 dB of isolation over 30 % fractional bandwidth between transmit and receive ports [2].

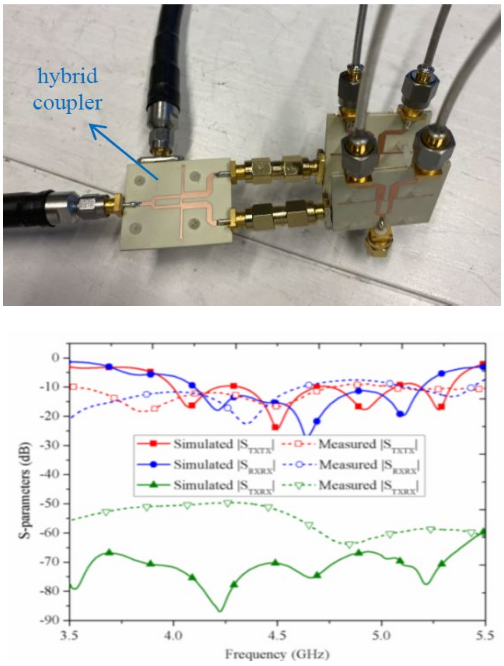

Figure 2. A feeding antenna network with over 50 dB Tx-Rx isolation.

In a full-duplex MIMO system with N transmit and M receive antenna, the self-interference channel can be modelled as an $N \times M$ matrix **H**. Beamforming methods aim to create a precoding matrix so that the transmitted signal matrix **X** falls into the null-space of **H**, i.e., $\mathbf{H}^H\mathbf{X} = 0$ and hence the self-interferences at the receiver are nullified. If $N > M$, there are at least (N-M) zero eigenvalues of **H** with the corresponding eigenvectors $\mathbf{Q}_\Omega$. In this ideal case, the transmitted signal vectors spanned by $\mathbf{Q}_\Omega$ will fall into the null-space of **H,** satisfying the condition $\mathbf{H}^H\mathbf{X} = 0$. This beamforming method works well if the channel matrix **H** is perfectly known, and the DSP in the transmitter has sufficiently high precision. However, if N is much larger than M, the communication performance of the receiver is degraded due to poor receive beamforming quality. In addition, there are always errors in the self-interference channel estimation and digital signal processing. We have revealed the trade-off of beamforming cancellation performance versus the number of transmit and receive antennas as well as precoding errors. We have also proposed a joint beamforming and analog SI cancellation structure to relax this trade-off [3].

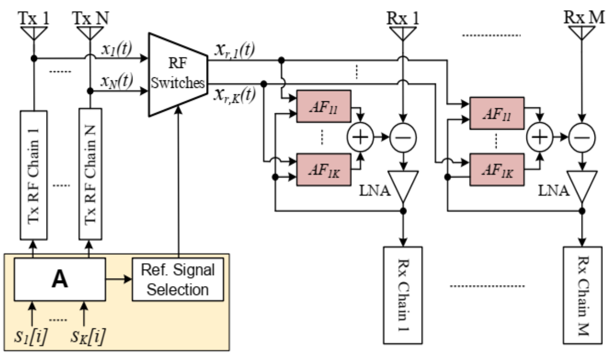

Figure 3. Joint beamforming and beam-based analog SI cancellation.

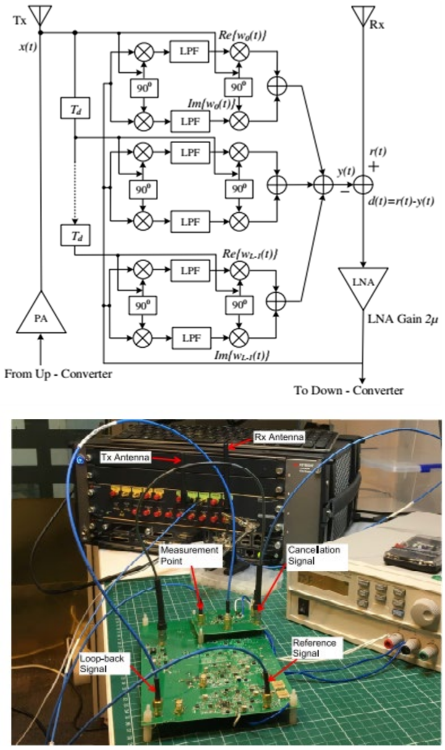

Figure 4. Proposed purely analog adaptive filter.

Analog Domain Cancellation

A critical task in analog domain cancellation is to synthesize the weighting coefficients in the adaptive filter to generate the cancellation signal. Conventional methods require complicated and power-thirsty digital signal processing to attain the weighting coefficients. We have developed a novel adaptive filter, named the Analog Least Mean Square (ALMS) loop, which can be implemented purely by analog components without any digital signal processing [4]. We have shown that the level of cancellation achieved by this filter can be estimated based on its components' parameters [5]. We have evaluated this filter under various scenarios, such as different transmitted signal properties, such as multi-carrier signalling in OFDM systems [6], [7] and deterministic signalling in radar systems [8]. These works show that the filter performs well with different schemes. Furthermore, the impacts of hardware impairments such as IQ imbalances on the performance of the ALMS loop have been investigated in [9]. We show that the filter is robust to the frequency-independent IQ imbalances. In particular, under a severe condition of IQ imbalance, the performance of the filter is only degraded by a maximum level of 3.5 dB, which can be easily compensated in other domains. We have developed a prototype of this filter using off-the-shelf components and demonstrated an average of 40 dB SI cancellation over 20 MHz bandwidth [10]. The structure and its prototype are presented in Figure 4, while the cancellation performance of the ALMS loop is demonstrated in Figure 5. Table 1 explicitly summarises the ALMS loop's advantages over other adaptive filtering structures found in the literature [11]. Clearly, the ALMS loop requires fewer extra modules than other methods, while providing a sufficiently high level of SI cancellation for satisfying the requirements of the RF stage.

	[1, 2]	[3]	[4, 5]	[6, 7]	ALMS loop [8–12]
No DSP involvement				✓	✓
No additional Tx chain	✓			✓	✓
No DAC or ADC				✓	✓
No channel state information (CSI) requirement	✓	✓		✓	✓
No additional down-converter			✓		✓
Sufficient SIC demonstrated		✓	✓		✓

Table 1. Comparison of ALMS loop and other adaptive filtering for analog SI cancellation [11].

Another advantage of this filter is that it can be easily adopted for full-duplex MIMO systems in which conventional methods face a huge signal processing complexity. We have proposed a novel beam-based analog SI cancellation structure for full-duplex MIMO systems [12]. For an $N \times M$ full-duplex MIMO system, conventional methods would require $N \times M$ adaptive filters for SI cancellation. With our beam-based structure, this number is reduced to $K \times M$ with $K \ll N$. Our recent work shows that this adaptive filter is also applicable for a dual-polarization full-duplex MIMO, which employs both vertical and horizontal polarizations for transmitter and receiver, for potentially achieving four-fold data throughput [13].

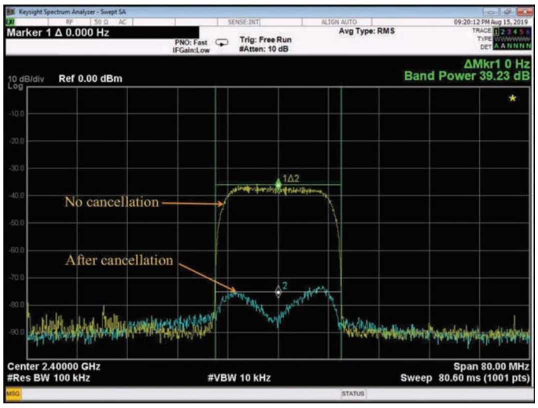

Figure 5. Experimental result for SI cancellation of the ALMS loop.

Joint Analog and Digital Cancellation

A crucial problem in digital cancellation is to estimate the SI channel from the residual SI after the first two stages. Therefore, characterising the noise behaviours of the adaptive filter in the analog domain is necessary for efficiently combining the two stages of SI cancellation. We have investigated the noise caused by the filter in the analog domain and revealed a mechanism to reduce this noise. A protocol for joint analog domain and digital domain cancellation while optimizing communication performance has been proposed [14]. We have also designed a unique training sequence to efficiently estimate the SI channel for beamforming and digital cancellation, while providing a reference signal for synthesizing the weighting coefficients in the adaptive filter.

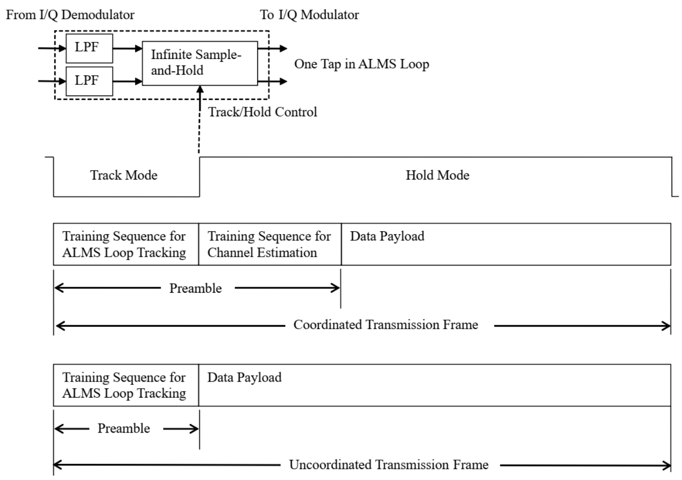

Figure 6 Transmission protocol for joint analog and digital cancellation.

Conclusions

Full-duplex technology is crucial to solve the urgent problem of frequency shortage. To enable the full-duplex operation, a sufficient level of cancellation needs to be achieved to mitigate the SI at the receiver. The UTS team has developed a world-leading, simple solution to mitigate the SI, and a complete full-duplex system will be developed soon.

Selected UTS publications on Full-Duplex

[1] A. Sabharwal, P. Schniter, D. Guo, D. W. Bliss, S. Rangarajan, and R. Wichman, "In-band full-duplex wireless: Challenges and opportunities," IEEE Journal on Selected Areas in Communications, vol. 32, no. 9, pp. 1637–1652, 2014, doi: 10.1109/JSAC.2014.2330193.

[2] H. Zhu and Y. J. Guo, "Wideband Dual-Polarized Antenna for Full-Duplex Systems with High Tx-Rx Isolation Using Passive Interference Cancellation," IEEE Transactions on Antennas & Propagation.

[3] X. Huang, A. T. Leb, and Y. Jay Guo, "Transmit Beamforming for Communication and Self-Interference Cancellation in Full Duplex MIMO Systems: A Trade-Off Analysis," IEEE Transactions on Wireless Communications, 2021, doi: 10.1109/TWC.2021.3053542.

[4] X. Huang and Y. J. Guo, "Radio Frequency Self-Interference Cancellation With Analog Least Mean-Square Loop," IEEE Transactions on Microwave Theory and Techniques, vol. 65, no. 9, pp. 3336–3350, 2017, doi: 10.1109/TMTT.2017.2654218.

[5] A. T. Le, L. C. Tran, X. Huang, Y. Jay Guo, and J. Y. C. Vardaxoglou, "Frequency-domain characterization and performance bounds of ALMS loop for RF self-interference cancellation," IEEE Transactions on Communications, vol. 67, no. 1, 2019, doi: 10.1109/TCOMM.2018.2867514.

[6] A. T. Le, L. C. Tran, and X. Huang, "On Performance of Analog Least Mean Square Loop for Self-Interference Cancellation in In-Band Full-Duplex OFDM Systems," in IEEE Vehicular Technology Conference, 2017, vol. 2017-June. doi: 10.1109/VTCSpring.2017.8108364.

[7] A. T. Le, L. C. Tran, and X. Huang, "Cyclostationary analysis of analog least mean square loop for self-interference cancellation in in-band full-duplex systems," IEEE Communications Letters, vol. 21, no. 12, 2017, doi: 10.1109/LCOMM.2017.2755024.

[8] A. T. Le, Y. Nan, L. C. Tran, X. Huang, Y. J. Guo, and Y. Vardaxoglou, "Analog Least Mean Square Loop for Self-Interference Cancellation in Generalized Continuous Wave SAR," in IEEE Vehicular Technology Conference, 2018, vol. 2018-Augus. doi: 10.1109/VTCFall.2018.8690717.

[9] A. T. Le, L. C. Tran, X. Huang, and Y. J. Guo, "Analog Least Mean Square Loop with I/Q Imbalance for Self-Interference Cancellation in Full-Duplex Radios," IEEE Transactions on Vehicular Technology, vol. 68, no. 10, 2019, doi: 10.1109/TVT.2019.2933869.

[10] A. T. Le, L. C. Tran, X. Huang, and Y. J. Guo, "Analog least mean square loop for self-interference cancellation: A practical perspective," Sensors (Switzerland), vol. 20, no. 1, 2020, doi: 10.3390/s20010270.

[11] A. T. Le, L. C. Tran, X. Huang, Y. Jay Guo, and L. Hanzo, "Analog Least Mean Square Adaptive Filtering for Self-Interference Cancellation in Full Duplex Radios," IEEE Wireless Communications, vol. 28, no. 1, 2021, doi: 10.1109/MWC.001.2000210.

[12] A. T. Le, L. C. Tran, X. Huang, and Y. J. Guo, "Beam-Based Analog Self-Interference Cancellation in Full-Duplex MIMO Systems," IEEE Transactions on Wireless Communications, vol. 19, no. 4, 2020, doi: 10.1109/TWC.2020.2965441.

[13] A. T. Le, X. Huang, and Y. Jay Guo, "Analog Self-interference Cancellation in Dual-polarization Full-duplex MIMO Systems," IEEE Communications Letters, 2021, doi: 10.1109/LCOMM.2021.3095918.

[14] X. Huang, A. T. Le, and Y. Jay Guo, "ALMS Loop Analyses with Higher-Order Statistics and Strategies for Joint Analog and Digital Self-Interference Cancellation," IEEE Transactions on Wireless Communications, 2021, doi: 10.1109/TWC.2021.3074628.