Analog Self-Interference Cancellation By Means of a Synchronised Signal Injection

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***Abstract*—Full-duplex communications have the potential to double the spectral efficiency. Self-interference hinders the realization of full-duplex communications, thus significant suppression needs to be achieved to enable simultaneous transmit and receive. This paper presents a digitally-assisted analog self-interference cancellation by pre-coding a cancellation waveform on an auxiliary transmitter using a modified copy of the transmitted signal. Over 30 dB self-interference cancellation has been achieved over a bandwidth of 20 MHz.**

***Index Terms*—digitally-assisted cancellation, full-duplex, self-interference cancellation.**

I. Introduction

Wireless communications systems nowadays operate in half-duplex to separate the transmitter and the receiver in the time domain as in time-division duplex (TDD), or the frequency domain as in frequency-division duplex (FDD). The transmit power is required to be higher than the received power since there is a path loss between the transmitter and the distant receiver. The transmitted high power couples into the radio's receiver, causing self-interference (SI), which can compress the low-noise amplifier (LNA) in the receiver. SI has been avoided by TDD and FDD, leading to an inefficient usage of time and frequency resources.

Suppressing the SI to the receiver's noise floor enables simultaneous transmit and receive (STAR) operation. Self-interference cancellation (SIC) has the potential to double the spectral efficiency, but it introduces several technical challenges to the transceiver architecture and antenna design. The SI has higher power than the received signal of interest. Since the transmitted signal is known at the radio unit, the SIC method subtracts the SI at the receiver. However, the SI signal contains multiple copies of the transmitted signal, arriving with different amplitudes, phases, and delays [1]. An alternative method is the one demonstrated in [2] in which some of the TX power is injected into the receiver so that the isolation between two closely-separated antennas is improved.

SIC protects the receiver from the high-power signal coming from the power amplifier (PA) in the transmitter. Subtracting the SI from the received signal can effectively isolate the receiver from the transmitter. However, the coupling from the transmitter takes multiple paths as a result of reflections of the surrounding surfaces. Multiple copies of the coupling at the receiver require various stages to mitigate the SIC. Therefore, to mitigate the SIC at the receiver, a copy of the transmitted waveform is required in addition to the channel response between the transmitter and receiver of the same device.

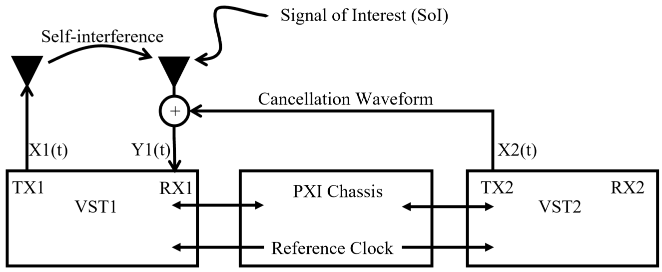

Fig. 1. Diagram of the analog cancellation system using National Instruments Vector Signal Transceivers (VSTs) connected with a computer on the PXI chassis. Phase lock is achieved using a precise 100-MHz connection in the chassis backplane.

Various stages of SIC operate in different domains to remove the SI from the receiver. These are the propagation/antenna domain, analog domain, and digital domain. A combination of cancellations in these domains can accomplish a better cancellation than using only one domain. These domains involve passive and active cancellation techniques. Passive cancellation weakens the interference through separation between the antennas. The active cancellation is estimation-based, reconstructing the SI to be subtracted from the received signal [3], [4].

This paper deals with analog SIC using an auxiliary transmitter that generates a cancellation waveform to be subtracted at the receiver. For a successful SIC, the cancellation waveform has to contain a copy of the transmitted signal and a channel model between the antennas of the transmitter and receiver. The transmitter and reciever of the same device are connected which helps having a copy of the transmitted waveform at the receiver.

II. Analysis

A replica of the transmitted signal must be subtracted to cancel the coupling from the transmitter into the receiver. The replica is typically obtained from the output of the transmitter's PA, which would include the distortions of the transmitter. In this section, the replica of the transmitted signal is generated through an auxiliary transmitter since the transmitted waveform is foreknown.

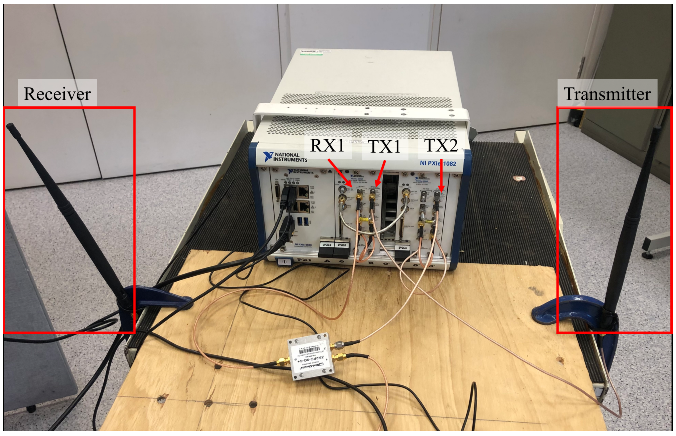

Fig. 2. Setup of the analog cancellation system using transmitting and receiving antennas with an injection of a cancellation signal using vector signal transceivers (VSTs) connected with a computer on the PXI chassis.

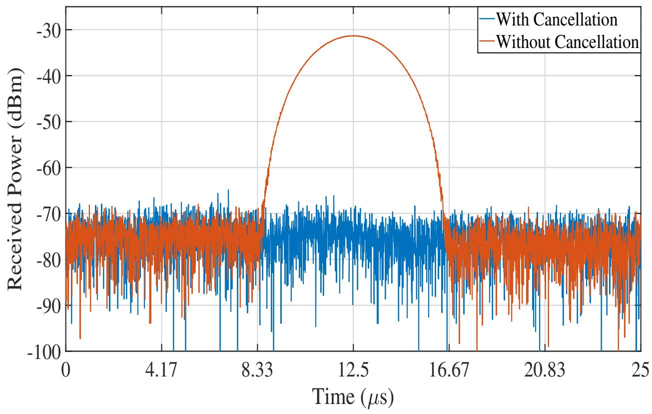

Fig. 3. Cancellation of a pulse waveform in the time domain.

The canceller system, as shown in Fig.1 uses two National Instruments (NI) PCI eXtensions for Instrumentation (PXI) vector signal transceivers (VSTs) connected with the same chassis. TX1 and RX1 are the transmitter and the receiver of the same device with a coupling between their antennas. The system models the channel throughout the calibration stage using transmitter TX1 and receiver RX1 on the VST when the cancellation waveform (TX2) is off. Channel modeling is implemented by exciting the channel with a test signal and correlating it with the received signal to find the impulse response as a complex coefficient. This method is known as channel sounding [5]. This helps to get the channel response as follows [6]:

$$h(t,\tau) = \sum_{i=1}^{L} a_i(t)\delta(t-\tau_i), \tag{1}$$

where L is the number of the direct path and multipath components, a_i represents the amplitudes and phases of each path, and τ_i represents the delays of paths.

After finding the channel response, the TX2 transmits the cancellation waveform, a delayed and scaled version of the transmitted waveform, as in Fig. 1. The scaling is in complex form as it includes the amplitude and phase of the signal. The two VSTs are synchronized using the 100-MHz reference clock and a constant time delay is used to synchronize the injection with the received signal. This synchronization was achieved on the 2 VSTs in [7]. The setup of the VSTs with the cancellation system is shown in Fig. 2. It shows two antennas for transmission and reception with a combiner to add the antiphase cancellation waveform.

The cancellation starts with a calibration phase to determine the channel between the transmitters and the receiver. Assuming a silent channel with no noise added, the received signal is as follows:

$$Y1 = K_{11}X1 + K_{12}X2, \tag{2}$$

where K_{11} is the complex coefficient between the transmitter (X1) and the receiver (Y1) when the cancellation waveform (X2) is off $\left(K_{11} = \frac{Y1}{X1}\middle| X1 = 0\right)$, and K_{12} is the complex coefficient between the canceller transmitter (X2) and the receiver (Y1) when the transmitter (X1) is off $\left(K_{12} = \frac{Y1}{X2}\middle| X2 = 0\right)$.

After calibrating and finding the coefficients K_{11} and K_{12}, and hence no leakage is desired at the receiver, the received signal is considered to have the value of zero in (2), and this helps to find the cancellation waveform as follows:

$$X2 = -\frac{K_{11}}{K_{12}}X1. \tag{3}$$

This formula performs amplitude and phase correction of the transmitted signal to allow subtraction of the replica of the transmitted signal at the receiver. The cancellation waveform and the transmitted signal are correlated. This allows the signal of interest, which is not correlated with the transmitted signal, to be received since the cancellation happens by adding an anti-phase version of the coupled signal of the transmitter into the receiver.

III. Implementation and Measurement

Fig. 3 demonstrated the cancellation by showing the received signal before and after applying the cancellation waveform. The cancellation waveform is the transmitted signal shifted and scaled with the coefficients calculated in the calibration stage. Cancelling the Gaussian pulse has brought the leakage to the noise level, showing a cancellation of over 30 dB. Fig. 4 shows the cancellation over a wider band using a raised cosine waveform. This shows the capabilities of a wideband operation of the cancellation after considering the channel model.

IV. Conclusion

A cancellation method using a correlated cancellation waveform has been presented using a vector signal transceiver. The subtraction of the cancellation waveform from the received

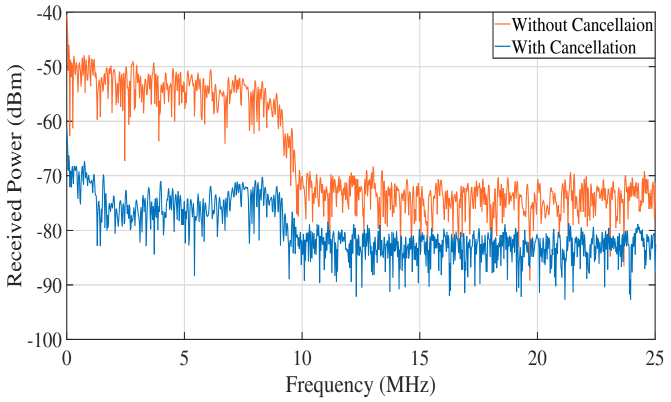

Fig. 4. Cancellation of a 20 MHz BW raised cosine signal over the frequency with a centre frequency of 2.4 GHz. Cancellation of about 20 dB across the 20 MHz signal has been achieved.

signal brings the self-interference cancellation to the noise floor, achieving over 30 dB self-interference cancellation for a 20 MHz bandwidth. This cancellation is a wideband cancellation and sufficient to be merged with other cancellation methods to give higher cancellation depth.

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