Four-Tap RF Canceller Evaluation for Indoor In-Band Full-Duplex Wireless Operation

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***Abstract*— Analog self-interference mitigation techniques are currently being investigated in a variety of operational settings for In-Band Full-Duplex (IBFD) systems. The significant multipath effects of realistic environments, such as inside buildings, can severely limit performance. The influence of different transceiver parameters on the effectiveness of a four-tap RF canceller, built using a tapped delay line architecture, was characterized with a set of indoor measurements. The prototype canceller showed up to 30 dB of cancellation over bandwidths ranging from 10 to 120 MHz centered at 2.45 GHz, and produced a combined analog system isolation greater than 85 dB.**

***Index Terms*— Adaptive canceller, analog cancellation, IBFD, in-band full-duplex wireless communication, interference cancellation, RF cancellation, simultaneous transmit and receive, STAR.**

I. Introduction

In-band full-duplex (IBFD) wireless operation can help alleviate the frequency spectrum congestion issues faced by current system designers. IBFD, also referred to as Simultaneous Transmit And Receive (STAR), is the concept of transmitting and receiving on the same frequency band at the same time. This idea can be applied to 5G cellular, cognitive radio and wireless relay applications, among others, to reduce spectrum crowding, which can enable advanced system architectures with the result of providing end-users with more capable devices [1].

Many legacy systems avoided this paradigm because, when not addressed, the interference that results from concurrent transmit and receive operation severely limits system performance. In order to make IBFD feasible, designers must incorporate different isolation-enhancement or self-interference cancellation techniques. The performance of these isolation-improvement methods needs to be evaluated over several different transceiver configurations as well as operational environments so that the cancellation techniques can be confidently incorporated into useful systems.

Since different wireless systems operate using various signal bandwidths and over a diverse set of ranges, in order to determine the applicability of a certain cancellation method, it should be investigated over both instantaneous bandwidth and transmit output power level. Additionally, while it is important to understand a technique's performance limitations during measurements in isolated environments, it should also be characterized in practical operation scenarios, such as indoor settings, to provide an indication of realistic results.

This paper will focus on the performance of an analog canceller that is intended to be part of a multi-layered system architecture to enhance isolation for IBFD [2]. The analog cancellation layer is responsible for reducing the self-interference signal before the input to the receiver, and is typically implemented as an RF tapped delay line with a certain number of taps. Several different RF canceller designs of this type have already been researched and measured in realistic indoor environments [3], [4]. Both of these results, however, did not include performance evaluations over a wide range of signal bandwidths or transmit power levels, which will be discussed in this paper.

The system and operational environment are described in Section II, while the results of several different measurement scenarios are presented in Section III. Conclusions are derived in Section IV.

II. System Description

A. Architecture

A tapped delay line canceller can be incorporated into a basic IBFD system with the use of directional couplers as illustrated in Fig. 1. This RF canceller architecture is preferred over others because it not only samples the transmitted signal, but also captures the transmitter output noise, which allows it to also be cancelled at the receiver input and not degrade sensitivity. The system diagram is shown with two unique antennas, one for transmit and one for receive, but these general concepts also apply to single-antenna IBFD systems.

Additionally, Fig. 1 depicts the self-interference channel as hi(t), which represents the combination of both direct path coupling between the transmit and receive antennas as well as multipath effects from the surrounding environment. This interference channel can be decomposed, as

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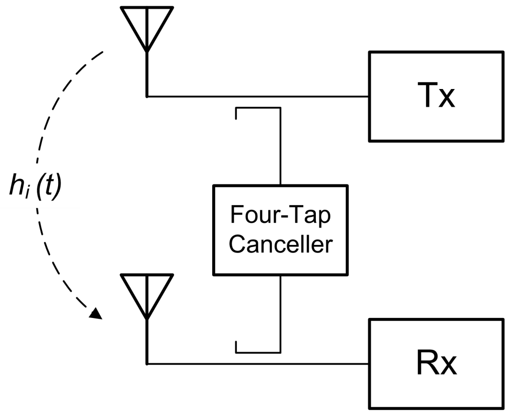

Fig. 1. Basic in-band full-duplex wireless system utilizing a four-tap RF canceller.

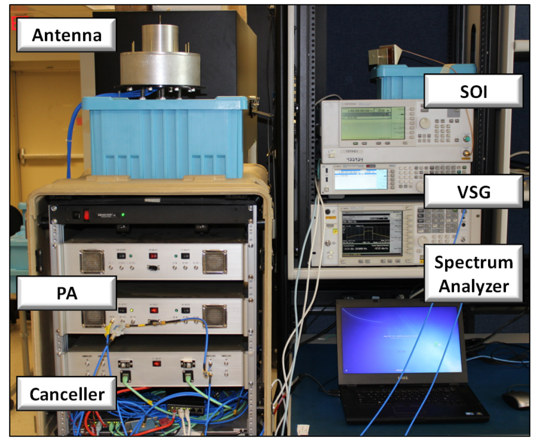

Fig. 2. Test setup in laboratory.

shown in [5], to

$$h_i(t) = h_{i,0}(t) + \sum_{n=1}^{N} h_{i,n}(t), \quad (1)$$

where $h_{i,0}(t)$ is the direct path and $h_{i,n}(t)$ are the multipath contributions. Antenna isolation improvements can be made to both dual- and single-antenna configurations to effectively reduce the $h_{i,0}(t)$ coupling, but do not address the unknown multipath effects that also exist. These multipath signals are obviously dependent on the operational environment, and an RF canceller should be designed to be as flexible as possible to be able to respond to them. The specific canceller selected for this system has four non-uniform pre-weighted taps to effectively extend the range of reflections it can address while also limiting its insertion loss, and is described in detail in [5].

B. Environment

Fig. 2 shows an IBFD prototype system using directional couplers with 10 dB coupling coefficients that was constructed to match the diagram depicted in Fig. 1. An integrated high-isolation omni-directional antenna was selected for the transmit and receive antennas, and effectively reduces the direct path coupling, $h_{i,0}(t)$, to approximately 55 dB [6]. An N5182B vector signal generator (VSG) from Agilent Technologies followed by an external power amplifier (PA) comprised the transmitter function. The VSG allowed the canceller to be evaluated using a realistic OFDM signal centered at 2.45 GHz and dynamically change the operational signal bandwidth. The PA provided both the desired output power levels as well as the inclusion of typical noise and distortion products.

This transmit output signal was coupled into the above-mentioned RF canceller configured with fixed tap delays. The first tap was aligned in time with the residual direct path component, while the second, third and fourth taps were set to 4.0, 8.0 and 12.0 ns delays, respectively.

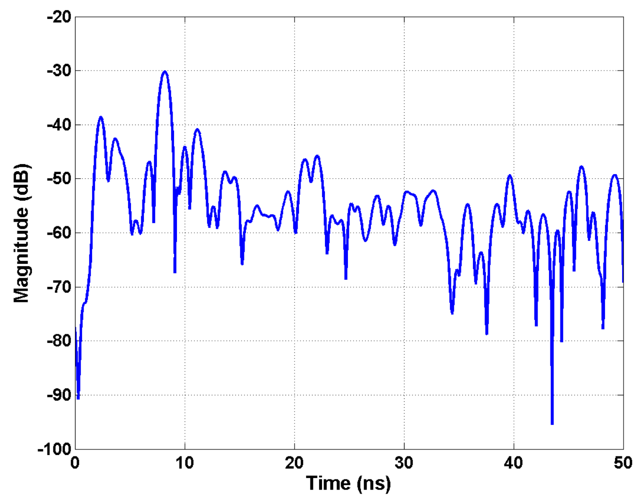

Fig. 3. Time-domain transmission response of in-band full-duplex system operating in an indoor environment.

Finally, Agilent Technologies' E4440A spectrum analyzer was utilized as the receiver, while an E8247C signal generator from Agilent Technologies was used to synthesize a signal-of-interest (SOI).

As can be seen in Fig. 2, the operational environment chosen for this canceller evaluation is an indoor laboratory setting, which is characteristic of many wireless nodes operating inside buildings. In order to gain an understanding of the multipath coupling, $h_{i,n}(t)$, inside the laboratory a time-domain transmission (TDT) measurement was conducted. Fig. 3 plots the magnitude response of the TDT measurement, and illustrates the remaining direct path coupling at roughly 2 ns and the strongest multipath component at approximately 8 ns. If significant multipath elements are defined as having magnitudes greater than -50 dB, the environment is shown to be rich in multipath out to 50 ns, which intuitively makes sense for this indoor operation.

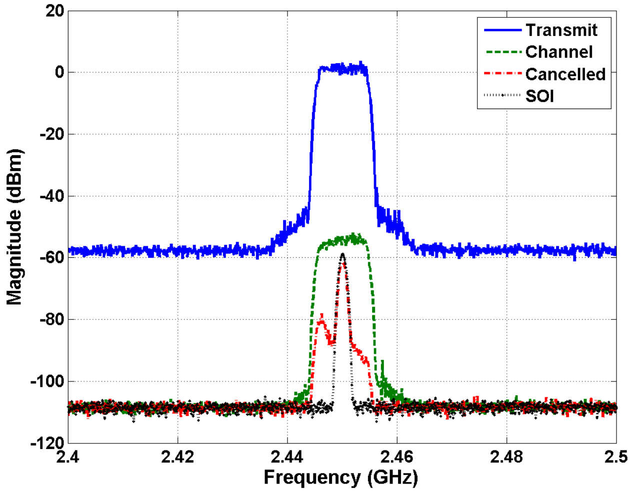

Fig. 4. Magnitude responses of transmit, channel, cancelled and SOI for +20 dBm OFDM over 10 MHz.

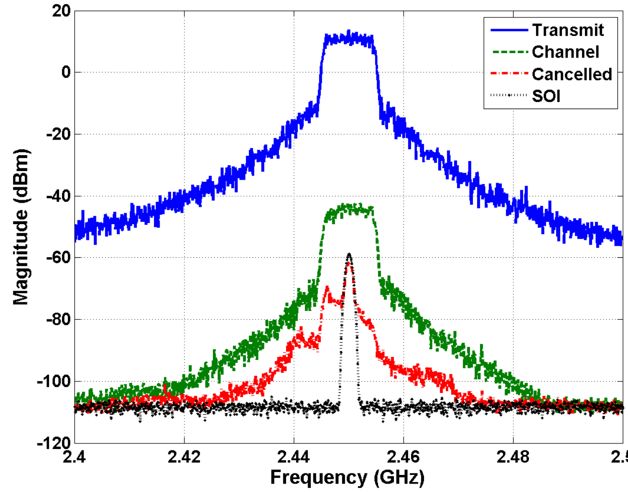

Fig. 5. Magnitude responses of transmit, channel, cancelled and SOI for +30 dBm OFDM over 10 MHz.

III. Results

The canceller was tuned to mitigate the effects of the indoor environment by using the adaptive Dithered Linear Search (DLS) algorithm described in [5]. The transmitter was first configured to output an OFDM signal over a 10 MHz bandwidth centered at 2.45 GHz with +20 dBm of total output power. This waveform and power level are representative of many handheld wireless devices that can be used for both communications or bulk data transfer. The transmitter output spectrum is indicated in Fig. 4, and shows a signal with good linearity, minimal adjacent-channel leakage and an elevated noise floor that resulted from increasing the internal spectrum analyzer attenuation level.

Fig. 4 also shows the received self-interference signal before the RF cancellation is activated, which is influenced by the channel response and thusly labeled. As can be seen, the channel is roughly 55 dB lower than the transmit signal due to the effect of the high-isolation antenna previously mentioned [6]. A CW signal representing an example SOI is also present approximately 5 dB below the received self-interference, and is consequently undetectable without either advanced decoding techniques or further interference mitigation.

The RF canceller algorithm was set to target this self-interference over the operational band, and produced the cancelled trace shown in Fig. 4. After this additional isolation improvement, the SOI signal-to-noise (SNR) ratio is visibly enhanced from roughly -5 dB to +20 dB, and should now be able to be decoded after digitization. For this indoor system configuration, the RF canceller provided 32.4 dB of average cancellation, and yielded a combined average system isolation of 88.3 dB.

While the cancellation for typical handheld devices should be evaluated, it is also worthwhile to investigate a canceller's performance with higher transmit power levels that are characteristic of wireless nodes that cover larger areas. Fig. 5 plots the transmitter output over the same frequency band, but with the output power increased to +30 dBm. This higher level clearly introduces non-linear distortion terms from the PA as seen in the increased amount of adjacent-channel power. Since the high-isolation antenna is completely passive and still under its maximum power capability, the received signal is again reduced by 55 dB. The SOI was also present during this measurement, but its level was kept fixed and resulted in an SNR of roughly -15 dB before tuning. Once again, the canceller was then adapted to the channel, and yielded the cancelled response shown in Fig. 5. This reduced the high-power self-interference signal, and improved the SOI's SNR to approximately 15 dB. For this setup, the canceller produced an average cancellation of 31.5 dB, and an average total isolation of 87.1 dB when combined with the antenna.

In order to determine the canceller's applicability to systems that are allocated different instantaneous bandwidths or dynamically change them, the transmitter's signal bandwidth was swept in addition to the output power level. While [3] provided measured canceller results for 20 and 100 MHz bandwidths, and [4] included data for 20 and 80 MHz bandwidths, Fig. 6 shows measured canceller performance for bandwidths ranging from 10 to 120 MHz. As expected, the cancellation resulting from a device with only four taps decreases as instantaneous bandwidth increases. This performance can be modeled using a two-term exponential model of the form

$$C_{4-tap}(bw) = Ae^{B\cdot bw} + Ce^{D\cdot bw} \tag{2}$$

where bw is the instantaneous bandwidth in MHz, and parameters A = 24.1, B = -0.0058, C = 18.4 and D

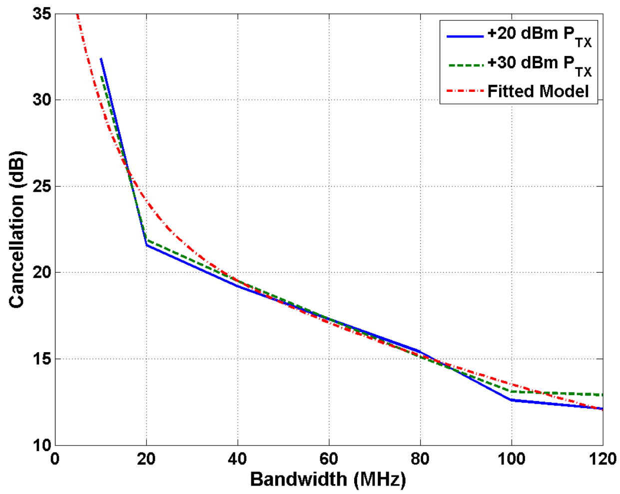

Fig. 6. Cancellation magnitude versus instantaneous bandwidth centered at 2.45 GHz.

= −0.0969. This fitted model is also plotted in Fig. 6 and closely matches the measured data, which indicates that it could be used to estimate cancellation performance for other systems operating in a similar environment. It is also worth noting that this canceller provided roughly the same results for both +20 and +30 dBm transmit power levels (P_{Tx}) over these different bandwidths as illustrated in Fig. 6. All of these RF cancellation and subsequent total analog isolation results are summarized for the different instantaneous bandwidths (BW) listed in Table 1.

IV. Conclusion

A four-tap RF canceller was integrated into a prototype IBFD transceiver system for the purpose of evaluating its operation in a typical indoor environment that was rich in multipath effects. The canceller was shown to effectively improve the SNR of a SOI by providing more than 30 dB of cancellation over a 10 MHz band centered at 2.45 GHz. The transceiver's output power was then changed between +20 and +30 dBm, while its instantaneous signal bandwidth was varied between 10 and 120 MHz. Through a series of measurements, the dependence of the canceller's performance on these parameters was captured, which allowed a two-term exponential model to be created. This model can be utilized to estimate the expected cancellation performance for future IBFD systems operating in similar indoor settings.

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TABLE I
PERFORMANCE SUMMARY FOR DIFFERENT BANDWIDTHS

Parameter	Cancellation		Total Isolation		Units
P_{Tx}	+20	+30	+20	+30	dBm
BW = 10 MHz	32.4	31.5	88.3	87.1	dB
BW = 20 MHz	21.6	21.9	77.8	77.9	dB
BW = 40 MHz	19.2	19.5	75.7	75.9	dB
BW = 80 MHz	15.4	15.1	74.3	73.9	dB
BW = 100 MHz	12.6	13.1	71.2	71.7	dB
BW = 120 MHz	12.1	12.9	68.6	69.3	dB

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