Active Cancellation of Self-Interference for Full-Duplex Amplify and Forward Wi-Fi Relay

Sergey Shaboyan, Alireza S. Behbahani, and Ahmed M. Eltawil

***Abstract*—This letter presents a Wi-Fi compliant self-interference (SI) active cancellation (AC) technique for amplify and forward full-duplex relay (AF-FDR) utilizing orthogonal frequency division multiplexing. First, we describe the system model of AF-FDR, where the relay transparently extends the range of the main access point (AP) to reach a station located outside the AP's radio coverage. We highlight the SI (and its suppression) impact on FDR, due to simultaneous transmission/reception on the same frequency. We then present a novel Wi-Fi compliant estimation technique of the SI channel and its delay parameters, which are later used for AC, achieving SI suppression of up to an additional 35 dB. The proposed AF-FDR system is simulated in a fading channel environment with Doppler frequency of up to 10 Hz. Simulation results show cancellation gains within 1 dB of static channels with an SI training overhead of 1.5%.**

***Index Terms*—In-band, full-duplex, self-interference, suppression, Wi-Fi, extender.**

I. Introduction

ADDITION of relay station (RS) to an existing Wi-Fi network is a common solution when wireless coverage extension is required in the absence of a connection to the backbone network. Half-duplex (HD) Wi-Fi relays employ two different frequencies, time slots, or orthogonal spreading codes to prevent the transmitted signal from interfering with its own receiver. In contrast full-duplex relays (FDR) utilize wireless resources more efficiently by transmitting and receiving simultaneously on the same frequency band, creating the potential of doubling the system throughput, when compared to their Half Duplex (HD) counterparts [1]. Although FDR has higher transmission efficiency, it suffers from Self Interference (SI) since the transmitted signal by the FDR is received as an in-band blocker by its own receiver. The SI signal results in system instability, and poor signal to interference plus noise ratio (SINR) of the signal that is intended to be relayed [2]. In order to use a FDR for higher efficiency, SI must be coherently canceled in order to provide stability and a satisfactory level of SINR of the received signal, before amplifying and forwarding it. To achieve sufficient SI suppression FDR relies on cancellation across multiple domains (spatial, analog and digital cancellation).

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Numerous techniques are available for SI suppression including passive (eg. antenna separation, directional antennas etc.) and active (analog and digital) cancellation [3]. Active cancellation (AC) is based on the knowledge of the SI channel state information and its boundary in time. To estimate channels under severe timing and frequency offsets, a customized frame structure of alternating pilots has been proposed [4]. However, changing the current standards to accommodate FDRs is either unlikely or will delay the adoption of FDR systems. Thus, in order to benefit from FDR, it is necessary to find means to perform SI cancellation while remaining standard compliant.

In this letter Amplify and Forward Relay (AFR) station is considered. We identify and analyze impairments due to wireless channel effect and synchronization errors on the received signal by AFR. Techniques are developed enabling AFR to perform channel estimation, synchronization error estimation and compensation, while maintaining compliance with Wi-Fi packet structure. Specifically, this letter presents the following contributions:

- A novel estimation strategy of SI channel and time delay is presented that makes use of existing procedures in Wi-Fi protocol, and avoids any software/hardware modifications of the other network nodes.
- A collision detection technique is presented, allowing validation of acquired channel estimate based on none-acknowledgeable packets in random access networks.
- Performance of the system in the presence of dynamic channel effects and synchronization errors is evaluated.

The remainder of this letter is organized as follows. In Section II a Wi-Fi network extended by FDR is described and challenges are outlined. In Section III time and frequency misalignments are described and their impacts on SI cancellation are highlighted. In Section IV, SI channel estimation and time alignment techniques are proposed. Performance results of the simulated system under different channel conditions is presented and compared in V. This letter is concluded in Section VI.

Notation: We use (*) to denote convolution, $(.)^*$ to denote conjugate and *arg*[.] to denote argument of a complex number. Time domain variables are represented as lowercase letters, while frequency domain variables use uppercase. Furthermore, bold lowercase letters denote vectors.

II. System Model

Figure 1 illustrates a Wi-Fi network consisting of an access point (AP) and stations (ST). Some stations are located outside the coverage of AP and do not receive service, e.g., ST2. For simplicity we will assume that the transmitted signal strength by AP is negligible outside of the AP's radio coverage area. To extend the coverage, a FDR station is placed at

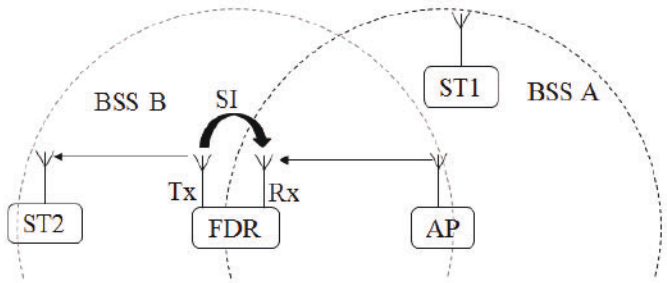

Fig. 1. Diagram of full duplex relayed Wi-Fi Network.

the boundary of the AP cell. All the stations including FDR and AP utilize Orthogonal Frequency Division Multiplexing (OFDM), that employs N_{FFT} subcarriers with inter-carrier spacing $\Delta f = f_s/N_{FFT} = 1/(N_{FFT}\,T_s) = 1/T_{sym}$, where T_s is sampling period, f_s is sampling frequency and T_{sym} is one OFDM symbol duration.

A. Relay Station

The relay station is classified to be Amplify and Forward (AF) type, however it is assumed to have the ability to construct and transmit certain control/management packets defined in the Wi-Fi standard. The relay station receives and transmits Wi-Fi packets on the same frequency and in the same time slot. The signal that FDR is aiming to receive is the signal of interest (SOI). The transmitted signal by FDR is also received by its own receiver, causing SI, thus the received signal by the FDR station can be modeled as

$$r(t) = s^{rx}(t) + y^{rx}(t) + w(t) \tag{1}$$

where $s^{rx}(t)$ and $y^{rx}(t)$ are SOI and SI components of the received signal and $w(t)$ is Additive White Gaussian Noise (AWGN).

In general, SI power is orders of magnitude larger than SOI, due to the fact that the distance between Tx and Rx antennas of the FDR is significantly smaller compared to the distance between any transmitting node and the FDR. In order to successfully receive SOI and re-transmit it with high gain, while maintaining stability, a proper isolation between Tx and Rx chains of the FDR is required [5], to avoid positive feedback. This is difficult to achieve only with passive SI suppression. Active suppression relies on the accurate knowledge of the SI component in the received signal. Hence we will detail the channel and timing misalignment impact on AC at FDR, in Section III.

B. Channel Model

SOI channel, h^{soi}, is modeled to reflect path loss and Rayleigh fading effects. Since received packets are transmitted by nodes, randomly located in the cell, h^{soi} is modeled to reflect random discontinuity of SOI channel from packet to packet. SOI is impacted by carrier frequency offset and sampling time offset due to the local oscillator (LO) mismatch Δf_c.

The SI channel, h_{si}, is modeled to reflect path loss and Rayleigh fading effects. There are three main consideration to make regarding SI channel as follows:

1) Due to the fixed relative position of SI Tx and Rx antennas, h_{si} is modeled to maintain channel continuity from packet to packet.
2) It is assumed that a passive SI suppression of 60 dB is achieved by using reconfigurable directional antennas as previously described by Shaboyan *et al.* [1]. Using reconfigurable directional antennas, effectively cancels the line of sight SI component and results in a Rayleigh channel observed for the SI channel rather than a high K Ricean channel.
3) The SI signal does not experience either Clock Frequency Offset (CFO) or Sampling Time Offset (STO) because both the transmitter and receiver are co-located at the FDR and share the same clock frequency.

Finally, AWGN is added to the composite signal consisting of SOI and SI.

III. Channel and Misalignment Effects on FDR

Each wireless node generates its clock signal locally. Clock frequency mismatches result in a frequency mismatch Δf_c between the transmitter LO and the receiver LO. As a result, the received signal will experience CFO. The Digital to Analog Converter (DAC) at the transmitter and the Analog to Digital Converter (ADC) at the receiver are also driven by asynchronously generated clock signals, thus, after digitization, the received signal samples will experience STO as well. Each signal component in $r(t)$ as shown in (1) is subject to time and/or frequency offsets with different amounts, since the received signal by FDR consists of two signal components transmitted by two different transmitters. SOI component in the received signal $r(t)$ is transmitted by the remote node thus, it will be impacted by CFO, and STO as well as channel delay. SI component in received signal $r(t)$ is transmitted by FDR, therefore it will only experience channel delay. To capture time and frequency misalignments, the received i^{th} block of data u_i by FDR can be written as

$$\begin{aligned} u_i(n) = {} & e^{j\frac{2\pi\varepsilon n}{N_{FFT}}} s_i^{tx}(n-\theta) * h_i^{soi}(n) \\ & + y_i^{tx}(n-\tau) * h_i^{si}(n) + w(n), \end{aligned} \tag{2}$$

where $s^{tx}(t)$ and $y^{tx}(t)$ are SOI and SI components of the transmitted signal. $h^{soi}(n)$ and $h^{si}(n)$ represent path loss and fading of SOI and SI channels respectively. ε is the relative carrier frequency error, defined as $\varepsilon = \Delta f_c/\Delta f$, θ represents time shift of SOI due to STO plus channel delay, and τ represents time shift of SI due to channel delay. Time offset θ is a gradually increasing quantity, which can have integer, as well as, fraction parts $\theta = \theta_{in} + \theta_{fr}$. Offset τ is relatively constant and can be treated as integer quantity.

A. Amplify and Forward Full-Duplex Relay

In AF mode, FDR is transparently relaying every packet without decoding its content. This strategy relaxes MAC requirements at the expense of allowing unnecessary retransmissions. Recall that AC relies on subtraction of known transmitted SI from the signal being received. After Digital Cancellation (DC), i^{th} block of the received signal d_i can be expressed as

$$\begin{aligned} d_i(n) &= u_i(n) - y_i^{tx}(n-\hat{\tau}) * \hat{h}_i^{si}(n) \\ &= e^{j\frac{2\pi\varepsilon n}{N_{FFT}}} s_i^{tx}(n-\theta) * h_i^{soi}(n) + w_i^{si}(n) + w(n), \end{aligned} \tag{3}$$

where $\hat{\tau}$ is the estimated time offset of SI component and $\hat{h}^{si}(n)$ is SI channel estimate. $w^{si}(n)$ is the residual SI after DC. Analog cancellation takes the same approach but operations are carried out in analog domain before the receiver ADC. From (3) it is obvious that even when FDR does not decode SOI, it still has to estimate SI channel and its delay, in

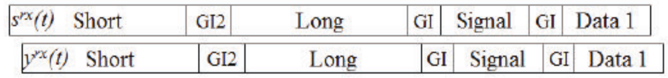

Fig. 2. Received Signal by FDR in Wi-Fi Traffic.

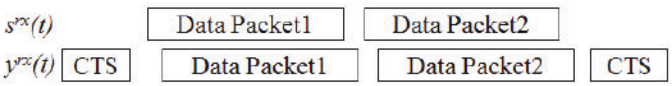

Fig. 3. Transmission of CTS-to-self packets by AF-FDR.

order to minimize residual SI $w^{si}(n)$, before amplifying and re-transmitting d_i.

IV. Proposed SI Channel Estimation and Alignment

As described earlier AF-FDR requires time offset detection of SI component as well as SI channel estimate. During relaying, it receives two overlapping packets, where overlap corrupts both training and data fields, as shown in figure 2. Since all transmitted packets must comply with Wi-Fi standard, FDR cannot use a customized packet structure, which could avoid overlap of training fields during re-transmission.

Proposed solution: In this letter, we propose that the FDR transmits control/management frames periodically to train and update the SI channel estimate accordingly using transmit Clear-To-Send (CTS) frame to itself, which is an already defined technique in Wi-Fi. CTS-to-self is a method of reserving medium for upcoming data transmission, for a specified duration [6]. Since FDR only needs to perform training during CTS-to-self, and has no intention of reserving the channel, it will set Duration field to be 0.

In general, there are 3 different scenarios that can occur as FDR proceeds with transmitting CTS-to-self, aiming for accurate channel estimate.

Case 1: When FDR is powered up it goes through an initialization phase, where it collects information about the network as well as valid SI channel estimates $\hat{h}^{si}$. In this phase the validity of $\hat{h}^{si}$ is verified by rejecting the outliers from multiple channel estimates followed by statistical averaging.

Case 2: When FDR gains access to the medium, transmission of CTS frame has started and no other station is allowed to transmit. As a result received signal consists of SI only, and the received i^{th} block of pilot data can be expressed as

$$p_i(n) = y_i^{tx}(n-\tau) * h_i^{si}(n) + w(n). \quad (4)$$

Using $p_i(n)$ from (4) FDR estimated the time delay of SI by correlating the received signal with locally stored training sequence, and searches for a peak position as described below.

$$\hat{\tau} = \arg\max_n \left[\sum_{m=1}^{W_d} p_i(m) \cdot p_i^{si*}(m+n) \right], \quad (5)$$

where $p_i^{si}(n)$ is the local copy of i^{th} block of SI preamble, and W_d is the correlation window width. Once position of SI is determined, the least square (LS) estimation of its channel can be carried out in frequency domain as

$$\hat{H}_i^{si}(k) = \frac{P_i(k)}{Y_{i,\hat{\tau}}^{tx}(k)} = \frac{Y_{i,\tau}^{tx}(k) H_i^{si}(k) + W(k)}{Y_{i,\hat{\tau}}^{tx}(k)}, \quad (6)$$

TABLE I

Simulation Parameters

OFDM Parameters	Value	Signal Parameters	Value
OFDM Subcarriers	64	Channel Type	D
Data Packet Duration	1.6ms	AWGN Power	-100 dBm
Cyclic Prefix (CP)	$3.2\mu s$	Rx SOI Power	-70 dBm
Symbol Duration (CP+FFT)	$16\mu s$	Rx SI Power	-65 dBm
CTS+DIFS Duration	$130\mu s$	Tx Power	+15dBm
Inter-carrier spacing	78125 Hz	Carrier Frequency	2.5 GHz

where $\hat{H}_i^{si}(k)$ is the i^{th} SI channel estimate. $P_i(k)$, $Y_i^{tx}(k)$, $W(k)$ are frequency domain representations of $p_i(n)$, $y_i^{tx}(n)$, $w(n)$ respectively. After acquiring the recent SI channel estimate, FDR uses it to cancel SI from the received signal $u_i(n)$. As a result the i^{th} block of received data packet after AC is given by (3). Since AF-FDR is not interested in decoding SOI, it will amplify and retransmit d_i as the next step.

Case 3: Due to the random access mechanism of Wi-Fi network, it is possible that upon transmitting CTS-to-self by FDR, another station begins transmitting simultaneously. The two transmissions will collide, contaminating received CTS, and will result in corruption of the new SI channel estimate. Note that there is neither collision sense (CS) mechanism, nor CTS-to-self acknowledgement. Cyclic Redundancy Code (CRC) field of a Wi-Fi frame allows receiver to test validity of the packet, however that requires decoding the packet, which AF-FDR is unable to do. To check, whether the training signal has been contaminated or not, we propose the following technique.

First the FDR buffers the frame and detects the i^{th} block boundary of SI. Then it uses the previous channel estimate $\hat{h}_{i-1}^{si}(n)$ to perform subtraction of Tx copy of SI training from Rx training signal $p_i(n)$ as

$$\delta_i = \frac{1}{N_{FFT}} \sum_{n=1}^{N_{FFT}} \left| p_i(n) - y_i^{tx}(n-\hat{\tau}) * \hat{h}_{i-1}^{si}(n) \right|^2, \quad (7)$$

where δ is the received residual power after subtraction. If after performing self-subtraction of CTS-to-self frame, there is still significant residual power left, then the CTS-to-self has collided and the new channel estimate is discarded. However, if after performing self-subtraction on $p_i(n)$, the remaining power of δ is below a predefined threshold, then CTS-to-self was successful, and channel estimate is updated with the new one.

$$\hat{h}^{si}(n) = \begin{cases} \hat{h}_i^{si}(n) & \delta_i < \eta \\ \hat{h}_{i-1}^{si}(n) & otherwise, \end{cases} \quad (8)$$

where η is a predefined power threshold level.

Given there was no collision, the remaining power δ, after self-subtraction of CTS, depends on the difference between the current SI channel $h_i^{si}(n)$, and the previous SI channel estimate $\hat{h}_{i-1}^{si}(n)$, which is a function of the coherence time of the channel. Section V presents numerical simulation results to quantify the performance of the proposed techniques.

V. Simulation Results

The AF-FDR system is simulated according to the parameters listed in Table I. The aim is to relay Wi-Fi data packets without amplifying SI. FDR has passive SI cancellation capability of 60dB [1]. FDR transmits CTS-to-self packets periodically to acquire SI channel and delay estimates, which

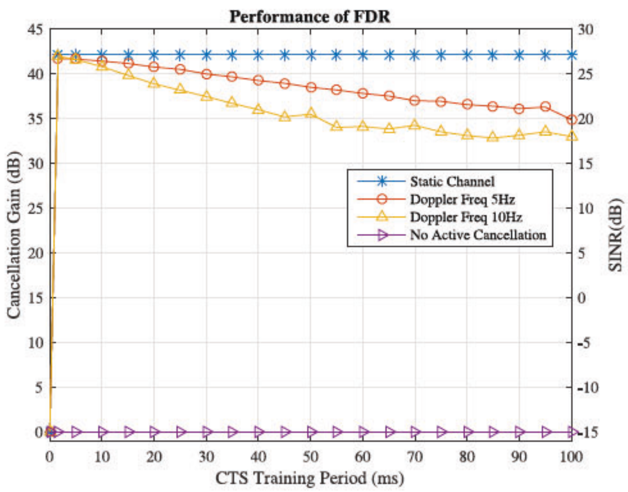

Fig. 4. Active Cancellation Gain vs. CTS-to-self period.

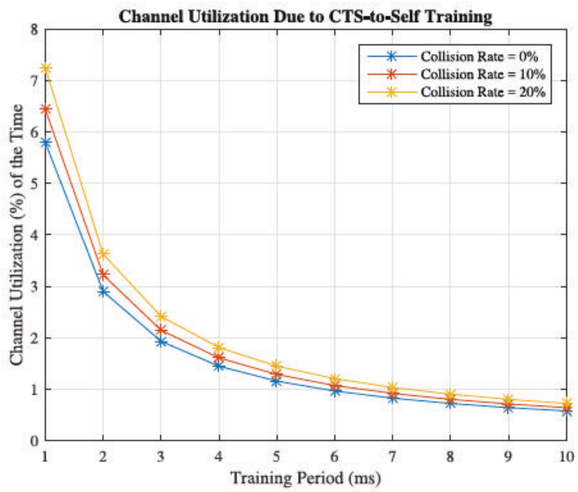

Fig. 5. Percentage of Time the Channel is Occupied by CTS-to-self.

are used to perform AC on every consecutive data packet until next SI training cycle.

To quantify the impact of SI channel estimation frequency on SI cancellation, the FDR system is simulated for different CTS-to-self transmission periods and the cancellation gain is plotted in Figure 4, for static as well as dynamic channels. For CTS transmission periods that are less then 5ms, cancellation gains are almost identical for static and dynamic channels.

As the training frequency of SI channel is reduced, packets that have experienced a fading channel exhibit a degradation in cancellation gain commensurate with the Doppler of the channel. This effect can be reduced by increasing the frequency of CTS training, at the expense of increased channel utilization shown in Figure 5, which illustrates the percentage of time that channel is occupied by the CTS plus its associated distributed interframe space (DIFS), as a function of the training period.

Figure 5 suggests, that in lightly loaded networks, where packet collision rate is negligible, SI channel estimation can be done as often as every 1ms, with approximately 6% channel utilization. However increasing the CTS-to-self transmission period slightly, e.g., up to 5ms, lowers channel utilization

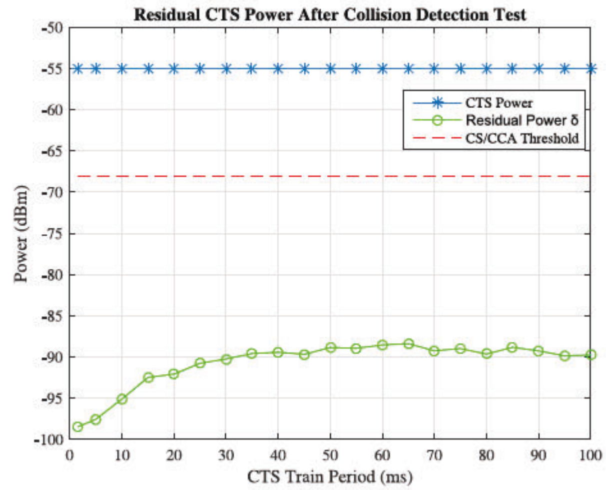

Fig. 6. Residual Power of CTS-to-self in 10Hz Doppler Channel.

down to 1.5% with less than 1dB cancellation gain loss at 10 Hz Doppler.

To determine whether or not the received CTS-to-self packet is contaminated, FDR performs collision detection test on received CTS-to-self frame described by (7), (8). Figure 6 illustrates power of received CTS-to-self packet and residual power δ, in a fading channel with a Doppler frequency of 10Hz. The graph shows that as the previous estimate ages, as long as no collision occurs, residual power increases over time, showing a increase of 10dB over a duration of 100ms. Figure 6 further suggests that a good value for the predefined threshold η is -85 dB for this system eqs. (8).

VI. Conclusion

This letter presented active suppression of SI by AFR in Wi-Fi OFDM networks. The major challenges are SI channels and delay estimation, while maintaining compliance with the standardized Wi-Fi packet structure and procedures. A novel SI channel estimation using self CTS technique is presented, that allows SI suppression below noise floor even under severe channel conditions, without requiring hardware/software changes of existing wireless nodes. Simulation results are presented showing the effectiveness of the proposed technique in relation to channel utilization cost.

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