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Exploring Design Tradeoffs and Rate Gain Regions in Full-Duplex Wireless Communications

Abstract: - Conventional HD wireless networks operated by using distinct time slots or frequency (freq.) sub-bands for transmission and reception within the same family. Therefore, the wireless research community aims to develop FD operation to enable simultaneous transmission along with reception inside a single time/ freq. channel. This research aims to conduct an analytical investigation of the conditions under which real FD systems may attain higher data rates compared to analogous HD systems. The primary obstacle in real FD systems is to the uncancelled self-interference (SI) signal, which arises due to a confluence of hardware along with implementation defects. First, provide a signal model that encompasses the impact of notable impairments, including oscillator phase noise (PN), along with low-noise amplifier (LNA) noise figure, along with mixer noise, along with analog-to-digital converter quantization noise. The rate gain area (RGA) is examined in this research using the comprehensive signal model. A~1.2x to ~1.4x that of HD systems for short-range applications like class-3 Bluetooth. To get the same rate gain with Class-1 Bluetooth, −70dB in-band PN must be paired with 50dB passive SI suppression.

Keywords: Design Trade-off; Rate Gain; FD; Wireless Communication; Analog Cancellation; Digital Cancellation; HD

INTRODUCTION

Given the anticipated need for communication networks to support higher data rates, it is imperative to enhance the spectral efficiency of these networks. Despite the potential benefits of advanced techniques like MIMO along with OFDM in enhancing spectral efficiency, existing wireless communication systems are still inadequate in meeting the aforementioned requirements [1].

A significant drawback of existing deployed systems is their limited ability to function as HD systems, using either time-division or even freq.-division techniques to provide bidirectional communication. The primary

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obstacle in achieving Full-Duplex (FD) transmission arises from the significant power disparity across the SI signal generated by the transmitting node along with the desired signal-of-interest that the receiver aims to decode. Several recent studies have empirically shown that, under certain circumstances and with the implementation of suitable SI cancellation techniques, real FD systems may outperform half-duplex (HD) systems [2].

Nevertheless, one must note that existing FD wireless systems do not achieve superior performance compared to HD transmission in all operational scenarios. This limitation might be primarily attributed to the existence of poor SI cancellation. This research article draws inspiration from the aforementioned finding and seeks to comprehensively analyze the obstacles encountered in FD functioning. In order to advance our comprehension of the limitations of practical FD systems, we employ a signal model that encompasses narrowband FD along with HD systems [4]. This model incorporates four key sources of transceiver noise: PN in the transmitter and receiver, noise from the LNA, noise from the mixer, and quantization noise from the Analog-to-Digital Converter (ADC). This study addresses the issue of bidirectional FD transmission in the presence of passive suppression along with active cancellation techniques [3] Review of literature is being discussed in section II.

LITERATURE REVIEW

Table 1: Literature review on performance comparison between FD and HD

Author & Year	**Research Contribution**	**Remark**
Han et al., (2019) [8]	The inclusion of HD mode with a complex protocol architecture might have also been appealing in terms of its practical implementation.	The allocation of resources for multi-hop connections was achieved by the use of a quasistatic resource partitioning unit.
Shahsavari et al., (2022) [7]	This paper provided a description of rateless coded HD and FD protocols that used opportunistic relaying. It also conducted an examination and comparison of the attainable rates of these protocols.	It was assumed that there existed a limit on peak power as well as a constraint on average power.
Alnabelsi et al., (2022) [5]	This analysis assessed the break-even system identification (SI) level and demonstrated the instances in which the frequency division FD mode may have provided enhanced capacity compared to its high-definition HD equivalents.	The occurrence of loop interference in frequency domain FD relay systems was mitigated to a level that was below the break-even point.
Velmurugan et al., (2023) [4]	This study aimed to determine the end-to-end channel capacity of the HD and FD modes within the context of infrastructure-based amplify-and-forward (AF) protocols.	Both loop interference and interference resulting from frequency reuse were seen to be at an equivalent level as the power of the receiver noise.
Kurma et al., (2023) [6]	This study aimed to ascertain the outage probability in correlated lognormal channels for both the HD along with FD modes.	Correlated lognormal channels were regarded as significant in the field.

One of the primary obstacles faced in the implementation of a FD wireless device pertained to the significant power disparity across the SI caused by the device's own broadcasts and the desired signal received from a distant source.

METHODOLOGY

In this section, use the comprehensive signal model, incorporating the aforementioned four noise sources, alongside various SI cancellation mechanisms, to systematically examine the operational domains in which FD systems exhibit superior performance compared to HD systems in relation to achievable rate, while operating under identical conditions. In a given situation where a freq. division radio is used, it is crucial for the receiver antennas (RAs) to possess the ability to attenuate the signal interference (SI) by roughly 95 dB. This is necessary to prevent the FD node's own broadcasts from excessively compromising its reception quality. The FD radio in question operates with a transmit power (TP) - 0 dBm and encounters a noise floor of around -90 dBm. To provide more clarification, it should be noted that in real-world systems, freq. division radios have the potential to introduce distortions to the digital baseband representation of the transmitted signal. Both linear distortions, caused by signal attenuations along with reflections from the environment, among other factors, along with nonlinear distortions, triggered by circuit power leakage, along with nonflat hardware freq. response, along with higher order signal harmonics, are present [11]. In the context of a standard WiFi radio, it is common to use an 80-MHz bandwidth. The reception noise floor is often measured at -90 dBm, while the TP is set at 20 dBm. This information is visually represented in Figure 1.

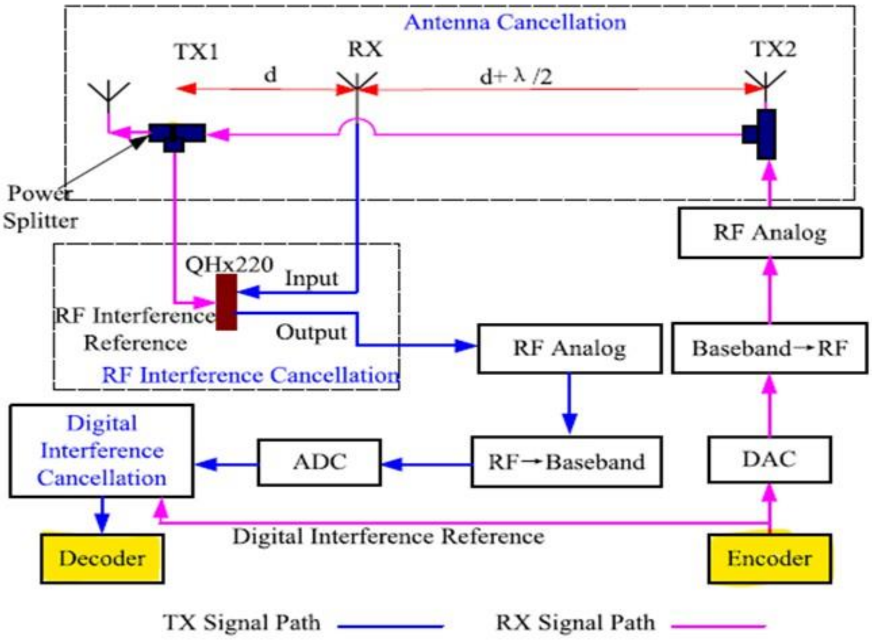

Figure 1: Block diagram of a full-duplex transceiver with analog or digital self-interference cancellation [1].

In an FD system, a SI cancellation mechanism, whether digital or analog, is used to lower the SI signal's impact. Also, digital along with analog cancellation need understanding the sent signal and the SI channel. The study assumes a freq.-flat fading channel, where the channel state information for every transmitter-receiver connection is considered to be completely known at the reception side

Digital Cancellation

To effectively remove the remaining power of the SI signal after analog cancellation, it is necessary to estimate the components of the SI channel. These components include both the leakage over from the analog cancellation circuit and the delayed reflections of the SI signal from the surrounding environment [1]. The residual SI may be separated into two components: linear and nonlinear. The bulk of the SI power may be calculated using current methods, such as the least-square and MMSE-based approaches. The nonlinear distortions of the defective analog canceling circuits produce the latter.

The SINR (Signal-to-Interference plus Noise Ratio) for digital cancellation system may be expressed as the final FD outcome.

$$\mathrm{SINR}_{\mathrm{DC}}^{\mathrm{FD}} = \frac{P_x L_B |h_{BA}|^2}{P_{\phi,A}+P_{\phi,B}+P_{z,\mathrm{DC}}+P_{\mathrm{g,DC}}} \quad (1)$$

Where, the symbols DC and FD stand for digital cancellation and FD, respectively.

$P_x = E\{|X_A|^2\} = E\{|X_B|^2\}$ is the power of transmitted signal, $E\{\}$ stands for expectation process, while $P_{\emptyset,A}$, $P_{\emptyset,B}$ are the computed phase noise powers (NPs) for SI and the signal of interest.

$$P_{\phi,A} = P_x L_A |h_{AA}|^2 (\mu_A^t + \mu_A^r) = P_x L_A |h_{AA}|^2 \mu \quad (2)$$

$$P_{\phi,B} = P_x L_B |h_{BA}|^2 (\mu_B^t + \mu_A^r) = P_x L_B |h_{BA}|^2 \mu \quad (3)$$

Where, μ_i^t, μ_i^r, i ∈ [A, B] are the total phase NP of the transmitter and receiver normalized.

For several PLL systems, approximate formulations of the PSD of the PN might be found [8]. But accurate phase noise PSD is often determined by using a manufactured tuner that uses a PLL. For the digital cancellation technique, $P_{z,\mathrm{DC}}$, $P_{q,\mathrm{DC}}$ the receiver and quantization NP are computed in terms of the LNA power gain.

For the SI and signal of interest, respectively, define the instantaneous received signal strength (RSSI) as $RSSI_A = P_x L_A |h_{AA}|^2, RSSI_B = P_x L_B |h_{BA}|^2$

We get, $SINR_{DC}^{FD} = \dfrac{RSSI_B}{\eta RSSI_A + \eta RSSI_{B+\zeta}}$

Where, $\eta = \mu + \sigma_q^2 + P_{th} N_{m-} P_{th}, \zeta = P_{th} N_l$

A) Analog Cancellation

SI inversion may be achieved by an FD radio by the straightforward process of inverting a signal's phase. The capacity to modify the phase may only be possible within a narrow range of frequencies, which in turn restricts its ability to cancel out signals to the fullest extent. A precise signal inversion may be achieved at the central freq. However, the inverted signals will depart from 180 degrees on both sides of the central freq., resulting in noticeable phase distortion.

In order to achieve a sufficient cancellation performance and minimize flaws, the FD radio must possess the capability to quickly adjust the analog circuit to adapt to changing environments. An adaptive approach is needed to respond to changes in the channel and update the cancellation circuits' parameters (such as the phase along with amplitude of the RF reference signal based on the inverse of the SI) often and quickly [5].

The SINR obtained from the analogue cancellation approach can be expressed as

$$SINR_{AC}^{FD} = \frac{P_x L_B |h_{BA}|^2}{P_{\phi,A} + P_{\phi,B} + P_{z,\mathrm{AC}} + P_{\mathrm{g,AC}}} \quad (4)$$

where the symbol AC denotes analog cancellation.

The FD system SINR for digital along with analog cancellation techniques is given by equations (1), (4).

B) Rate Gain Region for Digital and Analog Cancellation

The area of FD rate gain for both analog and digital canceling techniques. The area of received signal-of-interest intensity at which a FD system outperforms a HD system in terms of rate gain is known as the RGA. Finding the RGA makes it simple to investigate the circumstances in which FD systems perform better than their HD equivalents [6]. RGA can be obtained by solving the following inequality

$$R^{FD} > R^{HD} \quad (5)$$

The rate gain zone refers to the area where the FD rate of each communication connection exceeds its HD rate. The study may be applied to various FD systems' topologies, such as those described in references [7]. In these architectures, just one node (either the base-station or even relay node) operates in FD mode and communicates with two HD nodes. Thus, we determine the RGA for either of two nodes involved in communication. The same outcomes are applicable to the other node, but with distinct parameter values.

D) Rate gain area (RGA) for digital cancellation scheme

For the digital cancellation system, the simplified RGA is expressed as

$$RSSI_{B,min} \cong \begin{cases} \frac{\eta RSSI_A}{\sqrt{\eta}}, & RSSI_A \geq \frac{\zeta}{4\eta\sqrt{\eta}}, \\ \frac{2\eta^2 RSSI_A^2}{\zeta}, & \frac{\zeta}{\eta} \leq RSSI_A < \frac{\zeta}{4\eta\sqrt{\eta}}, \\ 2\eta RSSI_A, & RSSI_A < \frac{\zeta}{\eta} \end{cases} \tag{6}$$

In this instance, it is considered that the received SI signal's strength is high enough wherein the noise introduced by the SI signal's presence ($\eta\, RSSI_A$) is greater than the receiver noise floor i.e. $\eta\, RSSI_A > \zeta \text{ or } RSSI_A > \frac{\zeta}{\eta}$

Where, η combination of phase, along with receiver, along with quantization noises; inside practical fabricated circuits; also, all of these noise components are typically $\ll 1$.

E) Rate gain area (RGA) for analog cancellation

The RGA for the analog cancellation scheme may be determined using the same procedures as the digital cancellation scheme since the SINR relations in the two types of cancellation schemes are identical. Approximation for the RGA in analog cancellation scheme is

$$RSSI_{B,min} \cong \begin{cases} \frac{\mu RSSI_A}{\sqrt{\eta}}, & RSSI_A \geq \frac{\zeta}{4\mu\sqrt{\mu}}, \\ \frac{2\mu^2 RSSI_A^2}{\zeta}, & \frac{\zeta}{\eta} \leq RSSI_A < \frac{\zeta}{4\mu\sqrt{\mu}}, \\ 2\mu RSSI_A, & RSSI_A < \frac{\zeta}{\mu} \end{cases} \tag{7}$$

From equation (6) and (7) the area where FD systems perform better than HD systems for all given permutations of system characteristics and operating circumstances may be easily predicted using equations (6) and (7).

RESULT AND DISCUSSION

Mixer and quantization noise are both reduced by the use of analog cancelation. The overall NP linked to the SI signal ($\eta RSSI_A$), which is made up of all noise components, determines the RGA for the digital cancellation method, as per equations (6) and (7). On the other hand, the RGA in the analog cancellation scheme relies simply on the phase NP ($\mu RSSI_A$). Low PN systems benefit most from analog cancellation. Thus, the benefit of analog cancellation becomes apparent only in situations when the PN is dominated by either mixer noise or quantization. As a result, implementing analog cancellation in high PN systems requires more hardware complexity and does not improve performance over digital cancellation schemes [3].

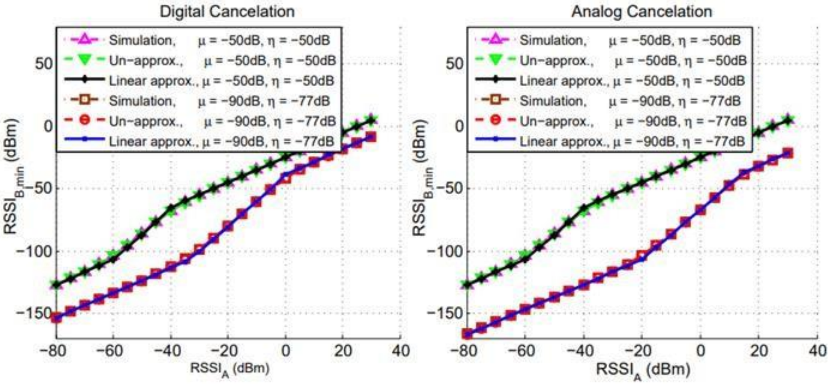

Figure 2: Analytical and simulation results for digital and analog cancellation [1]

Phase, along with quantization, along with mixer noise are dominated by the bottleneck in the digital cancelation technique. Modern wireless technology often has a down conversion mixer with a noise figure of around 10dB [4], which yields a normalized mixer NP of about 104dBm in a 1MHz bandwidth. Furthermore, the normalized quantization NP that results is about -77dBm, assuming that a 12-bit ADC is employed. The total in-band PN of the 2.4GHz oscillators is −50dBc within a 1MHz bandwidth, indicating that the oscillators' PN is often significantly greater than those values [7].

The first trade-off is the complexity of the hardware in exchange for an increase in the RGA. The aforementioned finding indicates that in some situations when PN is dominated by either mixer or quantization noise, using analog cancellation might lessen the noise impact and enhance system performance. Reducing the transmission range in order to increase the RGA is the second tradeoff. Raising passive suppression to enable larger noise levels is the third trade-off.

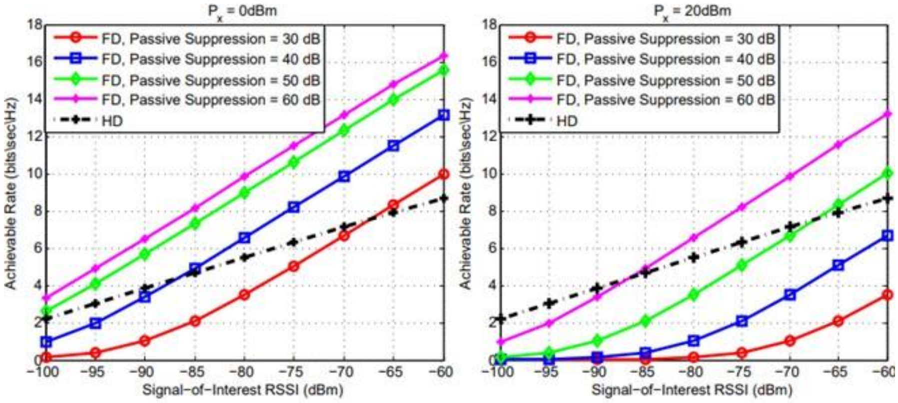

Figure 3: Achievable rate gain for full duplex and half duplex system [1]

The received signal-of-interest strength; the same in all simulated scenarios determines the HD system's performance. In this simulation, the transmission range (distance across the two communicating nodes) is raised with the TP to maintain the same received signal-of-interest intensity as shown in figure 3. Achievable rate for FD and HD systems with total PN $\mu=-60$dB and TP of 0dBm and 20dBm. The rate of gain in FD reduces as the TP increases. This suggests that, for a fixed distance D, reducing the TP increases the likelihood of FD systems outperforming HD systems.

CONCLUSION

Through the modelling of various transmitter and receiver radio impairments, proposed a signal model for a single input single output narrowband FD system in this study. When compared to the traditional HD method, FD approaches may greatly increase the possible spectral efficiency as well as the related network throughput, if the SI experienced at the FD nodes can be much decreased. A mathematical model is developed to approximate the RGA by using piecewise linear functions. This approximation takes into account all system parameters along with radio impairments. It applies to both analogue and digital self-interference cancellation approaches. The model is based on the signal representation in the logarithmic domain. The findings indicate that a 40dB passive SI suppression in conjunction with a −60dBc in-band PN might reach a rate of around ~1.2x to ~1.4x that of HD systems for short-range applications like class-3 Bluetooth. To get the same rate gain with Class-1 Bluetooth, −70dB in-band PN must be paired with 50dB passive SI suppression.

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