Residual Self-Interference Cancellation and Optimal Control with RIS for Full-Duplex Communication

Course Final Project: Group 31

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***Abstract*—This project is a study and implementation of Full-Duplex Communication Systems, which enable simultaneous transmission and reception on the same frequency band. While full-duplex communication offers significant benefits in terms of increased spectral efficiency and reduced latency, it also poses challenges such as self-interference and transmit power consumption. To address these challenges, we propose the use of superimposed signaling technique to overcome data detection ambiguity and help in residual self-interference cancellation to improve system performance. We also use a Reconfigurable Intelligent Surface (RIS) to optimize control in full-duplex communication systems. We evaluate the effectiveness of these techniques through simulations and demonstrate their potential for improving the performance of full-duplex communication systems. Our findings suggest that these techniques can significantly enhance the capacity and reliability of full-duplex communication systems, making them a promising solution for future wireless networks.**

I. Introduction

Full-duplex communication offers significant benefits over traditional half-duplex communication systems, where only one party can transmit at a time. By allowing both parties to send and receive data at the same time, full-duplex communication can potentially double the capacity of wireless networks and improve the quality of service for users [2] . This is particularly important in applications such as video streaming, online gaming, and real-time communication, where low latency and high throughput are critical.

However, full-duplex communication also poses challenges that must be addressed before it can be widely adopted. One major challenge is self-interference, which refers to the interference that remains after a signal is transmitted and received on the same frequency band. Self-interference can significantly degrade system performance and limit the achievable data rates in full-duplex communication systems.

To address this challenge, various techniques have been proposed in the literature. One approach is to use superimposed signaling techniques to overcome data detection ambiguity caused by self-interference. In FD communication systems, self-interference cancellation is performed in two stages:

- **Passive cancellation** [3]: the radio frequency (RF) antennas are well-isolated to minimize the amount of interference.
- **Active cancellation**: [4] the residual interference signal from the previous stage is cancelled either at RF or at the digital baseband. Due to channel estimation errors, the RF canceller cannot completely remove the interference. Hence, the residual interference after the RF canceller is still higher than the receiver noise floor and needs to be cancelled via digital processing at baseband.

However, effective self-interference cancellation at baseband requires accurate knowledge of the digital channels, which are the channels observed by the receiver at baseband [4] after the passive and RF cancellation [5] stages. Consequently, for reliable FD communication first the digital channels are estimated and then the received signal is processed for data detection. This however, is not bandwidth efficient because it requires pilot transmission (defined as traditional method).

Another approach is to use residual self-interference cancellation using superimposed signalling [1] to reduce self-interference levels and improve system performance without channel estimates. Additionally, Reconfigurable Intelligent Surface (RIS) [7] has recently emerged as a promising technology for optimizing control in full-duplex communication systems.

In this paper, we present a study on Full-Duplex Communication Systems and evaluate the effectiveness of these techniques through simulations. We propose a novel method that combines superimposed signaling with residual self-interference cancellation and RIS to improve the performance of full-duplex communication systems. Our simulation results demonstrate that our proposed method outperforms conventional methods in terms of bandwidth and power efficiency. Overall, this paper provides valuable insights into the challenges and opportunities associated with implementing full-duplex communication systems and highlights the potential of these systems for future wireless networks.

II. System Model

We consider the data detection problem for the single-input single-output (SISO) FD communication system, as shown in Fig. 1. Nodes a and b each have a pair of antennas, which is used for simultaneously transmit and receive on the same frequency band. Due to the inherent symmetry of the problem,

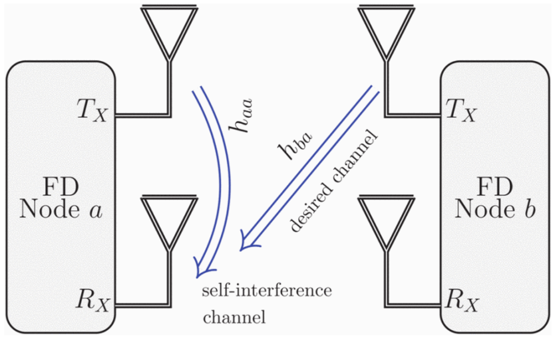

Fig. 1. Full duplex system with single transmit and receive antenna. The single antenna at each node is shown separately for the transmission and reception for ease of illustration. Source: [1]

we only investigate the data detection problem for node a, as identical results are expected for node b.

The received signal at node a is given by

$$\mathbf{y}_a = h_{aa}\mathbf{x}_a + h_{ba}\mathbf{x}_b + \mathbf{w}_a \tag{1}$$

where, $\mathbf{y}_a \triangleq [y_{a_1}, \cdots, y_{a_N}]^T$ is the N×1 vector of received symbols, $\mathbf{x}_a \triangleq [x_{a_1}, \cdots, x_{a_N}]^T$ is the N×1 vector of self-interference symbols, $\mathbf{x}_b \triangleq [x_{b_1}, \cdots, x_{b_N}]^T$ is the N×1 vector of desired communication symbols, $\mathbf{w}_a \triangleq [w_{a_1}, \cdots, w_{a_N}]^T$ is the N×1 vector of independent identically distributed (IID) Gaussian noise with zero mean and variance σ^2, i.e., $w_{ai} \sim \mathcal{CN}(0, \sigma^2)$).

We will make the following assumptions same as of that of the paper [1].

- Since the digital channels are the channels observed after the passive and RF cancellation stages, the direct line-of-sight (LoS) components of these channels have already been canceled and the residual components are due to the scatterers [6].
- We assume channel to be quasi-static and h_{aa} and h_{ba} are flat-fading and Rayleigh distributed with zero mean and variance one, i.e., $h_{aa}, h_{ba} \sim \mathcal{CN}(0, 1)$.
- The transmitted symbols are modulated using the modulation set $\mathcal{A} = \{A_1, A_2, \ldots, A_M\}$, with size M Modulation set $\mathcal{A}$ contains all constellation points of any given standard modulation constellation, such as M-ary phase shift keying (MPSK) modulation, and the transmitter is likely to send each constellation point with equal probability.
- When RIS is used, we don't consider the channel effect on its output for ease of implementation.

III. Data Dectection in FD Communication using Traditional Method

A. Using one pilot set

Channel estimation-based detection is a widely used technique in wireless communication systems to detect data signals. In this method, the unknown channel between the transmitter and the receiver is estimated first, and then the data signal is detected using the estimated channel. The estimation of the unknown channel is based on pilot symbols, which are known to both the transmitter and the receiver.

The conventional steps for channel estimation-based detection are as follows:

Define the modulation scheme and the transmitted data symbols.

- Generate pilot symbols and insert them into the transmitted signal.
- Transmit the signal through the wireless channel.
- Receive the signal at the receiver.
- Extract the pilot symbols from the received signal.
- Estimate the channel using the pilot symbols.
- Equalize the received signal to remove channel distortion.
- Perform maximum likelihood (ML) detection to detect the data symbols.
- Calculate the bit error.

B. Our Optimized Traditional method

To further improve the efficiency of this traditional method, we will insert the pilots for x_a and x_b differently. Example, say x_a will be made $[Px_a[0]]$ and x_b will be made $[[0]x_aP]$ for transmission. We can see that this way is a big waste of bandwidth. There are multiple ways to increase the efficiency of this method, of which we will not be concentrating in this work.

IV. Data Detection in FD Communication using Superimposed Signalling

In this sub-section, we first derive a MAP symbol detector for the FD communication system. Then we show that this detector suffers from the detection ambiguity problem because of the symmetry of conventional modulation constellations around the origin.

A. MAP Detector

The maximum MAP symbol detector for the SISO FD communication system presented in Section II is given by

$$\tilde{x}_{b_i} = \max_{x_{b_i}} f(x_{b_i}|\mathbf{y}_a).$$

where the marginal probability distribution $f(x_{b_i}|\mathbf{y}_a)$,

We will use a different method to find the marginal probability distribution than the reference paper [1]. We will consider remark 1 in the paper, stating that The posterior PDF $f(x_{b_i}|\mathbf{y}_a)$ is independent of both the self-interference and communication channels, i.e., h_{aa} and h_{ba}. Hence, the MAP detector is independent of the channel estimates. In other words, the symbols can be detected without requiring the interference or communication channel to be estimated. The MAP detector also directly detects the symbols without requiring a separate self-interference cancellation stage.

Also, the posterior PDF $f(x_{b_i}|\mathbf{y}_a)$ does not have a unique maximum if and only if x_{bi} comes from a symmetric modulation set $\mathcal{A}$.

B. Superimposed Signalling

We have seen above that the data detection ambiguity in FD communication in the absence of channel estimates arises because of the symmetry of the modulation constellation around the origin. Consequently, an obvious approach to resolve the data detection ambiguity is to alter the symmetry of the modulation constellation around the origin and create a suitable asymmetric modulation constellation.

One simple way to achieve an asymmetric modulation constellation around the origin is to add (superimpose) a constant known signal to the transmitted signal. We call this approach superimposed signalling.

If both nodes a and b superimpose a common constant and known signal P to the transmitted symbols, then (1) can be written as:

$$\mathbf{y}_a = h_{aa}(\mathbf{x}_a + P) + h_{ba}(\mathbf{x}_b + P) + \mathbf{w}_a. \qquad (5)$$

We can observe that superimposed signalling increases the average energy per symbol of the modulation constellation. Conventional (symmetric) modulations operate under an average transmit power constraint, which places limits on the average energy per symbol. In the traditional method, the extra power in the pilots is used for channel estimation. In our case, we do not use the extra power for channel estimation. Rather, we use it only for achieving an asymmetric modulation constellation. Consequently, to ensure that the proposed method does not exceed the average transmit power constraint, we shift the modulation by $P \triangleq \sqrt{E_p}$, where E_p is the average energy used for channel estimation in conventional pilot based channel estimation systems.

V. Reconfigurable Intelligent Surface

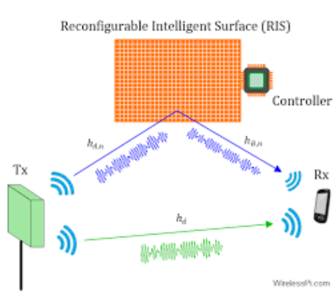

Fig. 2. Reconfigurable Intelligent Surface (RIS)

In our project, we aimed to simulate the behavior of a reconfigurable intelligent surface (RIS) through computational modeling. Since it is not feasible to directly code the complex behavior of RIS, we designed a simulation model that takes incident angle and signal as input and provides a constant angle and signal as output. To implement this simulation model, we assumed that a node can only receive signals coming at a specific angle. Thus, if the received signal arrives at an angle other than the one specified in the RIS, the node will reject it. By incorporating this assumption into our simulation model, we were able to emulate the behavior of a real RIS and study its characteristics. To implement this simulation model, we also made the assumption that the channel coefficient remains constant, and only the angle changes.

VI. Simulation Results

A. Marginal Probability

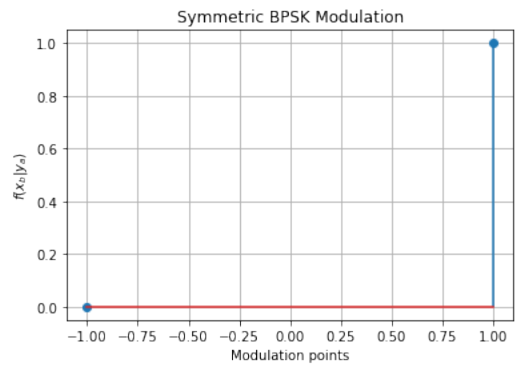

Fig. 3. Symmetric BPSK Modulation

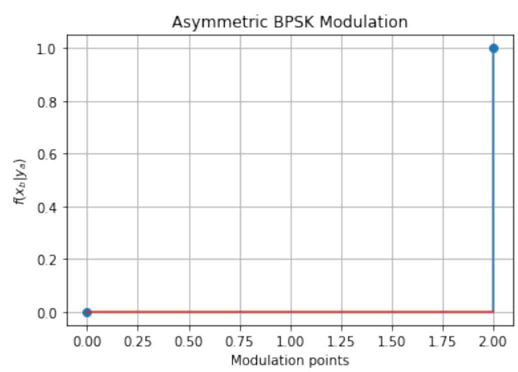

Fig. 4. Asymmetric BPSK Modulation

As per the reference paper, we have chosen [1], we expect the marginal probability for symmetric BPSK modulation to be 0.5 for both the symbols, which we didn't observe in our case. We conclude that this could be because different equations were considered for the marginal PDF calculated. This, however, doesn't distort the larger image we aim to see, i.e, superimposed signalling giving us a lower BER. We observe that for SNR = 5dB, the BER for symmetric constellation is approx. 0.05 and for asymmetric constellation we get a BER of approx. 0.07. We observe that the BER drastically reduced for asymmetric BPSK modulation when compared with symmetric BPSK modulation.

B. Plots

In this section, we present the simulation results. First, we demonstrate that detection without channel estimation, using a symmetric modulation constellation, can result in ambiguity. Then we show that this ambiguity is resolved once the modulation set is shifted to an asymmetric modulation set,

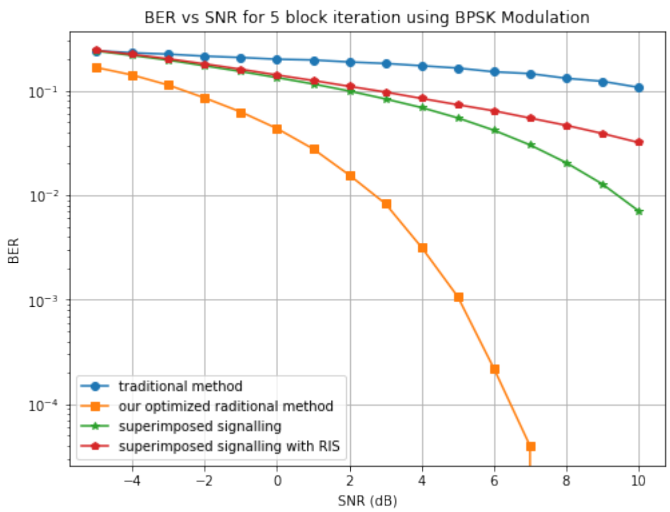

Fig. 5. BER vs SNR plots

i.e., a known signal is superimposed on the data signal. We find the minimum power required for superimposed signaling to resolve the ambiguity problem. Finally, we investigate the BER vs SNR performance of the proposed detector.

We observe that our proposed optimized traditional gives us a very good result as the channel estimated by this method is accurate upto 0.1%.

VII. Conclusion

In conclusion, Full-Duplex Communication Systems have the potential to significantly enhance the capacity and reliability of wireless networks. However, self-interference remains a major challenge that must be addressed before full-duplex communication can be widely adopted. In this research project, we presented a study on Full-Duplex Communication Systems and proposed novel techniques to overcome self-interference challenges.

Our proposed techniques include superimposed signaling and Reconfigurable Intelligent Surface (RIS). Through simulations, we demonstrated that these techniques can significantly improve the performance of full-duplex communication systems in terms of bandwidth and power efficiency. But as we can see that on using RIS the results are not as desirable due to not considering some parameters to run the simulation.

Our findings provide valuable insights into the challenges and opportunities associated with implementing full-duplex communication systems. They also offer practical solutions for improving wireless network performance. The proposed techniques have the potential to significantly enhance the capacity and reliability of wireless networks, making them a promising solution for future wireless communication applications.

Overall, this research paper contributes to advancing the state-of-the-art in Full-Duplex Communication Systems by proposing novel techniques for overcoming self-interference challenges. The findings presented in this project provide a foundation for further research in this area and offer practical solutions for improving wireless network performance. But on using RIS, we are not getting that optimal solution.Our future aim is to make it work using RIS as well.

References

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