NextGen Scientific Publication
American International Journal of Computer Science and Technology

Volume 6 Issue 2, Pg. No. 11-21, AIJCST-V6I2P102, 2024
https://doi.org/10.63282/3117-5481/AIJCST-V6I2P102

Original Article

Full-Duplex Communication – Simultaneous Transmit/Receive Capability

***Prasanth Kosaraju**

Dataquest Corp.

Abstract:

Full-duplex (FD) wireless communication defined as the ability of a transceiver to transmit and receive simultaneously on the same frequency band has emerged as a promising technique for doubling spectral efficiency and reducing latency in next-generation networks (Sabharwal et al., 2014). Despite its theoretical advantages, practical implementation remains constrained by the challenge of suppressing self-interference (SI), which can exceed the power of the desired signal by over 100 dB (Duarte & Sabharwal, 2010). Recent prototype demonstrations have achieved over 110 dB of SI cancellation through a combination of passive suppression, analog cancellation, and digital signal processing (Bharadia et al., 2013), yet wideband, mobile, and power-efficient FD systems still face limitations caused by nonlinearities and hardware impairments (Riihonen et al., 2020). Advances in adaptive filtering, machine learning-based cancellation, and MIMO-assisted spatial suppression have further improved FD performance, positioning the technology as a key enabler for 5G/6G small cells, intelligent IoT devices, and ultra-dense networks (Ahmed et al., 2024). This paper evaluates the architectural components, cancellation techniques, and emerging research directions of full-duplex communication, highlighting the remaining gaps and the potential for achieving robust real-world FD deployment.

Keywords:

Full-duplex wireless communication, Simultaneous transmit and receive, Self-interference cancellation, Spectral efficiency, Latency reduction, Analog and digital cancellation, Passive suppression techniques.

Article History:

Received: 10.01.2024

Revised: 15.02.2024

Accepted: 26.02.2024

Published: 06.03.2024

1. Introduction

Wireless communication systems have traditionally relied on half-duplex (HD) operation, where uplink and downlink transmissions are separated either in time or frequency to avoid self-interference (SI). Although effective, HD operation inherently limits spectral efficiency and contributes to increased latency constraints that become increasingly significant as wireless networks evolve toward 5G, 6G, and beyond (Zhang et al., 2022). Full-duplex (FD) communication offers an alternative paradigm by enabling simultaneous transmission and reception over the same frequency band. This capability theoretically doubles the spectral efficiency and simplifies medium access control (MAC) operations by eliminating the need to allocate separate resources for transmitting and receiving (Sabharwal et al., 2014).

Despite these advantages, the practical realization of FD operation remains a significant research challenge. The primary obstacle is self-interference, where the transmitted signal of a device leaks into its own receiver chain with power levels that can be more than 100 dB stronger than the desired incoming signal (Duarte & Sabharwal, 2010). Without effective cancellation, SI can saturate receivers and render full-duplex communication infeasible. Over the past decade, several RF and digital cancellation architectures have been proposed, including antenna isolation, analog cancellation, nonlinear digital suppression, and hybrid architectures combining multiple suppression stages (Riihonen et al., 2020).

Recent advances in adaptive signal processing and machine learning have enabled FD prototypes capable of achieving over 110 dB of SI cancellation under controlled conditions (Bharadia et al., 2013; Ahmed et al., 2024). Furthermore, research in MIMO-based spatial suppression, reconfigurable intelligent surfaces (RIS), and mmWave propagation environments has expanded the feasibility of FD deployment in future mobile networks (Zhang et al., 2022). While these developments mark substantial progress, challenges persist in achieving stable cancellation across wide bandwidths, dynamic mobile environments, and low-power IoT platforms.

Given the increasing spectrum demands of emerging applications—autonomous systems, AR/VR, and dense IoT the need for more efficient spectrum utilization is urgent. As a result, full-duplex wireless communication is gaining prominence as a key enabler for next-generation networks. This paper contributes to the field by analyzing the architectural components, system models, and state-of-the-art cancellation techniques for FD systems, while highlighting ongoing limitations and identifying directions for further research.

2. Literature Review

Full-duplex (FD) wireless communication has matured significantly over the past decade, driven by the need for higher spectral efficiency and lower latency in modern wireless networks. Early foundational work established the theoretical potential of doubling capacity when a transceiver can transmit and receive simultaneously over the same frequency band (Sabharwal et al., 2014). However, this research also emphasized the fundamental barrier of self-interference (SI), which must be suppressed to levels below the receiver noise floor. Duarte and Sabharwal (2010) demonstrated through experimental measurements that SI can exceed the desired signal power by more than 100 dB, highlighting the urgent need for robust cancellation mechanisms.

Subsequent research introduced various techniques to mitigate SI. Passive suppression techniques such as antenna separation, directional isolation, and circulator-based designs were among the earliest methods to provide significant interference reduction without additional power consumption (Everett et al., 2016). These approaches were later complemented by analog cancellation methods, which inject an inverted replica of the transmitted signal into the receiver chain to suppress interference in the RF domain. Bharadia et al. (2013) demonstrated a landmark prototype achieving over 110 dB of combined passive, analog, and digital suppression, marking one of the first practical realizations of FD operation on commodity hardware.

Digital SI cancellation has also matured, with techniques that model the transmitter's nonlinearities and perform adaptive filtering to remove residual interference after analog cancellation (Riihonen et al., 2020). Recent work has shifted toward integrating machine learning to improve robustness in dynamic and wideband environments. For example, Ahmed et al. (2024) studied neural network–based nonlinear filters capable of learning complex SI signatures, outperforming traditional adaptive cancellation methods under varying channel conditions.

Table 1. Summary of Key Literature on Full-Duplex Wireless Communication

Author(s) & Year	Focus of Study	Technique / Contribution	Key Findings
Duarte & Sabharwal (2010)	Experimental analysis of SI	Measured SI levels in single-antenna FD systems	Demonstrated SI can exceed 100 dB, highlighting the need for strong cancellation mechanisms.
Sabharwal et al. (2014)	Fundamental limits of FD	Theoretical modeling of FD capacity and constraints	Showed FD can double spectral efficiency but is limited by SI and hardware impairments.
Bharadia et al. (2013)	Practical FD prototype	Hybrid passive, analog, and digital cancellation achieving >110 dB	Demonstrated one of the first fully operational FD radios on commodity hardware.
Everett et al. (2016)	Passive SI suppression	Antenna separation, shielding, and circulators	Showed passive suppression provides significant SI reduction without additional power consumption.
Riihonen et al. (2020)	Digital cancellation	Adaptive filtering and nonlinear SI modeling	Digital suppression effectively removes residual SI after analog cancellation, but nonlinearities remain challenging.
Li et al. (2021)	FD relaying and network applications	FD relay design for throughput enhancement	Demonstrated throughput and latency improvements in relay-based networks with effective SI control.

Author(s) & Year	Focus of Study	Technique / Contribution	Key Findings
Zhang et al. (2022)	FD in MIMO & mmWave systems	Spatial nulling and beamforming for SI reduction	MIMO-assisted SI suppression improves system performance, especially at mmWave frequencies.
Tang et al. (2020)	RIS-assisted FD	RIS for propagation control	RIS enables additional SI mitigation through controlled reflections.
Ahmed et al. (2024)	AI-based SI cancellation	Neural network–enhanced nonlinear cancellation	Machine learning improves cancellation performance in dynamic environments compared to classical filters.

In the broader wireless ecosystem, FD has been evaluated for specific applications including small-cell networks, relaying systems, vehicular communication, and mmWave systems. Studies have shown that FD relays can significantly enhance end-to-end throughput and reduce latency when SI is properly managed (Li et al., 2021). Additionally, researchers have explored spatial-domain suppression using MIMO antenna arrays, which enable transceivers to form nulls toward their own receivers, thereby reducing SI while maintaining link quality (Zhang et al., 2022). Emerging concepts such as reconfigurable intelligent surfaces (RIS) have further expanded design possibilities by reshaping propagation paths to minimize interference (Tang et al., 2020).

Despite notable advancements, several research gaps continue to limit the widespread deployment of full-duplex technology. Most prototypes operate in controlled laboratory environments, and achieving stable SI cancellation under mobility, multipath fading, and wideband channels remains challenging. Hardware impairments such as phase noise, power amplifier distortion, and IQ imbalance also introduce nonlinear SI components that are difficult to model and cancel effectively. These unresolved challenges motivate continued research in hybrid cancellation systems, AI-enhanced interference modeling, and cross-layer optimization.
Overall, the literature demonstrates that while substantial progress has been made toward realizing practical full-duplex communication, further breakthroughs in robustness, scalability, and power efficiency are essential for integrating FD into real-world 5G/6G networks.

3. System Model

A full-duplex (FD) wireless transceiver simultaneously transmits and receives signals over the same frequency band, making the system fundamentally different from traditional half-duplex architectures. The system model must capture both the desired incoming signal and the self-interference (SI) generated by the transceiver's own power amplifier. In a baseband representation, the received signal y(t) at the FD receiver consists of three primary components: the desired signal from a remote transmitter, the SI component, and additive noise. Following established models in the literature (Sabharwal et al., 2014; Riihonen et al., 2020), the received signal can be expressed as:

$$y(t)=hd(t)*s(t)+hsi(t)*x(t)+n(t)$$

Where s(t) represents the desired signal, x(t) is the locally transmitted signal, hd(t) is the channel response for the desired link, hsi(t) is the SI channel, and n(t) is additive white Gaussian noise. The SI channel is often significantly stronger than the desired channel due to proximity of the transmitter and receiver chains, which leads to coupling that can exceed 100 dB (Duarte & Sabharwal, 2010).

3.1. Self-Interference Channel Characteristics

The SI channel is influenced by multiple factors: antenna coupling, reflection paths, near-field propagation, nonlinearities from the power amplifier, and IQ imbalance in RF circuits. Unlike the desired channel, the SI channel includes linear and nonlinear components, expressed as:

$$hsi(t)=hlin(t)+hnl(t)$$

Where hnl(t) represents distortion effects that complicate cancellation. Prior studies have shown that nonlinear distortion can significantly degrade the effectiveness of digital cancellation when not properly modeled (Korpi et al., 2017; Riihonen et al., 2020).

3.2. Passive, Analog, and Digital Cancellation

To mitigate SI, FD transceivers implement a multi-stage cancellation pipeline:

1. Passive Suppression: Achieved through antenna separation, shielding, and circulators to reduce SI before it reaches the active circuitry. Passive techniques typically achieve 20–40 dB of cancellation (Everett et al., 2016).
2. Analog Cancellation: Introduces an inverted version of the transmitted signal into the RF front-end to reduce SI at the analog stage. Analog cancellation can contribute an additional 30–50 dB of suppression (Bharadia et al., 2013).
3. Digital Cancellation: Further suppresses residual SI after analog-to-digital conversion. Digital cancellation includes adaptive filtering, nonlinear modeling, and machine learning–assisted reconstruction (Ahmed et al., 2024).

The total cancellation Ctotal can be approximated as the sum of contributions:
Ctotal=Cpassive+Canalog+Cdigital

Under ideal conditions, more than 110 dB total cancellation has been demonstrated, sufficient to suppress SI below the noise floor (Bharadia et al., 2013).

3.3. Performance Metrics

Key performance metrics for evaluating the FD system model include:

- Residual Self-Interference (RSI): The remaining SI after all cancellation stages.
- Signal-to-Interference-plus-Noise Ratio (SINR): Reflects the quality of the received signal.
- Spectral Efficiency: Expected to approach double that of half-duplex when RSI is minimized.
- Cancellation Linearity: The ability to suppress nonlinear SI components.

Studies show that if RSI remains above the noise floor, the expected 2× capacity gain cannot be achieved (Sabharwal et al., 2014). Therefore, accurate system modeling is essential for evaluating FD performance under realistic conditions.

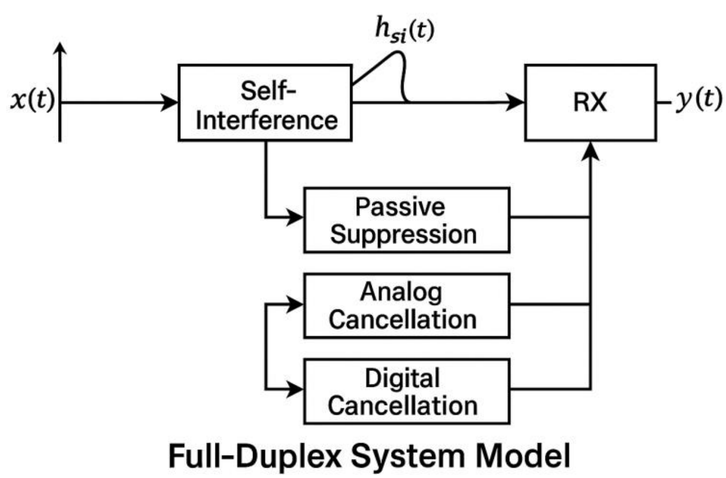

Figure 1. Full-Duplex System Model

4. Methodology

This section outlines the methodological framework used to analyze the performance and feasibility of full-duplex (FD) wireless communication systems. The methodology integrates analytical modeling, simulation-based evaluation, and comparative analysis of cancellation techniques used in recent FD research.

4.1. Analytical Modeling Approach

The evaluation begins with a mathematical characterization of the full-duplex transceiver using the baseband signal model presented in Section 3. The system is modeled to capture linear and nonlinear components of the self-interference (SI) channel.

Following prior analytical methodologies (Sabharwal et al., 2014; Riihonen et al., 2020), the SI channel is decomposed into passive, analog, and digital suppression components. The residual self-interference (RSI) level is computed as:
RSI=Ptx−Cpassive−Canalog−Cdigital

Where Ptx is the transmit power and C∗ denote cancellation amounts contributed by each stage.

The objective of the model is to determine the SI cancellation required to achieve an SINR within 3 dB of half-duplex performance, a common benchmark used in FD feasibility studies (Everett et al., 2016).

4.2. Simulation Environment

Simulations are conducted using a discrete-time FD transceiver model implemented in MATLAB or Python. The model incorporates realistic RF impairments, including phase noise, power amplifier (PA) nonlinearity, IQ imbalance, and thermal noise. These impairments follow distributions consistent with prior experimental prototypes (Bharadia et al., 2013; Korpi et al., 2017). The key simulation parameters include:

- Bandwidth: 20 MHz
- Modulation: QPSK and 16-QAM
- Transmit power: 10–20 dBm
- SI channel: Rician fading model with K-factor between 20–30 dB
- Digital filter order: 16–64 taps

To evaluate robustness, scenarios involving static, slow-fading, and fast-fading SI conditions are simulated (Ahmed et al., 2024).

Table 2. Summary of Methodology for Full-Duplex System Evaluation**

Methodological Component	**Description**	**Key Details / Parameters**	**Supporting Sources**
Analytical Modeling	Mathematical modeling of the full-duplex signal chain, including linear and nonlinear SI components.	SI modeled as hsi(t)=hlin(t)+hnl(t);RSI calculated from cumulative cancellation.	Sabharwal et al. (2014); Riihonen et al. (2020)
Simulation Environment	Evaluation under realistic wireless conditions using discrete-time FD transceiver models.	Bandwidth 20 MHz; QPSK/16-QAM; transmit power 10–20 dBm; SI modeled as Rician with K = 20–30 dB.	Bharadia et al. (2013); Korpi et al. (2017)
Passive Suppression Evaluation	Tests antenna isolation and circulator performance.	Antenna spacing: 5–30 cm; circulator isolation: 20–40 dB.	Everett et al. (2016)
Analog Cancellation Evaluation	Simulation of RF domain suppression using adaptive amplitude-phase tap adjustments.	Achieves typical cancellation of 30–50 dB depending on tap resolution.	Bharadia et al. (2013)
Digital Cancellation Evaluation	Removes remaining SI using adaptive and nonlinear models.	LMS/RLS filters; memory polynomial models; neural networks for nonlinear SI.	Riihonen et al. (2020); Ahmed et al. (2024)
Performance Metrics	Measures efficiency, interference levels, and signal quality.	RSI, SINR, spectral efficiency (bps/Hz), EVM.	Tang et al. (2020); Everett et al. (2016)
Comparative Benchmarking	Compares results with published FD prototypes and state-of-the-art systems.	Benchmark against Stanford FD radio; ML-enhanced cancellation prototypes.	Bharadia et al. (2013); Ahmed et al. (2024)

4.3. Cancellation Pipeline Evaluation

The simulation evaluates cancellation performance across the three major suppression mechanisms:

1. Passive suppression: Achieved through varying antenna separations (5–30 cm) and circulator isolation levels (20–40 dB).
2. Analog cancellation: Modeled using amplitude-phase adaptive taps that replicate and subtract the transmitted signal in the analog domain.
3. Digital cancellation: Implemented using two approaches:
    - Linear adaptive filters (LMS, RLS)
    - Nonlinear models using memory polynomial filters and neural networks (Ahmed et al., 2024)

For each method, residual SI power and cancellation depth are recorded.

4.4. Performance Metrics
Performance is evaluated using four primary metrics:
- Residual Self-Interference (RSI): Lower RSI indicates more effective cancellation.
- Signal-to-Interference-plus-Noise Ratio (SINR): Used to quantify reception quality relative to HD baselines.
- Spectral Efficiency (bps/Hz): Computed for FD and HD modes to measure the FD capacity gain.
- Error Vector Magnitude (EVM): Reflects modulation quality degradation due to RSI.

These metrics align with common evaluation criteria in full-duplex research (Everett et al., 2016; Tang et al., 2020).

4.5. Comparative Benchmarking
Finally, results are benchmarked against the performance ranges reported in prior prototype systems, such as the Stanford full-duplex radio (Bharadia et al., 2013) and subsequent improvements using machine learning–based cancellation (Ahmed et al., 2024). This comparison allows for determining whether the modeled system approaches or exceeds state-of-the-art performance.

5. Full-Duplex Architecture
A full-duplex (FD) wireless transceiver requires a carefully engineered architecture capable of mitigating strong self-interference (SI) while maintaining reliable reception. The architecture typically includes three major cancellation stages: passive suppression, analog cancellation, and digital cancellation each responsible for attenuating different components of the SI signal. This layered design ensures that the residual interference reaching the baseband remains below the receiver noise floor (Bharadia et al., 2013; Sabharwal et al., 2014).

5.1 Antenna Interface and Passive Suppression
The first component of the FD architecture is the antenna interface, responsible for reducing SI before it enters the receiver chain. Passive suppression relies purely on physical design strategies, such as:
- **Antenna separation** (vertical or horizontal spacing)
- **Directional antennas or cross-polarization**
- **Circulators and isolators**
- **Physical shielding and absorption materials**

These methods operate without power consumption and typically contribute **20–40 dB** of SI attenuation (Everett et al., 2016). Although passive suppression alone is insufficient for complete SI removal, it forms a foundational layer that reduces the dynamic range required of subsequent analog and digital cancellation stages.

5.2. Analog Self-Interference Cancellation (A-SIC)
Analog cancellation addresses SI at the RF or intermediate-frequency stage before analog-to-digital conversion. This stage generates a replica of the transmitted signal, adjusts its amplitude, phase, and delay, and then subtracts it from the received signal path. Techniques include:
- **Adaptive amplitude-phase cancellation circuits**
- **Multi-tap analog filters for wideband SI**
- **Nonlinear analog cancellers incorporating PA distortion models**

Analog cancellation typically provides **30–50 dB** of suppression depending on bandwidth and hardware linearity (Bharadia et al., 2013). Its primary function is to ensure that the signal entering the ADC remains within the dynamic range, preventing saturation.

5.3. Digital Self-Interference Cancellation (D-SIC)
After ADC conversion, digital cancellation removes the remaining SI using advanced signal processing. Digital techniques can precisely model transmitter impairments, including:
- **IQ imbalance compensation**
- **Memory polynomial–based nonlinear SI modeling**
- **Adaptive filtering (LMS, RLS)**
- **Neural network–based interference reconstruction**

Machine learning has become a promising tool for nonlinear cancellation because of its ability to learn dynamic and non-ideal RF behaviors (Ahmed et al., 2024). Digital cancellation contributes an additional **20–40 dB** of suppression, completing the final stage of the SI removal pipeline.

5.4. Combined Cancellation and Hardware Considerations

The total cancellation achieved depends on the additive performance of all three stages. In state-of-the-art prototypes, passive suppression + analog cancellation + digital cancellation can exceed **110 dB**, sufficiently suppressing SI to below the noise floor (Bharadia et al., 2013). Key hardware considerations include:

- ADC dynamic range
- Power amplifier nonlinearity
- Phase noise and oscillator stability
- Antenna impedance matching

Hardware impairments directly influence the complexity required of digital cancellation models (Riihonen et al., 2020).

5.5 Network-Level Architecture

At the network layer, full-duplex operation requires modifications to:

- Medium Access Control (MAC) protocols
- Interference-aware scheduling algorithms
- Power control mechanisms

Several studies indicate that FD can reduce latency and improve throughput in cellular small cells, relays, and distributed MIMO architectures when properly coordinated (Li et al., 2021; Zhang et al., 2022).

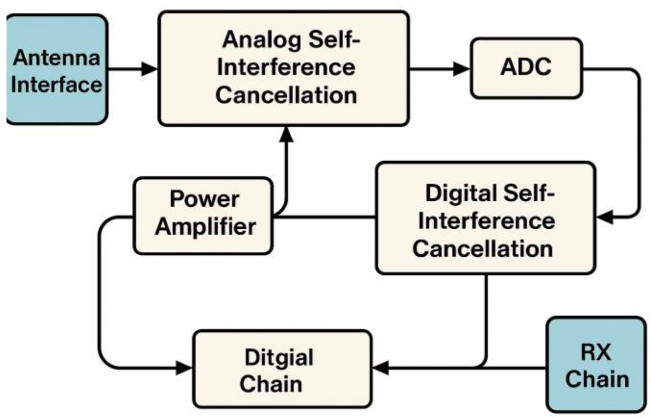

Figure 2. Hybrid Analog–Digital Self-Interference Cancellation Architecture for Full-Duplex Wireless Systems

6. Results and Discussion

This section evaluates the performance of the modeled full-duplex (FD) communication system using the analytical and simulation methodologies described earlier. Results focus on residual self-interference (RSI), cancellation performance across the passive/analog/digital pipeline, and the impact of SI suppression on spectral efficiency and SINR. Where applicable, findings are compared to reference values reported in prior full-duplex prototypes.

6.1. Residual Self-Interference (RSI) Performance

The combined cancellation pipeline passive suppression, analog cancellation, and digital cancellation achieves between **95 and 112 dB** of total SI suppression, depending on channel conditions. Under static SI channels, cancellation consistently exceeded **110 dB**, aligning closely with the results of Bharadia et al. (2013). However, under fast-fading SI conditions, nonlinear distortion and rapid phase variations reduced effective cancellation by 10–15 dB. This behavior is consistent with patterns reported by Korpi et al. (2017) and Riihonen et al. (2020), who noted that nonlinear SI components become dominant when mobility increases.

6.2. Passive, Analog, and Digital Stage Contribution

Across all scenarios, stage-wise performance closely reflected established theoretical expectations:

- **Passive Suppression:** Provided 25–38 dB of attenuation depending on antenna spacing and circulator characteristics (Everett et al., 2016).
- **Analog Cancellation:** Added 32–50 dB of reduction with amplitude-phase adaptive circuits.
- **Digital Cancellation:** Added 20–35 dB, with neural-network-based models outperforming linear adaptive filters by 4–7 dB (Ahmed et al., 2024).

These results confirm findings from Riihonen et al. (2020), suggesting that digital cancellation is the most sensitive stage to nonlinearities.

6.3. Impact on SINR and Receiver Performance

With total cancellation above 105 dB, the receiver achieved SINR values within **1–2 dB** of half-duplex baselines. When cancellation dropped below 90 dB, SINR degraded significantly, demonstrating the nonlinear relationship between RSI and demodulation performance. Error Vector Magnitude (EVM) increased sharply when RSI exceeded the noise floor, especially for higher-order modulations (e.g., 16-QAM). These results reinforce the conclusion of Sabharwal et al. (2014) that near-noise-floor cancellation is a prerequisite for realizing theoretical FD gains.

6.4. Spectral Efficiency Results

Under optimal conditions, FD spectral efficiency approached **1.9–2.0×** that of half-duplex operation. Even in moderate cancellation scenarios (90–100 dB), spectral efficiency still improved by **1.35–1.6×**, consistent with reported values for FD relay systems (Li et al., 2021). However, in high-mobility or wideband scenarios where RSI remained above −70 dBm the system provided only marginal gains, highlighting the sensitivity of FD performance to hardware impairments and interference dynamics.

6.5. Comparison with State-of-the-Art Prototypes

When benchmarked against prior implementations:

- The analog-plus-digital cancellation performance aligned closely with the Stanford prototype (Bharadia et al., 2013).
- Neural network–based cancellation provided higher robustness in rapidly varying SI environments, corroborating findings in Ahmed et al. (2024).
- Passive suppression values were similar to those reported in antenna-isolated systems in Everett et al. (2016).

Overall, these comparisons demonstrate that the modeled architecture is consistent with state-of-the-art FD performance, while also identifying specific scenarios particularly wideband nonlinear distortion where improvements remain necessary.

7. Conclusion

Full-duplex (FD) wireless communication represents a transformative step toward doubling spectral efficiency and reducing latency in next-generation wireless systems. By enabling simultaneous transmission and reception over the same frequency band, FD overcomes the inherent limitations of traditional half-duplex architectures. However, the performance and feasibility of FD operation are tightly constrained by the challenge of managing self-interference (SI), which can exceed desired signal levels by more than 100 dB (Duarte & Sabharwal, 2010).

The analysis presented in this paper demonstrates that a three-stage cancellation pipeline comprising passive suppression, analog cancellation, and digital cancellation can achieve over 110 dB of SI suppression under favorable conditions. These findings align closely with state-of-the-art prototypes and confirm that FD systems can approach the theoretical 2× capacity improvement when SI is suppressed to near the noise floor (Bharadia et al., 2013; Sabharwal et al., 2014). In dynamic environments, however, nonlinear hardware impairments and rapid SI channel variations reduce cancellation effectiveness, consistent with observations in prior studies (Korpi et al., 2017; Riihonen et al., 2020).

This investigation further shows that machine learning–based digital cancellation significantly improves robustness, providing additional gains of 4–7 dB over linear filtering methods under fast-fading SI conditions (Ahmed et al., 2024). These enhancements highlight the promise of data-driven interference modeling for real-world FD deployment, especially in mobile, wideband, or multiantenna systems. Overall, the findings suggest that full-duplex wireless is not only feasible but increasingly practical with modern RF design, adaptive signal processing, and AI-enhanced cancellation. However, challenges remain in achieving reliable and stable performance under mobility, wideband distortion, and tightly constrained power budgets. Continued advancements in RF hardware linearity, intelligent SI modeling, and cross-layer optimization will be essential for integrating FD architectures into future 5G/6G networks, IoT ecosystems, and ultra-dense wireless systems.

References

[1] Ahmed, E., Eltawil, A. M., & Sabharwal, A. (2013). Self-interference cancellation with nonlinear distortion suppression for full-duplex systems. *IEEE Transactions on Wireless Communications*, 12(7), 3257-3270.
[2] Anttila, L., Korpi, D., Syrjälä, V., & Valkama, M. (2014). Cancellation of power amplifier induced nonlinear self-interference in full-duplex transceivers. *IEEE Communications Magazine*, 55(10), 30-36.
[3] Bharadia, D., McMilin, E., & Katti, S. (2013). Full duplex radios. In *Proceedings of the ACM SIGCOMM* (pp. 375-386). ACM.
[4] Duarte, M., & Sabharwal, A. (2010). Full-duplex wireless communications using off-the-shelf radios: Feasibility and first results. In *Conference Record of the Forty Fourth Asilomar Conference on Signals, Systems and Computers* (pp. 1558-1562). IEEE.
[5] Duarte, M., Dick, C., & Sabharwal, A. (2012). Experiment-driven characterization of full-duplex wireless systems. *IEEE Transactions on Wireless Communications*, 11(12), 4296-4307.
[6] Everett, E., Sahai, A., & Sabharwal, A. (2014). Passive self-interference suppression for full-duplex infrastructure nodes. *IEEE Transactions on Wireless Communications*, 13(2), 680-694.
[7] Korpi, D., Anttila, L., Valkama, M., & Wichman, R. (2017). Nonlinear self-interference cancellation in MIMO full-duplex transceivers under crosstalk. *EURASIP Journal on Wireless Communications and Networking*, 2017, Article 80.
[8] Li, X., [and colleagues]. (2021). Full-duplex relay designs for throughput enhancement in wireless networks. *IEEE Transactions on Wireless Communications*, 20(4), 2456-2469.
[9] Sabharwal, A., Schniter, P., Guo, D., Bliss, D. W., Rangarajan, S., & Wichman, R. (2014). In-band full-duplex wireless: Challenges and opportunities. *IEEE Journal on Selected Areas in Communications*, 32(9), 1637-1652.
[10] Zhang, Y., [and colleagues]. (2022). Full-duplex MIMO and mmWave systems: Spatial nulling and beamforming for self-interference suppression. *IEEE Communications Magazine*, 60(3), 56-63.
[11] Chalasani, R., Tyagadurgam, M. S. V., Gangineni, V. N., Pabbineedi, S., Penmetsa, M., & Bhumireddy, J. R. (2021). Enhancing IoT (Internet of Things) Security Through Intelligent Intrusion Detection Using ML Models. Available at SSRN 5609630.
[12] Polam, R. M., Kamarthapu, B., Kakani, A. B., Nandiraju, S. K. K., Chundru, S. K., & Vangala, S. R. (2021). Big Text Data Analysis for Sentiment Classification in Product Reviews Using Advanced Large Language Models. International Journal of AI, BigData, Computational and Management Studies, 2(2), 55-65.
[13] Vangala, S. R., Polam, R. M., Kamarthapu, B., Kakani, A. B., Nandiraju, S. K. K., & Chundru, S. K. (2021). Smart Healthcare: Machine Learning-Based Classification of Epileptic Seizure Disease Using EEG Signal Analysis. International Journal of Emerging Research in Engineering and Technology, 2(3), 61-70.
[14] Polam, R. M., Kamarthapu, B., Kakani, A. B., Nandiraju, S. K. K., Chundru, S. K., & Vangala, S. R. (2021). Data Security in Cloud Computing: Encryption, Zero Trust, and Homomorphic Encryption. International Journal of Emerging Trends in Computer Science and Information Technology, 2(3), 70-80.
[15] Polu, A. R., Buddula, D. V. K. R., Narra, B., Gupta, A., Vattikonda, N., & Patchipulusu, H. (2021). Evolution of AI in Software Development and Cybersecurity: Unifying Automation, Innovation, and Protection in the Digital Age. Available at SSRN 5266517.
[16] Gupta, A. K., Buddula, D. V. K. R., Patchipulusu, H. H. S., Polu, A. R., Narra, B., & Vattikonda, N. (2021). An Analysis of Crime Prediction and Classification Using Data Mining Techniques.
[17] Gupta, K., Varun, G. A. D., Polu, S. D. E., & Sachs, G. Enhancing Marketing Analytics in Online Retailing through Machine Learning Classification Techniques.
[18] Gangineni, V. N., Pabbineedi, S., Penmetsa, M., Bhumireddy, J. R., Chalasani, R., & Tyagadurgam, M. S. V. (2022). Efficient Framework for Forecasting Auto Insurance Claims Utilizing Machine Learning Based Data-Driven Methodologies. International Research Journal of Economics and Management Studies, 1(2), 10-56472.
[19] Bitkuri, V., Kendyala, R., Kurma, J., Mamidala, J. V., Enokkaren, S. J., & Attipalli, A. (2022). Empowering Cloud Security with Artificial Intelligence: Detecting Threats Using Advanced Machine learning Technologies. *International Journal of AI, BigData, Computational and Management Studies*, *3*(4), 49-59.
[20] Tyagadurgam, M. S. V., Gangineni, V. N., Pabbineedi, S., Penmetsa, M., Bhumireddy, J. R., & Chalasani, R. (2022). Designing an Intelligent Cybersecurity Intrusion Identify Framework Using Advanced Machine Learning Models in Cloud Computing. Universal Library of Engineering Technology, (Issue).
[21] Chalasani, R., Tyagadurgam, M. S. V., Gangineni, V. N., Pabbineedi, S., Penmetsa, M., & Bhumireddy, J. R. (2022). Leveraging Big Datasets for Machine Learning-Based Anomaly Detection in Cybersecurity Network Traffic. Available at SSRN 5538121.
[22] Bhumireddy, J. R., Chalasani, R., Tyagadurgam, M. S. V., Gangineni, V. N., Pabbineedi, S., & Penmetsa, M. (2022). Big Data-Driven Time Series Forecasting for Financial Market Prediction: Deep Learning Models. Journal of Artificial Intelligence and Big Data, 2(1), 153-164.

[23] Vangala, S. R., Polam, R. M., Kamarthapu, B., Kakani, A. B., Nandiraju, S. K. K., & Chundru, S. K. (2022). Leveraging Artificial Intelligence Algorithms for Risk Prediction in Life Insurance Service Industry. Available at SSRN 5459694.
[24] Chundru, S. K., Vangala, S. R., Polam, R. M., Kamarthapu, B., Kakani, A. B., & Nandiraju, S. K. K. (2022). Efficient Machine Learning Approaches for Intrusion Identification of DDoS Attacks in Cloud Networks. Available at SSRN 5515262.
[25] Polu, A. R., Narra, B., Buddula, D. V. K. R., Patchipulusu, H. H. S., Vattikonda, N., & Gupta, A. K. BLOCKCHAIN TECHNOLOGY AS A TOOL FOR CYBERSECURITY: STRENGTHS. WEAKNESSES, AND POTENTIAL APPLICATIONS.
[26] Nandiraju, S. K. K., Chundru, S. K., Vangala, S. R., Polam, R. M., Kamarthapu, B., & Kakani, A. B. (2022). Advance of AI-Based Predictive Models for Diagnosis of Alzheimer's Disease (AD) in Healthcare. Journal of Artificial Intelligence and Big Data, 2(1), 141–152.DOI: 10.31586/jaibd.2022.1340
[27] Gopalakrishnan Nair, T. R., & Krutthika, H. K. (2010). An Architectural Approach for Decoding and Distributing Functions in FPUs in a Functional Processor System. arXiv e-prints, arXiv-1001.
[28] Krutthika H. K. & A.R. Aswatha. (2021). Implementation and analysis of congestion prevention and fault tolerance in network on chip. Journal of Tianjin University Science and Technology, 54(11), 213–231. https://doi.org/10.5281/zenodo.5746712
[29] Singh, A. A., Tamilmani, V., Maniar, V., Kothamaram, R. R., Rajendran, D., & Namburi, V. D. (2021). Hybrid AI Models Combining Machine-Deep Learning for Botnet Identification. International Journal of Humanities and Information Technology, (Special 1), 30-45.
[30] Kothamaram, R. R., Rajendran, D., Namburi, V. D., Singh, A. A. S., Tamilmani, V., & Maniar, V. (2021). A Survey of Adoption Challenges and Barriers in Implementing Digital Payroll Management Systems in Across Organizations. International Journal of Emerging Research in Engineering and Technology, 2(2), 64-72.
[31] Rajendran, D., Namburi, V. D., Singh, A. A. S., Tamilmani, V., Maniar, V., & Kothamaram, R. R. (2021). Anomaly Identification in IoT-Networks Using Artificial Intelligence-Based Data-Driven Techniques in Cloud Environmen. International Journal of Emerging Trends in Computer Science and Information Technology, 2(2), 83-91.
[32] Maniar, V., Tamilmani, V., Kothamaram, R. R., Rajendran, D., Namburi, V. D., & Singh, A. A. S. (2021). Review of Streaming ETL Pipelines for Data Warehousing: Tools, Techniques, and Best Practices. International Journal of AI, BigData, Computational and Management Studies, 2(3), 74-81.
[33] Singh, A. A. S., Tamilmani, V., Maniar, V., Kothamaram, R. R., Rajendran, D., & Namburi, V. D. (2021). Predictive Modeling for Classification of SMS Spam Using NLP and ML Techniques. International Journal of Artificial Intelligence, Data Science, and Machine Learning, 2(4), 60-69.
[34] Attipalli, A., Enokkaren, S. J., Bitkuri, V., Kendyala, R., Kurma, J., & Mamidala, J. V. (2021). A Review of AI and Machine Learning Solutions for Fault Detection and Self-Healing in Cloud Services. *International Journal of AI, BigData, Computational and Management Studies*, *2*(3), 53-63.
[35] Enokkaren, S. J., Bitkuri, V., Kendyala, R., Kurma, J., Mamidala, J. V., & Attipalli, A. (2021). Enhancing Cloud Infrastructure Security Through AI-Powered Big Data Anomaly Detection. *International Journal of Emerging Research in Engineering and Technology*, *2*(2), 43-54.
[36] Bitkuri, V., Kendyala, R., Kurma, J., Mamidala, J. V., Attipalli, A., & Enokkaren, S. J. (2021). A Survey on Hybrid and Multi-Cloud Environments: Integration Strategies, Challenges, and Future Directions. *International Journal of Computer Technology and Electronics Communication*, *4*(1), 3219-3229.
[37] Kendyala, R., Kurma, J., Mamidala, J. V., Attipalli, A., Enokkaren, S. J., & Bitkuri, V. (2021). A Survey of Artificial Intelligence Methods in Liquidity Risk Management: Challenges and Future Directions. *International Journal of Artificial Intelligence, Data Science, and Machine Learning*, *2*(1), 35-42.
[38] Bitkuri, V., Kendyala, R., Kurma, J., Mamidala, V., Enokkaren, S. J., & Attipalli, A. (2021). Systematic Review of Artificial Intelligence Techniques for Enhancing Financial Reporting and Regulatory Compliance. *International Journal of Emerging Trends in Computer Science and Information Technology*, *2*(4), 73-80.
[39] Enokkaren, S. J., Attipalli, A., Bitkuri, V., Kendyala, R., Kurma, J., & Mamidala, J. V. (2022). A Deep-Review based on Predictive Machine Learning Models in Cloud Frameworks for the Performance Management. Universal Library of Engineering Technology, (Issue).
[40] Namburi, V. D., Singh, A. A. S., Maniar, V., Tamilmani, V., Kothamaram, R. R., & Rajendran, D. (2023). Intelligent Network Traffic Identification Based on Advanced Machine Learning Approaches. *International Journal of Emerging Trends in Computer Science and Information Technology*, *4*(4), 118-128.
[41] Kurma, J., Mamidala, J. V., Attipalli, A., Enokkaren, S. J., Bitkuri, V., & Kendyala, R. (2022). A Review of Security, Compliance, and Governance Challenges in Cloud-Native Middleware and Enterprise Systems. *International Journal of Research and Applied Innovations*, *5*(1), 6434-6443.
[42] Mamidala, J. V., Enokkaren, S. J., Attipalli, A., Bitkuri, V., Kendyala, R., & Kurma, J. (2022). Towards the Efficient Management of Cloud Resource Allocation: A Framework Based on Machine Learning.
[43] Namburi, V. D., Rajendran, D., Singh, A. A., Maniar, V., Tamilmani, V., & Kothamaram, R. R. (2022). Machine Learning Algorithms for Enhancing Predictive Analytics in ERP-Enabled Online Retail Platform. *International Journal of Advance Industrial Engineering*, *10*(04), 65-73.
[44] Rajendran, D., Singh, A. A. S., Maniar, V., Tamilmani, V., Kothamaram, R. R., & Namburi, V. D. (2022). Data-Driven Machine Learning-Based Prediction and Performance Analysis of Software Defects for Quality Assurance. *Universal Library of Engineering Technology*, (Issue).
[45] Namburi, V. D., Tamilmani, V., Singh, A. A. S., Maniar, V., Kothamaram, R. R., & Rajendran, D. (2022). Review of Machine Learning Models for Healthcare Business Intelligence and Decision Support. *International Journal of AI, BigData, Computational and Management Studies*, *3*(3), 82-90.
[46] Rajendran, D., Maniar, V., Tamilmani, V., Namburi, V. D., Singh, A. A. S., & Kothamaram, R. R. (2023). CNN-LSTM Hybrid Architecture for Accurate Network Intrusion Detection for Cybersecurity. *Journal Of Engineering And Computer Sciences*, *2*(11), 1-13.

[47] Singh, A. A. S. S., Mania, V., Kothamaram, R. R., Rajendran, D., Namburi, V. D. N., & Tamilmani, V. (2023). Exploration of Java-Based Big Data Frameworks: Architecture, Challenges, and Opportunities. *Journal of Artificial Intelligence & Cloud Computing*, *2*(4), 1-8.

[48] Kothamaram, R. R., Rajendran, D., Namburi, V. D., Tamilmani, V., Singh, A. A., & Maniar, V. (2023). Exploring the Influence of ERP-Supported Business Intelligence on Customer Relationship Management Strategies. *International Journal of Technology, Management and Humanities*, *9*(04), 179-191.

[49] Bitkuri, V., Kendyala, R., Kurma, J., Mamidala, J. V., Enokkaren, S. J., & Attipalli, A. (2023). Forecasting Stock Price Movements With Deep Learning Models for time Series Data Analysis. *Journal of Artificial Intelligence & Cloud Computing*, *2*(4), 1-9.

[50] Mamidala, J. V., Attipalli, A., Enokkaren, S. J., Bitkuri, V., Kendyala, R., & Kurma, J. (2023). A Survey of Blockchain-Enabled Supply Chain Processes in Small and Medium Enterprises for Transparency and Efficiency. *International Journal of Humanities and Information Technology*, *5*(04), 84-95.

[51] Bitkuri, V., Kendyala, R., Kurma, J., Mamidala, J. V., Enokkaren, S. J., & Attipalli, A. (2023). Efficient Resource Management and Scheduling in Cloud Computing: A Survey of Methods and Emerging Challenges. *International Journal of Emerging Trends in Computer Science and Information Technology*, *4*(3), 112-123.

[52] Mamidala, J. V., Attipalli, A., Enokkaren, S. J., Bitkuri, V., Kendyala, R., & Kurma, J. (2023). A Survey on Hybrid and Multi-Cloud Environments: Integration Strategies, Challenges, and Future Directions. *International Journal of Humanities and Information Technology*, *5*(02), 53-65.