

3-5 適応型同一帯域内全二重中継による柔軟な無線通信エリアの構築に向けて

3-5 *Advanced Full-Duplex Relay Technologies for Resilient Wireless Networks*

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大規模な災害や事故発生直後の緊急対応時、特にプラント等の複雑な構造を持つ建物内や地下・トンネル内等では、通信インフラ利用が困難となり得る。現場の状況把握及び対応には、通信インフラでの低遅延性等を維持しながら、周波数チャネルを拡大することなく、柔軟に通信エリアを制御できる技術が必要となる。同一帯域内全二重 (In-band Full-duplex: IBFD) 中継は、同一帯域内での送受信を同時に中継器で行うことで、高い周波数利用効率と低遅延性を両立できる。一方、中継器での残留自己干渉及び変動する電波伝搬特性への追従が課題となる。本稿では、自己干渉に応じた適応フィルタを用いるアナログ・デジタル統合型干渉キャンセル手法と、中継局の位置及び送信電力の統合最適化手法を提案する。これらによって、動的な電波伝搬特性下でも自己干渉を抑制し、柔軟な通信範囲の制御が行えることを計算機シミュレーションで確認した。

Resilient wireless networks are critical for maintaining reliable communication in challenging wireless environments, such as industrial plants, underground facilities, and tunnels, where access to conventional communication infrastructure may be limited. In-band full-duplex (IBFD) relay systems improve spectrum efficiency and offer low-latency communication by enabling simultaneous transmission and reception on the same frequency band. Nevertheless, their practical deployment is limited by self-interference and varying channel conditions. This paper presents two primary contributions to resilient full-duplex relay networks: length-adaptive two-step self-interference cancellation (SIC) design and a joint relay location and power allocation optimization framework. The proposed SIC approach enhances interference suppression under varying channel conditions, while the optimization framework identifies optimal relay deployment and transmission parameters. Simulation results indicate notable improvements in achievable data rates and communication reliability under practical self-interference conditions. These technologies support the development of robust, spectrum-efficient, and low-latency resilient wireless networks.

1 Introduction

Reliable wireless communication is essential for next-generation resilient networks supporting applications such as factory automation, autonomous robotics, industrial Internet of Things (IIoT), public safety, and disaster response. These applications require ultra-reliable low-latency communication (URLLC) to satisfy stringent latency and reliability requirements while maintaining connectivity under challenging operating conditions. However, wireless networks deployed in harsh or dynamic environments often experience severe propagation conditions due to obstacles, damaged infrastructure, or limited coverage, making it

difficult to maintain reliable, low-latency connectivity.

To address these challenges, NICT has been conducting research on resilient wireless communication technologies. A key requirement is the rapid deployment of communication systems that can provide reliable connectivity with minimal transmission delay under challenging propagation conditions. Low-latency, non-regenerative relay systems are attractive candidates since they can improve and extend wireless communication coverage without requiring complex signal decoding and encoding. By directly forwarding signals, these relays enable rapid network deployment while maintaining low processing latency.

In-band full-duplex (IBFD) technology has attracted

considerable attention as a promising solution for improving spectral efficiency in future wireless networks [1]. Unlike conventional half-duplex (HD) relays, an IBFD relay simultaneously transmits and receives signals on the same frequency band, potentially doubling spectral efficiency while reducing end-to-end communication latency [2]. These characteristics make IBFD relays well-suited for resilient wireless networks that require spectrum-efficient, low-latency communication. Consequently, IBFD has been identified as one of the key enabling technologies for International Mobile Telecommunications (IMT)-2030 and future 6G networks [3].

However, the practical implementation of IBFD relays is limited by self-interference (SI). SI occurs when a relay's transmitted signal leaks into its own receiver, interfering with the desired incoming signal. Self-interference cancellation (SIC) techniques [4]–[6] are therefore required to estimate and suppress the interference signal. Although recent advances have significantly improved SIC performance, residual self-interference (RSI) remains a major factor affecting the achievable performance of practical full-duplex relay systems [7].

In addition to interference suppression, communication performance strongly depends on relay deployment and power allocation. In challenging wireless environments, channel conditions vary considerably with relay location due to obstacles, terrain, and infrastructure conditions. Furthermore, transmit power allocation directly affects communication reliability, achievable throughput, and interference levels. Therefore, relay location and power allocation should be jointly optimized to maximize communication performance under adverse channel conditions.

To realize practical IBFD relay systems for resilient wireless networks, NICT has pursued research on technologies that improve both the physical-layer performance and the end-to-end communication efficiency of relay systems. These efforts include mitigating self-interference and optimizing relay deployment under practical propagation conditions, providing the foundation for reliable and resilient wireless communications.

Building upon these research efforts, this study presents two complementary technologies for resilient full-duplex relay networks. The first is a length-adaptive two-step SIC framework, in which analog self-interference cancellation (ASIC) is followed by adaptive digital self-interference cancellation (DSIC) to mitigate residual self-interference under varying channel conditions. The second is a joint relay

location and power allocation optimization framework for determining suitable relay deployment and transmission parameters. Overall, these technologies improve communication reliability, spectral efficiency, and network resilience across a wide range of resilient wireless applications.

The present work represents an intermediate stage toward the realization of resilient wireless networks. Future research will investigate multi-relay systems, mobile relay platforms such as unmanned aerial vehicles (UAVs), and adaptive optimization techniques for dynamically changing wireless environments. These developments are expected to further enhance the robustness and flexibility of next-generation resilient wireless networks.

2 System Model

An amplify-and-forward in-band full-duplex (AF-IBFD) relay architecture is considered, as illustrated in Fig. 1. The AF-IBFD relay actively amplifies and forwards the received signal while simultaneously transmitting and receiving on the same frequency band. Such characteristics make IBFD relays particularly attractive for resilient wireless networks, where communication links may be disrupted by obstacles, damaged infrastructure, or challenging propagation conditions.

The source node (S) and destination node (D) each employ a single antenna, while the robot relay (R) is equipped with one receive antenna and one transmit antenna operating in full-duplex mode. Due to severe attenuation and blockage caused by obstacles or infrastructure conditions, the direct link between S and D is assumed unavailable [1]. This models practical scenarios in which direct communication is unavailable or unreliable, requiring relays to restore

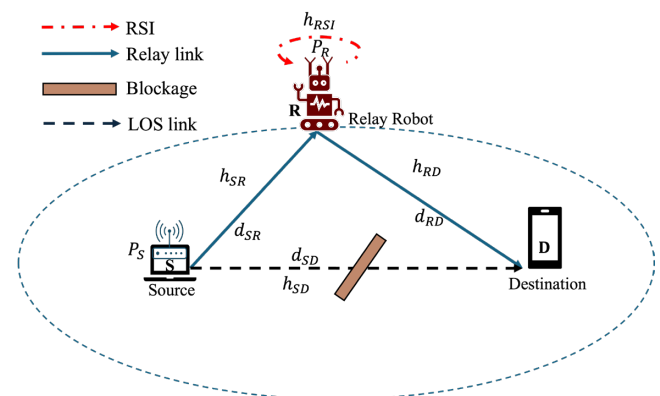


Fig. 1 Amplify-and-forward in-band full-duplex relay system with residual self-interference.

or extend connectivity between the source and destination. The channels of the $S - R$, $R - D$, and $S - D$ links are denoted by h_{SR} , h_{RD} , and h_{SD} , respectively, with distance d_{SR} , d_{RD} , and d_{SD} . The relay is assumed to move on an ellipse with foci at S and D , satisfying $d_t = d_{SR} + d_{RD}$. This constraint models practical deployment limitations, where relay placement is restricted by obstacles, infrastructure conditions, terrain, or operational constraints while maintaining a bounded end-to-end communication distance.

In addition, residual self-interference at the relay is modeled by the channel coefficient h_{RSI} , which represents the leakage between the transmit and receive antennas during full-duplex operation. This interference remains after SIC and degrades the received signal quality at the relay. The transmit powers of the source node and relay are denoted by P_S and P_R , respectively, and satisfy the total power constraint $P = P_S + P_R$.

It is worth noting that practical wireless environments may contain strong reflectors such as buildings, vehicles, and surrounding structures. However, the considered scenario assumes heavily obstructed propagation, resulting in predominantly non-line-of-sight (NLOS) conditions in which a stable line-of-sight (LOS) component cannot be consistently maintained. Under such conditions, Rayleigh fading serves as a conservative and widely adopted model for performance evaluation. We consider narrowband operation with a carrier frequency of 4.9 GHz and a bandwidth of 20 MHz. In this regime, the channel can be reasonably modeled as frequency-flat, and RSI is approximated as constant.

3 Proposed Technologies

3.1 Self-Interference Cancellation (SIC)

Practical IBFD relay systems require effective suppression of self-interference to achieve high communication performance, as shown in Fig. 2. The relay transmits an amplified and delayed version of the received signal $r(k)$ at k th timeslot, defined as $x(k) = A r(k - 1)$, where A is the relay amplification factor. The SI signal after passing through the SI channel $\mathbf{h}_{si}$ is given by $x_{si}(k) = x(k) * \mathbf{h}_{si}$, where $*$ denotes the convolution operation. Then, the received signal at the relay can be expressed as

$$y(k) = r(k) + x_{si}(k) \cdot \dots \cdot (1)$$

Since the power of the SI signal is often much larger than that of the desired received signal, effective cancellation is required before signal detection.

To address this challenge, a two-stage SIC technique was investigated. The proposed framework consists of an analog SIC followed by a digital SIC to suppress the interference signal while maintaining low processing complexity.

In the first stage, a feedforward analog cancellation technique is employed to suppress the dominant SI component before analog-to-digital conversion (ADC). The analog SIC generates an estimate of the SI signal and subtracts it from the received signal, thereby reducing the interference power and preventing receiver saturation. After analog cancellation, the residual SI signal still exists.

In the second stage, the proposed method estimates the residual SI channel and reconstructs the residual SI signal in the digital domain. By subtracting the reconstructed signal from the received signal, the residual interference can be significantly reduced. Unlike conventional approaches that

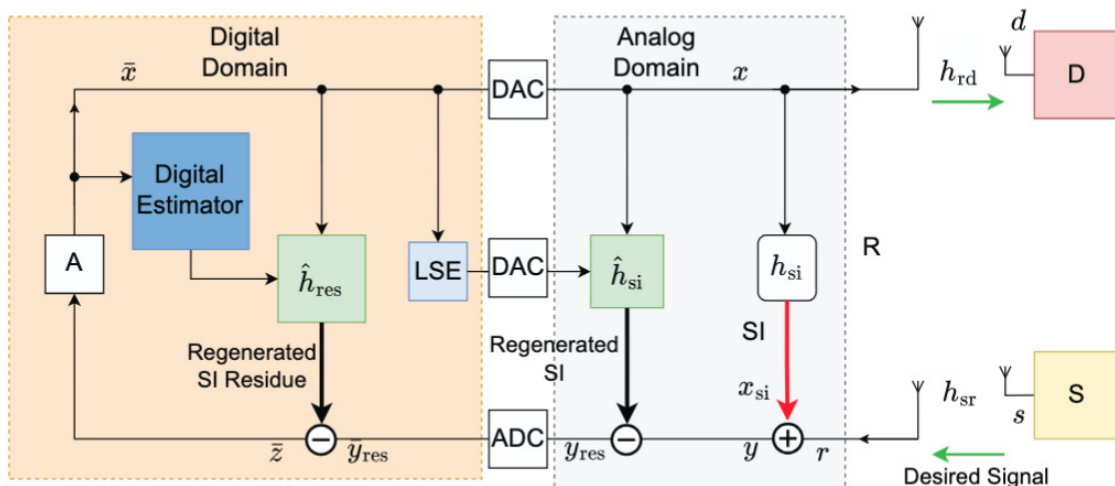


Fig. 2 System model of AF IBFD relay system with dual-step self-interference cancellation.

use a fixed filter length, the proposed method adaptively determines the filter length according to the interference environment. This approach aims to achieve effective interference suppression while minimizing computational complexity and processing delay, which are important requirements for low-latency relay systems.

The objective is to minimize the reconstruction error between the estimated residual SI signal and the residual SI signal after ASIC, while the constraint ensures that the error vector magnitude (EVM) after DSIC remains below the target threshold. The details of the proposed algorithm can be found in [8] [9].

Applying the proposed optimization algorithm yields an optimal filter length of 15. As shown in Fig. 3, the resulting DSIC achieves additional SI suppression beyond that provided by ASIC alone. These results demonstrate that effective residual SI cancellation can be achieved with a short filter length, thereby reducing implementation complexity and processing delay. Consequently, the proposed approach is well-suited for low-latency, full-duplex relay systems in resilient wireless networks.

3.2 Relay Location and Power Allocation

Although the proposed SIC technique significantly reduces self-interference, practical IBFD relay systems still experience a non-negligible level of RSI. Consequently, the overall performance of an IBFD relay system depends not only on the effectiveness of SIC but also on network deployment and resource allocation. In practical wireless environments, communication links may experience severe degradation due to obstacles, infrastructure conditions, and

varying propagation conditions. Therefore, appropriate relay placement and transmit power allocation, while accounting for the remaining RSI, are essential for maintaining reliable communication and maximizing network performance.

This section presents an optimization framework designed to maximize the achievable data rate of an IBFD relay system. The end-to-end performance is characterized by the received signal-to-interference-plus-noise ratio (SINR), which can be expressed as [10]

$$\Gamma(\rho_d, \rho_p) = \frac{K_{SR}K_{RD}d_{SR}^{-\nu}d_{RD}^{-\nu}\gamma_s\gamma_r}{K_{RD}d_{RD}^{-\nu}(\epsilon\gamma_r^2 + \gamma_r) + K_{SR}d_{SR}^{-\nu}\gamma_s + \epsilon\gamma_r + 1}, \dots (2)$$

where γ_s and γ_r denote the source and relay signal-to-noise ratios (SNRs), respectively, and ϵ represents the RSI level after SIC. K_{SR} and K_{RD} denote the path-loss coefficients of the source-to-relay and relay-to-destination links, respectively, and ν is the path-loss exponent. This expression explicitly shows how relay location and power allocation jointly affect the achievable communication performance.

Two optimization variables are jointly considered to manage relay deployment and power allocation. The first variable is the relay location distance ratio, $\rho_d = d_{SR} / d_t$, which represents the normalized source-to-relay distance relative to the total distance. The second variable is the power allocation ratio, $\rho_p = P_{SR} / P$, which specifies the fraction of the total transmit power allocated to the source node.

Based on the above SINR model, a data-rate maximization problem is formulated. The optimization problem is initially non-convex because of the coupling among relay location, power allocation, and RSI. To address this challenge, the Lagrangian Dual Transform (LDT) and Quadratic Transformation (QT) techniques [11] are employed to reformulate the problem into a convex optimization framework. A low-complexity iterative algorithm is then developed to efficiently determine the optimal relay location and power allocation while ensuring convergence. The details of the proposed algorithm can be shown in [10].

3.2.1 Impact of Relay Location and Power Allocation on Data Rate

The impact of relay location and power allocation on the achievable data rate is investigated using a 3D surface plot in Fig. 4. The achievable data rate is observed to be a non-convex function of both the relay location ratio and the power allocation ratio, exhibiting two local maxima with comparable values, one of which yields a slightly higher performance. As the system moves away from these regions, the data rate decreases, highlighting the sensitivity of system

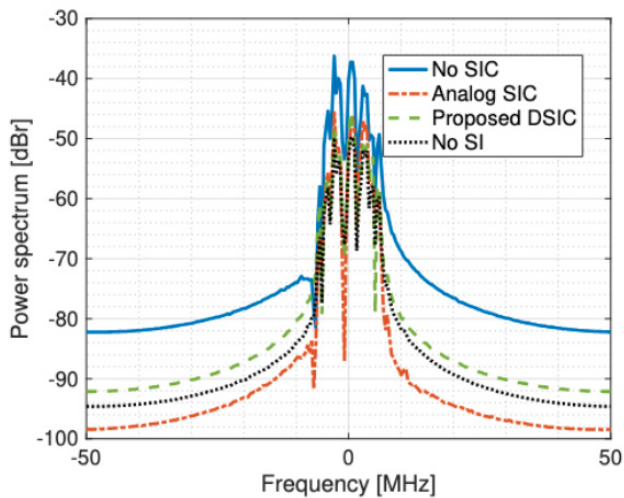


Fig. 3 Comparison of the baseband power spectrum of the received signals.

performance to both parameters and the importance of their joint optimization.

3.2.2 Impact of RSI on Relay Location and Power Allocation

Figures 5 and 6 illustrate the optimal relay location and power allocation ratio under different RSI levels. As shown in Fig. 5, the optimal relay location shifts toward the destination as the source power allocation increases, since a stronger source-relay link allows the relay to be placed farther from the source without performance degradation. Under higher RSI levels, the relay is positioned closer to the source to mitigate pathloss and SI effects. Fig. 6 shows that the optimal power allocation ratio increases with the relay distance ratio, indicating that more power should be allocated to the source as the relay moves toward the

destination, particularly under severe RSI conditions. These results highlight the coupling between relay location and power allocation, motivating their joint optimization for reliable full-duplex relay-assisted systems.

3.2.3 Performance Comparison

Figure 7 compares the average achievable data rate versus transmit power for different schemes. The proposed jointly optimized IBFD scheme achieves the highest data rate across all transmit power levels, demonstrating the benefit of joint optimization. In contrast, schemes that optimize only relay location or power allocation yield limited gains, whereas the non-optimized IBFD scheme saturates early due to RSI. The HD scheme with optimization shows only marginal improvement due to the inherent half-duplex constraint. Overall, the results confirm the

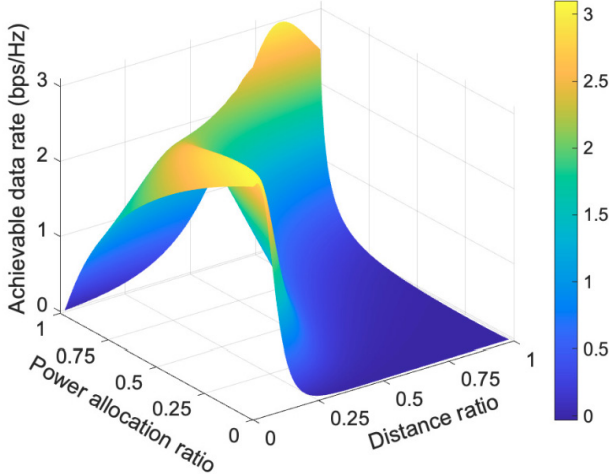


Fig. 4 3D surface plot of the data rate for all possible distance ratios and power allocation ratios ($P = 10$ dBm, $\epsilon = -75$ dB).

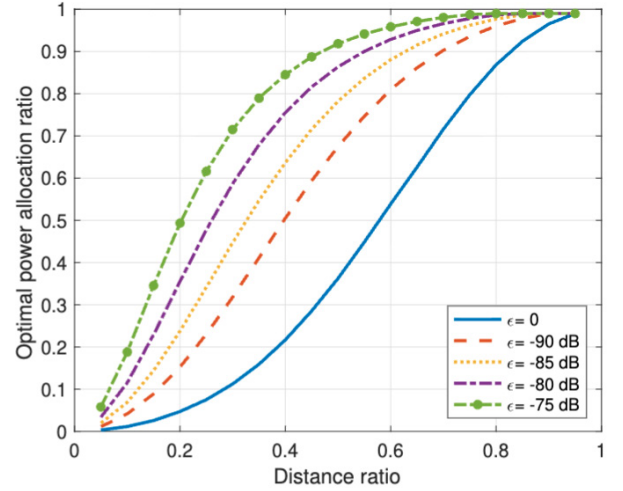


Fig. 6 Optimal power allocation at different relay distance ratios for different RSI levels ($P = 10$ dBm).

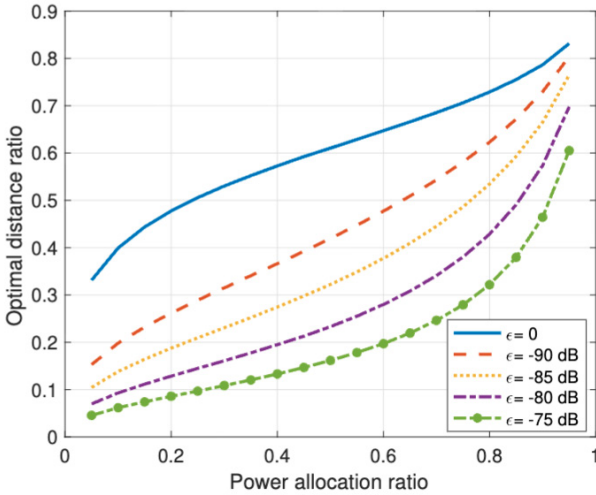


Fig. 5 Optimal relay location at different power allocation for different RSI levels ($P = 10$ dBm).

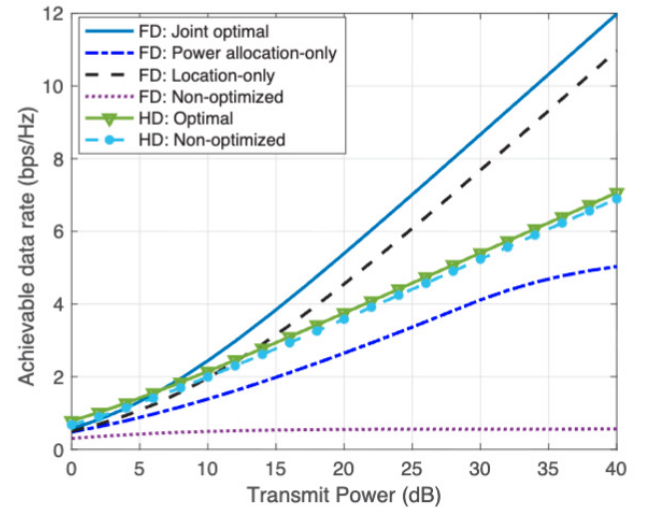


Fig. 7 Data rate comparison of the proposed FD and HD schemes.

effectiveness of the proposed joint optimization for IBFD systems.

4 Conclusion

This study investigated an IBFD relay system for resilient wireless communications in the presence of self-interference, focusing on two-step self-interference cancellation and the joint optimization of relay location and power allocation. Simulation results demonstrated that the proposed SIC method effectively reduces residual self-interference, while the joint optimization improves the achievable data rate under practical operating conditions. These results demonstrate the potential of the proposed technologies to enhance the reliability and spectral efficiency of resilient wireless networks. Future work will extend the proposed framework to multi-relay systems, mobile relay platforms such as UAVs, and adaptive optimization techniques for dynamically changing wireless environments, thereby improving the scalability and adaptability of resilient wireless communication systems. In addition, experimental validation using real-world wireless testbeds will be conducted to assess the practical applicability of the proposed technologies for challenging wireless environments.

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