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In-Band Full-Duplex for Integrated Sensing and Communication: A Review and Perspective on Advances in Electromagnetics, Antennas, and Propagation

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(Invited Article)

ABSTRACT The capability to simultaneously transmit and receive signals in the same frequency band, known as in-band full-duplex or simultaneous transmit and receive, increases the spectral efficiency and decreases the latency of communication systems. Moreover, sensing systems can also benefit from this capability. However, the primary challenge for successful implementation remains the susceptibility to self-interference (SI). This article reviews various approaches to overcome the challenges presented by SI, focusing primarily on those that can be addressed by taking advantage of knowledge and understanding of electromagnetics, antennas, and propagation.

INDEX TERMS 6G communications, array antennas, circulators, in-band full-duplex (IBFD), integrated sensing and communication (ISAC), interference cancellation, multiple-input multiple-output (MIMO), radio frequency (RF) cancellation, self-interference (SI), simultaneous transmit and receive (STAR), wireless communications.

INTRODUCTION

Integrated sensing and communication (ISAC) is based on the property that electromagnetic waves can simultaneously carry information as well as sense the physical environment. Leveraging this property through appropriate design, ISAC systems can share hardware, waveforms, and spectral resources, thus reducing cost and spectral congestion as well as acquiring new functionalities compared to systems solely dedicated to either communication or sensing functions. Hence, ISAC has been considered an innovative technology for 6G wireless communications [1], [2]. Sensing systems are intrinsically in-band full-duplex (IBFD), due to the fact that the frequency of an electromagnetic wave reflected by an obstacle does not change, other than for the Doppler effect. In the field of communications, the use of IBFD or the capability to simultaneous transmit and receive (STAR) enables nodes to transmit and receive in the same frequency band and at the same time, which challenges the traditional assumption in wireless network design where uplink and downlink communications are

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multiplexed in either time and/or frequency. The IBFD capability enhances spectral efficiency and decreases latency. Increasing spectral efficiency allows network providers to push higher data rates through the limited spectrum, which in turn allows them to support more users and diverse services [3].

This article reviews IBFD because it plays a crucial role in ISAC [4], [5], [6]. Applications include, but are not limited to: 1) smart cities where environment-aware communications are enabled by allowing base stations to perform sensing while exchanging communication signals [7], [8], [9]; 2) smart manufacturing, powered by the Industrial Internet of Things (IIoT), is transforming traditional production systems into intelligent, interconnected ecosystems. By integrating advanced sensors and real-time data analytics, smart manufacturing enables dynamic decision-making, predictive maintenance, and adaptive production processes; and 3) automotive applications, where sensing signals from adaptive radar cruise control and collision warning need to be exchanged simultaneously with safety communication messages [10], [11].

The primary challenge in IBFD systems comes from self-interference (SI), i.e., the strong unwanted signal from the transmitter that leaks into the receiver. If not sufficiently canceled, SI can overwhelm the receiver, degrading system performance [12], [13], [14]. In fact, the implementation of IBFD on current ISAC systems is considered too challenging, and antenna separation methods or bistatic ISAC systems are likely to be used to achieve a sufficient SI cancellation. However, when IBFD technology is sufficiently developed, future ISAC systems will be monostatic, which would constitute a great advancement [15].

Simple Considerations

For successful IBFD-ISAC systems, it is crucial to mitigate SI to a level approaching the receiver's thermal noise floor. The fundamental concept of IBFD operation is straightforward; however, the primary challenge has always been rooted in RF hardware limitations. In an ideal scenario, if analog-to-digital conversion could be performed with arbitrary resolution, self-interference cancellation (SIC) would be trivial. However, practical analog-to-digital converters (ADCs) have finite dynamic range and resolution. This becomes particularly problematic since the SI signal can be more than 100 dB stronger than the desired signal from a distant transmitter.

Fig. 1 illustrates the power levels in a successful IBFD scenario, where the ADC's dynamic range dictates the necessary degree of analog cancellation—typically beyond traditional cancellation alone [16]. As a result, the key bottleneck in realizing IBFD lies in leveraging electromagnetics, antenna design, and propagation techniques to effectively suppress SI before it reaches the ADC.

Classification of SIC Approaches: Antenna Level, Analog RF Front-End, and Digital Domain

This section provides an overview of the fundamental principles and key characteristics of SIC. SI suppression in IBFD transceivers can leverage three domains of operation [3]; the three domains are as follows.

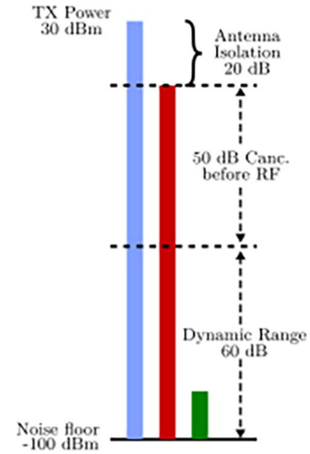


FIG. 1. **Illustrative example of the signal power levels at the outputs of the different SIC modules in IBFD.**

1) *Antenna Domain*: A core concept of antenna-domain suppression is to control the distance between transmit and receive modalities. In all-antenna IBFD systems (such as single antenna systems), each antenna operates in both transmission and reception simultaneously. Consequently, SI in such systems arises from two sources: an antenna's own transmission and signals transmitted by other antennas in multiantenna configurations. In large-scale antenna deployments, such as massive multiple-input multiple-output (MIMO) and mmWave systems, implementing an all-antenna IBFD approach can be highly complex. To address this, a more practical alternative is the split-array architecture. In split-array systems, a subset of antennas functions in transmit mode while others operate in receive mode, significantly reducing or even eliminating both forms of SI present in all-antenna configurations. An alternative approach for multiantenna system is to leverage symmetries in the electromagnetic field radiated by the transmitter so as to create either nulls at the locations of the receivers or opposite signals that cancel each other out [17]. A special case is single-antenna systems where SIC may be achieved via polarization diversity or through defected ground structures (DGSs).
2) *Analog/RF Domain:* Since antenna-based SIC techniques cannot entirely eliminate SI, analog cancellation is applied at the RF front-end before the signal reaches the ADC. This process involves estimating the SI and subtracting it from the received signal. Given that the receiver inherently *knows* the signal it is transmitting, it can recover its intended message after compensating for the channel effects.
3) *Digital Domain:* This is similar to the analog domain but performed on digital signals—after the variable gain amplifier and ADC.

Our objective is to provide a conceptual understanding of the key ideas that have emerged in electromagnetics, antennas, and propagation to enable the development of IBFD technology for

ISAC systems. This article is structured according to the following. Reduction of SI through antenna design is addressed in "IBFD Approaches Based on Antenna Design" section. Then, approaches based on the analog RF front-end to reduce SI are discussed in "IBFD Approaches Based on Analog/RF Front-Ends" section. Digital domain approaches are only briefly mentioned in "IBFD Approaches Based on Digital Domain Techniques" section, as they are not the main focus of this article. Finally, some directions for future research are provided in "Directions for Future Research" section.

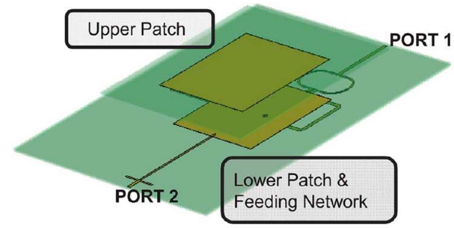
IBFD APPROACHES BASED ON ANTENNA DESIGN

Here, we consider three major categories organized based on the number of antennas in the system.

Single Antenna Systems

The majority of available literature on IBFD antennas addresses antenna isolation techniques and SIC strategies from the perspective of two or more antennas. However, the use of multiple antennas in an IBFD-ISAC system may be undesirable in several applications where smaller form factor requirements mandate that designers develop dense and tightly coupled integrated electronic systems (such as mobile phones). This problem is alleviated by collocating the transmitter and receiver chains in the near proximity and sharing the same antenna aperture for simultaneous transmission and reception of signals, also known as shared or single antenna systems. The primary technique that is predominantly used to attain SIC for such single or shared antenna systems involves the use of circulators to prevent signal leakage from the transmitter to the receiver unit (discussed in "IBFD Approaches Based on Analog/RF Front-Ends" section). In this section, we primarily emphasize standalone antenna design techniques that aid in the enhancement of port-to-port isolation without discussing the RF front-end system-level circuitry. It is worthy of mention that although there are numerous contributions on this topic, we choose to highlight some of the major approaches that can enhance the port-to-port isolation in single antenna system. It should also be noted that standalone single-antenna design techniques cannot attain the required isolation > 110 dB that is typically desirable for IBFD systems. The isolation levels are generally achievable by utilizing some combination of antenna isolation, RF front-end cancellation, and digital signal processing techniques. Nevertheless, robust and minimally self-interfering antenna designs contribute significantly toward achieving that goal.

The major approach to enhancing the port-to-port isolation in a two-port single antenna system [1 port for transmit (TX) and 1 port for receive (RX)] is to exploit the antenna's polarization diversity. By exciting a dual-polarized antenna using an orthogonal feed-configuration topology, the antenna radiates distinct orthogonally polarized beams in the TX and RX modes, thereby minimizing the signal interference between the transmitter to the receiver [18]. In [18], the isolation is further enhanced by making use of a multilayer configuration and feeding the structure using an aperture-coupling mechanism



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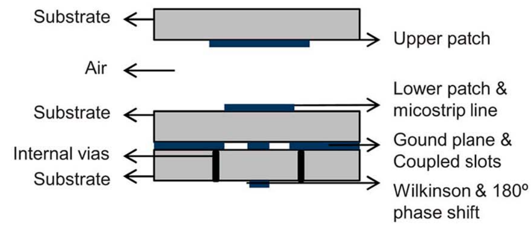

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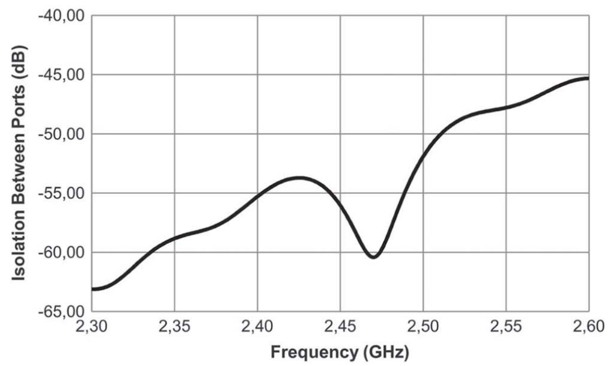
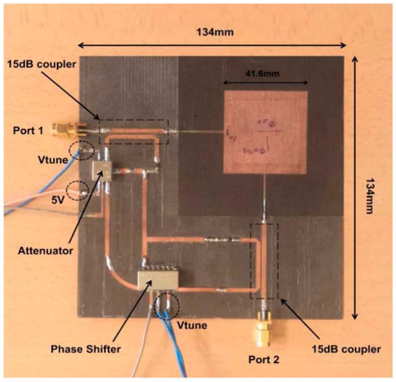


(c)

FIG. 2. (a) Slot-coupled antenna structure. (b) Layered stack-up (side view). (c) Antenna S_{21} response [18]. Copyright 2014 IEEE.

through slots in the ground plane. Fig. 2 shows the structure of the antenna and the corresponding port-to-port isolation depicting the S_{21} response. Using this design technique, an isolation greater than 55 dB over a 10 MHz bandwidth centered around 2.4 GHz was achieved.

Another methodology to enable SIC in single antennas is to exploit device mechanisms that can destructively interfere and cancel out the leakage signal at the receiver port. Although the RF cancellation techniques generally require separate front-end hardware architecture, this section focuses only on microwave techniques that are directly part of the antenna design cycle without the need for any external hardware requirements. In [19], the authors achieve a port-to-port isolation by adopting a two-pronged approach: first, by designing an orthogonally polarized antenna at 2.4 GHz, and second, by constructing a coupled feed-forward loop from the transmitter to the receiver port, thereby enhancing further cancellation of port-to-port leakage. Using this method, the authors were able to obtain a peak isolation of 80 dB within the band of interest. The authors in the series of publications [20], [21] utilize differential feeding mechanisms to strengthen the port-to-port isolation response. Primarily, the symmetry of the structure is utilized to couple an



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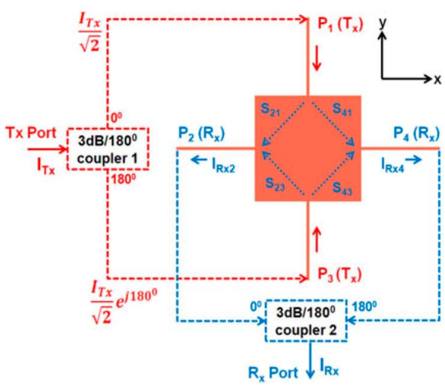
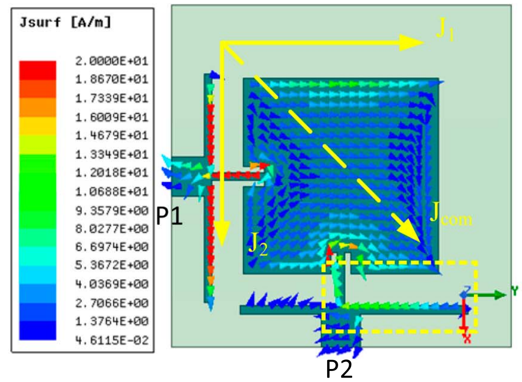


(b)

FIG. 3. (a) Circularly polarized antenna with feed-forward topology. Reprinted with permission from [19]. Copyright 2016 Wiley Periodicals, Inc. (b) Differential feeding mechanism for reducing port-to-port coupling [20]. Copyright 2018, IEEE.



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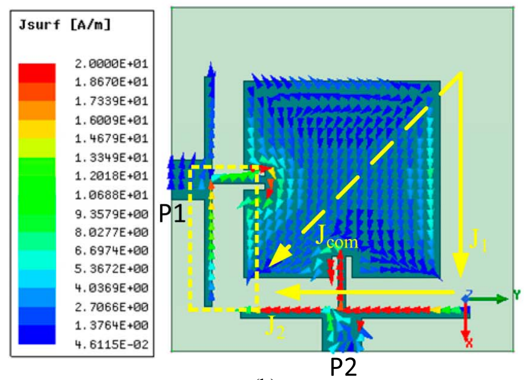


(b)

FIG. 4. Current distribution of full-duplex textile antenna at 2.45 GHz when: (a) port 1 is excited; and (b) port 2 is excited [22]. Copyright 2020, IEEE.

equal amount of energy to both receiver ports (due to a differential feeding topology), which are then nullified by employing 3 dB/180° coupler. In practice, the 3 dB/180° coupling mechanism is implemented using a ring-hybrid coupler. Fig. 3(a) shows the antenna structure with a coupled feed-forward loop from the transmitter to the receiver port [19], whereas the differentially fed circularly polarized antenna geometry of [20] is presented in Fig. 3(b).

Finally, the authors in [22] and [23] use perpendicularly oriented half-wavelength strips at the port locations to design IBFD antennas at 2.45 GHz for textile and wearable applications. Using this approach, the authors were able to engineer induced currents on the strips that are oppositely directed to the transmitter-to-receiver port leakage currents. Therefore, the resultant electromagnetic effects are neutralized, yielding a significant enhancement in antenna terminal isolation. Fig. 4 shows the current distribution when port 1 and port 2 are excited, respectively [22]. The yellow rectangular highlighted region demonstrates the cancellation of surface currents due to being oppositely directed, which aids in higher isolation. Furthermore, the presence of the strips produces another added resonance which is stagger tuned with the dominant mode resonance of the patch. This serves to further improve the −10 dB impedance bandwidth of the antenna system.

In the preceding part, we provided an overview of the schemes that utilize dual polarization to enable full-duplex operation on a single antenna. Among these, the full-duplex scheme employing a copolarized antenna is often preferred over the dual-polarized antenna scheme in many practical ISAC scenarios, where a radar return is often of the same polarization as the transmitted signal. The copolarization approach eliminates the need to allocate polarization resources, thereby allowing the full-duplex system to achieve enhanced channel capacity. A single IBFD antenna offers the advantages of miniaturization and ease of integration. For a single IBFD antenna, dual polarization is inherently orthogonal, facilitating high isolation between the two ports. However, for copolarized IBFD antennas, coupling exists between the operating modes excited by the transceiver ports, resulting in poor isolation between the ports. To ensure optimal performance in full-duplex systems, copolarized full-duplex antennas require decoupling techniques to achieve high isolation in the antenna domain. Depending on the method of decoupling, these techniques can be classified into two categories: coupling blocking and coupling cancellation.

In addition to limiting the propagation of coupling energy, another approach to achieve high isolation is to introduce new coupling paths to cancel the original coupling between the ports. A common method for achieving this is the introduction of parasitic resonators [24], [28], [29] or parasitic dielectric surfaces [25], which facilitate additional decoupling. As illustrated in

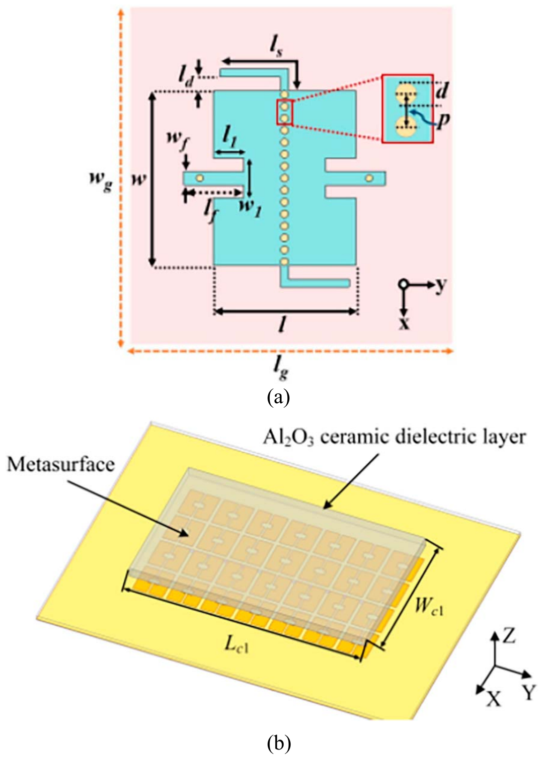


FIG. 5. Decoupling of IBFD antenna utilizing parasitic structures for isolation improvement. (a) Parasitic resonator [24]. (b) Parasitic dielectric layer [25].

Fig. 5(a), in [24], two L-shaped branches are extended from the center of the antenna. These branches reach the resonance length, significantly altering the energy coupling between the two ports. By incorporating the parasitic L-shaped branching structure, the isolation was improved from 7.2 dB to a maximum of 60.8 dB. In addition to surrounding the antenna with parasitic structures, the inclusion of a parasitic dielectric layer above the antenna also introduces additional coupling, thereby providing the potential for decoupling. In the design presented in Fig. 5(b), the authors incorporated a decoupled ceramic dielectric layer above the antenna. The parasitic dielectric layer demonstrates a more stable frequency response and has the potential to enable broadband decoupling. The IBFD antenna loaded with a dielectric layer in the literature [25] achieved an isolation of higher than 50 dB over a 2.5% relative bandwidth.

Parasitic structure-based decoupling methods often require substantial physical space to achieve the necessary resonant dimensions. An alternative approach involves modifying the internal structure of the antenna to introduce additional coupling mechanisms for decoupling purposes [26], [27], [30], [31], [32], [33], [34], [35], [36]. This method eliminates the need for external structures, resulting in a more compact antenna design. As shown in Fig. 6(a), loading the capacitance at the end of the shorting pins alters the coupling relationship inside the antenna, thereby enabling improved isolation [26]. This configuration achieves a peak isolation of 30 dB near the 2.4 GHz band. In [27], the authors propose a stacked integrated cavity antenna that incorporates a patch antenna. As shown in

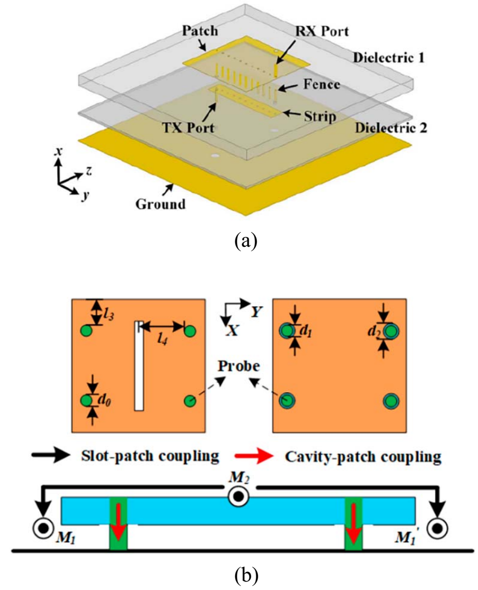


FIG. 6. IBFD antenna with internal antenna structure modified for decoupling. (a) Capacitance loaded pins [26]. (b) Decoupling probes [27].

Fig. 6(b), probes are inserted to introduce internal coupling between the cavity and the patch. This internal coupling is effectively canceled with the external coupling between the slot and the radiating aperture of the patch, resulting in a peak isolation of greater than 40 dB.

Overall, the primary challenge in designing full-duplex antennas with copolarization lies in achieving high port isolation. Although numerous full-duplex antenna designs have been developed to provide high isolation, they commonly suffer from issues such as distortion of the radiation pattern and limitations in decoupling bandwidth. Even after decoupling is achieved, residual currents often persist on adjacent antenna elements, leading to beam tilting and reduction in the broadside gain of the IBFD antenna. Therefore, decoupling techniques capable of preserving the integrity of the radiation pattern are regarded as one of the key technologies for future IBFD antennas. Furthermore, current copolarized IBFD antennas are only capable of achieving isolation levels greater than 50 dB at specific frequencies or over very narrow bandwidths. Introducing additional resonances to broaden the decoupling bandwidth is thus essential for enhancing the overall performance of IBFD-ISAC systems.

Multiple Antenna Systems

An effective strategy to tackle SI is the use of multiple antenna systems, where separate antennas are designated for TX and RX [37], [38]. This setup unlocks valuable spatial degrees of freedom that can be cleverly used to suppress SI at the hardware level. By combining this physical separation with smart signal processing techniques, recent research shows that it is possible to dramatically reduce interference without altering standard communication protocols. This section explores innovative approaches that use such TX-RX antenna

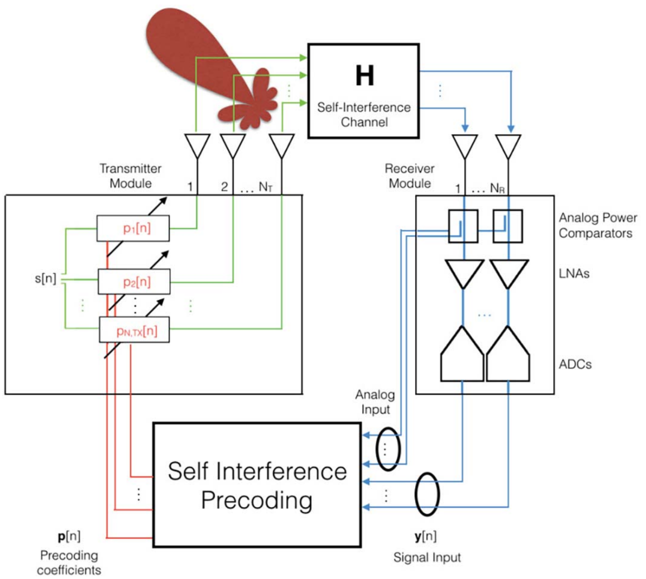


FIG. 7. Proposed system model for SIC for multiantenna full duplex radio systems [41].

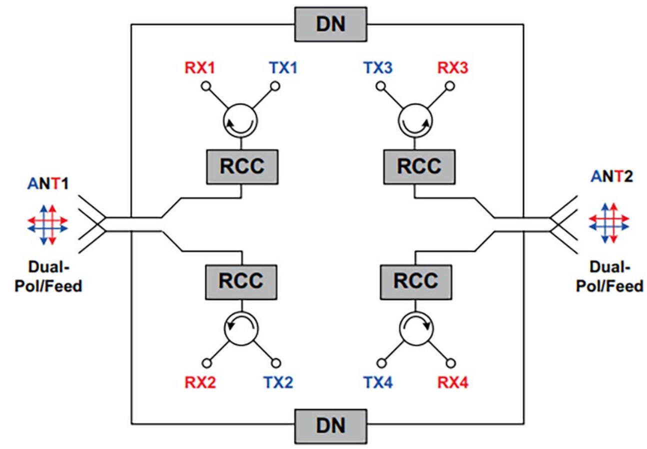


FIG. 8. Proposed system model for SIC for 4 × 4 MIMO full-duplex using all possible methods. [43].

pairings to enable practical high-performance SIC in IBFD systems [39], [40].

In [41], the authors present an innovative method for reducing SI by taking advantage of spatial processing with multiple antennas. In these setups, one antenna handles TX while another handles RX at the same frequency, but the close proximity of antennas causes strong SI that can easily overload the receiver. To solve this, the authors propose a two-step approach that completely avoids the need for digital-domain cancellation or training sequences, both of which are ineffective when the receiver is saturated. Instead, the method uses space-time precoding at the transmitter to shape the outgoing signal in such a way that it naturally avoids interfering with the receiver—by forcing it into the "null space" of the interference channel between the TX and RX antennas.

The first step uses the cyclic Jacobi technique (CJT) [42] with analog power readings to blindly estimate this null space and keep the receiver from saturating. Once the receiver is safely within its operating range, the second step uses a local search algorithm (the Nelder–Mead simplex method) to fine-tune the precoding for even stronger interference cancellation. This technique enables reliable full-duplex operation even in small devices with minimal antenna isolation, reducing interference close to the system's noise floor—all without changing the existing communication protocol for a possible communication-centric ISAC design. Fig. 7 illustrates how the system uses a feedback loop of analog measurements and digital adjustments to suppress SI, making this approach highly relevant for practical multiantenna FD systems where one antenna is dedicated to TX and the other to RX [41].

In [43], the authors present a comprehensive study on mitigating SI in IBFD MIMO systems. To address this challenge, the article introduces a hybrid approach that combines passive antenna-domain suppression with active RF cancellation. Specifically, the RF front-end of a 2 × 2 MIMO IBFD radio is engineered to suppress SI through both physical antenna isolation and circuit-level cancellation [43]. Three methods for suppression of the antenna domain are discussed: spatial separation, use of circulators, and dual-polarized antennas.

In their implementation, the authors employ antenna separation along with a reflection-controlled circulator to minimize SI coupling. For active cancellation, a dedicated RF board is designed to recreate and subtract the residual SI signal from the receiver path. This board includes four SI reference generators, each composed of three-tap circuits with attenuators, phase shifters, and true time delay elements, to emulate the interference accurately [41]. This setup achieves a wide cancellation bandwidth of 100 MHz centered at 3.55 GHz. Experimental results demonstrate over 30 dB of passive suppression and an additional 60 dB of cancellation through active circuitry, highlighting the effectiveness of this dual-stage approach. Fig. 8 illustrates the system architecture, emphasizing the use of separate TX and RX antennas alongside carefully tuned RF cancellation paths. Together, these methods showcase a practical and scalable solution for realizing high-performance IBFD MIMO radios that push the boundaries of next-generation wireless systems [43].

In [44], the authors present a compelling visualization of the antenna's performance, highlighting its capability to maintain high isolation between the TX and RX paths, even under copolarized operation. This is achieved through a monostatic dual-polarized STAR antenna system, which leverages a beamforming network (BFN) capable of generating 0°, ±90°, ±180°, and ±270° phase progressions. These phase shifts are used to excite the TX and RX ports of four dual-polarized antenna elements arranged in a sequential rotation array (SRA) [45], [46]. The carefully engineered phase progression, combined with the geometric symmetry of the array, enables intrinsic cancellation of coupling between the TX and RX ports at the BFN output—leading to theoretically infinite isolation as shown in Fig. 9. The effectiveness of this approach is further reinforced by full-wave simulations, which explore the influence of

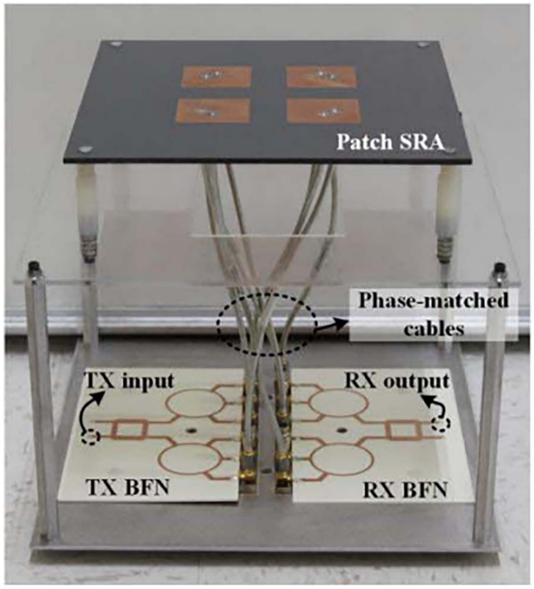
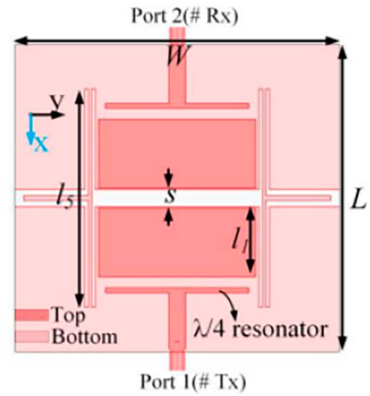


FIG. 9. Monostatic copolarized full-duplex [44].



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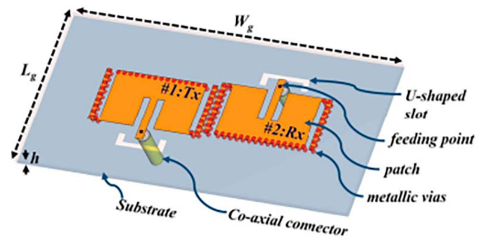

(b)

FIG. 10. Decoupling of IBFD antenna utilizing DGS for high isolation. (a) DGS loaded between antennas [47]. (b) DGS loaded on the radiation aperture [48].

element spacing and potential imbalances within the BFN. To mitigate practical imperfections, such as those introduced by nearby scatterers or residual BFN mismatches, an additional cancellation layer is implemented, enhancing overall system robustness. Experimental validation of the STAR system was carried out in the (2.4 to 2.5) GHz ISM band, where the prototype demonstrated impressive measured isolation exceeding 47 dB and return losses above 22 dB [44]. Moreover, the antenna exhibits strong dual circular polarization performance, with realized gains above 7 dBic, broadside axial ratios below 1.6 dB, and symmetric radiation beams—making it highly suitable for full-duplex systems requiring polarization agility. The study also demonstrates the STAR system's potential for wideband operation using a quad-ridge horn antenna element, reinforcing its adaptability to diverse IBFD scenarios. Overall, the insights presented in Fig. 9 emphasize the design's practical viability, offering a sophisticated yet efficient solution to SI challenges in modern wireless systems [44].

Finally, another approach to reduce SI based upon only electromagnetic propagation is the use of a DGS, which is widely employed in antenna decoupling design to limit energy propagation. As illustrated in Fig. 10 in [47], a DGS structure is incorporated between the slits of two antennas, effectively blocking the coupling energy and enhancing the peak isolation to 39 dB near the 2.4 GHz band. Fig. 10(b) demonstrates another DGS decoupling configuration. In [48], the DGS structure is applied to the radiation aperture, effectively restricting the energy coupling between the TX and RX. This configuration achieves an isolation of greater than 54 dB in the 5.9 GHz band, with a peak isolation approaching 90 dB.

Array Antenna Systems

IBFD systems can utilize antenna arrays to enhance their directivity for applications such as radar, point-to-point communications links, and their combination in ISAC. These arrays are typically constructed using a directional antenna element (i.e., patch) that is repeated in either one or two dimensions to create linear or square/rectangular arrays, respectively. The spacing between the elements is nominally half the wavelength of the operating frequency, and while this spacing allows the array to electronically scan with minimal angle ambiguities, it presents a significant challenge in terms of SI for different array architectures [49].

Two predominant IBFD array types exist and differ in how full-duplex is enabled among the elements, either at the aperture- or the element-level. As seen in Fig. 11, the former divides the antenna elements into subarrays where a collection of elements is assigned to transmit and the others to receive, which enables IBFD operation using both sides concurrently. The latter, on the other hand, is created using individual elements that are capable of simultaneously transmitting and receiving, such as in the copolarized single-antenna systems previously discussed. This enables IBFD operation using all of the elements within the array, and while challenging to implement, it offers certain advantages over its aperture-level counterpart. Both types will be expanded upon next.

Aperture-level IBFD arrays often leverage fully digital backends that contain data converters for every element within the array [50]. This provides for the dynamic assignment of the transmit and receive subarrays based on the specific application or functional need. For this IBFD array type, SI is strongest at the boundary between the transmit and receive subarrays, and is dictated by the mutual coupling between neighboring elements.

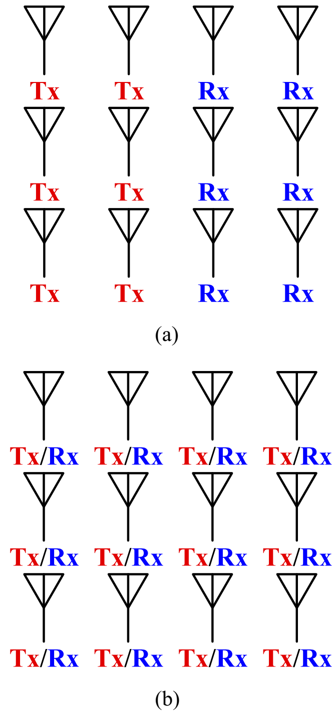

FIG. 11. Antenna array architectures that provide IBFD at: (a) aperture level; and (b) element level.

This SI is typically suppressed using three techniques that provide cancellation in the propagation and digital domains, all of which utilize digital signal processing [51]. The first mechanism that reduces the SI present at the receiver inputs is digital-adaptive transmit beamforming, which creates near-field nulls in the direction of the receive elements. With proper design of the system power levels, this step allows the remaining SI to be sampled by the receiver and subsequently enables the second and third techniques. These consist of digital-adaptive receive beamforming, which is similar to the transmit operation but in the reverse spatial direction, and digital cancellation using an observation of the transmit signal.

Several prototype arrays have been demonstrated using this IBFD aperture-level architecture, and have contained between 8 and 72 total elements, where the transmit and receive subarray sizes have been evenly split. For the eight-element systems, total transmit-to-receive isolations of 140.5 and 160.8 dB have been reported over 1 and 100 MHz bandwidths at 2.45 GHz [52], [53]. Also, at 2.4 GHz over 20 MHz bandwidths, a 16-element linear array produced 45 dB of isolation [54], and a 72-element rectangular array yielded 87 dB [55]. Additionally, arrays with center frequencies of 10 GHz have been demonstrated with 40 and 50 elements and measured isolations of 13.8 dB over 200 MHz [56] and 20 dB over 100 MHz [57], respectively.

Element-level IBFD arrays require the use of an antenna interface device to enable the sharing of a single antenna between transmit and receive. As discussed in the next section, these devices include magnetic- and non-magnetic-based circulators, electrical balanced duplexers, quadrature couplers, and other circuits [58]. When the antenna interface achieves low insertion loss for both the transmit and receive paths, element-level architectures can outperform aperture-level designs by eliminating the reduction of array gain that results from dividing the aperture. For this approach, SI is not only generated within each element but also among all neighbors, as opposed to being concentrated on the boundary of aperture-level designs, and necessitates the use of different mitigation strategies.

These different SI types require element-level arrays to incorporate unique RF/analog circuits in addition to digital techniques, which could explain why their research to-date has been limited. Two different designs have been demonstrated for arrays with three and eight elements. The first utilized magnetic-based circulators for the antenna interfaces, multitap RF cancellers that were connected between the elements, and nonlinear digital cancellation, all to suppress the various SI paths. This approach produced a prototype that was capable of providing a total isolation of 103 dB over a 20 MHz bandwidth at 2.45 GHz [59]. The second design incorporated non-magnetic-based circulators with antenna impedance tuners, analog-adaptive receive beamforming, and nonlinear digital cancellation to generate 100 dB of isolation over a 16 MHz bandwidth at 0.73 GHz [60].

Last, it is worth-mentioning that the scattering and reflection of electromagnetic waves caused by nearby antennas and obstacles can significantly impact the performance of these IBFD systems, by adversely affecting their SIC levels. The problem is even more pronounced in the context of ISAC, where the antenna systems are required to sense the channel and its surrounding environment. This issue can be mitigated by employing channel-aware methods in the propagation domain, such as the Transmit Beamforming technique [39] that can dynamically and adaptively respond to such scattering environments.

IBFD APPROACHES BASED ON ANALOG/RF FRONT-ENDS

Analog cancellation is employed at the RF front-end before the signal reaches the ADC.

RF Circulators

One approach to analog cancellation is based on RF circulators. Circulators are three-port nonreciprocal devices that direct signals between ports, ensuring isolation between TX and RX paths. These components act as duplexers by forwarding the transmitted signal to the antenna while routing received signals to the receiver with minimal leakage [61]. However, their effectiveness is constrained by factors such as environmental reflections, component imperfections, and frequency-dependent behavior. An analog SIC technique that leverages the RF circulator's inherent secondary SI signals to cancel primary SI, reducing reliance on conventional feed-forward methods is introduced in [62] and [63]. This approach simplifies the SIC circuit by eliminating components like samplers and phase shifters. A key innovation is the adjustable impedance mismatched terminal circuit at the antenna port, which dynamically

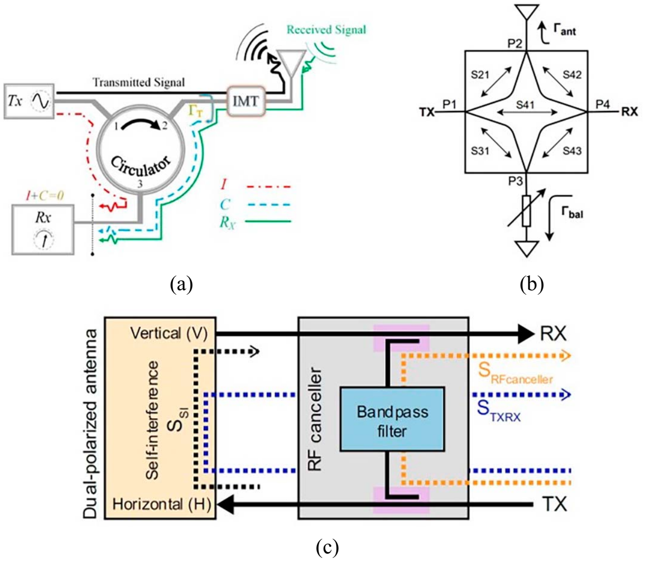

FIG. 12. Schematic of SIC approaches based on analog RF: (a) passive SIC approach based on a circulator [62]; (b) analog cancellation based on EDB approach [64]; and (c) frequency-domain SIC based on RF BPF [65].

modifies the secondary SI signal's frequency response as shown in Fig. 12(a).

Electrical Balance Duplexing (EBD)

Another approach to analog cancellation is EBD, which enhances isolation by employing a hybrid coupler and a tunable impedance network. The impedance network generates an SI signal that counteracts the SI introduced by antenna mismatches, as shown in Fig. 12(b). However, since antenna impedance varies with environmental conditions, real-time tuning is necessary to maintain effective cancellation. Also, in [64], an EBD-based solution is proposed where the balancing network splits the incident signal into in-phase (I) and quadrature (Q) components using a Wilkinson power divider and a Schiffman 45-degree phase shifter. These components are reflected through tunable resistors, dynamically adjusting the reflections to optimize cancellation. Digital control strategies improve the precision and flexibility of impedance tuning, increasing system bandwidth.

Time-Domain Analog Cancellation

Time-domain analog SIC techniques focus on generating a copy of the SI signal and destructively combining it with the received signal [66]. This can be implemented at the RF, intermediate frequency (IF), or baseband (BB) stages. In RF-tapping [67], a portion of the transmitted signal is sampled at the power amplifier (PA) stage and split into multiple paths. Each signal tap is delayed, attenuated, and phase-shifted before recombination to suppress interference. A similar implementation at IF is proposed in [68], where TX signal tapping and recombination occur at IF frequencies. The effectiveness of time-domain analog cancellers depends on the number of signal taps.

1) Single-tap cancellers are effective against direct TX-RX coupling but struggle in multipath environments.
2) Double-tap cancellers provide improved bandwidth and mitigate single reflections.
3) Multitap cancellers offer the highest SI suppression by adapting to multipath reflections, but they require complex hardware and computationally intensive tuning algorithms.
4) Digital domain suppression further reduces residual interference postdigitization.

The tradeoff between complexity and performance remains a key challenge in deploying multitap cancellers for real-world applications [69].

Frequency-Domain SIC

In addition to time-domain techniques, frequency-domain SIC methods have been explored to address SI over a wide bandwidth. A technique proposed in [70] employs frequency-domain equalization (FDE) to model the SI channel and counteract interference. This method uses multiple tunable RF bandpass filters (BPFs) to replicate the frequency response of the SI channel, as shown in Fig. 12(c). Since this technique operates at RF, it captures nonidealities introduced by transmission components. By continuously adjusting the filter parameters (e.g., center frequency, gain, and phase shift), the system can dynamically adapt to changing environmental conditions.

Digitally Assisted Analog SIC

A hybrid approach to SIC involves integrating digital processing with RF analog techniques. Fully digital SIC methods involve digitizing both the transmitted and received signals and subtracting SI in the digital domain [71]. However, a digitally assisted hybrid SIC approach can provide a balance between performance and complexity.

A notable hybrid canceller, as proposed in [72], integrates an RF vector multiplier (RF-VM) with a finite impulse response (FIR) digital filter. In this method,

1) A portion of the TX signal is extracted using a coupler and routed to the RF-VM.
2) The RF-VM adjusts the signal's amplitude and phase to create a SI counteract at the RX.
3) The RF-VM is controlled by a FIR digital filter, which models the interference cancellation path.
4) A linear least-squares (LLSs) algorithm dynamically computes the optimal control parameters.

By leveraging real-time digital adaptation, this hybrid technique enhances SIC performance while maintaining practical implementation feasibility.

IBFD APPROACHES BASED ON DIGITAL DOMAIN TECHNIQUES

Digital-domain SIC is typically achieved through the regeneration of the SI signal using *digital* filters that aim to replicate and subtract the interfering signal from the received signal. This process, however, is significantly complicated by nonlinear distortions introduced by components in the transmitter and receiver chains, particularly the PAs. These nonlinearities distort the SI signal in a manner that is not easily modeled or canceled using traditional linear filtering techniques. As a result, accurately characterizing and compensating for these distortions becomes essential for effective cancellation. Prior work has analyzed the impact of transmit and receive PA nonlinearities on the performance of digital SIC methods, highlighting the need for advanced nonlinear modeling and adaptive signal processing techniques to address these challenges [71], [73], [74].

The PA in the transmitter is often the primary source of nonlinear distortion in IBFD wireless systems, making it a critical component to model accurately for effective SI regeneration. To mitigate the impact of this distortion, it is essential to incorporate a reliable model of the PA's behavior into the SIC process. PAs can be characterized using either physical models or behavioral models. Physical models aim to capture the detailed internal mechanisms of the amplifier, offering high accuracy but at the cost of increased computational complexity. In contrast, behavioral models provide a simplified representation of the PA's input–output relationship. While they are generally less computationally intensive, they also tend to be less accurate, particularly when modeling complex nonlinearities. A notable challenge in modeling PAs is accounting for memory effects, which arise due to dynamic interactions within the amplifier over time. Memory effects of nonlinear PAs manifest as frequency-dependent or bandwidth-dependent nonlinear responses.

A comprehensive SI model for single-antenna IBFD radios has been proposed, accounting for a wide range of practical impairments. This model incorporates in-phase and quadrature (I/Q) imbalances at both the transmitter and receiver, nonlinear distortions across all transceiver components, the impact of the receiver's noise figure, and the effects of phase noise introduced by the I/Q mixers in both the transmit and receive paths. These considerations enable a more accurate and realistic characterization of SI, which is essential for designing robust digital cancellation techniques. The detailed formulation of this model can be found in [75].

Cancellation via Model-Based Signal Processing

Once the behavioral model of the PA and other nonlinear RF components is selected, its parameters are trained using an adaptive algorithm like least mean squares (LMSs) or recursive least squares (RLS) algorithm, and the trained model is used to generate and subtract the SI signal from the received signal [76], [77], [78], [79]. The LMS algorithm, a form of stochastic gradient descent, is widely used for digital SIC due to its simplicity and ease of implementation [80]. The main limitation of using LMS algorithms for SIC is the slow convergence rate. A simple LMS-based optimizer has been proposed in [81] that achieves the optimal convergence rate for SIC while maintaining low computational complexity. Recently, a new SIC algorithm was introduced in [82], which combines orthogonal basis functions with the LMS algorithm to enhance both convergence speed and mean squared error performance. Another approach is to use the RLS algorithm, which adaptively estimates model coefficients to minimize the mean squared error and offers faster convergence than LMS. However, RLS is known for its high computational complexity. To address this, a low-complexity variant of RLS for digital SIC has been proposed in [76].

Cancellation via Machine Learning

Recently, neural networks have been applied to model and cancel the SI [80], [83], [84], [85], [86], [87]. It has been demonstrated in [83], [87], [88], and [89] that the use of a deep neural network can reduce computational complexity by up to 36% when compared to non-deep neural network-based solutions [90]. Most current deep neural network-based methods combine estimation of the typically time-invariant nonlinear distortion and the time-varying SI propagation channel, which must be periodically reacquired [91].

As such, these approaches require *online* training, since they do not make use of information from previous time intervals.

Deep neural network and transfer learning: This can be addressed by decoupling the time-varying SI propagation channel from the estimation of the time-invariant nonlinear distortion and utilizing *transfer learning* to combine elements of both off-line and on-line training while accumulating information across time intervals [92], [93].

DIRECTIONS FOR FUTURE RESEARCH

The role of antennas and analog/RF front-ends will always remain critical to achieve the required levels of SIC for IBFD-ISAC systems. In addition, small overall system size and robustness to unpredictable and fast changes in the environment will always be important for advancing IBFD technologies. For example, the proximity of antennas to other objects affects mutual coupling among antenna elements, which in turn affects the SIC capability of the overall system. Therefore, advances that reduce the susceptibility of an IBFD system to changes in the environment are important for future implementation of practical IBFD-ISAC networks. Hence, one related direction of improvement is the multiphysics modeling of the entire RF systems by combining diverse governing equations, typically done in separate solvers. Another related direction is improving measurement methods for IBFD antennas, which becomes more challenging for antenna arrays that are sometimes integrated with BFNs. IBFD antenna array systems present unique SI challenges that, when mitigated, can open opportunities for applications that require directionality. These future research areas also include novel antenna interface architectures [94] and efficient signal processing algorithms [95].

Furthermore, implementing IBFD presents significant challenges. Although IBFD has the potential to markedly enhance the performance of a wide range of wireless systems and applications, integrating it into legacy systems is problematic because these systems were not originally designed to manage the additional complexity and interference that IBFD introduces. Each new emerging application may require its own set of novel solutions [16]. For example, while most physical layer security studies assume half-duplex operation, IBFD transceivers are well suited for such applications due to their ability to jam eavesdroppers while receiving the signal of interest. In this context, designing an optimal jamming waveform to maximize the secrecy while mitigating SI is challenging. Similarly, defense can use IBFD capability in electronic warfare—intended interference becomes electronic attack and spectrum monitoring becomes signals intelligence.

Finally, as previously mentioned, many currently consider IBFD technology too challenging to incorporate into current ISAC systems, and instead will employ a bistatic or multistatic approach initially. Future ISAC implementations, however, will preferably adopt monostatic-IBFD systems that offer robust SIC suppression and provide for more compact solutions. We also anticipate that the joint design and optimization of ISAC systems will lead to the incorporation of IBFD. In this case, the SI signal should not be eliminated completely. Hence, SI cancellation developed for communications could potentially remove the key signals required in sensing. To enable IBFD-ISAC, it is necessary to admit reflections from the surrounding objects and avoid canceling useful echo signals, while ensuring sufficient mitigation of the direct SI channel between RX and TX [7].

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