

In-Band Full-Duplex: The Physical Layer

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ABSTRACT | In this article, we review the key concepts and the progress in the design of physical-layer aspects of in-band full-duplex (IBFD) communications. One of the fundamental challenges in realizing IBFD is self-interference that can be up to 100 dB stronger than signals of interest. Thus, we start by reviewing state-of-the-art research in self-interference cancellation, addressing both model-based and emerging machine learning-based methods. Then, we turn our attention to new wireless systems with many degrees of freedom for which the traditional IBFD designs do not gracefully scale and, hence, require many innovations to enable IBFD. We provide an extensive review of basic concepts and state of the art in massive multiple-input-multiple-output IBFD. Then, we consider the mmWave band IBFD and review advanced physical-layer architectures. The above review provides the proper context to discuss IBFD innovations and new challenges for sixth-generation networks and beyond, where wireless networks are envisioned to be multifunctional, combining communications with functions such as sensing, cognitive radios, physical-layer security, and wireless power transfer. We conclude this article with a status update on the adoption of IBFD in communication standards.

KEYWORDS | Cross-link interference; in-band full-duplex (IBFD); integrated sensing and communication (ISACs); mmWave; multiple-input multiple-output (MIMO) systems; reconfigurable intelligent surface (RIS); self-interference cancellation.

I. INTRODUCTION

One of the key metrics in wireless network design is spectral efficiency, measured by bits/s/Hz. 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. Over the decades, increases in spectral efficiency have come from a plethora of ideas made possible by a combination of algorithms and hardware technologies. For example, improvements resulting from better error-correcting codes were coupled with breakthroughs in faster computing platforms. While it is impossible to predict the next breakthrough, it is perhaps not surprising that many of the influential ideas have originated by questioning the basic assumptions of existing design foundations.

A foundational assumption in network design has been that radios cannot simultaneously transmit and receive in the same frequency band. As a result, all network designs multiplex uplink and downlink communications in either time and/or frequency. The concept of in-band full-duplex (IBFD) communications is conceptually simple and was, in fact, studied by Shannon in two-way channels [1]. The challenge has always been hardware-centric. The transmitted signal is also received and can be more than 100 dB stronger than the signal coming from the intended transmitter farther away. If analog-to-digital conversion can be performed to arbitrary resolution, then canceling self-interference is conceptually easy. However, practical analog-to-digital converters (ADCs) have finite dynamic range and resolution that have presented the

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main bottleneck in realizing IBFD. The two simultaneous demonstrations of IBFD for communications [2], [3] using off-the-shelf radios challenged the decade-old assumption. The two works proposed suppressing, or canceling, the self-interference *before* the downconverted signal reaches the analog-to-digital conversion stage. The two demonstrations generated equal parts of skepticism and interest from the community. On the one hand, they challenged a basic premise of wireless networks, and hence, skepticism was highly justified. However, the use of off-the-shelf radios to demonstrate their concepts evoked some confidence in the results, and, concurrently, the high spectral efficiency benefits of IBFD operation in relay links despite residual self-interference [4] was observed in theory. These together spurred significant research on IBFD, e.g., [5], [6], [7], [8], [9], and many references in the sequel.

The concept of IBFD has a long history in the context of radars. Short-to-medium range radars have used IBFD technology for decades. Perhaps, the first use of IBFD dates back to the 1940s in continuous-wave radar systems, which use either monostatic (shared antenna) or bistatic (two separate antennas) architectures to transmit and receive simultaneously. The main issue for efficient implementation of continuous-wave radar systems in the early days was “transmitter leakage,” i.e., self-interference. Early efforts to address the issue were based on passive physical isolation-based antenna separation in colocated monostatic and bistatic systems and the use of circulators in shared-antenna systems. However, in order to limit the transmitter leakage, transmit power had to be curtailed, which, in turn, reduced the maximum detectable range of targets. For increasing the dynamic range and, consequently, the maximum target detection range of continuous-wave radars, effective self-interference cancellation was essential. To this end, in 1963, an analog circuit-based “feed thru nulling” approach was demonstrated, which achieved a self-interference suppression of 60 dB [10]. However, the implementation had several disadvantages; namely, the ferrite vector modulators used in the canceller were slow and had low bandwidth, while the milled blocks used to control the RF phase around the cancellation path were costly to produce. In 1990, an analog closed-loop cancellation technique was proposed to implement continuous-wave X-band radars with a shared antenna [11]. Beyond the early work, improved leakage cancellation techniques have also been proposed, including hybrid solutions where self-interference cancellation is addressed in one analog and one digital stage [12], [13]. Recent work has also proposed wideband leakage cancellers for continuous-wave radar systems [14].

Returning to the present day from the above historical note, in this article, we will review progress in IBFD communication systems that pose new challenges beyond those encountered by radars. Our objective is to provide a conceptual understanding of the key ideas that have emerged in the development of IBFD wireless networks.

In Section II, we first outline the basics of self-interference. Then, we review both the early and

state-of-the-art methods that address nonlinearities in radios and explore modern learning-based methods. Our exposition on self-interference and methods for its suppression is deliberately concise as there are excellent reviews and tutorials available on the topic [6], [15], [16], [17]. Instead, in this article, we dive deeper into the innovation in IBFD in the context of recent and emerging networks: massive multiple-input-multiple-output (MIMO) IBFD in Section III, mmWave IBFD in Section IV, IBFD for emerging multifunction networks in Section V, and the status of IBFD adoption in communication standards in Section VI. In the following, we summarize the key points of Sections III–VI.

In Section III, we review the methods that were developed to address the special needs of massive MIMO IBFD. The concept of massive MIMO was proposed in [18] the same year as the two IBFD papers. In massive MIMO systems, the base stations are equipped with a large number of antennas, ranging from tens to hundreds, for simultaneous transmission to a small number of users. The key benefit of devoting a large number of degrees of freedom per user makes network management much easier while allowing a frequency reuse of one due to reduced intercell interference. Since massive MIMO systems are better suited for time-division duplex (TDD) operation, it was fortuitously aligned with IBFD that requires TDD operation. However, self-interference reduction techniques developed for a small number of antennas (see Section II) were ill-suited for massive MIMO systems as analog circuit-based designs do not scale well for large numbers of antennas. This challenge gave rise to digital precoding and receive processing-based solutions that are discussed in Section III.

In Section IV, we review the innovations to achieve IBFD in the mmWave spectrum. The last decade also saw a major push to adopt mmWave spectrum into cellular and Wi-Fi standards, especially due to the availability of large unused spectrum, in excess of multiple GHz. Propagation studies demonstrating the practical feasibility of mmWave-based networks [19] were instrumental in catalyzing that move. For practical coverage, the use of large antenna arrays is critical in mmWave bands. However, massive MIMO combined with wide bandwidths poses a major challenge for achieving power-efficient digital-to-analog and analog-to-digital conversions. Thus, all-digital beamforming is not practically feasible in mmWave bands, and hence, hybrid beamformers are the workhorses. Hybrid beamforming further constrains the precoding and combining opportunities available in sub-6-GHz massive MIMO systems, which have much smaller bandwidths. This unique set of challenges spurred a significant body of research in enabling IBFD mmWave networks and is the topic of Section IV.

In Section V, we look ahead into an emerging concept for next-generation networks and the potential role of IBFD in empowering new concepts. As fifth-generation (5G) networks got deployed, the wireless community is actively researching innovative technologies and ideas for the sixth generation (6G). The idea of multifunction networks has emerged, where the networks support

new functions in addition to communications. One of the dominant multifunction modalities is integrated sensing and communications (ISACs), where the electromagnetic transmission/reception also opens the possibility for performing many sensing operations. Other opportunities include joint power transfer and communications and joint jamming and communications. IBFD has emerged as an important foundational technology to enable diverse multifunction possibilities and is the topic of Section V.

Finally, in Section VI, we discuss the adoption of IBFD in communication standards. Specifically, we discuss the progress in cellular standards, fixed access technologies, and TV broadcasting. The most progress has been made in the specification of Data Over Cable Service Interface Specification (DOCSIS 4.0), which will use IBFD to increase rates of both uplink and downlink and reduce asymmetry in access. Similarly, the Advanced Television Systems Committee standard (ATSC 3.0) will use IBFD for single-band broadcasting and backhaul to reduce the cost of backhaul. Recently, 3rd Generation Partnership Project (3GPP) completed the study of subband full-duplex, which may pave the way to commercial deployments of IBFD in 5G-Advanced and 6G. The discussion of multifunction networks for next-generation standards (see Section V) further highlights the importance of IBFD, and there is a growing consensus that IBFD will be an important component technology for next-generation networks.

Finally, considering the significant body of research in IBFD, we recognize that we may not have covered several important subtopics and related citations.

II. CHARACTERISTICS OF SELF-INTERFERENCE

Opportunity: IBFD can increase the spectrum efficiency and reduce the latency.

Challenge: The coupling between the transmit and receive signals of IBFD radio generates a high-powered self-interference at the receiver side.

Solution Approaches: We can use a combination of propagation, analog, and digital self-interference cancellation and address the non-linearities in radios using learning-based methods.

This section begins by outlining the fundamental challenge of self-interference and the self-interference channel statistical characteristic. Then, we explore the three cancellation domains and related tradeoffs. Finally, we introduce the new body of research that proposes learning-based self-interference cancellation to address the nonlinearities in radios.

A. Challenge of Self-Interference

The coupling between the transmit and receive signals of an IBFD radio generates a high-powered self-interference at the receiver side, which shadows the signal

of interest coming from the remote transmitter. As a consequence, the main challenge when implementing an IBFD radio is the self-interference mitigation that is required to reduce the self-interference to the noise floor, with desirable suppression levels typically exceeding 100 dB [20]. If the receiver knew the transmitted signal and its backscattered echoes perfectly, it would be straightforward to subtract the contribution of the transmitted signal from the received signal and cancel the interference. However, the receiver only knows the digital baseband signal completely, and due to the imperfections in the analog radio frequency (RF) chain and the backscattered reflections from the environment (self-interference channel), the receiver does not have the full information about the received signal on carrier frequency.

IBFD in Wireless Transceivers: In conformance tests of wireless transceivers, distortion in the transmitted signal is typically quantified as error vector magnitude (EVM) that sums up the effects of different impairments. The EVM is experimentally measured as the square root of the error power over a reference (ideal) signal power. Specifications define maximum EVM limits for certified devices depending on modulation because higher order modulation requires smaller EVM levels to facilitate successful detection in the receiver. For example, in long-term evolution (LTE), the maximum allowed EVM levels for base station transmitters are 17.5%, 12.5%, 8%, 3.5%, and 2.5% for QPSK, 16 quadrature amplitude modulation (QAM), 64 QAM, 256 QAM, and 1024 QAM symbol constellations, respectively [21], corresponding to -32 to -15 -dB power levels for the distortion of the transmitted signal. Thus, the maximum signal-to-noise ratio (SNR) of the received signal can never exceed 32 dB.

When the transmitter and interferers are located within a comparable distance from the receiver, the EVM levels are tolerable. However, when the interfering signal is much stronger than the signal of interest, as may happen for IBFD transceivers, high EVM can significantly degrade the performance of an IBFD transceiver. For example, user equipment and a base station in LTE typically transmit at 20 and 46 dBm, respectively. Therefore, the 17.5% EVM distortion of the signal that the base station is transmitting is already on the level of the signal that the user equipment is transmitting. Given the path loss, the received signal from the user equipment at the base station is much weaker than the EVM distortion introduced by the base station transmitter making self-interference cancellation mandatory.

B. Statistical Characterization of the Self-Interference Channel

In this section, we discuss the statistical characterization of the self-interference channel. The self-interference channel consists of both direct and multipath paths. As a result, the self-interference channel can be modeled as a multipath channel with an exponential power delay profile

consisting of a quasi-static component due to the antenna configuration in the transceiver and the time-varying part due to reflections and specular components from the physical environment [22], [23].

Although effective, electromagnetic isolation between transmit and receive antenna arrays falls short of mitigating the self-interference below the noise floor. The self-interference channel can be modeled as a multipath channel consisting of a quasi-static component due to the antenna configuration in the transceiver and a time-varying part due to reflections and specular components from the surrounding environment. Therefore, characterization of the self-interference channel is important to effectively suppress the self-interference.

1) *Sub-8-GHz Channels*: We first review measurements and development of site-specific geometry-based stochastic channel models to characterize the self-interference channel. Mean isolation at 2.6 GHz for indoor deployment was investigated in [24], and wideband self-interference channels in the range of 2.45–2.75 GHz were studied in [25].

Duarte et al. [22] characterized the distribution of the self-interference channel before and after active cancellation using extensive measurements in the 2.4-GHz band. Before applying active cancellation the authors noted with high likelihood, there is a strong line-of-sight component, and the magnitude of the self-interference channel can be modeled as a Ricean distribution with a large K -factor. After applying active cancellation, the strong line-of-sight component is reduced; hence, the magnitude of the self-interference channel can be modeled as a Rician distribution with a smaller K -factor. The authors presented a characterization of the K -factor values before and after active cancellation and experimentally characterized the strong correlation in a reduction in K -factor (ranging from 15 to 40 dB) as a function of increased self-interference.

Venkatasubramanian et al. [26] focused on the domains of delay, Doppler, polarization, and spatial and considered characterizing the self-interference channel in terms of the power delay profile, Rician K -factor, power Doppler spectra, and antenna correlation. The power delay profiles measured across the 2.2–2.7-GHz band in an anechoic chamber and terrace of a building presented in [27] indicated that the self-interference channel can be represented as a multipath model with two components, namely, one component due to antenna coupling and another component due to reflections from the environment. The power delay profile of the self-interference channel was experimentally studied in [28] by considering an IBFD orthogonal frequency-division multiplexing (OFDM) system operating on 5-, 10-, and 20-MHz bandwidths. Moreover, the work also statistically modeled the self-interference channel by fitting Rayleigh and Rician probability distributions to the data. In [29], power delay profiles for three scattered bands (2–3, 3–4, and

5.9–6.9 GHz) measured in an indoor office environment were reported. Self-interference channel characteristics of outdoor cross-polar street-level wireless channels over 2.9–4.1- and 5.9–7.1-GHz bands were presented in [30].

In order to model the reflected path self-interference component, in [31], the geometry-based concentric ellipses model and the geometry-based concentric circles model for microcell and macrocell IBFD systems have been developed. The main advantage of such analytical models is their wider applicability in environments beyond measurements.

2) *mmWave Channels*: Measurements of the self-interference channel for the mmWave bands are considered in [32], [33], [34], and [35]. These works reveal the distinctive spatial features of the mmWave self-interference channel. As a result, performance improvements are observed depending on the angular difference of the transmitting and receiving antenna arrays. In [32], a self-interference channel at 27.925-GHz center frequency has been measured using an 18-bit pseudonoise sequence, and the measured channel has been found to have a long propagation delay due to reflections from nearby objects. He et al. [33] presented an indoor measurement study conducted for an IBFD system operating at 60 GHz with a 2-GHz bandwidth. In particular, both the communication and self-interference channels have been measured by varying antenna spacing and polarization configuration. In the measured setup, it has been reported that extending the antenna spacing from 5 to 20 cm results in a self-interference suppression of 27 dB, while, due to polarization, a self-interference isolation of 10 dB can be realized. In [34], measurement results of the self-interference radio channels obtained by means of two 8×8 phased arrays, a 20-dBi horn antenna, and a vector network analyzer operated at 27.5 GHz and over a sweep 2-MHz bandwidth were reported. Askar et al. [34] have also presented results to show the connection between the power delay profile of the self-interference channel and the beamforming directions in azimuth and elevation. The extensive volume of measurements for a 28-GHz self-interference channel reported in [35] reveals the significant dependency of the transmitting and receiving phased array directions and the self-interference.

C. Self-Interference Cancellation Domains

For successful IBFD communications, it is important to suppress self-interference to a level close to the receiver's thermal noise floor. This section outlines the fundamental characteristics of self-interference cancellation. The companion papers in this special issue will provide an overview of self-interference cancellation circuit techniques [36].

Self-interference suppression in IBFD transceivers can leverage three domains of operation [16]; the three domains are given as follows.

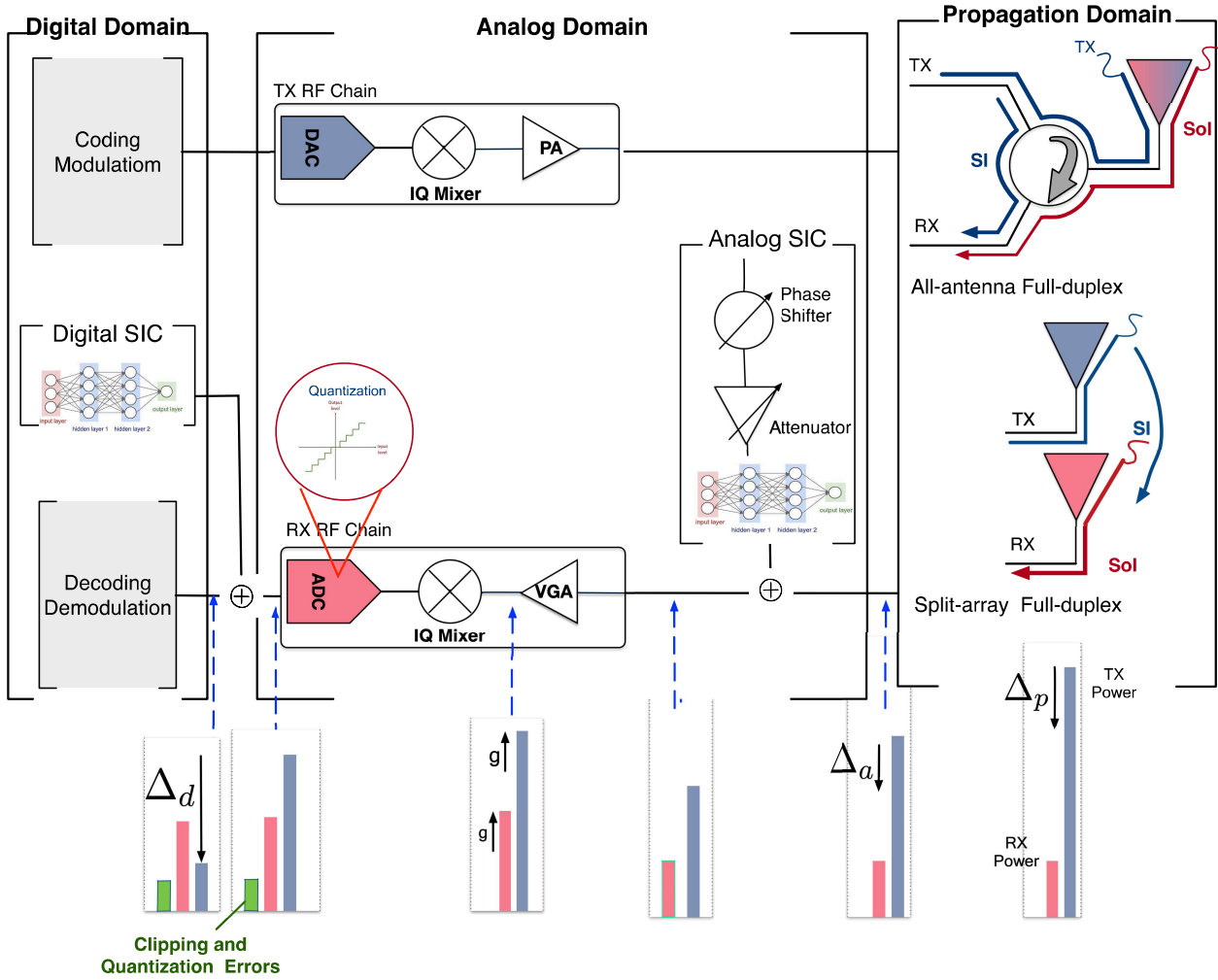


Fig. 1. Self-interference suppression can leverage three domains—propagation, analog, and digital. The figure demonstrates the three domains in which self-interference can be suppressed. Improving IBFD performance will require tradeoffs between transmit power, VGA gain, ADC design, and the mitigation of self-interference in the propagation, analog, and digital domains.

- 1) *Propagation domain* (denoted by Δ_p): The main idea of propagation-domain suppression is to manage the distance between transmit and receive modalities. In *all-antenna* IBFD, each antenna simultaneously transmits and receives. The self-interference in all-antenna systems has two components—antenna's own transmission and transmissions from all other antennas for multiantenna systems [37] [see Fig. 2(a)]. In the case of many-antenna systems, such as massive MIMO and mmWave systems discussed in Sections III and IV, all-antenna can be prohibitive complexity. A simpler architecture, which we label as *split-array*, is often used (see Fig. 1). In split-array systems, a subset of antennas are in transmit mode, while others are in the receive mode, thereby eliminating or reducing both forms of self-interference seen in all-antenna systems.
- 2) *Analog domain* (denoted by Δ_a): Estimate the self-interference, and subtract it from the received signal. Since the receiver *knows* the signal that it is transmitting, it can extract its own message after correcting for the channel effect.

- 3) *Digital domain* (denoted by Δ_d): This is similar to the analog domain but performed on digital signals—after the variable gain amplifier (VGA) and ADC. As the computational power of semiconductors has been growing exponentially as per Moore's law, cancellation in the digital domain is preferred to the analog domain.

When different interference suppression mechanisms are suitably combined, IBFD communication can be successful. Also, advanced nonuniform sampling can be utilized to maximize the dynamic range [38].

D. Cancellation Tradeoffs

Fig. 1 illustrates the fundamental tradeoff between transmit power, mitigation of self-interference in the propagation and analog domains (Δ_p and Δ_a), and mitigation in the digital domain. The self-interference modeling developed in [39] is applicable for more elaborate performance analysis that includes various nonidealities of transceiver chains.

The propagation- and analog-domain techniques are used to reduce the ADC quantization noise that affects

the signal of interest. Indeed, the ADC quantization noise affecting the signal of interest is a function of the difference in dynamic range between the signal of interest and self-interference observed at the input of the ADC. This is because the dynamic range of the total received signal, which is the sum of the signal of interest, self-interference signal, and thermal noise, needs to be matched to the ADC dynamic range to avoid saturating the ADC. Thus, when using an ADC, the more one reduces the self-interference before the ADC (by increasing $\Delta_p + \Delta_a$), the larger the number of bits that are left for quantizing the signal of interest. Note that the digital-domain techniques are useless if the receiver is saturated, i.e., the desired signal is drowned in the self-interference signal, which can be much stronger. In addition, Fig. 1 shows that IBFD systems should always aim at maximizing the ADC range irrespective of Δ_p , Δ_a , and Δ_d .

Note that the quantization incurs two sources of errors.

- 1) Clipping errors are introduced whenever the magnitude of the input signal exceeds the dynamic range of the quantizer.
- 2) Quantization errors appear due to the finite bit resolution.

This leads to a tradeoff in selecting the VGA gain g in Fig. 1 since decreasing the VGA gain reduces quantization errors but increases the probability of clipping, while increasing the VGA gain reduces clipping errors but increases the relative strength of the quantization errors [40]. Properly selecting the gain is, thus, an important factor in designing IBFD receivers.

E. Learning-Based Self-Interference Cancellation Methods

A significant body of research has proposed self-interference cancellation using traditional model-based approaches [15]. First, to achieve high levels of self-interference cancellation, nonlinear effects of the various stages of the IBFD transceiver need to be accurately modeled. In general, such modeling is performed with the help of polynomial models. However, their implementation complexity rapidly grows with the highest considered order of the nonlinearity. Second, the propagation channel is dynamic and time-varying. Thus, it is critical for self-interference cancellation methods to adapt analog cancellation by employing a channel-aware algorithm to dynamically adjust the cancellation parameters, e.g., delay and attenuation of the mirrored self-interference signal before subtracting it from the received signal. Likewise, digital cancellation techniques that are adaptive make use of channel estimation. As a result, such schemes can suffer from the compound effect of modeling inaccuracies and high training overheads in time-varying nonlinear self-interference channels.

As an alternative to traditional schemes, neural networks and machine learning-based techniques have been proposed to perform self-interference cancellation. The

learning-based methods have been shown to achieve similar performance to that of traditional techniques while possessing additional desirable characteristics suitable for real-time implementation.

1) *Deep-Learning for Analog-Domain Self-Interference Cancellation Tuning*: Analog self-interference cancellation gets considerably complicated with wideband signals and consequently with a multipath self-interference channel. Attenuation of the first signal paths is not sufficient due to multipath components caused by a radio propagation environment not known beforehand. Building the cancellation signal in an analog domain requires multipath analog filters that are challenging to implement. Furthermore, even when the transceiver stays in a fixed position, movement in the environment changes the reflected paths making the tracking of the signal paths necessary. Many deep learning-based approaches have been proposed to improve the analog-domain self-interference cancellation adaptability: Chen et al. [41] use one layer rectified linear unit (ReLU) neural network, and Mohammadian et al. [42] jointly estimate the channel, phase noise, and in-phase (I) and quadrature-phase (Q) imbalance in multicarrier MIMO IBFD wireless systems using pilot-aided deep learning-linear minimum mean-square error estimator. Furthermore, deep learning can accelerate IBFD tuning in dynamic interference environments [43], [44], [45].

2) *Nonlinear Residual Self-Interference Modeling*: Digital-domain self-interference cancellation can be accomplished by self-interference regeneration using digital filters. The nonlinear distortion introduced at the transmitter and receiver is a key challenge for this cancellation. The effect of the transmit and receive power amplifier nonlinearities on the digital self-interference cancellation techniques was analyzed in [46], [47], and [48]. It was observed that the phase noise is a bottleneck for perfect self-interference cancellation while using two different oscillators for transmission and reception [49], [50], [51]. A scenario with a common oscillator for both the transmitter and receiver sides was also analyzed in [52].

A power amplifier in the transmitter typically causes the most significant distortion, and to regenerate self-interference, it is necessary to model the distortion. Power amplifiers can be modeled by physical and behavioral models. The latter is computationally less demanding and also less accurate. Memory effects of nonlinear power amplifiers manifest as frequency- or bandwidth-dependent nonlinear responses and have been modeled by behavioral models, such as Volterra series [53], memory polynomial [54], piecewise linear functions [55], and Wiener and Hammerstein models [56]. A comprehensive self-interference model for single-antenna IBFD radios, considering all impairments including the transmitter and receiver I/Q imbalances, nonlinear distortions in all the transceiver components, receiver's noise figure, and the phase noise effect at both the transmitter and receiver I/Q mixers, was provided in [57].

3) *Cancellation via Machine Learning*: Once the behavioral model of the power amplifier has been selected, its parameters are trained using an adaptive algorithm, such as least mean squares, normalized least mean squares, or recursive least-squares algorithm, and the trained model is used to generate and subtract the self-interference signal from the received signal [58], [59], [60], [61]. Recently, neural networks have been applied to model and cancel the self-interference [62], [63], [64], [65], [66]. It has been demonstrated in [62], [66], [67], and [68] that the use of a deep neural network can reduce computational complexity by up to 36% compared to nondeep neural network-based solutions [69]. Most current deep neural network-based methods combine estimation of the typically time-invariant nonlinear distortion and the time-varying self-interference propagation channel, which must be periodically reacquired [70]. 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 self-interference propagation channel from the estimation of the time-invariant nonlinear distortion and utilizing *transfer learning* to combine elements of both offline training and online training while accumulating information across time intervals [71], [72].

4) *Predistortion*: Modeling the impairments distorting the transmitted signal and subtracting the distorted signal from the received signal improve the performance of self-interference cancellation. It decreases self-interference, but it does not improve the quality of the transmitted signal as such. If the characteristics of nonlinear distortion can be extracted in the digital domain, it would be more useful to predistort the transmitted signal to compensate for the distortion. Even when the predistortion does not linearize the power amplifier response perfectly, digital self-interference cancellation would become easier to implement. In addition, predistortion will reduce out-of-band interference and EVM and improve SNR at the destination as well.

III. MASSIVE MIMO IBFD

Opportunity: It is preferable for massive MIMO systems to operate uplink and downlink in the same spectrum, which is a requirement for IBFD.

Challenge: Self-interference cancellation techniques do not efficiently scale to massive MIMO base-stations with a large number of antennas.

Solution Approaches: Large numbers of antennas can be used for beamforming to jointly suppress self-interference while maximizing overall communication performance objectives.

In this section, we will review the opportunities, challenges, and methods for achieving massive MIMO IBFD.

After identifying the opportunity and challenges of achieving massive MIMO IBFD in Section III-A, we spend the rest of this section reviewing the split-array methods that have gained acceptance to achieve practical massive MIMO IBFD. In this section, we will focus on all-digital architectures where the transmit/receive processing is performed in baseband; such architectures are suitable for small bandwidth systems commonly used in sub-6-GHz bands. In contrast, for very large bandwidth systems encountered in mmWave systems, all-digital approaches are not practically feasible and will be discussed in Section IV.

A. Opportunity and Challenge of Massive MIMO IBFD

One of the key 5G technologies is massive MIMO that signifies the use of many antennas, ranging from tens to hundreds, serving a small number of users per time-frequency slot. As proposed in [18], the concept triggered a large body of work in the last decade, leading to its adoption in the 5G standards [73].

The key benefit of massive MIMO comes from closed-loop beamforming, where the base station can direct energy to mobile handsets based on the downlink channel information. However, in frequency-division duplex (FDD) networks, where the uplink and downlink are in different frequency bands, the traditional feedback-based closed-loop beamforming does not scale for massive MIMO [74]. As a result, massive MIMO systems have gravitated toward time-division duplexing (uplink and downlink are in the same frequency band) and leverage channel reciprocity to enable closed-loop beamforming. Fortunately, this opens the door for the use of IBFD for cellular systems employing massive MIMO technologies.

The opportunity for using IBFD is coupled with a new challenge—the IBFD methods designed for nodes with a small number of antennas do not scale well for massive MIMO systems. To appreciate the challenge, consider a multiantenna node with N antennas. Our goal is to achieve simultaneous transmit and receive for *all* antennas, labeled as *all-antenna* IBFD. In this case, the cancellation of self-interference, caused by own transmission and the transmissions from all the other antennas, requires an analog canceller with $O(N^2)$ complexity [see Fig. 2(a)]. However, the real challenge is not simply the size of the canceller, but the fact is that it has to be programmable. Recall that self-interference from other antennas is a combination of the direct path between the antennas and unknown backscatter due to environmental reflections. Thus, for effective self-interference cancellation, the analog canceller mechanism has to be able to adjust the coefficients of the canceller circuit. Thus, the cancellers have to be programmable, which implies that the overall analog canceller complexity makes an analog cancellation-based solution very challenging.

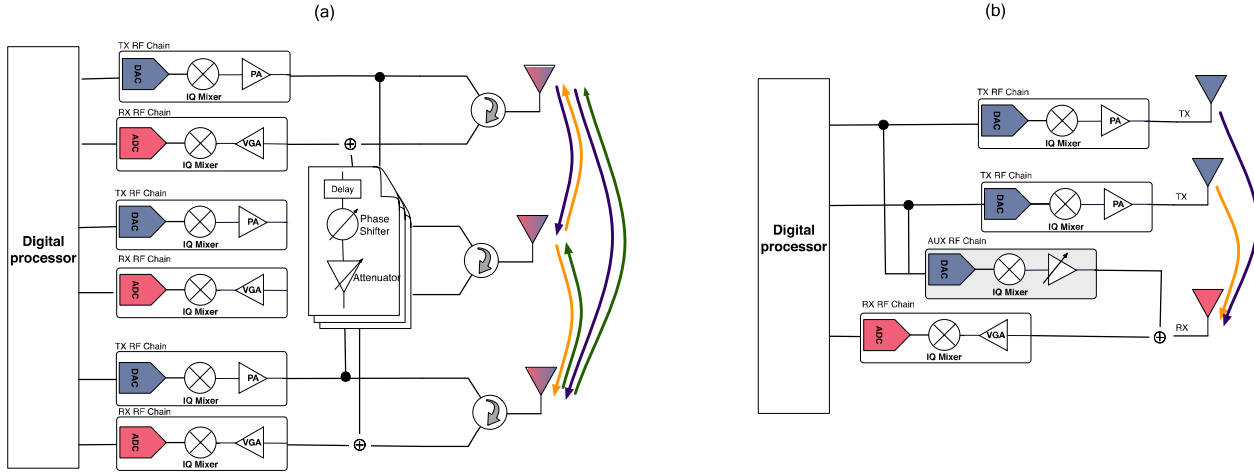


Fig. 2. All-antenna versus split-array architectures span different points in complexity-performance design space. (a) All-antenna IBFD architecture: an analog cancellation path is required for each TX-RX pair. With N -antenna, it leads to $O(N^2)$ analog canceller complexity [37]. (b) Split-array IBFD architecture: it uses an auxiliary transmit chain to cancel self-interference in the analog domain [75]. In split-array architectures, antennas are assigned fixed roles—they either transmit or receive. The transmit/receive roles can be fixed or adaptively assigned based on the needs of the system.

As a result, analog cancellation-based multiantenna designs have been limited to few-antenna systems, e.g., two-antenna [37], [76].

B. Split-Array IBFD

1) *Fixed Split-Array Architectures*: The complexity of analog cancellation with increasing numbers of antennas has prompted the search for alternate architectures. Early on, the research community started to explore *split-array* architectures. In a split-array architecture, each antenna is assigned a fixed role of a transmitter or a receiver. That is out of a total of N antennas, N_T 's are transmitters, and other N_R 's are receivers.

The split-array architecture has a clear capacity disadvantage—the resulting system will have lower capacity compared to *all-antenna* IBFD systems shown in Fig. 2. In all-antenna array systems, all N spatial degrees of freedom are available for transmission *and* reception. In split-array architectures, both transmission ($N_T < N$) and reception ($N_R < N$) modes have fewer degrees of freedom and, hence, lower resulting capacity.

Overall, split-array architectures seem like a regressive idea. The whole point of IBFD communication was to use antennas to simultaneously transmit *and* receive. However, in the split-array architectures shown in Figs. 2–4, we are doing exactly the opposite and devoting some antennas to transmit and others to receive function.

The capacity loss comes with the advantage that the resulting system has lower analog circuit complexity than the half-duplex array since it is built using those radios. As a concrete example, consider the architecture proposed in [75], where the authors proposed and experimentally demonstrated a system with two transmit antennas and

one receive antenna [see Fig. 2(b)]. The key feature of the architecture is that it uses an *auxiliary transmit chain* to cancel the sum of self-interference from multiple antennas at the receive antenna. The system in [75] used three forms of self-interference suppression: 1) path loss from the antenna placement, e.g., on a mobile device to increase path loss between transmit and receive pairs; 2) a dedicated auxiliary transmit chain for canceling self-interference at the receive antenna; and 3) digital cancellation in the baseband for additional suppression of residual self-interference [see Fig. 2(b)].

For both analog and digital cancellation, the knowledge of the self-interference channel is essential. The method proposed in [75] utilized the existing packet structure in wireless networks, where the packet header consists of orthogonal training. Using the existing pilots, the receive chain can estimate the instantaneous self-interference channel between all transmit–receive pairs. The experimental evaluations demonstrated a median interference reduction of 85 dB, with a minimum of 70 dB and a maximum of 100 dB.

The architecture in Fig. 2(b) generalizes to $(N_T, 1)$ antenna system with N_T transmit antennas and one receive antenna without any change. Since there is only one receive antenna, a single cancellation circuit suffices to cancel interference.

The above split-array architecture has been generalized for the universal case of multiple transmit *and* multiple receive antennas in [77] shown in Fig. 3. The key innovation is the use of multiplexers (MUXs) and demultiplexers (DEMUXs) for signal routing to reduce the complexity of analog self-interference cancellation. As shown in Fig. 3, the input of each analog canceller tap is connected to a corresponding N_k -to-1 MUX, which allows routing of any

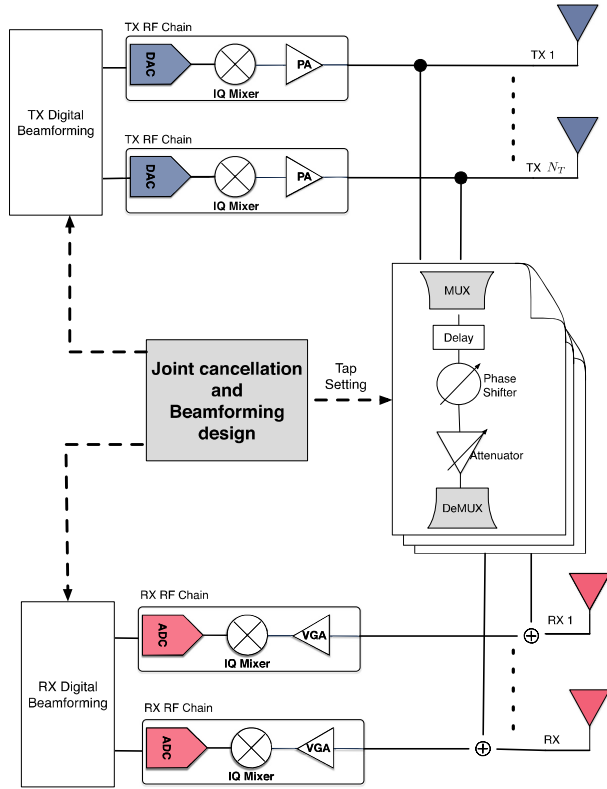


Fig. 3. Generalized split-array architecture. In [77], a generalization of the split array architecture was proposed. The analog canceller consists of N taps that are connected via MUXs/DEMUXs to the outputs of the transmit RF chains and the inputs of the receive RF chains. The figure also depicts the processing blocks dedicated to transmit digital beamforming and receiver digital beamforming and to the design of the joint analog cancellation and digital beamforming.

of the N_k transmit RF chain signals to the input of the tap. The connection from each transmit RF chain to each MUX input can be done via power dividers or directional couplers [78], [79]. After processing, the output of each tap is connected to a 1-to- M_k DEMUX, which routes the canceling signal at the output of the tap to one of the adders located just before the receive RF chains. The architecture was later improved in [80] to further reduce the analog complexity of the routing circuit such that the complexity of the resulting architecture does not increase with the number of receive chains.

The impact of hardware impairments and constraints has been studied in [81], [82], and [83]. Fukui et al. [82] designed an auxiliary-transmitter-based self-interference cancellation method that is effective in the presence of I/Q imbalance and nonlinear distortion. The proposed method first estimates the local transceiver channel to create a signal for self-interference cancellation. The authors also calculate the theoretical self-interference cancellation limit of the proposed approach. Their results demonstrate that a general adaptive algorithm is essential to obtain performance gains over prior approaches. They also demonstrate

that the self-interference cancellation limit is improved by adjusting the propagation delay of the self-interference signal and the canceling signal in addition to sharing one local oscillator in the local transceiver.

While the split-array architecture reduces the analog circuit complexity, the decision about the number of transmit and receive antennas has to be made at design time—this can reduce the utility of the resulting design for the following reasons. Since the uplink/downlink data traffic is time-varying, it is important to have the flexibility to adapt the number of antennas dedicated to transmit and receive modes over time.

2) *Adaptive Split-Array Architectures:* To ensure flexibility in the number of antennas assigned to uplink or downlink at any given time, *adaptive split-array* architectures have been studied, which adaptively assign transmit and receive roles to the antennas. Overall, these architectures show promise in many practical regimes of operation and, hence, have been considered for adoption in actual products.

Everett et al. [84] considered the case of a traditional base station with N half-duplex transceivers. At any time, $0 \leq N_T \leq N$ antennas can be in the transmit mode, and the remaining antennas $N_R = N - N_T$ can be in the receive mode (see Fig. 4). More generally, some antennas can also be turned off, but, often, switching off antennas provides no benefit to the overall capacity objective. The assignment of antenna roles is labeled a *configuration* in [84]. An example configuration is shown in Fig. 4, where the antennas are divided into two subarrays; the figure also depicts self-interference, uplink and downlink channels, and potentially interference between mobile handsets. The architecture in [84] relies only on transmit beamforming to reduce self-interference and, in the process, completely eliminates the need for analog cancelers. The same concept was earlier formulated in [85] among other variations of

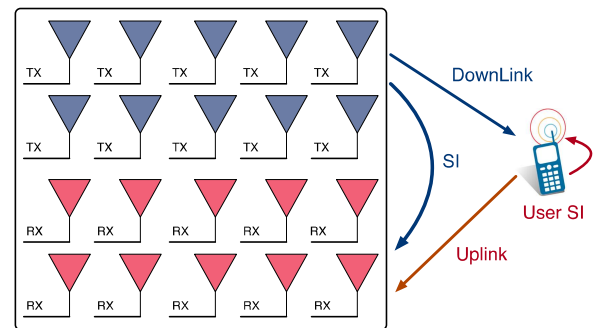


Fig. 4. Flexible split-array operation can be achieved by adaptively assigning transceivers either transmit or receive roles. An example division of transmit and receive roles for each antenna in a large array, borrowed from [84]. Any antenna can be adaptively assigned to transmit or receive based on the system's uplink and downlink data needs. The antennas can be colocated, e.g., in a single base station, or distributed, e.g., across multiple base stations connected with a fiber backhaul.

spatial-domain suppression in the context of MIMO relaying and also simultaneously proposed by Doane et al. [86]. In [84], the “null-space projection” approach of Riihonen et al. [85] was branded as *SoftNull*, in which the architecture uses beamforming to reduce self-interference by sacrificing some transmit degrees of freedom.

Everett et al. [84] experimentally evaluated the *SoftNull* system using a 72-element array. For the split with 36-antenna transmit and 36-antenna receive, 50 dB of self-interference cancellation could be achieved using only precoding by sacrificing 12 out of 36 transmit degrees of freedom for outdoor low scattering cases. For the same 50-dB gain, 20 transmit antennas had to be devoted to self-interference suppression in indoor environments that tend to have a higher number of backscattered paths. As a result of sacrificing the transmit degree of freedom for self-interference cancellation, IBFD rate gains over half-duplex are no longer available in all cases. For example, in low-SNR outdoor cases or high-scattering indoor environments, *SoftNull* rate gains over TDD are either very low or unavailable [84].

For simplicity, the *SoftNull* design decoupled self-interference cancellation optimization from downlink beamforming. Gowda and Sabharwal [87] considered the joint design of downlink beamforming and self-interference. Being labeled *JointNull*, the authors demonstrated that the joint design provided up to 15 dB of *extra* self-interference suppression compared to *SoftNull*. Gowda and Sabharwal [87] also studied the design of different configurations, i.e., which antenna should be assigned to transmit or receive mode. While the problem of finding the optimal configuration is exponential in complexity, the authors provided a physics-inspired reduction in search complexity resulting in an intuitive result. That is, good configurations are such that they minimize the “length of the boundary” separating the transmit and receive subarrays, which, in turn, minimizes the overall self-interference. Rajamäki and Wichman [88] explored sparse antenna array geometries in terms of self-interference and beamforming capability. da Silva et al. [89] pose configuration design as a binary nonlinear optimization problem to minimize the sum mean square error of the received data symbols. The authors propose equivalent formulations using iterative convex approximations and a binary relaxation. The proposed algorithm is guaranteed to converge to a stationary solution of the relaxed problem with much smaller complexity than an exhaustive search of the original combinatorial problem.

Similar to *SoftNull*, Doane et al. [86] utilized adaptive transmit beamforming to reduce the self-interference below the acceptable levels of the receive elements in the array. This approach also combined adaptive receive beamforming and observation-based digital cancellation to further suppress the self-interference to the receiver noise floor. The combination of these three techniques was demonstrated using an eight-element linear array with

four elements dedicated to transmitting and the other four elements to receiving. The prototype system measured 140.5 dB of total isolation over a 100-MHz bandwidth centered at 2.45 GHz [90]. With this three-step cancellation concept verified, focus has shifted to a fully digital 8×8 array panel design that can be scaled to arbitrarily large dimensions [91], [92], [93] with complexity reduction and distributed processing being considered [94].

3) *Precoder Design and Optimization*: The key ingredient in the split-array architectures, adaptive or otherwise, is the precoder design to optimize the overall system performance. The precoder design has to balance between self-interference suppression that impacts uplink capacity and the transmit beamforming that impacts downlink capacity.

Riihonen et al. [85] developed precoding and beamforming techniques for different numbers of data streams with respect to the total number of antennas. Huang et al. [95] analyzed the performance of transmit beamforming for both optimized precoding and self-interference cancellation in IBFD MIMO transceivers. Instead of directly optimizing for the capacity, the authors use precoding error with reference to a desired precoding matrix designed without self-interference and use the precoding error as an indicator of communication performance. The proposed approach allows both analysis and systematic design of precoders to achieve different tradeoff points. In [96], a multipair massive MIMO relay channel was assumed, where the application of zero-forcing and maximum-ratio combining/maximum-ratio transmission for the processing of signals was considered. In order to reduce the self-interference effect, the authors proposed two techniques: 1) using a receive antenna array with a large number of antennas or 2) using a transmit array with a large number of antennas and low power. Moreover, an optimal power allocation scheme to maximize energy efficiency was also presented.

The split-array architecture has been studied extensively. Le et al. [97] propose a beam-based adaptive filter structure with analog least mean square loops to significantly reduce the complexity of self-interference cancellation in MIMO systems. Cummings et al. [98] extend the approach proposed in [79] to account for a fixed dynamic range of the transmit and receive channels. Chen et al. [99] proposed the use of lenses to improve the directivity of the array elements to reduce self-interference and demonstrate that low-cost lenses can further improve the performance of precoding-based methods.

Aryafar and Keshavarz-Haddad [100] proposed and implemented a hybrid IBFD design for hybrid beamforming systems with phased-array antennas called *PAFD*. *PAFD* employs separate transmit and receive antenna arrays for transmit or/and receive analog beamforming to maximize the main beam gains in the desired directions *and* also to reduce the self-interference. Experimental results provided in [100] demonstrate that, by sacrificing a small gain in

beamforming gain, PAFD is capable of achieving significant self-interference reduction gains. Specifically, with a linear antenna array, the self-interference can be reduced by more than 35 dB in indoor non-line-of-sight environments and by 40 dB in outdoor environments.

We close this section with a brief note on the use of IBFD in different network topologies. Infrastructure-based and ad hoc networks have inspired the use of IBFD terminals for: 1) two-way bidirectional; 2) base station; and 3) relay topologies. In a two-way bidirectional case, two terminals use IBFD for data flow in both directions. In the case of base station topology, the base station can engage in bidirectional communications and/or support simultaneous uplink/downlink with half-duplex nodes, that is, IBFD at the base station is useful even for the case of half-duplex mobile nodes. Finally, in the relay topology, an IBFD relay can simultaneously receive and transmit data from a source and relay it to a destination. For each topology, the IBFD operation can be enabled using any of the methods discussed above or in the next sections, depending on the frequency band of operation.

IV. mmWave IBFD DESIGNS

Opportunity: mmWave band enables large bandwidths to increase peak data rates.

Challenge: Hybrid analog-digital radio architectures are often used in mmWave systems, which are limited in the design space of IBFD mmWave systems.

Solution Approaches: Constrained precoding strategies combined with innovative radio architectures can enable mmWave IBFD.

In this section, we summarize the core ideas of methods to achieve IBFD in mmWave bands. In Section IV-A, we summarize the main challenges of developing IBFD in mmWave bands. In Section IV-B, we briefly summarize the commonly used radio architectures for mmWave half-duplex communications. In Section IV-C, we outline the key ideas to enable mmWave IBFD using the constrained hardware. Finally, in Section IV-D, we summarize the emerging directions in the development of new radio architectures that aim to combine the best of many worlds.

A. Challenges of mmWave IBFD

Concurrent with the massive MIMO development, another important trend has taken hold in the last decade. To address the challenge of limited available spectrum in the sub-6-GHz bands, there has been a move to higher bands, especially the mmWave spectrum [19]; the addition of mmWave bands is for traditional half-duplex systems to gain more spectrum for higher data rates. In mmWave bands, there is a large available spectrum, thereby opening the doors to achieving high data rates. However, several portions of mmWave bands suffer substantial attenuation

over a distance beyond the natural Friis' free space loss [101]. Thus, it is now a common practice to leverage beamforming gain from large antenna arrays, with up to 256 antenna elements, to counter the high pathloss in mmWave bands. Fortunately, due to the small wavelength of mmWave bands, it is easier to pack a large number of antennas in a small footprint.

However, while a large number of antennas solve one problem, they create a new one in the process. The combination of large numbers of antennas and large bandwidths means that processing all signals in the digital domain requires a large number of power-hungry analog-to-digital converters (ADCs) and digital-to-analog converters (DACs). Unfortunately, the required energy budget turns out to be impractical for most wireless systems. To address the power challenge, hybrid radio architectures that split processing of the signals in the digital and analog domains have become the workhorse of mmWave radio systems (see Section IV-B for a quick primer on mmWave beamforming architectures).

Since mmWave systems *have* to use large arrays, all-antenna all-digital IBFD systems are impractical for most applications. Thus, any practical mmWave IBFD has to combine limited degrees of design freedom of hybrid radio architectures with innovative methods to maximize data rates while managing SI. In this section, we address the key ideas in the literature that have addressed the mmWave IBFD design challenge.

B. Basics of Hybrid Beamforming

In this section, we briefly review the basics of hybrid beamforming architectures for half-duplex systems. The goal of beamforming is to achieve directional transmission and reception using multiple antennas. The beamforming control of amplitude and phase coefficients for each antenna aims to form beams to maximize receive SNR at specific points. In Section IV, we will leverage the background presented in this section to discuss the methods for mmWave IBFD.

1) *Digital Beamforming:* In digital beamforming architecture, an architecture implicitly assumed in Section III, each of N antennas is connected to the baseband via a dedicated ADC and a DAC. A dedicated DAC per antenna allows individual control of the amplitude and phase of each antenna for transmit beamforming. Similarly, a dedicated ADC per antenna allows full control for receive beamforming. However, N DACs and N ADCs come at significant power costs, especially for large bandwidths like those available in mmWave bands. Consequently, digital beamforming is used in lower frequency ranges (e.g., sub-6 GHz), which also tend to be small bandwidths (≤ 100 MHz) and not practical for mmWave systems that can have bandwidths in excess of 1 GHz.

2) *Analog Beamforming:* On the other end of the design is analog beamforming where beamforming-related

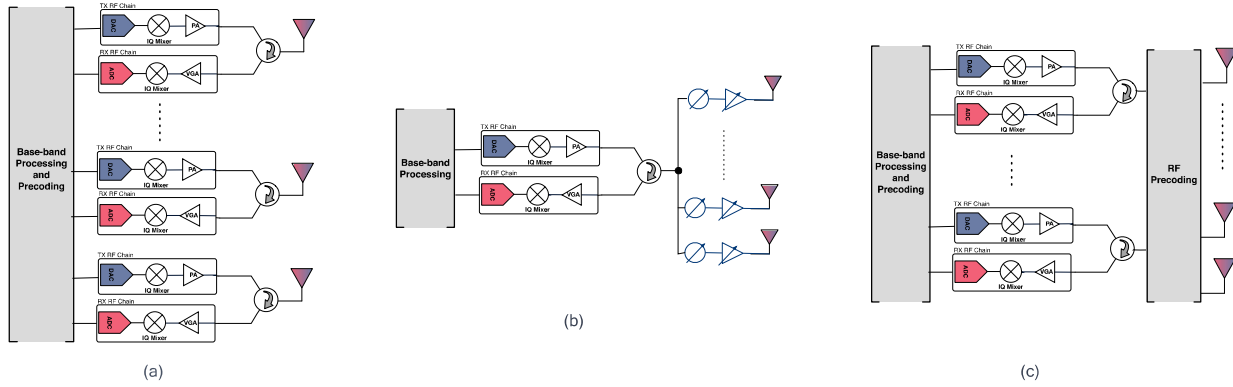


Fig. 5. Simplified view of three common classes radio architectures for beamforming. (a) Digital beamforming converts all radio signals into the digital domain and processes them in digital baseband (N TX RF chains and N RX RF chain N —very flexible beam patterns at large power cost). (b) Analog beamforming relies on beamforming in the analog domain, often using phase shifters; since all antennas transmit with the same amplitude, analog beamforming is limited in its capabilities compared to digital beamforming (one TX RF chain and one RX RF chain—power efficient but less diverse beam patterns). (c) Hybrid beamforming combines the digital and analog beamforming by performing a smaller than full dimension processing in digital and remaining in the analog domain; the architecture can be adapted to tune performance versus power consumption (number of TX and RX RF chains less than N —tradeoffs between flexibility of beam patterns and power cost).

processing occurs in the analog domain. See a simplified example in Fig. 5(b), with only one ADC/DAC pair connected to an analog phase-shifting circuit. Each antenna may also have the ability to perform individual phases and gain control. The phase-shifting and gain control circuits often operate in quantized steps. In the most constrained versions of analog beamforming, there may be no gain control, and a single phase shifter is used to control all antennas. Since analog beamforming often only uses one ADC and one DAC, the overall architecture is much more power efficient compared to the digital beamforming architecture. However, the power efficiency comes at the cost of losing flexibility in beam patterns that can be generated with analog beamformers.

3) *Hybrid Beamforming*: Hybrid beamforming spans the design space between the analog and digital beamforming architectures. Fig. 5(c) shows that a two-stage architecture part of the precoding (transmit) or combining (receive) is done in the digital domain and the rest in the analog domain. The number of RF chains and associated ADCs/DACs can be varied based on the power budget and desired flexibility in forming beam patterns. The architecture allows support for multiple streams, depending on the number of RF chains, thereby offering a method to span the complexity–capability tradeoff curve.

Note that many variations have been proposed to realize analog and hybrid beamforming, and by itself this topic is a rich area of research [102], [103].

Also, note that the transmitter and receiver architectures can have the same or different architecture in mmWave systems. For example, base stations often have a higher power budget and, hence, tend to have multiple ADCs/DACs, which provide greater flexibility in beamforming and the ability to serve more users simultaneously. In contrast, mobile devices will have a fewer (maybe only

one) ADC/DAC chain and often can only select one out of a finite number of predetermined beams.

The constraints in beamforming/beamsteering give rise to the problem of *beam alignment* where the objective is to find the transmit–receive beam pairs such that the link SNR is maximized, with problem-dependent constraints such as minimizing interference.

In the following sections, we discuss two different classes of mmWave IBFD systems: reusing existing half-duplex designs (see Section IV-C) and novel radio architectures (see Section IV-D).

C. Leveraging Half-Duplex Designs of Full-Duplex IBFD

In this section, we review the key ideas from an extensive body of work [104], [105], [106], [107], [108], [109], [110], [111], [112], [113], [114] toward achieving mmWave full-duplex communications using half-duplex hybrid beamforming. For the same reasons as discussed in Section III, split-array IBFD is more practical for mmWave systems as all practical systems use a large number of antennas. While many prior works do not explicitly specify their mode of operation, i.e., all-antenna or split-array full-duplex, we assume a split-array architecture in the subsequent discussion and recall in the split-array architecture; some antennas are in the transmit-only mode, while others are in the receive-only mode.

1) *Core Challenge*: In nearly all practical half-duplex mmWave systems (half-duplex or IBFD), both transmitter and receiver use multiple antennas to perform beamforming using variants of hybrid architectures. As a result, it is important that the transmitter and receiver align their beams to optimize end-to-end SNR to maximize achievable spectral efficiency. In a full-duplex mmWave system, there is an additional goal to reduce self-interference. While one could use the precoding ideas from Section III to manage

both objectives, the challenge in mmWave IBFD design is the reduced degrees of freedom due to hybrid beamforming architectures, as discussed in the previous section. Thus, the core challenge is that there is *less flexibility in hybrid architectures* to manage the downlink.

2) *Reusing Half-Duplex Designs Without Change*: Several research works have explored reusing existing half-duplex mmWave design components to enable IBFD. Often, a joint sum-rate objective, which is the sum of uplink and downlink rates, is chosen as the optimization criterion, e.g., [106], [109], [110], [115], and [116].

The resulting optimization problem is invariably nonconvex with uplink and downlink rates intricately coupled due to self-interference. Problem complexity is also determined by the assumed flexibility in the design of hybrid systems. For example, the phase shifters in analog beamforming could be assumed to be continuously variable (akin to high-resolution phase shifters) or quantized with very few bits of control. For the cases where some of the variables can take a finite number of values, the resulting problems often have a hybrid of continuous and discrete variables, converting them into even more challenging discrete nonconvex optimization problems. We highlight some of the proposed approaches for efficiently solving the resulting nonconvex problem.

Wei et al. [115] propose to convert the optimization problem to an equivalent weighted sum minimum mean square error problem for mathematical tractability and propose a low-complexity noniterative hybrid beamforming algorithm. The work in [117] has considered a mmWave multiuser cellular system where an IBFD MIMO base station transmits and receives from half-duplex downlink and uplink users simultaneously to jointly design the analog and digital transmit/receive beamformers based on two approaches, namely, the orthogonal matching pursuit algorithm and block diagonalization for sum-rate maximization. In [118], a novel hybrid beamforming design to maximize the weighted sum rate in a single-cell mmWave IBFD system in the presence of limited dynamic range noise due to nonideal hardware has been presented. According to the simulations in [118], the new design with only a few RF chains and at any noise level is capable of outperforming a fully digital half-duplex implementation.

A machine learning-based approach is proposed in [95] to contend with the nonconvexity of the objective function. In addition, the authors note that the performance of the optimization algorithms can be sensitive to the quality of the channel state information. Two learning-based methods were proposed to design hybrid beamforming methods for IBFD mmWave systems, i.e., extreme learning machine-based hybrid beamforming and convolutional neural network-based hybrid beamforming. To train the learning networks, simulated noisy channels are used as inputs, and select the hybrid beamformers calculated by the proposed algorithms as targets. Results demonstrate that learning-based schemes can be more robust and

improve spectral efficiency compared to competing methods in many cases.

3) *IBFD Beamforming Codebooks*: A bottleneck in the performance of methods that reuse half-duplex designs is that they are limited by the self-interference performance of existing half-duplex codebook designs. To address this shortcoming, several works have proposed designing beamforming codebooks to simultaneously maximize downlink spectral efficiency while reducing self-interference.

Satyanarayana et al. [119] propose an approach to designing mmWave IBFD hybrid beamformers. First, a fully digital solution with perfect channel state information is obtained. Then, the hybrid beamforming-based solution is obtained from the all-digital solution using a least-squares approximation. The key motivation of the proposed solution is to preserve the signal's dimensionality while mitigating self-interference and respecting the practical constraints.

The approach proposed in [111] leverages the slow time-varying nature of the angle of departure/angle of arrival. The transmit/receive RF beamformers were designed based on slowly time-varying angle-of-departure/angle-of-arrival information. This article also proposed a transfer block architecture to further reduce the required number of RF chains and power consumption without penalizing the rate.

A pruning-based approach is proposed in [120], where the system dynamically reduces the RF beam codebook, so that it is comprised of the RF beams that will prevent the receive chain from saturating due to the self-interference. The aim is to reduce the required number of beam measurements by eliminating those beams that have high self-interference. The advantages of this approach are obvious. It is important that practical systems might toggle between half-duplex and IBFD modes, e.g., depending on traffic needs. Thus, any beam codebook reduction method has to be adaptive such that the beam codebook is best suited for the current mode of the network operation.

4) *Experimental Results*: Complementing the algorithmic innovations, experimental results from multiple papers have solidified the real potential of mmWave IBFD. Roberts et al. [114] used a practical method to balance the goals of beam-alignment and self-interference management and demonstrated improved performance in self-interference reduction and downlink SNR compared to conventional methods. The design in [121] is a software-defined radio-based bidirectional 28-GHz IBFD link capable of achieving a total self-interference cancellation of 84 dB and a throughput gain of 1.7 in comparison to half-duplex operation. In another work conducted at 28 GHz, measurements of the self-interference channel show that more isolation can be achieved when the transmitter and receiver are steered away from each other, while no transmit or receive beams guarantee significant levels of isolation [122]. The IBFD transceiver design and 60-GHz

over-the-air experiments presented in [123] demonstrate the impact of factors such as transmit–receive antennas with varying separation, polarization, and beam steering with different angles’ influence on self-interference. Moreover, a two-step nonlinear self-interference cancellation scheme in case of insufficient self-interference isolation is also proposed.

D. Redesigned Full-Duplex Radio Architectures

In this section, we outline some of the innovative mmWave designs that have additional hardware to simplify the algorithmic problem, reduce costs, and/or improve self-interference suppression. We start with the simplest of the optimization—optimizing the design parameters of conventional hybrid beamforming to reduce self-interference while managing analog complexity. We then discuss novel designs that add new hardware with the goal of improving the resulting IBFD system performance while simultaneously managing the mmWave band design challenges.

1) *Low-Resolution Phase Shifters*: Motivated by the practical requirement of using low-resolution quantization for the phases in the phase shifter, Da Silva et al. [110] study the efficacy of IBFD mmWave communication with hybrid beamforming using low-resolution phase shifters. A new algorithm called LowRes is proposed to achieve near-optimal performance. The key result is that, even with only one-bit phase shifters, the resulting system can outperform half-duplex systems for a wide swath of practical design parameter space.

2) *Single RF Chain*: In [112], a single-stream point-to-point bidirectional IBFD link at mmWave bands is implemented to address the lack of amplitude control and finite resolution of phase shifters used in analog beamforming architectures. As a result, the design only employs a single RF chain in forward and reverse directions at each node. Simulation results reported in [112] confirm the effectiveness of their design against previous methods for phase shifter resolution values of few bits. Prior to that, Xiao et al. [104] present a design of mmWave IBFD that adopts an analog beamforming/combining structure to manage hardware complexity and circulators to enable IBFD mode. Hence, a configuration with separate transmit/receive arrays and a configuration with shared transmit/receive arrays are proposed, and they both use a single transmit RF and receive RF chain, respectively. It has been shown that the former array is flexible in self-interference cancellation, however, at the expense of some cost and area of the IBFD device.

3) *Joint Cancellation and Beamforming Design*: We next describe a *unified* hybrid IBFD massive MIMO architecture, which can be jointly optimized for various performance objectives and complexity requirements; it puts the complexity where it is needed across various domains: analog and digital transmit and receive beamforming and

analog and digital self-interference cancellations [124], [125]. The unified IBFD MIMO transceiver architecture of Fig. 6 includes N transmit and M receive antennas. All transmit antenna elements are attached to $N_T \leq N$ transmit RF chains; similarly, the receive antenna elements whose outputs are connected to $M_R \leq M$ receive RF chains. Similar to hybrid beamforming, distinct subsets of antennas are connected to different RF chains, via phase shifters. According to this architecture, each subarray is capable of realizing a predefined codebook of distinct analog beams. In the recent architecture of Roberts et al. [126] and Islam et al. [127], the analog self-interference canceller connects all outputs of the transmit RF chains with all inputs to the receive RF chains, which results in $N_T M_R$ attenuation lines. The unified IBFD MIMO architecture in Fig. 6 has even lower complexity analog self-interference cancellation. Only $K \leq N_T M_R$ self-interference attenuation lines appear in the analog canceller, which also includes two selection networks. The role of these networks is to decide which self-interference signals will be mitigated from which inputs to the receive RF chains. Each receive RF chain is characterized by a maximum input signal power level, above which saturation happens. This means that, when the self-interference signal is larger than the chain’s maximum allowable power level, this receive RF chain gets saturated. The role of the analog self-interference canceller is to suppress the self-interference signal power level below the latter threshold in order to avoid saturation. The unified IBFD MIMO architecture includes a module for jointly designing the parameters of the analog/digital self-interference canceller and analog/digital transmit/receive beamforming according to any desired communication objectives. The unified scheme deploys a novel analog canceller with $K \leq N_T M_R$ taps (i.e., its complexity does not scale with the number of transmit/receive antennas; hence, it is suitable for massive MIMO), which is jointly designed with the analog/digital transmit/receive beamformers.

V. MULTIFUNCTION RADIO SYSTEMS

Opportunity: Electromagnetic transmission and reception capabilities can be used for communications *and* for diverse novel radio applications – joint operation can efficiently utilize shared frequency bands, hardware, and waveforms.

Challenge: Naive time-division is often resource-inefficient; however limited foundational understanding on the principles of joint design and the resulting tradeoffs.

Solution Approaches: As a very active research area, progress is being made in both clean-slate redesigns, and repurposing existing designs to support multifunction operation.

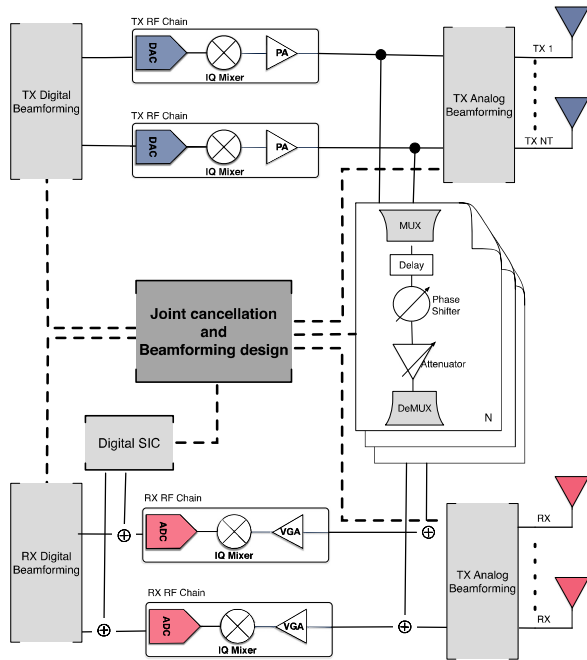


Fig. 6. Unified IBFD MIMO transceiver [124]. This hybrid-radio architecture puts the complexity where it is needed across various domains: analog and digital transmit and receive beamforming, and analog and digital self-interference cancellations.

In this section, we will overview how the historical manifestation of IBFD operation in radars (mentioned in the introduction) has first led to dual-function ISAC concepts and how the IBFD capability is then in the current world-leading research harnessed in the evolution of many other new multifunction concepts that the next-generation wireless networks could potentially support, as seen in Fig. 7. Thus, we discuss the emerging physical-layer functions of various forms of sensing and wireless power transfer, where the use of IBFD can facilitate the seamless integration of the transmit- and receive-side functions by relaxing the resource-sharing requirements.

A. Emergence of Other Functions and Necessity of IBFD in Multifunction Operation

Many wireless modalities use electromagnetic signals for sensing, e.g., all forms of radar, LiDAR, and all classes of light-based imaging. The last decade has witnessed a sharp rise of research in what is sometimes labeled as *wireless sensing*. Wireless sensing often uses spectral bands that are used for communications and often aims to repurpose communications transmissions/receptions and hardware. Examples include Wi-Fi imaging [128], [129], [130], [131], [132], [133], [134], [135], [136], [137], tomographic imaging [138], [139], gesture estimation [140], [141], [142], [143], [144], [145], heart rate estimation [146], [147], and respiratory rate estimation [148], [149], [150]. Examples of receive-side sensing include spectrum vacancy detection for cognitive radios and

legitimate spectrum surveillance for physical-layer security and radio signals' intelligence for electronic warfare.

Especially, given the foregoing history of IBFD radars, it is not surprising that radar-like sensing as an *additional* function in next-generation networks has now taken a strong hold in nearly all discussions on next-generation networks [151], [152], [153], [154], [155]. Labeled as ISAC, the new paradigm can simultaneously support both radar-based sensing and wireless communications applications in the same network, offering unique benefits. First, wireless networks are deployed for coverage. As a result, there is an opportunity to have a sensing layer with the same level of large-scale coverage, with potentially an incremental cost to an existing network. Second, wireless networks use diverse spectrum bands, ranging from sub-6 GHz to mmWave with the potential of using sub-THz and higher bands in next-generation networks. Such wide and diverse spectrum access packed into millions of wireless devices can open up the possibility of unique wide-area hyperspectral sensing applications.

Historically, the coexistence of radar and communications treated the other system as an interference source and designers worked to improve the tolerance of the other. In order to highlight the joint design of these systems, it is helpful to understand the basics of both radar and communications architectures.

1) *Basics of Radar Architectures*: A radar is a device that transmits a signal and, based on the received reflections, estimates the presence and speed of the target using the delay and Doppler frequency estimates. Radars can be categorized by their transmission type as either pulsed or continuous, as indicated in Fig. 8. As shown in Fig. 8, pulsed radars transmit for a short time (10% duty cycle is common) and then turn off the transmitter so that they can listen for returns. The pulsed transmit–receive process is repeated and often allows for higher transmit output powers and correspondingly long-range capabilities. The pulse radar is a time-division duplexed system, and hence, the self-interference is eliminated by turning off the receiver when transmitting. Pulsed radars are not useful for short-to medium-range systems, such as those envisioned in ISAC, and hence, we will not discuss them further.

In contrast to pulsed radars, continuous-wave radars simultaneously transmit and receive. A common method is to sweep the frequency of the transmitted signal waveform (i.e., increase and/or decrease) using a linear frequency-modulated (LFM) chirp. Fig. 8 highlights the fact that this architecture mixes the transmit output with the received signals, which effectively converts the radar returns to lower frequencies. Since the transmitter is active during reception, self-interference is a key concern for continuous-wave radars. Fortunately, the frequency conversion process allows for straightforward analog self-interference cancellation through the inclusion of a high-pass or bandpass filter at the mixer output instead of active adaptive RF filters that are typical for IBFD communications systems.

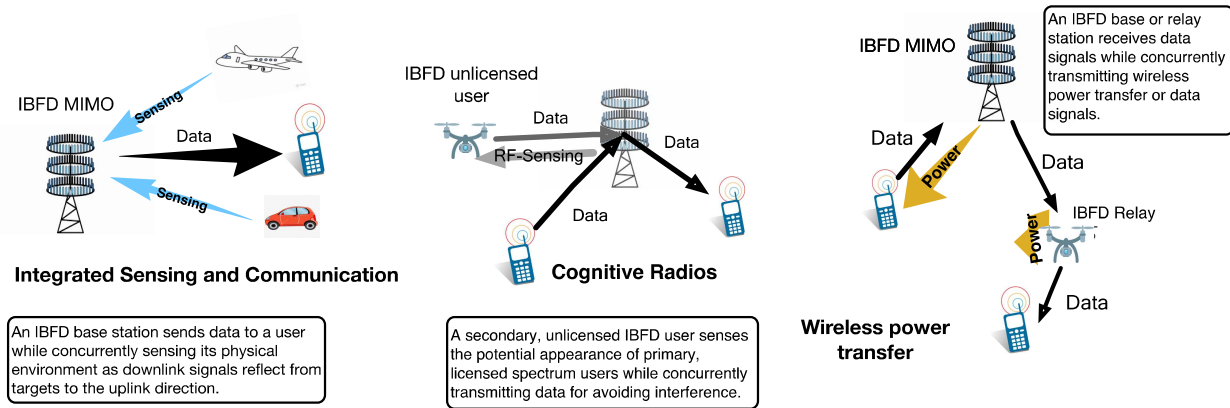


Fig. 7. Novel multifunction designs aim to deliver new services beyond communications. The leftmost figure shows ISACs. The middle figure shows a cognitive radio to enable concurrent spectrum sensing and communications; spectrum sensing is a special class of sensing to improve communications. The right figure shows wireless power transfer applications that simultaneously transmit and receive power and data.

Nevertheless, there has also been work [156] to transfer the IBFD communications technology to equivalent monostatic radars that transmit continuous waveforms using a direct conversion architecture when, e.g., noise-like, radar signals do not accommodate for the frequency-modulation architecture.

2) *Basics of Communications Architectures*: The communications portion of Fig. 8 highlights the packet structure of typical communications waveforms that are comprised of a preamble and data payload and is implemented using OFDM in many current systems. The goal of adding sensing to an existing communications system is to gain radar information by exploiting the communications waveform, where hardware and algorithmic changes are often required to support the sensing. Since typical communications data packets are too long to be used as radar pulses, the IBFD operation is inevitably required for these

ISAC systems [157], which can leverage the transceiver architectures and self-interference cancellation techniques that have extensively been investigated for IBFD communications systems.

3) *Beyond Radar in ISAC*: Although the other functions of Fig. 7 are overshadowed by the ISAC interest in the current research of civilian and commercial scope, multifunction radio systems can be conceptually diverse and more significant than the integration of radar into communication networks. The mature research on cognitive radios has already integrated receive-side spectrum sensing into communication devices over the last 20 years though joint cognitive spectrum sensing and communication are often not labeled as a dual-function network. The other potential functions emerge from the security and defense domain, as related in Section VII-A.

Receive-side sensing is also performed in physical-layer security schemes, where a legitimate surveillance system monitors spectrum usage for enforcing the law or protecting authorized users. This is conceptually similar to spectrum sensing for electronic warfare in combat systems. There is a high potential for integrating them with communication functions. As for a transmit-side function, jamming is a technique that, by design, occupies large power and bandwidth resources not only from the adversary but also from its own users and partners. Since jamming is central for physical-layer security and electronic attacks, it is beneficial to integrate it with receive-side functions such as communication reception, radar, and spectrum sensing. In fact, general multifunction radios are overshadowing the plain dual-function spectrum sharing between radars and communications in the current research and development of defense and military scope. Similarly, the concept of simultaneous wireless information and power transfer (SWIPT) integrates yet different functions with communication systems.

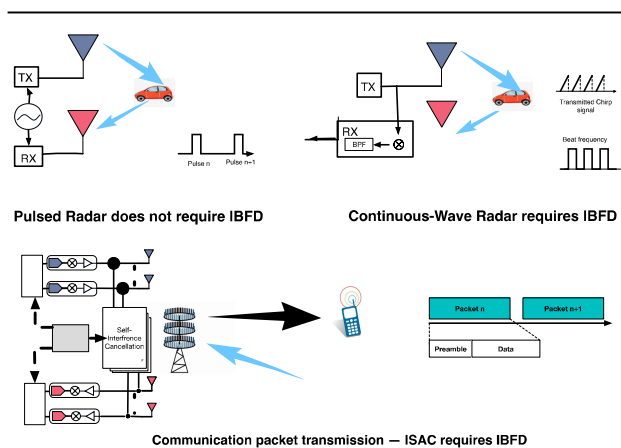


Fig. 8. Simplified radio architecture view of radar-based sensing and communications. The figure shows the basics of radio blocks in pulsed and continuous-wave radars and communications that form the basis of ISAC systems.

In summary, it is evident that a large body of active research and diverse emerging applications aim to use the same frequency band for other functions with communications, with the potential for multiple functions being jointly designed from all the way to hardware, signals, and resource management. While the combinations make sense from a reuse standpoint, they pose new challenges for the physical-layer design of every aspect that is shared between the two or more simultaneous functions, including spectrum access, hardware, and waveforms. For example, any true integration is not achieved if the communication function simply time-shares resources, which is often suboptimal for both spectral and energy efficiency. Thus, the use of IBFD can enable simultaneous operation of multiple functions and improve resource use efficiency. As highlighted in the previous sections, a significant impediment is suppressing the self-interference that results from transmitting and receiving within the same frequency band at the same time. Similar to other applications, there is not a single solution for every IBFD-multifunction system, and instead, the self-interference must be mitigated depending on the specific platform or installation site.

B. IBFD for ISAC

Beyond sensing-centric and communications-centric designs, there is a growing interest in “joint design and optimization,” where sensing and communication functions are jointly designed without being limited by any of their legacy counterparts [158]. These clean-slate future designs could offer the ability to dynamically prioritize the performance of the different functions and would not impose limitations on any existing standards. We also anticipate that the clean-slate joint design and optimization of ISAC systems will need to incorporate IBFD technology to offer a range of solutions because time-division duplexing between communications and sensing is inefficient in the first place even if the benefits of the functions’ integration are harnessed to the maximum without legacy restrictions [159], [160].

Researchers have focused their attention on several key topics of ISAC that can broadly be categorized as system performance bounds, base station deployments, general multifunction aspects, waveform design, measured performance, and state-of-the-art surveys. This work has included both sensing- and communication-centric designs and jointly optimized architectures, where the IBFD operation was considered in most cases to deconflict the spectral sharing. More often than not, the IBFD operation is an implicit assumption required for implementing proposed system concepts, which only highlights the importance of research on its physical-layer implementation and prospects.

1) *IBFD ISAC Beamforming Research*: Transmit beamforming was optimized to provide concurrent multiple beams for communication and sensing while effectively mitigating the cross-interference between different

communication users for a base station deployment. In addition, the receive beamforming was optimized to observe reflections from the radar targets while also canceling self-interference due to the required IBFD operation [161]. Further research was conducted on mmWave beamforming solutions for purely analog-based ISAC systems that maximized their beamforming gain in the sensing direction while controlling the beamformed power in the communications direction, canceling the self-interference, and eliminating the potential reflection from the communication direction and optimizing the combined radar pattern [162].

In a similar vein, the performance of mmWave massive-MIMO base station nodes was analyzed for a hybrid analog and digital beamforming use case, where the nodes were communicating with a downlink multi-antenna user and the same waveform was utilized at the base station receiver for sensing the radar targets in the surrounding environment [163]. The work in [163] was expanded to also include the ability to estimate the direction of arrival and the range of radar targets, which were randomly distributed within the coverage area [164]. The complete multiantenna ISAC waveform can be optimized in time, frequency, and spatial domains for MIMO radar processing with hybrid beamforming [165].

More generally, a multibeam framework using steerable analog antenna arrays was investigated to provide fixed subbeams for communications and packet-varying scanning subbeams for sensing, simultaneously from a single transmitting array [166]. The design of the arrays themselves and the resulting self-interference, maximum gain, and beamsteering range was simulated for a 28-GHz design with a 500-MHz bandwidth [167]. The operation of a multifunction IBFD transceiver that uses its frequency-shifting constant-envelope transmitted signal as the down-conversion carrier was assessed for a sensing-centric architecture [168]. A combination of self-interference cancellation approaches for IBFD and ISAC systems in the context of automated vehicles and urban air mobility was considered [169]. The critical research areas that require maturation before scalable-IBFD arrays can become a reality for ISAC applications were presented [91], [93].

2) *IBFD ISAC Measurements*: In terms of measurements, high-isolation IBFD prototypes using adaptive beamforming were discussed within the context of providing practical examples for both omnidirectional and directional ISAC architectures, demonstrating self-interference isolation levels of 104 and 140 dB, respectively [170]. The performance of OFDM-based radars using a 5G New Radio waveform has been measured for sensing moving targets using a system that incorporated 100 dB of self-interference cancellation [171]. In addition, the sensing performance of two systems implemented on top of 5G New Radio OFDM waveforms and 100 dB of self-interference cancellation was evaluated for a vehicular-sensing scenario (2.4 GHz with 4-m resolution

using a 40-MHz bandwidth) and an environmental mapping situation (28 GHz with 0.4-m resolution using a 400-MHz bandwidth) [161].

C. IBFD for Cognitive Radios

Cognitive radio technology is a broad concept where nodes flexibly share spectrum using diverse component technologies. Relevant to the current paper are cognitive radios that use physical-layer IBFD operation to both sense the spectrum and use the frequencies (so-called white spaces) that are temporarily and locally unused despite them being reserved for some other system to begin with. If allowed by regulations, this results in more efficient and economical spectrum usage. The primary network gets cheaper spectrum licenses, and the secondary network gets a wider spectrum for which they otherwise would not have access.

Secondary users need to sense which frequencies are vacant before transmitting their own data on them. Conventionally, these functions occur in a half-duplex manner so that spectrum sensing and spectrum access alternate like in TDD. The twofold benefit of IBFD operation for cognitive radios comes from the avoidance of interrupting spectrum access for sensing [172], [173]. First, simultaneous spectrum sensing during data transmission allows devices to immediately detect that a primary user has become active and cease transmission to avoid prohibited interference, where conventionally the transmission would continue until the next sensing period. Second, simultaneous transmission and reception allow devices to detect and immediately exploit white spaces that become vacant during the secondary user's transmission [174], [175]. A tri-band IBFD cognitive radio transceiver operating in the bands of 925, 1750, and 2450 MHz was proposed in [176] for tactical communications where the implementation results show that the proposed IBFD design exhibits a higher throughput and reliable spectrum sensing.

The 'listen-and-talk' IBFD procedure proposed in [177] uses a receive antenna for sensing and a transmit antenna to keep active or inactive on the basis of sensing results. Liao et al. [177] also analyzed the system to reveal a tradeoff between the secondary user transmit power and throughput while satisfying the sensing performance. In [178], an adaptive scheme for IBFD cognitive radio networks where the system operation switches among three modes, i.e., cooperative sensing, simultaneous sensing and transmission, and simultaneous transmit and receive, has been proposed.

According to the spectrum sensing outcome, an IBFD secondary system can adjust its polarization state to avoid interference with the primary system and suppress the self-interference. As evident from the results in [179], such a system can achieve efficient spectrum utilization and suffers no collisions with the primary system. In [180], a neural network capable of classifying the future channel occupancy status and a scheme that selects between the

sensing-and-transmission mode or the transmission-and-reception mode with the goal of increasing the secondary throughput and avoiding collisions to the primary user was proposed. A weak primary-to-secondary channel could cause poor sensing performance, and in order to alleviate the problem, spectrum sensing as opposed to traditional interference sensing can be adopted. Specifically in [181], a new transmit-sense-receive mechanism is proposed where each secondary user stops transmission so as not to disrupt the sensing operation of the other.

In IBFD cognitive radio networks, residual self-interference strongly affects the sensing performance. In certain cases, residual self-interference exhibits a nonwhite behavior, and uncertainties in colored noise give rise to an SNR wall in the most widely used detectors, such as the energy detector. To overcome the issue, in [182], features of primary signal and self-interference multipath channels have been taken into account to propose a generalized likelihood ratio test detector applicable to an OFDM system. Moreover, this detector has been shown to perform well when a 5G New Radio mixed numerology OFDM signal is used in the primary system making it an attractive solution for implementing IBFD cognitive radio networks. Colored residual self-interference also negatively impacts the sensing performance at mmWave widebands. As a solution, a real-time whitening procedure for blind eigenvalue-based detectors, which exhibits superior performance with respect to the offline whitening approach, has been proposed in [183].

The use of multiple antennas for spectrum sensing in IBFD cognitive radios has been considered in [184] where the approach employs underlay and interweave operational modes depending on the activity or inactivity of the primary user. Specifically, a throughput maximization problem by allocating energy to the sensing and transmission phases has been formulated to achieve a superior throughput in contrast to an interwave-only transmitting approach. In real-world cognitive radio networks, malicious attacks, such as primary user emulation attacks or spectrum sensing data falsification, can limit the sensing performance [185]. In [185], a machine learning-based approach for robust spectrum sensing against interference and malicious attacks in IBFD cognitive radio networks has been proposed.

D. IBFD for Wireless Power Transfer

Wireless power transfer can be realized in many different ways, but we consider only far-field RF transmission (that is similar to radio-based wireless communications) in this article. Plain wireless power transfer would be performed efficiently with a train of impulses or cophased multisines or it could be harvesting ambient communication transmissions [186]. SWIPT is a multifunction concept that integrates the two corresponding functions by transmitting signals that are purposed for both of them simultaneously. In fact, an SWIPT IBFD transceiver is even

simpler than a half-duplex transceiver because there is no need to switch between energy and information transfer.

Similar to the other multifunction systems, IBFD allows the integration of transmit-side wireless power transfer/SWIPT with a receive-side function, for which there are typical options: communication reception or energy harvesting [187]. In a dual-hop setup, the first source can initiate wireless power transfer to an IBFD relay such that next the relay can simultaneously receive information from the source and retransmit to the destination [188]. When the received signal is a communication signal from another transmitter, the transmitted wireless power transfer/SWIPT signal causes self-interference quite in the same way as a data signal in two-way IBFD communications. However, the specialized wireless power transfer/SWIPT signals may be more difficult to suppress in digital cancellation than communication signals, which requires more research and adaptation before applying IBFD technology. Simultaneous wireless energy transfer in the downlink and information transfer in the uplink is considered in [189], where applications cover Internet-of-Things (IoT) devices. The impact of residual self-interference is studied in [190].

When the received signal is an energy signal, there is nothing to decode in the receiver, and therefore, it is not necessary to cancel the self-interference. Instead, self-interference is a useful signal from an energy harvesting point of view. Thus, the structure of the transceiver is simpler than in the IBFD transceivers designed for simultaneous information transfer in the uplink and downlink. However, this “self-energy recycling” can be seen as a perpetual motion machine because, instead of causing the self-interference to be recycled, the harvested signal energy (that is anyway minuscule) could be directed toward the intended communication receiver, which minimizes the self-interference [191], [192].

Traditional single-antenna wireless power transfer/SWIPT systems suffer from issues such as severe attenuation, shadowing, and fading. As a result, the power transfer efficiency of single antenna systems is limited. In order to improve the power transfer efficiency, systems with multiple antennas that rely on beamforming, transmit, and/or receive diversity coupled with waveform design have been proposed [193], [194]. In the case of IBFD, by transmitting signals better adapted to fading conditions of the channel and by directing RF signals to energy-deprived receivers in combination with spatial-domain self-interference cancellation, multiple antenna techniques significantly help to improve the power transfer efficiency. Some papers have analyzed wireless power transfer/SWIPT in MIMO IBFD systems by designing information and energy beamforming in the case of point-to-point transmission [195], uplink/downlink transmission [196], relaying [197], and massive-MIMO systems [198]. Simulation results reported in these works demonstrate that the IBFD-based systems outperform traditional half-duplex solutions. Antenna selection is another low complexity scheme that can be adopted for IBFD multiple antenna wireless power trans-

fer [199]. Based on channel state information, antenna selection can assign transmit and receive antennas at an IBFD transceiver to maximize the information and energy harvesting performance while maintaining good self-interference isolation. When using mobile edge computing, Cheng et al. [200] proved the positive effects of IBFD communications and wireless power transfer in improving the efficiency of battery saving.

VI. IBFD PHYSICAL-LAYER STANDARDS IN WIRELESS AND WIRED NETWORKS

Opportunity: Increase spectral efficiency and flexibility of wireless and wired systems by introducing IBFD functionality.

Challenge: Self-interference and cross-link interference management, implementation complexity, identifying and implementing necessary hooks in the control plane, and interoperability with legacy devices, are some of the key challenges that need to be addressed to deployment.

Solution Approaches: Deploying IBFD relays that are transparent to end users, deploying IBFD only in access points while user equipments keep operating in half-duplex.

In this section, we provide an overview of how IBFD is making its way into current wireless and wired network standards. We discuss the role of IBFD in 5G networks, TV broadcasting, and the evolution of digital subscriber lines (DSLs). We briefly note that IBFD is also under discussion for inclusion in IEEE 802.11be [201], also known as the Wi-Fi 7 standard. IBFD is a potential option, especially for heavy-loaded cases, where the demand cannot be satisfactorily met with either TDD or out-of-band full-duplex.

A. 5G New Radio

In TDD, the uplink and downlink may use the entire bandwidth, divided in time between the two links. 5G New Radio supports a semistatic configuration of uplink and downlink and dynamic TDD in which the location of uplink and downlink slots within a radio frame can be changed. The number of uplink and downlink slots may also vary to adapt to asymmetric traffic patterns. To enable flexible use of radio resources, 3GPP Release 18, the initial release of 5G-Advanced, standardization work included a study item on the feasibility of simultaneous uplink and downlink in the same frequency band [202]. Possible IBFD features would then be included in the specifications from Release 19 onward.

The IBFD variant studied in 3GPP is referred to as subband nonoverlapping full-duplex (SBFD). In SBFD, the frequency band in SBFD slots is divided such that a base station may transmit and receive simultaneously in

nonoverlapping subbands. Thus, it is similar to FDD but without a duplex filter and a large guard band between the uplink and downlink. There may be guard subcarriers between uplink and downlink subcarriers within the same OFDM symbol to reduce self-interference. A radio frame consists of uplink, downlink, and SBFD slots, and user equipment still operates in half-duplex.

Nonidealities in the transceiver chain cause interference between the subbands, but the self-interference is not as severe as in the case of full-fledged IBFD. Therefore, SBFD is considered to be more amenable to implementation. The antenna array at the base station is divided into transmitter and receiver sections, corresponding to fixed split-array architecture, to reduce self-interference further. Apart from the self-interference, SBFD is subject to cross-link interference in the same vein as flexible TDD. Some interference scenarios arising due to SBFD are illustrated in Fig. 9. The case when neighboring half-duplex users transmit and receive simultaneously within the same SBFD slot should be avoided by scheduling, link adaptation, and power control mechanisms. The study [202] concluded that SBFD provides user-perceived throughput gain in the evaluation scenarios.

A fully fledged IBFD is seen as the second step after SBFD. In IBFD, spatial suppression is achieved by MIMO and spatially directive beams. This is also one of the emerging technology trends to enhance the radio interface in the 2030 time frame and onward according to the International Telecommunication Union [203].

B. Fixed Access Technologies

DSL technology uses the local loop of a telephone network, which was originally built up for analog telephone system communications over copper distribution networks. Over the years, DSL technologies have evolved to different variants, such as asymmetric DSL (ADSL) and ADSL2+, very-high-bit-rate DSL (VDSL) and VDSL2, and G.fast, reaching up to gigabit data rates.

Most versions of DSL use FDD, allowing legacy voice service and downstream and upstream data services to operate simultaneously in different frequency bands. The transmission in DSL suffers from echoes caused by impedance mismatches and imbalances in the transmission path. The sources of echoes are reflections of the transmitted signal from various points along the transmission path, hybrid circuits, transformers, and crosstalk between adjacent DSL lines causing the signal to bounce back. Thus, echo cancellation is required even when the upstream and downstream may not overlap in frequency.

Traditionally, DSL technologies have been designed to provide higher downstream speeds to accommodate the asymmetrical nature of user activities, such as web browsing, media streaming, and downloading files. With the advent of real-time gaming, live video streaming, and augmented and virtual reality, usage patterns are changing, calling for symmetrical uplink and downlink rates, and creating an opportunity for IBFD technology.

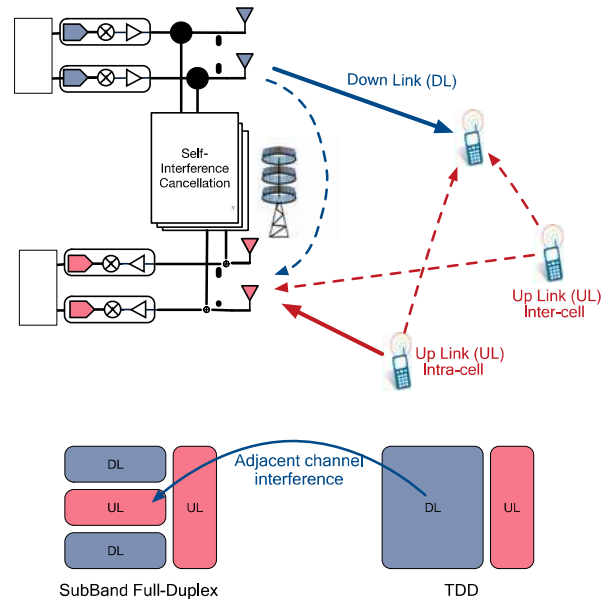


Fig. 9. Interference scenarios in subband full-duplex. Top: intersubband cochannel interference between user equipments in the serving cell and neighboring cell under the same operator. In addition, the base station is subject to self-interference between the uplink and downlink subbands and uplink interference from user equipment in the neighboring cell. Bottom: adjacent channel interference in the base station when the base station of a neighbor operator does not use the SBFD configuration.

The services of hybrid fiber-coaxial cable are defined in DOCSIS to obtain interoperability between the devices from different equipment vendors and between different cable operators. Asymmetry between the uplink and downlink is also a major problem in hybrid fiber-coaxial cable, and the recent DOCSIS 4.0 specification [204] includes IBFD capability to reduce the asymmetry and increase data rates in the upstream. The self-interference levels with respect to the signal of interest are 30–40-dB stronger [205]. Compared to wireless systems, the operation environment of DSL is different. The required frequency range for the cancellation is larger, nearly 600 GHz. The path loss in the coaxial channels is lower than in radio channels causing the self-interference signal to have long delays up to 3–5 μ s [206]. The self-interference channel is also subject to time variations because the echoes travel a long distance and small changes in the reflection coefficients in different parts of the network may change the overall channel response. Some companies have finished successful pilots of DOCSIS 4.0, modems are coming out in 2023, and network upgrades are planned in 2024 and 2025 by different operators.

C. ATSC and DVB-T2

The TV broadcasting industry is also facing pressure to make the use of spectrum more efficient and reduce costs. To this end, the next-generation digital television system ATSC 3.0 [207] has introduced single-frequency networks

that allow the transmitter towers to synchronize and transmit the same broadcast signal in the same frequency band.

In-band distribution link is a technology that enables wireless backhaul, provides a program feed to transmitter towers using IBFD, and replaces traditional fiber or microwave links. Field trials show 70–80-dB isolation levels between the transmitter and receiver antennas in the same antenna mast [208]. In addition, intertower communications networks will connect the transmit towers to form a communication network. ATSC 3.0 is being used in the United States and South Korea, where the penetration is 70% of the country's population.

Second-generation digital terrestrial television broadcasting systems (DVB-T2s) have been deployed in numerous countries around the world [209]. The network allows multifrequency and single-frequency configurations. The use of on-channel repeaters in DVB-T is an established and mature technique to extend coverage in single-frequency networks, and there are several products in the market. The deployment of on-channel repeaters requires careful network planning such that the spatial isolation between the transmitter and receiver is sufficient and high-level echoes from the environment can be reliably canceled.

The deployment of repeaters in DVB-T2 is network and operator-specific, and since the repeaters simply retransmit the DVB-T2 signal, they do not require standardization. The exception is the case when multiple relays are deployed in the same area in a multifrequency configuration. The relays transmit and receive at different frequencies, and their output streams need to be synchronized. This is carried out by a Transport Stream packet (T2-MIP) [210] injected in the over-the-air DVB-T2 signal. The packet is decoded by the repeaters so that they can apply the appropriate time delay when transmitting.

VII. EMERGING IDEAS

Opportunity: IBFD can improve the performance of various wireless systems and applications.

Challenge: IBFD is challenging to integrate into legacy systems, which may not have been designed to accommodate its unique characteristics and requirements. The challenge lies in optimizing the system and managing the interference added complexity that arises from incorporating IBFD-capable devices

Solution Approaches: Each new emerging application may require its own set of novel solutions, leveraging a mix of data-driven, new hardware designs like RIS and algorithmic innovations.

In this section, we highlight applications that benefit from incorporating IBFD and discuss future research directions. We discuss IBFD applied to physical-layer security, the coexistence of IBFD with the reconfigurable intelligent

surface (RIS), and highlight the integration of IBFD in cell-free massive MIMO. The list of potential applications for IBFD is by no means exhaustive, for example, applying IBFD to nonorthogonal multiple access [211], and IBFD coupled with unmanned aerial vehicle communications [212] are not discussed further. We concentrate on applications where IBFD creates new capabilities, such as in physical-layer security, or are predominantly based on employing multiple antenna elements (cell-free massive MIMO and RIS).

A. IBFD for Security and Defense

Wireless networks with different characteristics are increasingly supporting new use cases and applications that benefit everyone. As a consequence, the security of wireless networks has become a significant issue and has always been vital for defense systems. Traditional approaches to implement security have relied on encryption algorithms and key management techniques implemented at the upper and logical layers of communication networks. However, in several emerging scenarios, reasons such as the limited computational complexity of the Internet-of-Things or key management in ad hoc networks largely limit the deployment of conventional data encryption tools for security.

1) From Basics Toward IBFD Physical-Layer Security: There has been a significant interest among researchers in developing novel physical-layer security solutions based on random properties of the wireless channel. Shannon's work on symmetric key encryption systems [213] in 1948 and Wyner's work on the degraded wiretap channel [214] in 1975 laid the early foundations for characterizing the information-theoretic notion of secrecy. Later, it was shown that an increased level of wireless security can be achieved via diffusion and superposition properties of radio transmission [215]. These approaches exploit the phenomena of fading, interference, and path diversity to diminish the ability of potential eavesdroppers to decode desired user messages. In addition, random features of the wireless channel create opportunities for secret key generation and sharing by the involved parties eliminating the need to employ intensive cryptographic computations in mobile devices [216].

Most of the works on physical-layer security assume half-duplex operation. However, simultaneous transmission and reception capability under IBFD operation makes such transceivers well-suited to deploy physical-layer security solutions [217]. Specifically, an IBFD transceiver can transmit intended interference, i.e., jamming, to an eavesdropper while at the same time receiving the signal of interest. The superposition of the interference signal and the signal of interest at the eavesdropper results in a low signal-to-interference-plus-noise ratio to secure the transmission. However, this results in self-interference at the IBFD transceiver, which should be suppressed using self-interference cancellation techniques. Moreover, large

spatial degrees of freedom in IBFD multiantenna terminals can be used in several ways to suppress self-interference and transmit interference signals.

2) *Physical-Layer Security in IBFD Point-to-Point Links*: The pioneering work of Zheng et al. [218] on IBFD secrecy assumed a point-to-point system with an IBFD receiver and one eavesdropper, both equipped with multiple antennas. Due to the IBFD operation, the receiver, while receiving desired signals, transmitted jamming noise with the aim of lowering the secrecy performance at the eavesdropper. For this system, the authors designed an optimal jamming covariance matrix for maximizing the secrecy rate while suppressing self-interference. Moreover, it was reported that the IBFD operation is capable of yielding substantial secrecy gains compared with a half-duplex operation at the receiver. In [219], geographically distributed nodes are used to form a multiantenna destination and send jamming signals to the eavesdropper. Hence, it has been shown that macrodiversity and IBFD operation can be effectively used to guarantee secure communication.

In [220], the potential of an IBFD transceiver pair to securely communicate in the presence of an *Eve* has been studied by deriving the ergodic secrecy rate in closed-form. Specifically, both the cases of single user and multiuser decoding *Eve* have been considered. Their results show that IBFD mode has a high degree of secrecy compared to the half-duplex communication.

3) *Physical-Layer Security in IBFD Cellular Systems*: The secrecy outage performance of a downlink transmission system in the presence of randomly located eavesdroppers has been studied in [221] where the IBFD multiantenna base station applies a transmit antenna selection scheme or a transmit beamforming scheme to transmit to a user operating in either IBFD or half-duplex mode. As such, both the base station and the user are capable of transmitting artificial noise or jamming signals. The study in [221] has also reported several key results including the existence of an optimum jamming power to maximize the secrecy.

Securing IBFD multiantenna base station-empowered uplink and downlink transmission by considering self-interference suppression and physical-layer security involves the robust design of transmit beamforming [222], [223]. A beamforming design to minimize the power consumption of an IBFD multiantenna base station under secure uplink and downlink transmission and multiple eavesdroppers has been presented in [222]. A similar system model, however, considering a multiantenna eavesdropper, has been later studied in [223]. Assuming imperfect knowledge of the eavesdropping and residual self-interference channels, Kong et al. [223] have designed a beamforming vector and an artificial noise and proposed a transmission scheme for securing transmissions from the base station and uplink user.

More recently, in [224], sensing an aerial eavesdropper and securing uplink transmission using an IBFD base station transceiver has been analyzed. Sensing in this

system can be used to obtain partial channel knowledge of the aerial *Eve*, and therefore, it has been shown that the joint communication and sensing IBFD base station can outperform the operation of a traditional IBFD base station.

4) *Physical-Layer Security in IBFD Relay Links*: IBFD relays or destinations have also been proposed for secure cooperative communications. IBFD relays retransmit overhead signals while receiving, and the network should prevent an eavesdropper from decoding direct and relayed path useful signals. The resulting signal model at the eavesdropper is an intersymbol interference channel, which, in turn, lowers eavesdropping capacity compared to half-duplex systems [225]. The IBFD relay can also transmit jamming signals; however, jamming should not deteriorate the desired signal at the destination.

In [226], secure communication in multihop IBFD relaying systems is considered where decode-and-forward IBFD relays are used to transmit jamming signals to the eavesdropper at the same time receiving desired signals from the previous neighboring node. The secure cooperative network studied in [227] consists of a multiantenna IBFD destination capable of simultaneously transmitting jamming signals toward a single eavesdropper and receiving the desired signal. Jafarian et al. [227] have proposed optimum and several fixed transmit and receive beamformer designs to optimize the performance of the destination while degrading the performance of the eavesdropper.

5) *Other IBFD Physical-Layer Security Concepts*: A hybrid full/half-duplex node deployment strategy for ad hoc network operation has been studied in [228]. Factors such as associated costs, circuit power consumption, and self-interference mitigation level play a key role in the need for the hybrid deployment of IBFD and half-duplex nodes as their fraction determines the optimum secrecy performance.

Conversely to the above, IBFD technology can also be used for legitimate receive-side surveillance at the same time while transmitting information signals for communications or jamming for physical-layer security [168]. The transmit-side function causes self-interference to the spectrum monitoring for which IBFD approaches need to be applied when the two functions are efficiently integrated. Similar concepts have been studied in several publications with respect to cognitive radios.

6) *IBFD Defense Solutions*: Defense or military concepts that use IBFD capability [229], [230] are quite similar to what is described above although the terminology is different: physical-layer security becomes electronic warfare, intended interference becomes an electronic attack, and spectrum monitoring becomes signals intelligence; however, jamming and (tactical) communications are used in both domains, while radar is a more common term than sensing. Most combinations of typical transmit-side and receive functions of electronic warfare systems have been

considered in recent research to be integrated with the help of IBFD technology. The military tactical communication system may perform signals intelligence or jamming detection during information transmission and perform an electronic attack during information reception [229].

Electronic warfare systems get a significant advantage from integrating electronic attack and electronic support measures in the form of spectrum sensing [229]. A radar-centric frequency modulation-based system is especially advantageous for integrating all the aforementioned functions and radar sensing, where the limited communication rates are not so severe a drawback in the military domain since many tactical communication systems actually employ constant-envelope waveforms due to their robustness, where linear frequency modulation sweeps are also effective for jamming purposes [168].

B. Reconfigurable Intelligent Surfaces

Similar to multiantenna transceivers, an RIS is comprised of an array of reflecting or transmissive elements, where each element can apply a phase shift to an incident signal [231]. The function of an RIS is comparable to that of an amplify-and-forward relay, which is to relay the transmitted signal toward the destination and enhance the performance of the network. In contrast to an RIS, an amplify-and-forward relay actively amplifies the transmitted signal, thereby also amplifying the noise present in its input. When the amplify-and-forward relay operates in the full-duplex mode, it is crucial to manage the self-interference to ensure the stability of the relay. RIS employs only passive components, which eliminates the potential for noise amplification or self-interference and reduces power consumption. The lack of a power amplifier is compensated by multiple reflecting elements [232], [233].

At the heart of RIS-aided designs used with IBFD or otherwise, the main idea is to shape the propagation channel, as depicted in Fig. 10. In general, the communication system has no control over the channel propagation characteristics, except for controlling distance, e.g., base stations and access points are placed to ensure that the path loss to most locations is within a certain limit. With RIS, the goal is to gain partial control over the propagation paths, by having an RIS shape part of the channel propagation. The level of control depends on the aperture size of the RIS; the larger the aperture, the higher the control of the propagation channel. In addition, the placement of the RIS in relation to the nodes in the system determines which part of the propagation channel is controlled. We sample some recent works that have proposed the use of an RIS to improve IBFD performance for diverse network topologies and design objectives.

Tewes et al. [234] propose the use of an RIS to improve self-interference cancellation. Thus, the RIS is placed close to the transmitter with the objective of improving self-interference cancellation by forming a suitable cancellation signal in the analog domain. The authors use

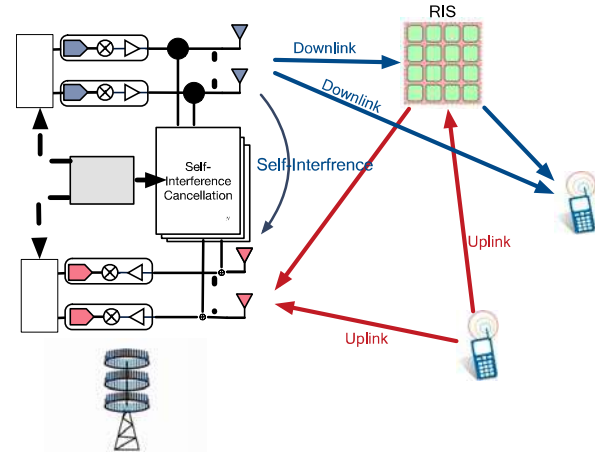


Fig. 10. RIS can be used to shape the propagation environment. There is potential to leverage RIS to shape the self-interference channel such as to reduce the complexity of analog self-interference cancellation and/or favorably improve the channels between the transmitter and the users.

a 256-element RIS prototype and present experimental evidence to demonstrate the efficacy of the proposal. With an initial spatial isolation of 44 dB between transmit and receive antennas, the proposed design provides an additional 59-dB suppression without any additional digital cancellation. A recent work [235] extends [234] to derive efficient algorithms to obtain the RIS phases and the precoding matrix and derive bounds on the performance.

The studies in [99] and [236] take a broader view of improving the overall performance of a wireless network by deploying RIS together with IBFD transceivers. The work in [236] considers a novel mmWave point-to-point IBFD system design without analog beamforming and a few antennas in IBFD nodes. The design employs two near-field RISs placed at each IBFD node to create a smart radio propagation environment assisting passive self-interference cancellation. The results demonstrate that superior performance compared to massive MIMO mmWave IBFD systems featuring hundreds of antennas can be achieved in terms of weighted sum rate. Chen et al. [99] study the multicell IBFD network, where the RISs are placed on cell boundaries to improve the performance of cell edge users. Users at the cell boundary often have the poorest performance due to the highest path loss and interference from neighboring base stations. Thus, the ability to shape both the channel and the interference patterns has the potential to boost the performance at cell edges. The results show that, with RIS, the requirements of self-interference cancellation can be relaxed without compromising the network performance.

RIS elements can only reflect incident signals, which is ineffective when wireless devices are located on both sides of the RIS. In order to overcome this limitation, simultaneously transmitting and reflecting RIS (STAR-RIS) technology can be used [237]. In particular, wireless sig-

nals incident upon an STAR-RIS can be reflected and transmitted to both sides of the STAR-RIS, allowing 360° smart radio coverage. Assuming an STAR-RIS-assisted IBFD system serving one downlink user and one uplink user, in [238], reflection and transmission coefficients of the STAR-RIS elements have been optimized to maximize the weighted sum rate for two protocols, namely, energy splitting and mode switching.

RIS-aided systems consisting of a large number of reflecting elements not only have higher dimensions but also nearly all problem formulations tend to be non-convex. Therefore, computation complexity becomes an important design consideration. The corresponding solutions proposed in the existing literature to many such complex problems are computationally intensive and do not guarantee optimal solutions. Moreover, prediction of RIS coefficients, beamforming vectors, and transmit power at transceivers using classical techniques in the presence of an increasing number of uplink/downlink users, RIS elements, unknown channel models, hardware impairments, and mobility conditions easily becomes a cumbersome task. One promising approach to solve such high-dimensional complex problems is to use emerging machine learning-based techniques [239]. However, this research direction is still in its infancy, and key questions related to when such data-driven approaches complement state-of-the-art system design philosophies remain to be answered through dedicated future research.

C. IBFD Cell-Free Massive MIMO

Cell-free massive MIMO offers several ways to improve the spectrum and energy efficiency. Selecting a few nearby antennas to serve each user and power allocation and use of multiple antennas are some of them [240]. Indeed, the low path loss, macrodiversity gain, and antenna gains enable cell-free massive MIMO networks to improve the throughput and achieve high coverage and reliability to outperform other systems, such as small cells [241].

The IBFD operation in cell-free massive MIMO offers additional opportunities to further improve the performance. In general, users will be much closer to the serving access points, and thus, a low transmit power can be used, which, in turn, helps to minimize the effect of self-interference. In early works on the performance of IBFD cell-free massive MIMO, the authors showed the importance of power control to mitigate self-interference [242]. By systematically allocating transmit and receive antennas at different access points to achieve downlink and uplink transmission, IBFD cell-free massive MIMO networks can exploit the path loss for passive self-interference suppression [243]. Then, the impact of imperfect channel state information and pilot contamination on spectral efficiency was studied in [244] and [245].

Efficient resource allocation in IBFD cell-free massive MIMO helps to improve the network throughput. The key motivation behind the work in [246] has been to propose a duplex mode selection scheme that flexibly assigns

each access point for uplink or downlink transmission. The results in [246] reveal that the flexible assignment exhibits a superior spectral efficiency compared to a fixed assignment where access points are equally divided for uplink and downlink transmission.

Additional self-interference cancellation can be realized if the access points are equipped with multiple antennas and use spatial processing techniques, such as null-space steering or beamforming [247]. The minimum mean square error receiver and zero-forcing precoder-based design of Wang et al. [244] is a spectrally efficient solution since the cancellation of the downlink-to-uplink interference results in a better uplink sum rate, while, to improve the downlink sum rate, a genetic algorithm-based user scheduling solution was also proposed. The conclusion of this article shows that different spatial signal processing of receive and transmit signals yields superior or inferior performance depending on their interference suppression capabilities.

Future practical implementation of IBFD cell-free massive MIMO should be facilitated by addressing the important challenges discussed next. Interuser interference due to simultaneous uplink and downlink transmission can cause significant performance degradation, while, in practice, efficient transceiver design and intelligent user scheduling would be effective in improving service quality. Future wireless systems beyond 5G New Radio would evolve to support new use cases through increased connection density and ultradense networks [248]. As the number of users grows, IBFD cell-free massive MIMO systems will require the development of scalable network architectures for which collective innovations in fronthaul designs, access point-user clustering schemes, low computational complexity signal processing, and resource allocation are essential. In addition, due to the existence of multiple connections among access points in the network and a user, high user mobility causes challenges for the practical implementation of IBFD cell-free massive MIMO systems. To this end, timely CSI acquisition and adoption of efficient kinds of calibration and synchronization would be necessary to guarantee quality-of-service requirements for each user. Solving the challenges of IBFD cell-free massive MIMO will benefit from a fresh look by considering machine learning techniques in the areas of channel and system parameter prediction, modeling of user mobility behavior and user traffic, interference cancellation, dynamic resource allocation, and intelligent network optimization.

VIII. CONCLUSION AND OUTLOOK

In a short time, IBFD communications have come a long way, inspiring a large body of insightful innovations, including its adoption in communications standards. As wireless networks evolve further to undertake new roles and support new functions, IBFD and its many variations are expected to become core functionality in increasingly more network implementations. This will likely keep the

research community occupied for many years to come. There are a number of open research topics, ranging from: 1) theoretical foundations to quantify the limits and tradeoffs, particularly in the case of IBFD multifunction networks; 2) physical-layer designs to achieve high spectral and power efficiencies including accurate but tractable signal models (e.g., nonlinearities and statistics of the

noise) and the design of novel waveforms; 3) network architectures to enable efficient resource management, especially with the emergence of new concepts (e.g., RIS and cell-free); and 4) experimental demonstrations of methods to validate algorithms beyond simulations and expose effects that are often not covered in signal models but have a large impact on the performance. ■

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