Dynamic Spectrum Sharing in 5G Wireless Networks with Full-Duplex Technology: Recent Advances and Research Challenges

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Abstract

Full-Duplex (FD) wireless technology enables a radio to transmit and receive on the same frequency band at the same time, and it is considered to be one of the candidate technologies for the fifth generation (5G) of wireless communications due to its advantages including potential doubling of the capacity, reduced end-to-end and feedback delays, improved network secrecy and efficiency, and increased spectrum utilization efficiency. However, one of the main challenges of the FD technology is the mitigation of strong Self-Interference (SI). Recent advances in different SI cancellation techniques such as antenna cancellation, analog cancellation and digital cancellation methods have led to the feasibility of using FD technology in different wireless applications. Among potential applications, one important application area is Dynamic Spectrum Sharing (DSS) in wireless systems particularly 5G networks, where FD can provide several advantages and possibilities such as Concurrent Sensing and Transmission (CST), Concurrent Transmission and Reception (CTR), improved sensing efficiency and secondary throughput, and the mitigation of the hidden terminal problem. In this direction, first,

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starting with a detailed overview of FD-enabled DSS, we provide a comprehensive survey of recent advances in this domain. We then highlight several potential techniques for enabling FD operation in DSS wireless systems. Subsequently, we propose a novel communication framework to enable CST in DSS systems by employing a power control-based SI mitigation scheme and carry out the throughput performance analysis of this proposed framework. Finally, we discuss some open research issues and future directions with the objective of stimulating future research efforts in the emerging FD-enabled DSS wireless systems.

Index Terms

Dynamic spectrum access, 5G Wireless, Full-duplex, Spectrum sharing, Cognitive radio, Self-interference mitigation.

I. Introduction

In order to deal with the rapidly expanding market of wireless broadband and multimedia users, and high data-rate applications, the next generation of wireless networks, i.e., fifth generation (5G) envisions to provide 1000 times increased capacity, 10-100 times higher data-rate and to support 10-100 times higher number of connected devices as compared to the current 4G wireless networks [2]. However, the main limitation in meeting these requirements comes from the unavailability of usable frequency resources caused by spectrum fragmentation and the current fixed allocation policy. In this context, one key challenge in meeting the capacity demands of 5G and beyond wireless systems is the development of suitable technologies which can address this spectrum scarcity problem [3]. Two potential ways to address this problem are the exploitation of additional usable spectrum in higher frequency bands and the effective utilization of the currently available spectrum.

Due to scarcity of radio spectrum in the conventional microwave bands, i.e., < 6 GHz, the trend is towards moving to millimeter wave (mmWave) frequencies, i.e., between 30 GHz and 300 GHz, since these bands provide much wider bandwidths than the traditional cellular bands in the microwave range, and also enable the use of highly directional antenna arrays to provide large antenna directivity and gain [4, 5]. In this direction, there are several recent research works examining the usage of mmWave for cellular communications [4–9]. With the help of statistical models derived from real-world channel measurements at 28 GHz and 73 GHz, it has been demonstrated that the capacity of cellular networks based on these derived models can provide an order of magnitude higher capacity than that of the current cellular systems [4].

Another promising solution to address the problem of spectrum scarcity is to enhance the utilization of available radio frequency bands by employing Dynamic Spectrum Sharing (DSS) mechanisms [10–13]. This solution is motivated by the fact that a significant amount of licensed radio spectrum remains under-utilized in the spatial and temporal domains, and thus it aims to address the paradox between the spectrum shortage and under-utilization. Moreover, recent advances in software defined radio, advanced digital processing techniques and wideband transceivers have led to the feasibility of this solution by enhancing the utilization of radio frequencies in a very flexible and adaptive manner.

A. Motivation

In contrast to the static allocation policy in current wireless networks, spectrum utilization in 5G wireless networks can be significantly improved by incorporating cooperation/coordination and cognition among various entities of the network. In this regard, several spectrum sharing mechanisms such as Carrier Aggregation (CA) and Channel Bonding (CB) [11], Licensed Assisted Access (LAA) [14], Licensed Shared Access (LSA) and Spectrum Access System (SAS) [15] have been studied in the literature with the objective of making the effective utilization of the available spectrum. The CA technique aims to aggregate multiple non-contiguous and contiguous carriers across different bands while CB techniques can aggregate adjacent channels to increase the transmission bandwidth, mainly within/across the unlicensed bands (2.4 GHz and 5 GHz) [11]. Besides, the LAA approach performs CA across the licensed and unlicensed carriers and aims to enable the operation of Long Term Evolution (LTE) system in the unlicensed spectrum by employing various mechanisms such as listen-before-talk protocol and dynamic carrier selection [14]. Moreover, the LSA approach is based on a centralized database created based on the priori usage information provided by the licensed users. The difference between LSA and SAS lies in the way that SAS is designed mainly to work with the licensed users which may not be able to provide prior information to the central database [15].

In addition, other spectrum sharing schemes such as spectrum trading, leasing, mobility and harvesting have been studied in order to enhance spectral efficiency as well as energy efficiency of future wireless networks [10]. Moreover, Software Defined Networking (SDN)-

based approach can be applied to manage the spectral opportunities dynamically based on the distributed inputs reported from heterogeneous nodes of 5G networks [16]. Besides the aforementioned coordination-based spectrum sharing solutions, another promising approach is Cognitive Radio (CR) technology, which aims to enhance spectrum utilization dynamically either with the opportunistic spectrum access, i.e., interweave or with spectrum sharing based on interference avoidance, i.e., underlay paradigms [12, 13]. With the first approach, Secondary Users (SUs) opportunistically access the licensed spectrum allocated to Primary Users (PUs) by exploiting spectral holes in several domains such as time, frequency, space and polarization [12, 17]. Whereas, the second approach aims to enable the operation of two or more wireless systems over the same spectrum while providing sufficient level of protection to the existing PUs [12].

The level of spectrum utilization achieved by DSS techniques can be further enhanced by employing Full-Duplex (FD)[1] communication technology. In contrast to the conventional belief that a radio node can only operate in a Half-Duplex (HD) mode on the same radio channel because of the Self-Interference (SI), it has been recently shown that the FD technology is feasible and it can be a promising candidate for 5G wireless [18, 19]. In general, an FD system can provide several advantages such as potential doubling of the system capacity, reducing end-end/feedback delays, increasing network efficiency and spectrum utilization efficiency [19]. Besides, recent advances in different SI cancellation techniques such as antenna cancellation, analog cancellation and digital cancellation methods [19–21] have led to the feasibility of using FD technology in various wireless applications. However, due to inevitable practical imperfections and the limitations of the employed SI mitigation schemes, the effect of residual SI on the system performance is a crucial aspect to be considered while incorporating FD technology.

Towards enhancing the sensing efficiency and throughput of a secondary system while protecting primary systems, several transmission strategies have been proposed in the literature. In this context, a sensing-throughput tradeoff for the Periodic Sensing and Transmission (PST) based approach in an HD CR, in which the total frame duration is divided into two slots (one slot dedicated for sensing the presence of Primary Users (PUs) and the second slot reserved for secondary data transmission) has been studied in several publications [22–24]. This tradeoff has

[1]Throughout this paper, by the term full-duplex, we mean in-band full-duplex, i.e., a terminal is able to receive and transmit simultaneously over the same frequency band.

resulted from the fact that longer sensing duration achieves better sensing performance at the expense of reduced data transmission time (i.e., lower secondary throughput). On the other hand, an FD transmission strategy such as Listen And Talk (LAT) [25, 26], which enables Concurrent Sensing and Transmission (CST) at the CR node, can overcome the performance limit due to the HD sensing-throughput tradeoff. In addition to this, the FD principle can enable the Concurrent Transmission and Reception (CTR) in underlay DSS systems. In this regard, this paper focuses on the application of FD technology in DSS wireless systems.

Recently, applications of FD technology in DSS systems have received significant attention [25, 27, 28]. Authors in [25] have presented the application scenarios with FD-enabled CR and highlighted key open research directions considering FD-CR as an important enabler for enhancing the spectrum usage in future wireless networks. However, the main problem with the FD-CR is that sensing performance of the FD-CR degrades due to the effect of the residual SI. One way of mitigating the effect of residual SI on the sensing performance of a CR node is to employ a suitable power control mechanism. In this context, existing contributions have considered CST method [25] in which the CR node needs to control its transmission power over the entire frame duration. However, this results in a power-throughput tradeoff which arises due to the fact that the employed power control results in the reduction of the SI effect on the sensing efficiency but the secondary throughput is limited. This subsequently results in a power-throughput tradeoff problem for an FD-CR node [25, 26]. In this regard, it is important to find suitable techniques to address this tradeoff problem.

B. Related work

In this subsection, we provide a brief overview of the existing survey works in three main domains related to this paper, namely, dynamic spectrum sharing, 5G wireless networks and full duplex communications. Also, we present the classification of the existing references related to these domains into different sub-topics in Table I.

Several survey papers exist in the literature in the context of dynamic spectrum sharing and spectral coexistence covering a wide range of areas such as spectrum occupancy modeling and measurements [29, 30], interweave DSS [31, 32, 34], underlay DSS [35–37], overlay DSS [38], MAC protocols for DSS [39], spectrum decision [43], spectrum assignment [44], security for DSS [40], learning for DSS [41, 42], DSS under practical imperfections [13], licensed spectrum sharing

TABLE I

CLASSIFICATION OF SURVEY WORKS IN THE AREA OF DYNAMIC SPECTRUM SHARING, 5G NETWORKS AND FULL-DUPLEX COMMUNICATIONS.

Main domain	Sub-topics	References
Dynamic spectrum sharing	Spectrum occupancy modeling and measurements	[29, 30]
	Interweave DSS	[31–34]
	Underlay DSS	[35–37]
	Overlay DSS	[38]
	MAC protocols for DSS	[39]
	DSS under practical imperfections	[13]
	Security for DSS	[40]
	Learning for DSS	[41, 42]
	Spectrum decision and assignment	[43, 44]
	Licensed spectrum sharing	[45]
	Coexistence of LTE and WiFi	[46]
Full duplex communications	Overview, challenges and research directions	[21]
	SI cancellation techniques	[19, 21]
	FD relaying	[47]
	Physical layer perspective	[48]
	FD cognitive radio	[25]
	MAC layer perspective	[48, 49]
5G wireless networks	5G overview, architecture and enabling technologies	[50–53]
	Energy-efficient 5G network	[53, 54]
	Massive MIMO system	[7, 55–57]
	mmWave communication	[7, 8, 58]
	Non-Orthogonal Multiple Access (NOMA)	[59, 60]
	Cellular and Heterogeneous Networks (HetNets)	[61–63]
	IoT, M2M and D2D	[64–67]

techniques [45], and the coexistence of LTE and WiFi [46]. Furthermore, the contribution in [37] provided a comprehensive review of radio resource allocation techniques for efficient spectrum sharing based on different design techniques such as transmission power-based versus SINR-based, and centralized versus distributed method, and further provided various requirements for the efficient resource allocation techniques.

In the context of 5G wireless networks, authors in [50] provided a detailed survey on 5G cellular network architecture and described some of the emerging 5G technologies including massive MIMO, ultra-dense networks, DSS and mmWave. Furthermore, the contribution in [51] provided a tutorial overview of 5G research activities, deployment challenges and standardization trials. Another survey article [52] provided a comprehensive review of existing radio interference and resource management schemes for 5G radio access networks and classified the existing schemes in terms of radio interference, energy efficiency and spectrum efficiency. In the direction of energy-efficient 5G communications, authors in [53, 54] provided a detailed survey of the existing works in the areas of energy-efficient techniques for 5G networks and analyzed various green trade-offs, namely, spectrum efficiency versus energy efficiency, delay versus power, deployment efficiency versus energy efficiency, and bandwidth versus power for the effective design of energy-efficient 5G networks [53]. In addition, several survey and overview papers exist in the area of 5G enabling technologies such as massive MIMO [7, 55–57], mmWave [7, 8, 58], Non Orthogonal Multiple Access (NOMA) [59, 60], cellular and heterogeneous networks [61–63], Internet of Things (IoT) [66, 68], Machine to Machine (M2M) communication [64–66] and Device to Device (D2D) communication [67].

Besides, there exist a few survey and overview papers in the area of FD wireless communications [19, 21, 25, 47–49]. The article [21] provided a comparative review of FD and HD techniques in terms of capacity, outage probability and bit error probability, and discussed three types of SI cancellation techniques, i.e., passive suppression, analog and digital cancellation, along with their pros and cons. Also, authors analyzed the effect of some of the main impairments such as phase noise, in-phase and quadrature-phase (I/Q) imbalance, power amplifier nonlinearity on the SI mitigation capability of the FD transceiver, and discussed a number of critical issues related to the implementation, optimization and performance improvement of FD systems. Furthermore, the authors in [47] considered a comprehensive review of in-band FD relaying as a typical application of in-band FD wireless, and discussed various aspects of in-band FD relaying including enabling technologies, performance analysis, main design issues and some research challenges. Moreover, another survey article [48] provides a comparison of existing SI cancellation techniques and discusses the effects of in-band FD transmission on system performance of various wireless networks such as relay, bidirectional and cellular networks. Besides, the comparison of existing MAC protocols for in-band FD systems has been presented in terms of various parameters and provided research challenges associated with the analysis and design of in-band FD systems in a variety of network topologies. In addition, the article [19] provides a general architecture for SI cancellation solution and presents some emerging applications which may use SI cancellation without significant changes in the existing standards. In the context of DSS, the recent article in [25] discussed a design paradigm for utilizing FD techniques in CR networks in order to achieve simultaneous spectrum sensing and data transmission, and discussed some emerging applications for the FD-enabled CR.

C. Contributions

Although several contributions have reviewed the applications of FD in wireless communications [20, 48], a comprehensive review of the existing works in the area of the applications of FD in DSS networks is missing in the literature. In contrast to [25] where authors mainly focused on the LAT protocol, this paper aims to provide a comprehensive survey of the recent advances in FD-enabled DSS systems in the context of 5G. First, starting with the principles of FD communications and SI mitigation techniques, we discuss the applications of FD in emerging 5G systems including massive MIMO, mmWave and small cell networks and highlight the importance of FD technology in DSS wireless systems. Subsequently, we provide a detailed review of the existing works by categorizing the main application areas into the following two categories: (i) CST and (ii) CTR. Then, we identify the key technologies for enabling FD operation in DSS systems and review the related literature in this direction. Besides, we propose a novel Two-Phase CST (2P-CST) transmission framework in which for a certain fraction of the frame duration, the FD-CR node performs Spectrum Sensing (SS) and also transmits simultaneously with the controlled power, and for the remaining fraction of the frame duration, the CR only transmits with the full power. In this way, the flexibility of optimizing both the parameters, i.e., sensing time and the transmit power in the first slot with the objective of maximizing the secondary throughput can be incorporated while designing a frame structure for the FD-enabled DSS system. Moreover, we carry out the performance analysis of the proposed method and compare its performance with that of the conventional PST and CST strategies. Finally, we discuss some interesting open issues and future research directions.

D. Paper Organization

The remainder of this paper is structured as follows: Section II introduces the main aspects of FD wireless communications, SI mitigation schemes and categorizes the applications of FD in DSS systems. Section III and Section IV provide a detailed review on the existing FD related works in DSS wireless systems. Subsequently, Section V highlights the key enabling techniques for FD operation in DSS systems while Section VI proposes a novel communication framework for FD-based DSS system and analyzes its performance in terms of the achievable secondary throughput. Finally, Section VII provides open research issues and Section VIII concludes this

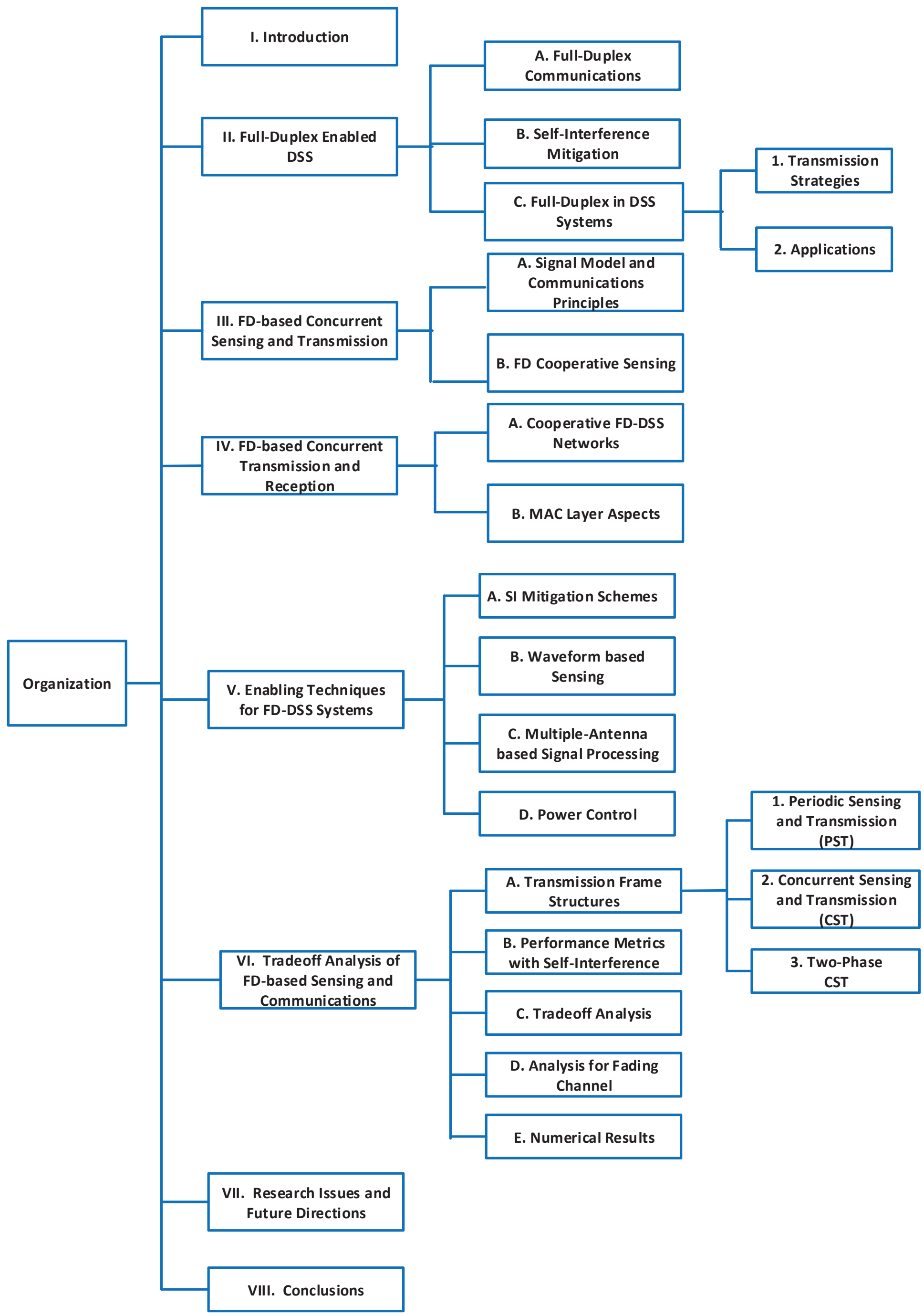


Fig. 1. Structure of the Paper

TABLE II

DEFINITIONS OF ACRONYMS AND NOTATIONS

Acronyms/Notations	Definitions	Acronyms/Notations	Definitions
ADC	Analog to Digital Converter	SR	Secondary Receiver
AF	Amplify and Forward	SU	Secondary User
CB	Channel Bonding	SI	Self-Interference
CA	Carrier Aggregation	SIS	SI Suppression
CST	Concurrent Sensing and Transmission	SAS	Spectrum Access System
CTR	Concurrent Transmission and Reception	SO	Sensing Only
CR	Cognitive Radio	SS	Spectrum Sensing
CRN	Cognitive Radio Network	SNR	Signal to Noise Ratio
CS	Channel Sensing	SINR	Signal to Interference plus Noise Ratio
CSS	Cooperative Spectrum Sensing	TS	Transmission-Sensing
CSI	Channel State Information	TR	Transmission-Reception
DAC	Digital to Analog Converter	TDOA	Time Difference of Arrival
DF	Decode and Forward	QoS	Quality of Service
DSS	Dynamic Spectrum Sensing	H_0	Noise only hypothesis
ED	Energy Detector	H_1	Signal plus noise hypothesis
FD	Full-Duplex	$\mathcal{P}_d$	Probability of detection
HD	Half-Duplex	$\mathcal{P}_f$	Probability of false alarm
i.i.d.	independent and identically distributed	$\sum$	Summation
LAA	Licensed Shared Access	τ	Sensing time
LAT	Listen and Talk	η	SI mitigation factor
LTE	Long Term Evolution	f_s	Sampling frequency
MAC	Medium Access Control	T	Frame duration
MIMO	Multiple Input Multiple Output	λ	Sensing threshold
MSE	Mean-Squared Error	$E[\cdot]$	Expectation
OFDM	Orthogonal Frequency Division Multiplexing	γ	SNR
PST	Periodic Sensing and Transmission	σ_w^2	Noise variance
PDF	Probability Density Function	D	Test statistic
PLNC	Physical Layer Network Coding	N	Number of samples
PT	Primary Transmitter	h	Channel fading coefficient
PR	Primary Receiver	L	Number of multi-paths
PU	Primary User	$\mathcal{P}(H_1)$	Probability of PU being active
RF	Radio Frequency	$\mathcal{P}(H_0)$	Probability of PU being idle
ST	Secondary Transmitter		

paper. In order to improve the flow of this paper, we provide the structure of the paper in Fig. 1 and the definitions of acronyms/notations in Table II.

II. FULL-DUPLEX ENABLED DSS IN 5G NETWORKS

In this section, we briefly describe FD communication principles, its advantages and research issues, existing SI mitigation approaches and the applications of FD in DSS wireless systems.

A. Full-Duplex Communications

In contrast to the traditional belief that a radio node can only operate in an HD mode on the same channel because of the SI, it has been recently shown that the FD technology is feasible and it can be a promising candidate for 5G wireless. In an FD node, CST in a single frequency band is possible, however, the transmitted signals can loop back to the receive antennas, causing the SI. A generic block diagram of an FD communication system with the involved processing blocks is shown in Fig. 2[2]. FD communications can be realized with two antennas [70] as depicted in Fig. 3. As noted, the transmitted signal may be picked up by the receiving part directly due to the loop-back interference and indirectly via reflection/scattering due to the presence of nearby obstacles/scatterers. Although some level of isolation between transmitted and the received signals can be achieved through antenna separation-based path-loss, this approach is not sufficient to provide the adequate level of isolation required to enable FD operation in DSS systems [70].

Theoretically, FD technology can double the spectral efficiency compared to that of the corresponding HD systems since it enables a device to transmit and receive simultaneously in the same radio frequency channel. However, in practice, there are several constraints which may restrict the FD capacity to much less than the theoretical one. The main limitations that restrict to achieve the theoretical FD gain include non-ideal SI cancellation, increased inter-cell interference and traffic constraints [71]. Out of these, SI is the main limitation in restricting the FD capacity and a suitable SI cancellation technique needs to be applied in practice. Even when the transmitted signal can be known in digital baseband, it is not possible to completely remove SI in the receiver because of the involved RF impairments, and a huge power difference between transmitted and received signals. In the literature, about $60 - 113$ dB of SI mitigation has been reported by using the combination of RF, analog and digital cancellation techniques [18, 72–75]. In Table III, we provide the employed SI cancellation technique, carrier frequency, bandwidth, SI isolation level and the FD capacity gain achieved in these works [21].

Furthermore, several existing works analyzed the capacity gain of FD in wireless networks with respect to the HD in various settings. The physical layer-based experimentation results presented in [72] showed that FD system provides a median throughput gain of 1.87 times over the traditional HD mode. The reason for the 1.87 times gain rather than the theoretical double capacity is shown to be due to the SNR loss caused due to the residual SI. On the other hand, even if SI is suppressed below the receiver noise or ambient co-channel interference, an FD transceiver

[2]For the detailed description of the involved blocks, interested readers may refer to [19, 69].

TABLE III

SI CANCELLATION CAPABILITY AND CAPACITY GAIN OF FD FROM THE EXISTING REFERENCES.

Reference	SI cancellation scheme	Carrier frequency	Bandwidth	SI isolation level	Capacity gain
[73]	Antenna cancellation+RF+digital cancellation	2.4 GHz	5 MHz	60 dB	1.84
[74]	Directional diversity+RF+digital cancellation	2.4 GHz	20 MHz		1.6-1.9
[18]	Antenna cancellation+Balun+digital cancellation	2.4 GHz	10 – 40 MHz	113 dB	1.45
[72]	Circulator+RF+digital cancellation	2.4 GHz	20 – 80 MHz	110 dB	1.87
[75]	SDR platform with dual polarized antenna +RF+digital cancellation	20 MHz	2.52 GHz	103 dB	1.9

may outperform its HD counterpart only when there is concurrent balanced traffic in both the uplink and downlink [76]. In [77], authors explored new tradeoffs in designing FD-enabled wireless networks, and proposed a proportional fairness-based scheduler which jointly selects the users and allocates the rates. It has been shown that the proposed scheduler in FD-enabled cellular networks almost doubles the system capacity as compared to the HD counterpart.

Authors in [18] have evaluated the performance of FD in an experimental testbed of 5 prototype FD nodes by using balun cancellation plus digital cancellation schemes and an FD-based MAC protocol, and have shown the improvement in the downlink throughput by 110 % and the uplink throughput only by 15 % considering the bidirectional traffic load. Despite the theoretical double capacity due to FD, only 45 % increase in the total capacity has been achieved in [18] due to the limited queue size at the access point. In addition, it has been shown that FD can reduce the packet losses caused due to hidden nodes by up to 88 % and FD can enhance the fairness in access point-based networks from 0.85 to 0.95.

The experimental results in [78] show that if the SI is cancelled in the analog domain before the interfering signal reaches the receiver front-end, then the resulting FD system can achieve rates higher than the rates achieved by an HD system with the identical analog resources. Moreover, authors in [75] presented a Software Defined Radio (SDR) based FD prototype in which the SI issue has been tackled by combining a dual-polarized antenna-based analog part and a digital SI canceler. It has been shown that the dual-polarized antenna with a high Cross Polar Discrimination (XPD) characteristic itself can achieve 42 dB of isolation, and by tuning different parameters of active analog canceller such as attenuation, phase shift and delay parameter, an additional isolation gain of about 18 dB can be obtained, thus leading to the total of isolation of 60 dB from analog cancellation. And from the digital canceller in the SDR platform, 43 dB of cancellation has been achieved. The test results showed about 1.9 times throughput improvement of the FD system as compared to an HD system by considering QPSK,16-QAM and 64-QAM constellations.

Besides enhancing the capacity of a wireless link, another potential advantage of FD in wireless networks is the mitigation of hidden node problem. Considering a typical WiFi setup with two nodes N_1 and N_2 trying to connect to the core network via an access point, the classical hidden node problem occurs when the node N_2 starts transmitting data to the access point without being able to hear transmissions from the node N_1 to the access point, thus causing collision at the access point [73]. This problem can be mitigated using the FD transmission at the access point in the following way. With the FD mode, the access point can send data back to the node N_1 at the same time when it is receiving data from N_1. After hearing the transmission from the access point, the node N_2 can delay its transmission and avoid a collision. Furthermore, in the context of multi-channel hidden terminal problem, the FD-based multi-channel MAC protocol does not require the use of out-of-band or in-band control channels in order to mitigate this problem [79]. As a result, the FD-based multi-channel MAC can provide higher spectral efficiency as compared to the conventional multi-channel MAC.

In addition to several advantages highlighted in Section I, FD communications can achieve various performance benefits beyond the physical layer such as in the Medium Access Control (MAC) layer. By employing a suitable frame structure in the MAC layer, an FD-CR node can reliably receive and transmit frames simultaneously. Specifically, the FD node is able to detect collisions with the active PUs in the contention-based network or to receive feedback from other terminals during its own transmissions [70]. This paper discusses the existing works, which aim to enhance spectrum utilization efficiency in DSS wireless systems, particularly CR systems.

Despite the aforementioned advantages, the following issues need to be addressed carefully in order to realize future FD wireless communications [48]: (i) strong loop-back interference, (ii) imperfect SI cancellation caused by hardware impairments such as Digital to Analog Converter (DAC) and Analog to Digital Converter (ADC) errors, phase noise, I-Q imbalance, power-amplifier non-linearity, etc., (iii) inaccurate channel knowledge which may result in imperfect interference estimation, (iv) total aggregate interference arising from the increased number of users (i.e., with a factor of two), (v) additional receiver components to cancel SI and inter-user interferences, thus may result in consumption of more resources (power, hardware), and (vi)

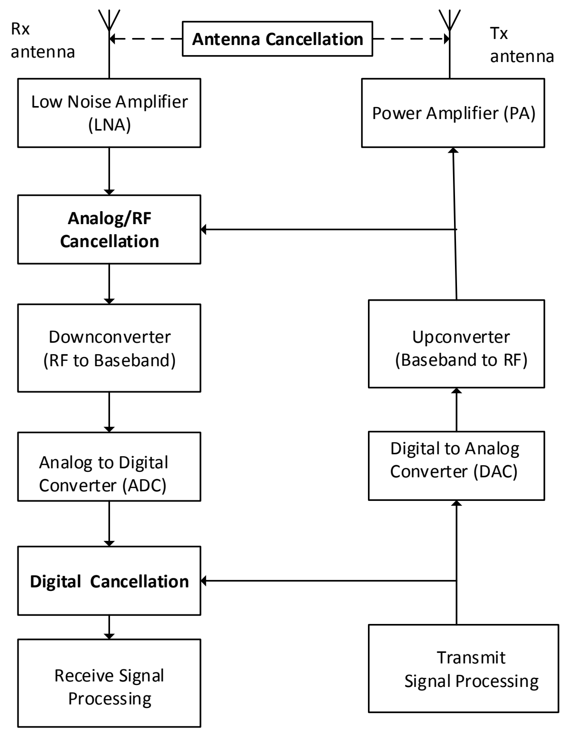


Fig. 2. Block diagram of full-duplex communications showing three different types of self-interference cancellation stages

synchronization issues in multiuser FD systems.

B. Self-Interference Mitigation

Even if the FD node has the knowledge of the signal being transmitted, a simple interference cancellation strategy based on subtracting this known signal from the total received signal still could not completely remove the SI. This is because the transmitted signal is a complicated non-linear function of the ideal transmitted signal along with the unknown noise and channel state information while the node knows only the clean transmitted digital baseband signal [19]. Furthermore, the SI power is usually much stronger than that of the desired signal due to the short distance between transmit and receive antennas. Therefore, suitable SI mitigation techniques must be employed in practice in order to mitigate the negative effect of SI.

The SI power can be about 100 dB stronger than the power of the desired received signal and the statistical model of residual SI depends on the characteristics and the performance of

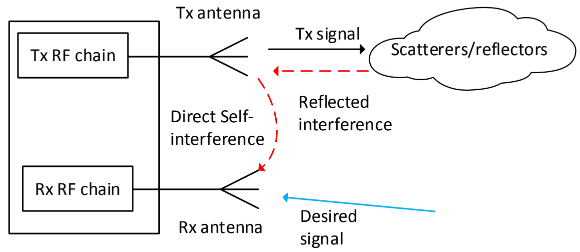


Fig. 3. An FD wireless node with two antennas

the employed SI cancellation schemes [48]. Besides the SI caused by the direct link between the transmitter and the receiver of the FD node, there may also exist the reflected interference signals due to the nearby partially obstructed obstacles. SI mitigation techniques enable the application of FD technology in future 5G wireless systems. These techniques can be broadly divided into two categories: (i) passive, and (ii) active. Furthermore, active SI suppression methods can be categorized into: (i) digital cancellation, and (ii) analog cancellation. Various existing passive, analog and digital SI cancellation techniques have been detailed and compared in [21]. In the following, we briefly describe the principles behind these three SI cancellation approaches.

Passive SI suppression can be mainly achieved by the following methods: (i) antenna separation [73], (ii) antenna cancellation [78], and (iii) directional diversity [74]. The first method suppresses the SI due to path loss-based attenuation between transmit and receive antennas while the second approach is based on the principle that constructive or destructive interference can be created over the space by utilizing two or more antennas. On the other hand, the third approach suppresses the SI due to separation between the main lobes of transmit and receive antennas caused by their directive beampatterns. Besides, polarization decoupling between transmit and receive antennas by operating them in orthogonal polarization will further improve the capability of SI suppression capability [80]. In this regard, authors in [80] have demonstrated that a decoupling level of up to 22 dB can be achieved by using antenna polarization diversity for an FD Multiple Input Multiple Output (MIMO) system.

In the digital domain cancellation methods, SI can be cancelled after the ADC by applying sophisticated digital signal processing techniques to the received signal. In these methods, the dynamic range of the ADC fundamentally limits the amount of SI that can be cancelled and a sufficient degree of the SI suppression must be attained before the ADC in order to have adequate isolation. In practice, one SI cancellation method is not generally sufficient to create the desired isolation and the aforementioned schemes must be applied jointly. For contemporary femtocell cellular systems, it has been illustrated in [70] that the limited ADC dynamic range can lead to a non-negligible residual SI floor which can be about 52 dB above the desired receiver noise floor, i.e., the noise floor experienced by an equivalent HD system. Furthermore, the digital domain cancellation can suppress SI only up to the effective dynamic range of the ADC. This leads to a serious limitation in designing digital SI techniques since the improvement of commercial ADCs in terms of effective dynamic range can be quite slow even if their capability has been significantly improved in terms of the sampling frequency. Therefore, it is important to develop SI suppression techniques which can reduce the SI before the ADCs.

Analog cancellation can be developed by using the time-domain cancellation algorithms such as training-based methods which can estimate the SI leakage in order to facilitate the SI cancellation [20]. Furthermore, in MIMO systems, the increased spatial degrees of freedom provided by the antenna may be utilized to provide various new solutions for SI cancellation. In addition, several approaches such as antenna cancellation, pre-nulling, precoding/decoding, block diagonalization, optimum eigen-beamforming, minimum mean square error filtering, and maximum signal to interference ratio can be utilized. The main advantages and disadvantages of the aforementioned approaches are highlighted in [20]. Furthermore, a simple correlation-based approach has been utilized in [81] and [27] to cancel the linear part of the SI.

Recently, the contribution in [82] studied the multi-user MIMO system with the concurrent transmission and reception of multiple streams over Rician fading channels. In this scenario, authors derived the closed-form expressions for the first and the second moments of the residual SI, and applied the methods of moments to provide Gamma approximation for the residual SI distribution.

C. *Full-Duplex in 5G Networks*

The current 4G wireless networks mostly use half-duplex Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) modes in which the downlink and uplink signals are separated in terms of orthogonal frequency bands and orthogonal time slots, respectively. The performance of both of these modes in meeting the performance metrics of a wireless system is limited by some inevitable constraints as highlighted in the following [83]. The performance of the FDD mode is constrained by the inflexible bandwidth allocation, quantization for the Channel State Information at the Transmitter (CSIT) and the guard bands between uplink and downlink. Similarly, parameters such as outdated CSIT, duplexing delay in MAC and the guard intervals between the uplink and downlink degrade the performance of the TDD mode. In contrast to this, FD-based transmission strategies can overcome the performance bottlenecks of TDD and FDD modes, and also can enhance the spectral efficiency of 5G networks [83].

The authors in [52] have provided a summary on the merits and demerits of several 5G technologies such as ultra-dense networks, massive MIMO, mmWave backhauling, energy harvesting, FD communication and multi-tier communication. Furthermore, several works in the literature have studied the applications of FD in various wireless networks such as massive MIMO, mmWave communication, and cellular densification, which are briefly described below.

1) Massive MIMO: Massive MIMO, also called large-scale MIMO, has been considered as one of the candidate technologies for 5G systems due to its several benefits brought by the large number of degree of freedoms. The main benefits of this technology include higher energy efficiency and spectral efficiency, reduced latency, simplification of MAC layer, robustness against jamming, simpler linear processing and inexpensive hardware [57, 84]. Several researchers have recently studied the applications of FD in massive MIMO systems in various settings [84–86].

Authors in [84] analyzed the ergodic achievable rate of the FD small cell systems with massive MIMO and linear processing by considering two types of practical imperfections, namely, imperfect channel estimation and hardware impairments caused due to the low-cost antennas. It has been shown that Zero Forcing (ZF) processing is superior to the Maximum Ratio Transmission (MRT)/Maximum Ratio Combining (MRC) processing in terms of spectral efficiency since the SI power converges to a constant value for the case of MRT/MRC processing but decreases with the number of transmit antennas for the case of ZF processing. Furthermore, since the SI power increases with the severity of the hardware imperfections, both the spectral efficiency and energy efficiency of uniform power allocation techniques becomes worse in the presence of hardware imperfections and it is crucial to investigate new power allocation policies taking the practical imperfections into account.

Another benefit FD can bring in wireless networks is in-band backhauling, which simultaneously allows the use of same radio spectrum to be utilized at the backhaul and access sides of small cell networks. In this context, authors in [85] analyzed the performance of a massive MIMO-enabled wireless backhaul network which is composed of a combination of small cells operating either in in-band or out-of-band mode. It has been shown that selecting a right proportion of the out-of-band small cells in the network and suitable SI cancellation methods is crucial in achieving a high rate coverage.

The combination of different 5G enabling technologies such as Massive MIMO, full duplex and small cells may provide significant benefits to 5G systems. In this regard, authors in [86] studied three different strategies of small cell in-band wireless backhaul in Massive MIMO systems, namely, complete time-division duplex, inband FD, and inband FD with interference rejection. The presented results in [87] demonstrate that SC in-band wireless backhaul can significantly improve the throughput of massive MIMO systems.

2) mmWave Communication: The main applications of mmWave communications in 5G networks are: (i) device to device communications, (ii) heterogeneous networks such as phantom cell (macro-assisted small cell), or the booster cell in an anchor-booster architecture, and (iii) mmWave backhaul for small cells [9]. In the literature, a few works have studied the feasibility of FD in mmWave frequency bands [88, 89]. The authors in [88] examined the possibility of mmWave FD operation in 5G networks by grouping the FD system into the following components: antenna systems, analog front-end and digital baseband SI cancellers, and protocol stack enhancements. The comparison of HD and FD operations has been presented in terms of data rate versus distance, and it has been demonstrated that the operation range for FD operations is SI limited whereas the range in HD operations is noise limited.

Enabling the in-band FD operation in wireless backhaul links operating in mmWave can offer several benefits such as more efficient use of radio spectrum and the re-use of hardware components with the access side. In the design of current multi-sector base stations, multiple panels are used to cover different sectors, and all the panels operate either in the receive or transmit mode at a given time since the transmission leakage from one panel can completely harm the weak signals received at the adjacent panels. In this regard, the authors in [89] examined the feasibility of an in-band mmWave wireless base-station with the option of enabling backhaul transmission on one panel while simultaneously receiving access or backhaul on an adjacent panel. The level of SI has been evaluated in both indoor and outdoor lab settings to understand the impact of reflectors and the leakage between adjacent panels. It has been demonstrated that about $70-80$ dB isolation is obtained for the backhaul transmission while enabling the operation of adjacent panels in the receive mode. Thus, considering a minimum of 110 dB of isolation requirement for the satisfactory performance, it is shown that only about $30-50$ dB of additional isolation is needed, demonstrating the possibility of using only the baseband techniques in the considered set-up without requiring significant changes in the RF side.

3) Cellular Densification: Although the FD technique is shown to enhance the spectral efficiency of a point to point link, the concurrent uplink and downlink operations in the same band result in additional intra-cell and inter-cell interference, and this may reduce the performance gains of FD cells in multi-cell systems. To address this issue, it is crucial to investigate suitable scheduling techniques in FD cellular networks, which can schedule the right combination of downlink and uplink users, and allocate suitable transmission powers/rates with the objective of improving some network performance metrics such as total network utility and fairness [77]. Another promising solution to address the issue of interference in multi-cell systems could be to deploy the combination of FD cells and HD cells in a network based on some performance objective. In this regard, authors in [90] proposed a stochastic geometry-based model for a mixed multi-cell system, composed of FD and HD cells, and assessed the SINR complementary Cumulative Distribution Function (CDF) and the average spectral efficiency numerically, for both the downlink and uplink directions. It has been shown that since a higher proportion of the FD cells increases average spectral efficiency but reduces the coverage, this ratio of FD cells to the total cells can be considered as a design parameter of a cellular network in order to achieve either a higher average spectral efficiency at the cost of the limited coverage or a lower average spectral efficiency with the improved coverage.

In addition, authors in [71] investigated the impact of inter-cell interference and traffic constraints on the performance of FD-enabled small cell networks. With the help of simulation results, it has been shown that about 100 % theoretical gain can be achieved only under certain conditions such as perfect SI cancellation, full buffer traffic model and the isolated cells. Also, it has been shown that both the inter-cell interference and the traffic significantly reduce the potential gain of the FD. Similarly, the authors in [91] have investigated the performance of two-tier interference-coordinated heterogeneous cellular networks with FD small cells, and have derived the closed-form expressions for outage probability and rate coverage by taking the interference coordination between macro and small cells into account. Furthermore, authors in [92] recently studied the problem of joint load balancing and interference mitigation in heterogeneous cellular networks consisting of massive MIMO-enabled macro-cell base stations and self-backhauled small cells. The problem has been formulated as a network utility maximization problem subject to dynamic wireless backhaul constraints, traffic load, and imperfect channel state information.

Moreover, in order to demonstrate the advantage of FD self-backhualing in emerging virtualized cellular networks, the contribution in [93] formulated the resource allocation problem in virtualized small-cell networks with FD self-backhauling and solved the problem by dividing it into sub-problems in a distributed manner. With the help of numerical results, it has been shown that a virtualized small cell network with the FD self-backhauling is able to take advantages of both network visualization and self-backhauling and a significant improvement in the average throughput of small cell networks can be obtained. Besides, the authors in [94] studied the problem of optimal spectrum allocation for small cell base stations considering both the inband and out-of-band FD backhauling. With the help of numerical results, it has been shown that the advantages of inband and out-of-band FD backhauling become evident only after a certain amount of SI is removed, and hybrid backhauling (with both inband and out-of-band backhauling) can provide benefits in both low and high SI mitigation scenarios by exploiting the benefits of both inband and out-of-band backhauling.

D. *Full-Duplex in DSS Systems*

The main enabling techniques for DSS in wireless networks can be broadly categorized into spectrum awareness and spectrum exploitation techniques [13]. The first category of techniques is responsible to acquire spectrum occupancy information from the surrounding radio environment while the second category tries to utilize the identified spectral opportunities in an effective manner while providing sufficient protection to the PUs. Spectrum awareness techniques mainly comprise of different approaches such as spectrum sensing techniques, database, beacon-based transmission, channel, Signal to Noise Ratio (SNR) estimation and sparsity order estimation techniques [95, 96]. On the other hand, spectrum exploitation techniques can be broadly classified into interweave, underlay and overlay based on the access mechanisms employed by the SUs [12]. Interweave paradigm allows the opportunistic secondary transmission in the frequency channels in which the primary transmission is absent [97] while the underlay paradigm enables the concurrent operation of primary and secondary systems while guaranteeing sufficient protection to the PUs [98, 99]. On the contrary, the overlay paradigm utilizes advanced coding and transmission strategies and requires a very high degree of coordination between spectrum sharing systems, which might be complex in practice [100, 101]. Out of these three paradigms, this paper discusses the application of FD in interweave and underlay systems.

As highlighted earlier in Section I, the main benefits of FD operation in DSS systems are: (i) CST, (ii) CTR, (ii) improved sensing efficiency and secondary throughput, and (iii) mitigation of the hidden terminal problem. By employing a suitable SI Suppression (SIS) technique at the CR node, both performance metrics, i.e., secondary throughput and the SS efficiency can be improved simultaneously. Furthermore, it can also decrease the collision probability under imperfect sensing compared to that due to the HD-based CR [102]. In practice, the employment of any SIS techniques cannot completely suppress the SI. Therefore, the effect of residual SI needs to be considered while analyzing various sensing performance metrics such as false-alarm and detection probabilities.

The traditional HD sensing is based on the assumption that a CR node employs a time-slotted frame which requires synchronization between primary and secondary networks. However, in practice, it is difficult to guarantee synchronization between primary and secondary networks since these networks may belong to different entities and may have different characteristics. In this context, investigation of suitable enabling techniques for non-time-slotted Cognitive Radio Networks (CRNs) is one critical issue and the exploitation of the FD capability enables CR nodes to achieve satisfactory performance in the non-time slotted frame [103].

In the following subsections, we provide an overview of different FD transmission strategies and the applications of FD principles in FD-DSS systems.

1) Transmission Strategies: In general, the following two FD modes of operation can be considered for the SU [102]: (i) Transmission-Sensing (TS) mode, and (ii) Transmission-Reception (TR) mode. In the TS mode, the SU can transmit and sense simultaneously. In this mode, sensing can be done over multiple short time slots instead of the long sensing slot to achieve a better tradeoff between sensing efficiency and the timeliness in detecting PU activity. For the TR mode, the SU transmits and receives data simultaneously over the same channel. In both TS and TR modes, an initial sensing period of a certain duration is needed in order to make a decision on the channel availability before starting the above actions. In the TR mode, since the SU is not able to monitor the PU activity continuously, the probability of collision with the PU transmissions increases.

In addition to the aforementioned modes of operation, authors in [104] analyzed the switching option to either switch to Sensing Only (SO) mode under the imperfect SI cancellation or to switch its operation to another frequency channel, i.e., Channel Switching (CS) if no PU activity information is available. In [104], the authors used a waveform-based sensing approach for the TS mode to enable the SU to detect the PU signal in the presence of the SI and noise. Furthermore, authors considered a set of the action states consisting of the aforementioned states TR, TS, SO and CS to investigate an optimal mode-selection strategy that maximizes an SU utility function subject to a constraint on the PU collision probability. Through numerical studies, it has been shown that the SU should operate in the TR mode if it has a high belief on the PU inactivity in a given channel, and the SU should switch to the TS mode to monitor any change in the PU activity while transmitting when this belief decreases. Further, at very low value of this belief, the best strategy is to switch to another channel.

In the conventional CR network, several existing works assume that the primary traffic has the time-slotted structure and the secondary network is synchronized with this time slotted structure (i.e., the cognitive device spends some time for SS and the remaining time for secondary system's data transmission in each time frame/slot) [24]. However, in practice, the primary traffic may not follow the frame structure of the conventional CR network, which means the PUs can change active/inactive status at any time during each secondary frame. In other words, the primary traffic can be non-time-slotted, for example in random access scenarios. In fact, the SUs cannot detect the PUs' state change when the SUs are transmitting. More specifically, secondary achievable throughput depends on the PU activity and the following different cases for the PU activity may arise in practice [105]: (i) PU is always not active during the SU's frame, (ii) PU is always active during the SU's frame, (iii) PU is initially active and then becomes inactive after a certain duration within the SU's frame period, and (iv) PU is initially inactive and then becomes active after certain time within the SU's frame period. In [105], authors utilized a continuous-time Markov chain model to analyze the achievable throughput of PUs and SUs considering FD SS scheme. It has been shown that PUs can maintain their required throughput and the SUs can increase their achievable throughput compared with the achievable throughput under the HD scheme. In addition, authors in [106] proposed a sensing and collectively transmit protocol, which enables the Secondary Transmitter (ST) to switch between SO and TS modes, taking the uncertainty in PU statistics into account.

Furthermore, in [107], authors studied a CST scheme considering that a CR may transmit and receive interchangeably over the time. When the CR node is operating in the receive mode, it receives the combination of the primary signal as well as the secondary signal. Assuming that the received signal can be correctly decoded at the secondary receiver in order to extract the secondary signal, the residual part is just the PU signal plus noise. By comparing this residual energy with the predefined threshold, the CR can make its decision about the presence or absence of the PU activity and can use this decision to transmit or not in the next frame.

For a given interference rejection capability of the FD system, the sensing performance degrades with the increase in the transmit power due to the corresponding increase in the SI. For sufficiently small values of transmit power, SI becomes negligible, however, the secondary throughput becomes limited. On the other hand, if the transmit power is considerably large, SI becomes problematic in limiting the secondary throughput since the available spectrum opportunities can be wasted due to large probability of false alarm caused by high SI. The above phenomenon results in the existence of a power-throughput tradeoff in the FD-CR system or in an LAT protocol. In other words, there exists an optimal power which results in the maximum secondary throughput [26].

Recently, in [108], a sliding-window based FD mechanism has been proposed in order to allow sensing decisions to be taken on the sample-by-sample basis. It has been shown that as compared to the existing HD periodic scheme and the slotted FD scheme, the sliding-window based scheme significantly decreases the access latency for the CR user.

2) Applications: The two main functionalities required by a CR node in DSS systems are [13]: (i) spectrum awareness, and (ii) spectrum exploitation. The first functionality enables a CR to acquire information about spectral opportunities by monitoring the surrounding environments while the second functionality enables to exploit the available opportunities efficiently. Spectrum awareness techniques may comprise of SS, database, environmental and waveform related parameter estimation techniques. On the other hand, spectrum exploitation techniques can be broadly classified into interweave, underlay, and overlay paradigms [12]. The detailed mapping of various spectrum awareness and exploitation techniques is provided in [13]. In this work, we are interested in the application of FD principles in interweave and underlay DSS paradigms.

The aspect of utilizing FD principles in order to enhance the dynamic spectrum utilization in DSS wireless networks has received significant attention lately in the literature. The existing FD

TABLE IV

EXISTING REFERENCES IN FD-DSS SYSTEMS AND THEIR MAIN CONTRIBUTIONS.

Main research theme	References	Contributions to 5G DSS networks
Transmission strategies	[20,97,99, 102,103]	1. Proposed frame structures to enable CST in 5G networks 2. Analysis of different modes of operation such as TS, TR, SO and CS
Performance analysis	[20,79,100, 104-107]	1. Performance analysis of different sensing techniques in the presence of residual SI and derivation of optimal detection thresholds to maximize some performance metrics 2. Verification of the existence of a tradeoff between the secondary transmit power and throughput, called power-throughput tradeoff 3. Power-allocation algorithms to enhance the spectral efficiency and energy efficiency of FD-enabled massive MIMO systems
Transceiver design	[108-110]	1. Mean-squared errors (MSE) based optimization problems have been studied for FD-based MIMO transceiver considering the case with channel uncertainties 2. FD precoding transceiver structure has been proposed for single-carrier and OFDM-based systems, and for both single and multi-user MIMO scenarios.
Self-interference mitigation	[21,76,99, 111,112]	1. Different SI cancellation techniques such as correlation based least square algorithm, optical SI cancellation techniques have been proposed. 2. Waveform based sensing and cyclostationary spectrum sensing have been studied to detect PU signal in the presence of residual SI.
Multi-antenna FD-DSS	[79,105, 113-116]	1. Use of directional multi-reconfigurable antennas and spatial filtering to enable CST 2. Antenna mode selection (transmit and sensing) based on CSI and optimization of the ratio of the transmit antennas to receive antennas to maximize the sum-rate of FD-based multi-user MIMO systems
Resource Allocation	[117-121]	1. Optimal power allocation policies for the ST and the relay in an FD-enabled CRN 2. Joint optimization of OFDM sub-carriers and the power allocation 3. Distributed power control scheme for underlay FD CR networks
Cooperative Sensing	[122-126]	1. Analysis of LAT method for cooperative spectrum sensing in the presence of residual SI 2. Derivation of collision and outage probabilities for CSS scheme in the context of non-time-slotted FD-CR networks considering both CST and CTR modes
Cooperative Relaying	[127-132]	1. Modeling of residual SI and cross-talk interference caused by imperfect channel estimation considering the FD relaying 2. Performance analysis of cooperative FD system with transmit imperfections 3. Proactive estimation scheme for the cross-channel gain by considering the ST to act as an FD AF relay for the primary transceivers to trigger the power adaption of a PT. 4. Application of Physical Layer Network Coding (PLNC) on decode and forward FD relaying to enable simultaneous transmissions from two sources to two destination nodes
FD-MAC Protocol	[98,133,134]	1. Implementation of packet fragmentation at the MAC layer in order to improve the performance of the FD-based CR networks. 2. Wireless FD cognitive MAC protocol which can efficiently solve the reactivation-failure problem in multi-channel non-time-slotted CRNs 3. Adaptive FD MAC protocol for CR networks without the need of synchronization among the SUs.
Physical layer security	[135,136]	1. Secrecy performance analysis of FD-enabled wirelessly-powered CR system, and derivation of upper and lower bounds of the probability of strictly positive secrecy capacity 2. A dual antenna selection mechanism to improve the secrecy in the primary network and data transmission in the secondary network

TABLE V

APPLICATION OF FULL-DUPLEX IN DSS SYSTEMS

Protocol layer	FD Mechanism	CR Paradigms	References
Physical layer	1. Concurrent sensing and transmission	Interweave	[25, 26, 106, 109, 110]
			[102, 104, 107, 108, 111, 112]
	2. Concurrent transmission and reception	Underlay	[113–123]
Medium access layer	Concurrent transmission and reception	Underlay	[103, 124, 125]

based DSS works deal with various aspects such as transmission strategies, performance analysis, transceiver design, SI mitigation, multiple-antenna signal processing, resource allocation (power, frequency), cooperative sensing, cooperative relaying, FD-enabled MAC protocol design and analysis, and physical layer security. The main available references in these areas are listed in Table IV, and are described in the related sections throughout this paper.

It is worthy to mention that all the references listed in Table IV mainly employ either one of the following FD principles: (i) CST and (ii) CTR. Also, as mentioned earlier in Section II-A, the FD technology can lead to benefits beyond the physical layer. From the physical layer perspective, the FD technology can be used for CST purpose in the interweave CR scenarios and for CTR purpose in the underlay CR scenarios. Besides, from the MAC layer perspective, FD technology at a CR node can be utilized with the objective of CTR. In Table V, we classify the existing works based on these two principles in relation to physical and MAC layers. In the following sections, we focus on these two FD mechanisms and discuss the current state of the art techniques.

III. FD-based Concurrent Sensing and Transmission in 5G DSS Networks

In order to meet the exponential increase in the demand of wireless broadband and multimedia services, it is extremely important to utilize the available spectrum in a flexible and effective manner in the 5G networks. The flexibility in the spectrum allocation under the existing regulatory constraints can be achieved by using a flexible platform, called spectrum toolbox as in [126], which can enable to flexible utilization of available radio frequencies by using different modes of spectrum sharing such as opportunistic access/interweave mode, spectrum coexistence/underlay mode or LSA/SAS mode. The main enablers of opportunistic spectrum sharing in 5G networks include spectrum sensing and dynamic frequency/channel selection, and a geolocation database. In order to utilize the available spectral opportunities effectively, it is crucial to acquire accurate and reliable information about the spectrum occupancy in the surrounding RF environment. In this direction, several existing works have demonstrated the importance of FD-based CST scheme in enhancing the performance of a sensing mechanism employed at the sensing node. In the following, we describe an interweave scenario with FD, communication principles behind FD-based CST and the related works in the areas of FD-based CST including cooperative sensing.

Figure 4 presents a typical interweave CR scenario with an FD-CR node equipped with two antennas. Of these two antennas, one is dedicated for SS while the other is dedicated for data transmission. It should be noted that in this application scenario, the secondary link (the transmission link between ST and Secondary Receiver (SR) still operates under either time division duplex or frequency division duplex mode. In the following subsections, we describe the detailed principle behind this application scenario and discuss the current state-of-the-art techniques.

A. Signal Model and Communications Principles

As discussed in the aforementioned sections, the key difference between the conventional HD-CR and the FD-CR is that in the FD-CR, a sensing device is capable of performing SS and data transmission simultaneously. Thus, in the FD-CR, SS is performed continuously which is different from the conventional HD-CR device where SS is performed in a different time slot than that of data transmission. Furthermore, an SU can monitor the PU activities during its transmission, thus improving the PU detection performance. Therefore, from the SU's viewpoint, transmitting while sensing increases the total transmission period, thus increasing the secondary throughput, and also reduces the probability of simultaneous secondary and primary transmissions [104].

Since the FD-CR performs both sensing and transmission simultaneously, the CR device will receive the following signal at the nth sampling instance [81]

$$r[n] = \sum_{l=0}^{L-1} h[l] s_{\mathrm{i}}[n-l] + s_{\mathrm{p}}[n] + w[n], \tag{1}$$

where $s_{\mathrm{i}}[n-l]$ is the self-transmitted signal, $h[l]$ is the lth multi-path channel coefficient from the direct leakage and reflection with L being the number of multi-paths, $s_{\mathrm{p}}[n]$ is the transmitted signal by the PU and $w[n]$ is the additive noise term. In the above formulation (1), since $s_i(n)$ is known to the receiver, the problem of SIS is reduced to the estimation problem of multi-path components, i.e., channel estimation. In this regard, authors in [127] proposed a preamble-based minimum mean square error based approach for SI mitigation considering the fact that many wireless systems transmit known preamble packets during transmission. Similarly, the contribution in [81] investigated a correlation-based approach in order to reliably estimate the multi-path channel coefficients which can then be utilized to mitigate the SI. Once the SI is removed, an SS scheme exploiting the phase difference is used as the test statistic where the

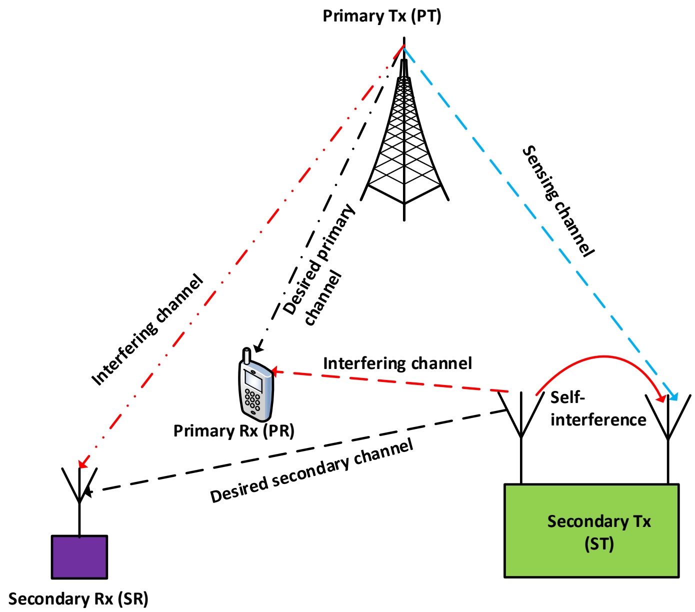


Fig. 4. A typical interweave CR scenario with an FD-CR node equipped with two antennas

distribution of the phases of the received samples follow uniform distribution in the case of the noise only signal and different from the uniform distribution in the case of signal plus noise case. As the test statistic does not utilize the noise information, this detection is considered robust against noise variance uncertainty [81].

Even after the application of different combination of SI techniques highlighted in Section II-B, there remains the effect of residual SI due to several factors such as limitations of SI mitigation techniques, hardware imperfections and estimation error while estimating the SI channel. To incorporate this residual effect in our analysis, we define a factor η whose value varies from 0 to 1, with 0 denoting the case with complete SI suppression and 1 capturing the case with no SI mitigation. Let H_1 denote the hypothesis of the PU signal presence and H_0 denote the hypothesis of the PU signal absence. The received signal under these hypotheses can be expressed as

$$r[n] = \begin{cases} \sqrt{\eta} s_{\mathrm{i}}[n] + s_{\mathrm{p}}[n] + w[n], & H_1 \\ \sqrt{\eta} s_{\mathrm{i}}[n] + w[n], \qquad n = 1, \cdots, N & H_0 \end{cases} \tag{2}$$

where η is used to represent the capability of an FD-based CR to mitigate the SI effect. If $\eta = 0$, the CR cancels the SI completely, otherwise, it can only mitigate its effect. As in [81], we consider a simple Energy Detector (ED) to detect the presence (absence) of $s_{\mathrm{p}}[n]$ considering the assumption that $s_{\rm i}[n], s_{\rm p}[n], w[n]$ are independent and identically distributed (i.i.d.) Gaussian random variables. Under such an assumption, one can treat $\sqrt{\eta}s_{\rm i}[n] + w[n]$ as an independent random variable with the variance $\sigma_w^2 + \eta \mathrm{E}\{|s_{\rm i}[n]|^2\}$ (i.e., amplified noise). From this explanation, one can notice that the ED in FD-CR scenarios can be treated as that of the conventional ED but with higher noise variance. The difference from the HD case is that the FD-based energy detector has to decide the presence of the PU signal in the presence of noise plus SI signal instead of making decision only in the presence of noise. Therefore, the sensing threshold becomes different since the total sensing noise in the FD case is contributed from both Additive White Gaussian Noise (AWGN) and the residual SI, and detection performance becomes different in the presence of residual SI. However, in the ideal case with perfect SI cancellation, the residual SI becomes zero and the problem becomes equivalent to the HD case.

One of the main requirements for sensing in 5G DSS networks is to achieve accurate sensing results in a timely manner. However, the conventional ED-based sensing suffers from long error delay (at least one sensing period) before correct decision can be made in the future sensing slots. This sensing error may occur rapidly in FD-based sensing due to the possibility of accommodating PU state changes during the sensing period. To address this, the feature of consequent sensing periods being adjacent in nature can be utilized to design new sensing strategies for FD-based sensing node. Utilizing this feature, authors in [81] proposed sliding window ED by enabling the overlapping of samples used for different sensing periods to reduce the delay of finding sensing errors. Furthermore, authors in [81] analyzed the effect of PU state change on the performance of FD sensing and showed significant degradation in the sensing performance of the conventional ED when PU changes states during the sensing period. In order to tackle this issue, a weighted ED, which assigns higher weights to the samples collected towards the end of the sampling period, seems promising.

Since in this DSS application, sensing and data transmission take place during the whole duration of the secondary frame and no sensing-throughput tradeoff exists. Also, finding an optimal sensing time is no longer an issue due to the reason that continuous sensing can be achieved under this design. Furthermore, better protection of primary receivers can be achieved due to lower probability of false alarm and higher secondary throughput can be achieved due to a longer data transmission period as compared to the periodic SS [107]. Since the SI cancellation is imperfect in practice, it leads to inevitable residual distortion. In this regard, the contribution in

[109] studied the effect of this residual distortion on the probability of detection of the PU signal compared to that in the HD scenario. It has been shown that the effect of this residual distortion can be compensated by using a longer integration period. Besides, two scenarios where both sensing and transmission can be performed with a single antenna or using two separate antennas have been compared. It has been shown that when the sensing and transmission take place in two separate antennas, the effect of residual SI is reduced but this creates a channel imbalance problem for which sensing provides different information compared to what the transmitting antenna would observe.

In addition, the recent contribution in [128] analyzed the performance of FD-enabled ED technique considering multiple sensing antennas at the CR node and derived the closed form expressions for probability of false alarm and probability of missed detection. Moreover, authors in [129] studied the problem of optimizing detection thresholds to maximize the FD sensing and the secondary throughput in both non-cooperative and cooperative settings. Moreover, the contribution in [130] evaluated the effects of In-phase and Quadrature (IQ) imbalance in FD-based ED in both non-cooperative and cooperative SS scenarios considering single channel and multiple-channel cases, and showed that the IQ imbalance and residual SI significantly degrade the sensing accuracy of FD-based DSS networks.

B. FD Cooperative Sensing

Cooperative Spectrum Sensing (CSS) has received significant attention in the CR literature because of its numerous advantages such as reliable decision, relaxed receiver sensitivity, higher throughput, and the mitigation of hidden node problem [33, 131]. Recently, some attempts have been made to exploit the advantages of the FD-CR in cooperative settings [110–112]. The work in [110] studied the LAT method for the CSS purpose in contrast to the traditional listen before talk method. The main advantage of the LAT method in CSS is that the secondary transmission becomes continuous and the sensing duration is no longer limited. However, the performance of CSS considering the LAT approach is deteriorated by the following factors: (a) SI, (b) interference between the cooperating SUs, and (c) the decrement in the number of sensing and transmit antennas. Similar to the case of FD-based local sensing, it has been shown in [110] that there exists a power-throughput tradeoff in LAT based CSS, i.e., there exists an optimal transmit power which yields the maximum throughput.

While applying cooperative schemes in FD CRNs, there may arise strong interference from the surrounding cooperative SUs which may lead to severe deterioration of their local sensing performance. This leads to certain differences in the application of FD in non-cooperative and cooperative CR scenarios. In this context, authors in [111] studied a robust FD based cooperative scheme by employing a confidence-only report rule and a reputation-based weighted majority fusion rule in order to alleviate the issue of interference and the impact of abnormal nodes, respectively. Moreover, authors in [112] studied a CSS scheme in the context of non-time-slotted FD-CR networks and derived collision and outage probabilities of the PU considering both CST and CTR modes. It has been shown that the CST mode is more robust than CTR mode in the presence of uncertain PU activities and the residual SI.

Although the CSS scheme can provide more reliable and quicker detection of the PUs, it faces significant challenges in meeting the statistical Quality of Service (QoS) requirements of CR networks. In this regard, the contribution in [132] has proposed a QoS-driven resource allocation scheme for a cooperative sharing model in CR networks under the Nakagami-m channel model, and the proposed scheme is shown to achieve the optimality under the statistical delay-bounded QoS constraints. Furthermore, authors in [133] evaluated the performance of two categories of cooperative FD schemes, namely, CST and CTR modes, in asynchronous CR networks. Subsequently, an analytical expression for the PUs' average throughput has been derived under asynchronous PU-SU condition for the aforementioned two FD modes by considering the impact of the interference from the SUs. With the help of numerical results, it has been shown that the CTR mode can provide similar achievable primary throughput as that of the CST mode when the number of cooperating SUs is sufficiently large.

In addition to the widely used primary's channel condition based exploitation of the spectrum, SUs can exploit the transmission opportunities during Automatic Repeat Request (ARQ) retransmissions of the primary network [134]. In this ARQ based spectral coexistence approach, the SUs exploit the structure of primary ARQ transmissions in order to utilize the under-utilized resources, leading to significant secondary rates while providing no harmful interference to the primary's performance. In this regard, authors in [135] proposed a cooperative protocol based on FD capability of the SUs, in which the SUs utilize the opportunities which arise during primary Automatic Repeat Request (ARQ) retransmission intervals for their data transmission while cooperating with the primary system at the same time by repeating the failed packet in an FD manner. It has been shown the proposed FD based cooperative protocol can significantly improve the throughput of both the primary and secondary as compared to other HD and non-cooperative protocols.

C. *Summary and Insights*

Starting with the importance of sensing of RF environments in 5G networks, this section provided a typical interweave DSS scenario and described the principles of communication for CST in 5G DSS networks. Subsequently, existing references which studied CST in various scenarios have been reviewed and the application of FD in cooperative sensing has been discussed by referring to the existing works.

Concurrent sensing and transmission is one of the main advantages that FD can bring to 5G DSS networks. The main difference between HD and FD operations at the sensing node is that sensing and transmission are performed in different time slots for the HD case while FD enables the CST operation. The advantage of this FD operation at the sensing node as compared to the HD is two-fold. On one hand, primary receivers can be sufficiently protected since the SU can monitor the channel occupancy conditions all the time and the detection performance will be enhanced. On the other hand, secondary throughput will be increased since the total transmission period will be increased as compared to the case of HD. In contrast to the HD case, no sensing-throughput exists in the FD sensing case [25, 107].

However, the mitigation of residual SI resulted from the imperfect cancellation is the main challenge in achieving the full performance gain from the FD and this requires the need of accurately estimating the coefficients of SI channel. In the literature, preamble-based minimum mean square error based approach [127] and correlation-based method [81] have been studied to estimate the multi-path channel coefficients in a reliable manner. Moreover, some works studied the detection performance of widely-studied ED technique in FD scenario in the presence of residual SI [109] and in non-time-slotted case [81, 128]. Authors in [109] proposed to use long sensing duration to compensate the effect of residual SI and to decide between single antenna and two-antenna FD transceiver implementations based on the tradeoff between residual distortion level and channel imbalance gain problem. The performance of FD-based ED is severely affected by the state changes in the PU statuses and the weighted ED proposed in [81] seems promising to enhance the detection performance in dynamic PU environment. In addition to the negative

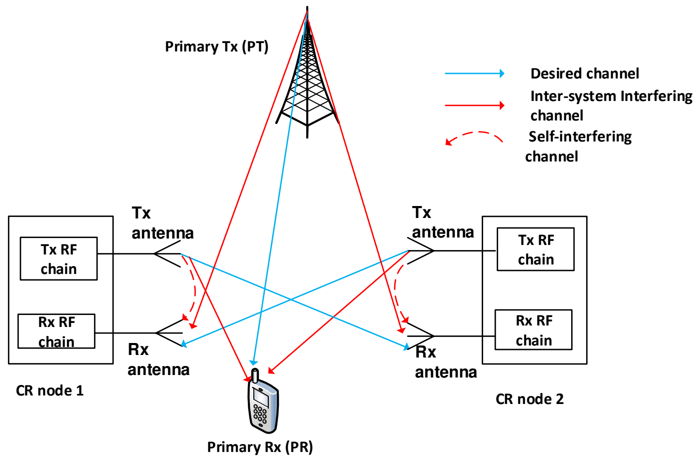


Fig. 5. A typical underlay CR scenario with FD-CR nodes equipped with two antennas

effects of residual SI and varying PU states, FD-sensing performance is also affected by the inevitable hardware impairments such I/Q imbalance [130] and it is crucial to investigate novel solutions to tackle the effects of these impairments.

IV. FD-based Concurrent Transmission and Reception in 5G DSS Networks

Another application of FD in 5G DSS networks is simultaneous transmission and reception in the same frequency channel. This application arises in underlay spectrum sharing scenarios, and cooperative relaying towards improving the utilization efficiency of the available radio frequencies. In the following, we provide a typical underlay DSS scenario and provide an overview of the existing works in the area of underlay DSS and cooperative relaying.

Figure 5 presents a typical underlay DSS scenario with FD-CR nodes equipped with two antennas in which the objective is to enable the CTR. As depicted in the figure, there occurs SI on both CR nodes and the primary receiver needs to be protected against the aggregated interference caused by simultaneous transmission from two CR nodes. Also, in the network scenario having multiple SUs and PUs, each SU experiences inter-user interference from other SUs and causes interference to the PUs. In this case, SUs need to manage their radio resources such as transmit power and antenna in such a way that the aggregated interference received at the Primary Receiver (PR) remains below the acceptable interference threshold.

In the following subsections, we provide an overview of the related works on underlay DSS, FD-based cooperative relaying and the MAC layer aspects of FD communications.

A. *Underlay DSS Networks*

In underlay DSS setting, authors in [136] proposed an iterative transceiver design method for FD-based MIMO system considering the following two optimization problems : (i) minimization of the sum Mean-Squared Error (MSE), and (ii) minimization of the maximum per-SU MSE. It has been shown that the solution to the first problem provides minimum total MSE while the solution of the second one can achieve almost the same MSE for all SUs. However, authors in [136] considered the assumption of perfect Channel State Information (CSI) at the transmitter, however, this is difficult to obtain in practice due to channel estimation errors and the lack of coordination between primary and secondary systems. To alleviate this assumption, authors in [137] studied the sum-MSE optimization problem with SU transmit power and PU interference constraints for FD-based MIMO system taking the channel uncertainties into account. Moreover, authors in [138] studied a spectrum sharing problem considering in-band FD PUs by using improper Gaussian signaling at the SUs. Subsequently, the outage probability at the SUs and a tight upper bound for the outage probability of the PUs were derived. It has been shown in [138] that improper signaling becomes advantageous when the maximum permissible Interference to Noise Ratio (INR) exceeds a desired interference threshold and the SU operates under a certain target data rate.

Recently, a few publications have applied FD principles in underlay DSS networks from the perspective of physical-layer security [139, 140]. By incorporating FD functionality at the secondary destination node, it can simultaneously perform the selection of the receive and jamming antennas in order to improve the secondary throughput and the secrecy performance of the primary system, respectively. Following this concept, authors in [139] proposed an FD dual antenna selection scheme for an underlay CR network and derived the outage probability for the secondary system as well as upper and lower bounds of secrecy outage probability for the primary system. In addition, authors in [140] studied a physical layer security problem for an underlay CR system considering FD operation at the wirelessly-powered destination node, which is equipped with one transmit antenna and one receive antenna capable of simultaneously receiving energy and information from the source.

The estimation of cross-channel gain from the ST to the PR is crucial in underlay spectrum sharing scenarios. In these scenarios, the ST can also act a relay for the PU signals. In this regard, the contribution in [121] proposed a cross-channel gain estimation scheme by assuming AF relaying capability at the ST. In the proposed scheme in [121], the relaying at the ST triggers the closed-loop power control between Primary Transmitter (PT) and PR, leading to the power adaptation at the PT. Then, by observing the changes in the power-levels, the ST estimates the cross-channel gain towards the PR. It has been shown in [121] that the FD relaying-assisted estimator performs better than the jamming-based estimator in terms of primary protection independent of the location of the PR. However, this approach may not be suitable for the scenarios causing large Time Difference of Arrivals (TDOAs) between the direct signal and the relayed signal since TDOA is a random variable and depends on the locations of the ST, PT and PR. To address this issue, authors in [141] proposed to introduce a time delay at the FD-based ST while performing AF relaying in order to force the TDOA to be large enough. Subsequently, an estimation algorithm was developed to estimate cross-channel gains in the large TDOA case and it has been shown that this delay-enabled method can precisely control the interference to the PR than the relay-assisted only approach.

B. Cooperative FD-DSS Networks

Wireless relays play a major role in CR communication systems because of its several advantages such as extended cell coverage and reduced power consumption. Recently, several authors have applied the FD concept in relay-based CR networks considering FD-CR nodes [119, 120]. An FD relay receives and retransmits concurrently in same frequency band while an HD relay receives and retransmits on different bands at different time. In [119], the authors provided the modeling of the residual SI and cross-talk interference caused by imperfect channel estimation considering the FD relaying. Furthermore, [119] also analyzed the impact of the residual SI on the outage probability and spectral efficiency considering three typical cooperative schemes.

The Physical Layer Network Coding (PLNC) enables a Decode-and-Forward (DF) strategy to jointly decode the information from the source nodes and forward the information to the destination. In the context of DSS networks, authors in [120] applied PLNC concept in an FD-CR system to ensure that two source nodes can transmit to two destination nodes in a single time slot assuming the availability of multiple spectrum bands. It has been concluded that the PLNC-based FD relay system can achieve better outage performance compared to its HD counterpart. Moreover, an ST may select between the options of cooperating with the PU and transmitting secondary data probabilistically based on some criteria for the secondary access. In this regard, authors in [122] studied a problem of finding optimal channel access probabilities for the SU in the cooperative context by taking into account the sensing outcome, FD capability at the ST and the probability of successful transmission.

Moreover, with the objective of enhancing the cooperation efficiency in cooperative FD-CR networks, the authors in [118] studied the cooperation between a primary system and a secondary system where the secondary base station relays the primary signal using Amplify-and-Forward (AF) or DF protocols, and in return, it can transmit its own cognitive signal. In this setting, closed-form solutions have been derived to solve the problem as the related residual interference power is scaled or not-scaled with the transmit power. The conclusion from [118] is that the aforementioned cooperation substantially increases the access opportunities for an SU in the licensed spectrum and improves the overall system spectral efficiency. In addition, authors in [115] proposed an opportunistic spectrum sharing protocol where the secondary system can access the licensed spectrum based on FD cooperative relaying. The joint optimization of Orthogonal Frequency Division Multiplexing (OFDM) sub-carrier and power allocation has been studied considering two phases of the relay operation. In the first phase, the CR node receives the primary signal on some particular sub-carriers and in the second phase, it serves as a DF relay by using a fraction of sub-carriers to forward the primary signal in achieving the target rate. In contrast to the traditional HD CR, the residual SI and the cross-talk interference caused by the imperfect channel estimation are additional overheads for the FD-CR relay. In this context, authors in [119] studied the impact of cooperative overhead on the outage probability and the spectral efficiency of three different types of cooperative schemes considering the FD relays. Moreover, authors in [123] analyzed the performance of OFDM-based underlay CR network considering the selection of FD relays. Subsequently, authors analyzed the outage probability of the considered network and showed that OFDM-based CR network with FD relay selection provides higher data rates than its HD counterpart.

C. MAC Layer Aspects

In addition to the ongoing developments in the physical layer, the design of the FD-CR requires necessary adaptations in the upper layers such as the MAC layer. The main drawback of an FD-based CR is that secondary data transmission may be interrupted by the appearance of the PU, hence deteriorating the Quality of Service (QoS) of the secondary link [124]. To address this issue, it is critical to investigate how the higher layers of the protocol stack such as MAC layer can support FD communications in DSS networks while improving the performance of these networks. In this context, authors in [124] have studied the implementation of packet fragmentation at the MAC layer in order to improve the performance of the FD-based DSS networks. It has been demonstrated that by dividing the SU packets into smaller independent segments, the packet dropping probability caused due to the unexpected appearance of the PU can be significantly reduced, and subsequently the QoS of the secondary link can be improved. In this way, only a single fragment can be dropped instead of the whole packet, thus allowing the remaining data to be transmitted later as the channel becomes free.

In non-time-slotted CRNs, due to the lack of synchronization between primary and secondary systems, the PUs may sense a busy channel when the PUs are reactivated during the SUs' transmission, thus creating a collision or entering into the backoff stage. This problem is known as reactivation-failure problem [103] and this problem cannot be addressed using the traditional HD-based sensing mechanism. In order to address this issue, recently authors in [103] developed the wireless FD cognitive MAC protocol which can efficiently solve the reactivation-failure problem in multi-channel non-time-slotted CRNs. The main design motivation behind this FD cognitive MAC protocol is that each SU transmits the request-to-send packet with a certain probability P and after the SU successfully receives clear-to-send packet since sending the last request-to-send packet, it is allowed to transmit data in the next slot.

Recently, authors in [125] studied an adaptive FD MAC protocol for CR networks in order to enable simultaneous sensing and access of the PU channels without requiring the need of synchronization among the SUs. Subsequently, authors analyzed the performance of the proposed scheme taking imperfect sensing, SI effects, and the dynamic status changes of the PU into account. It has been shown that the proposed FD-MAC protocol provides significantly higher throughput than the HD-MAC protocol.

D. Summary and Insights

This section provided an overview of the existing works in the area of underlay DSS and cooperative relaying and further discussed MAC layer aspects of FD for 5G DSS systems. As for the case of CST, the main problem in achieving the capacity of FD in 5G DSS networks is the residual SI.

In underlay DSS applications, guaranteeing the protection of primary receivers against the aggregated interference generated from all co-channel transmissions is another important issue. To address this, SUs need to carefully manage their radio resources in order to satisfy the interference threshold constraint at the primary receivers. In this regard, existing works have studied MSE-based optimization problems for FD-based MIMO system in different settings: (i) with perfect CSI assumption [136], and (ii) taking channel uncertainties into account [137]. Besides radio resource allocation, accurate estimation the cross-channel gain from the ST to PR is important to provide sufficient PU protection in underlay DSS networks. In this context, FD relaying-assisted estimator has been proposed in [121] and a delay-enabled method in [141] towards the improving the PUs protection. Furthermore, improper Gaussian signaling at the SUs has been shown to be advantageous in an underlay spectrum sharing problem under certain conditions [138]. From the physical layer security perspective, FD functionality can enable the concurrent selection of the receive and jamming antennas to improve the secondary throughput and the secrecy performance of the primary system. In this direction, some recent works have analyzed performance of FD-enabled underlay DSS system in various settings [139, 140].

Cooperation between primary and secondary system in DSS systems can significantly increase the access opportunities for the SUs and improve the system spectral efficiency [118]. An FD technique can be beneficial in 5G cooperative DSS systems in the following different ways. First, an FD-enabled relay can enhance the spectral efficiency of relay-based cooperative relaying systems since it simultaneously receives and retransmits in same frequency band. Second, PLNC concept can be applied at the FD-enabled relay node in order to enable the concurrent transmission from two source nodes to two destination nodes in a single time slot [120]. Third, the ST may act as a cooperative node and may probabilistically choose between the options of either cooperating with the PU or to transmit data to secondary receiver based on some performance criteria [122]. In addition, by applying a proper relay selection technique, higher data rates can be achieved as compared to the HD counterpart in relay-based cooperative DSS networks [123]. Despite these advantages, FD-based relay suffers from the residual SI and the cross-talk interference resulted due to imperfect channel estimation [119] and it is crucial to reduce the cooperative overhead in practical scenarios.

In addition to physical layer enhancements discussed above, efficient design of MAC layer

TABLE VI

ENABLING TECHNIQUES FOR FD-DSS SYSTEMS

Enabling Techniques	Principle	References
Self-Interference Mitigation Schemes	Combination of passive (antenna) and active (analog, digital) cancellation techniques	[19, 20, 142]
Waveform Based Sensing	To distinguish the self-interfering signal from the PU signal using some waveform-specific characteristics	[104, 143]
Multiple Antenna Signal Processing	To carry out adaptive spatial filtering with an antenna array	[25, 144, 145]
Power Control	To control the transmit power in order to reduce the impact of SI	[105, 113–115, 117]

significantly helps in achieving the potentials of FD in 5G DSS networks. The QoS of the secondary link may be degraded by the reappearance of the PU in DSS networks. In this regard, packet fragmentation can significantly enhance the performance of FD-DSS networks since the packet dropping probability is reduced due to the division of SU packets into smaller independent segments [124]. Another advantage of FD based MAC protocol is that it can address the reactivation-failure problem in DSS networks as demonstrated in [103]. In addition, FD-based MAC protocols can enable the concurrent sensing and access of the PU channels without the need of synchronization among the SUs and they can provide significantly higher throughput than the HD-based MAC protocol.

V. ENABLING TECHNIQUES FOR FD-DSS IN 5G SYSTEMS

As discussed in the aforementioned sections, there are several challenges in achieving the full capacity of FD technique in 5G DSS networks. In this regard, several works are investigating different ways to enable the application of FD in 5G DSS networks. In the following subsections, we discuss the key enabling techniques for the FD-enabled DSS systems. Furthermore, we list the main enabling techniques for the application of FD in 5G DSS networks and the corresponding references from the current-state-of-the-art in Table VI.

A. Self-Interference Mitigation Schemes

As discussed in Section II-B, by combining different SI cancellation techniques such as passive, analog (RF) interference cancellation, and the digital interference cancellation, FD wireless communications in general or FD-CR communication in particular have become feasible. In [142], authors proposed to employ antenna cancellation along with RF and digital cancellation in order to enable FD-CR operation. The main disadvantages of the antenna cancellation technique is that it requires periodic manual tuning of the FD related RF circuits, thereby rendering its practical implementation infeasible. Moreover, the capability of passive SI cancellation technique is limited by the device size due to its dependence on the antenna configurations and separation. Besides, the capability of analog SI cancellation is limited by hardware imperfections such as phase noise, and its performance degrades in wideband due to non-flat frequency response [21]. On the other hand, digital cancellation techniques can adapt distortions on the per-packet basis but their performance is limited by different transceiver imperfections such as power amplifier non-linearity and I/Q imbalance. Despite their advantages and disadvantages, in practice, the combination of these three types of techniques is needed in order to have a sufficient level of isolation between the received SI and the desired signal. The detailed description of various SI mitigation techniques can be found in [19–21].

Besides several RF front end based SI cancellation techniques discussed earlier, the authors in [146] proposed to employ an optical system at the RF front end in order to effectively cancel the SI in FD-enabled CR systems. In the proposed system set-up, the optical system receives a tap of the already known transmitted signal and is placed between the receiver antenna and a low-noise amplifier. The main advantage of using optical system for SI cancellation lies in the fact that it can inherit the wide-band performance and high-precision features of optical processing. Through experiments, it has been demonstrated that the proposed system is capable of providing about 83 dB isolation for a narrow-band signal, about 60 dB isolation for a 50 MHz frequency modulated signal and > 40 dB cancellation over 500 MHz of instantaneous bandwidth [146]. However, the investigation of suitable algorithms to enable the quick adaptation of optical system on time varying RF environments remains a crucial challenge to be addressed.

B. Waveform based Sensing

In order to carry out SS with an FD-CR having low SI rejection capability, it is crucial to distinguish the self-interfering signal from the PU signal to be detected. However, the simple and commonly studied energy detection technique cannot differentiate between a PU signal and a residual SI. In this context, suitable waveform based techniques which can distinguish the primary signal from the self-interfering signal need to be investigated. There exist only a few works along this direction in the literature.

Authors in [104] studied a waveform-based sensing approach for the TS mode to enable the SU to detect the PU signal in the presence of SI and noise. In addition, the authors in [143] have recently analyzed the performance of cyclostationary SS in FD CRs considering concurrent sensing and transmission. It has been shown that by tuning the cyclic features of the secondary signal appropriately, i.e., cyclic prefix duration or the subcarrier spacing, or making them different than that of the PU waveform, the effect of residual interference on the FD-CR sensing performance can be significantly mitigated.

C. *Multiple-Antenna based Signal Processing*

By employing multiple antennas at the FD-CR node, different multi-antenna based signal processing techniques such as beamforming and antenna selection can be employed [25]. By employing transmit beamforming, the FD-CR can simultaneously maximize its transmission power in the desired direction and can reduce interference to its own received sensing signals. Furthermore, the incorporation of multiple antennas at the FD-CR node provides the option of selecting a proper antenna configuration which can optimize the system performance. In this approach, simultaneous operation of sensing, transmitting and receiving signals may be carried out by dividing the total number antennas into different groups. However, the effect of mutual coupling and near-field effects need to be investigated in detail in future research works.

The FD-CR node can be equipped with redundant transmit antennas in order to form an adaptive spatial filter that selectively nulls the transmit signal in the sensing direction. Following this concept, authors in [144] proposed a spatial filtering approach in order to enable the CST in an FD-CR node. It has been shown that a wideband isolation level of about 60 dB can be obtained by the considered antenna system and by following the spatial filtering stage with active power cancellation in the radio-frequency stage and in the baseband stage, a total isolation greater than about 100 dB can be obtained. Furthermore, authors in [147] proposed to employ directional multi-reconfigurable antennas to enable CST in CR networks. The considered multi-reconfigurable antenna is capable of dynamically changing its radiation beam in one of the predefined directions. This feature allows the FD-CR transceiver to select the direction that maximizes the Signal to Interference plus Noise Ratio (SINR). It has been shown that the directionality of multi-reconfigurable antennas can significantly increase both the communication range and the rate of FD transmissions over omni-directional antenna-based FD transmissions.

Moreover, selecting an antenna either for sensing or transmission in an FD-CR node can introduce the spatial diversity to enable the CST scheme. In this context, authors in [145] studied antenna mode selection for CST in order to select one antenna for sensing and another for transmission based on their Channel State Information (CSI). Two different kinds of selection schemes, one based on the maximization of secondary throughput and another based on the ratio of sensing Signal to Noise Ratio (SNR) to transmitting SNR, have been studied. It has been shown that both schemes improves the throughput performance as compared to the case without antenna selection.

D. Power Control

By controlling the transmit power of the CR node, the impact of the SI on the sensing performance can be mitigated. However, there exists a power-throughput tradeoff in the FD-CR systems and the transmit power control should be carefully designed to achieve the efficient tradeoff. Furthermore, different constraints such as total or individual transmit power (in the MIMO case) may lead to different solutions. Besides, the incorporation of FD relay nodes into the cognitive relay networks may raise several issues [113]. The PU may suffer from the harmful interference from the ST and from the relay simultaneously. In order to satisfy the interference constraint at the PR, the CR node has to lower its transmit power, thus resulting in the performance degradation for the secondary system. In this context, authors in [113] investigated optimal transmission powers for the ST and the relay in an FD CRN with the objective of minimizing the outage probability. Furthermore, an outage-constrained power allocation scheme has been applied to reduce the amount of feedback overhead.

Moreover, the contribution in [114] investigated various power allocation mechanisms between the ST and the cognitive relay in a cognitive AF FD relay network. Subsequently, with the objective of maximizing the secondary throughput, authors developed the following three optimal power allocation algorithms: (i) optimal power allocation with instantaneous interference channel information, (ii) optimal power allocation with statistical interference channel information, and (iii) optimal power allocation with unknown interference channel information and the maximum acceptable interference at the PR. In addition, spectrum efficiency can be improved if the CR system operates in the FD mode by simultaneously transmitting and receiving information. In this context, authors in [115] proposed a two-phase opportunistic FD spectrum sharing protocol in which the secondary system works in the FD mode only in the first phase in the cooperative relaying. Subsequently, authors considered the joint optimization of OFDM sub-carriers and the power allocation in two phases with the objective of maximizing the transmission rate of the secondary system while guaranteeing desired transmission rate for the primary system.

In addition, authors in [116] studied the problem of power control in an underlay FD-CR network with the objective of guaranteeing a minimum SINR at each CR user while keeping the interference to the PUs below a prescribed threshold. Subsequently, in order to achieve the above goals, authors in [116] proposed a distributed power control scheme which integrates a proportional-integral-derivative controller and a power constraint mechanism. Moreover, authors in [117] studied the problem of joint decentralized channel and power allocation scheme for an FD-CR network. The channel allocation scheme in [117] focused on selecting whether a particular channel needs to be used in an FD mode or HD mode in order to maximize the achievable data rate.

E. Summary and Insights

Due to several limitations for the application of FD in 5G DSS networks such as the presence of strong SI, large amount of interference in the network scenario, detection of PU in the presence of residual SU and the effect of inevitable hardware impairments, it is crucial to investigate suitable techniques to address these limitations. In this regard, this section discussed the key enabling technologies for the applications of FD in 5G DSS applications. Mainly, SI cancellation techniques, waveform based sensing, multiple antenna-based signal processing have been discussed by referring to the current state-of-the-art.

In practice, a single SI cancellation technique is not sufficient to provide the level of isolation required to mitigate the effect of SI and three main techniques, namely antenna, analog and digital cancellation techniques have been investigated in the literature. The capability of antenna cancellation technique is mainly limited by the device size while the analog cancellation capability is limited by hardware imperfections such as phase noise. Similarly, the capability of digital cancellation is limited by ADC dynamic range and different transceiver impairments such as I/Q imbalance and power amplifier non-linearity. Therefore, the combination of antenna, analog and digital cancellation techniques as listed in Table III is needed to provide sufficient level of isolation in FD transceiver [21]. Several existing works have provided the detailed description on these techniques [19–21].

One of the main challenges in opportunistic DSS networks is to detect the presence of the PU is to distinguish SI signal from the PU signal, especially when PU received signal is weak. In this regard, waveform-based sensing which can differentiate the features of SI signal and the PU signal seems promising [104, 143]. Another approach to enhance the performance of FD-based DSS system is to employ multi-antenna based techniques such as antenna selection and beamforming. By dividing the total number of antennas into different groups, it may be possible to carry out simultaneous sensing, transmission and reception [25, 145]. Furthermore, by employing spatial filtering at the sensing node, transmit signal in the direction of sensing can be nulled out, thus enabling the CST [144]. Also, by using multi-configurable antennas, radiation beam can be controlled dynamically and this will enhance the communication range of FD and also the data rates.

Although it is possible to mitigate the effect of SI on the sensing performance by controlling the power of transmission on the secondary link, there occurs power-throughput tradeoff in FD-based DSS systems. Therefore, it is necessary to design power control policies carefully to achieve a desired tradeoff. In this direction, several existing works proposed various power allocation mechanisms in various settings [113–115]. Furthermore, in DSS systems, secondary achievable throughput is dependent on the PU activity since PU may leave or occupy the frequency channel at any time. It has been shown that FD-based SS scheme can enhance the achievable throughput of the PUs can maintain their required throughput and the SUs can increase their achievable throughput compared with the achievable throughput under the HD scheme. In addition to SI mitigation, power control mechanisms should also consider the PU interference constraint in order to provide sufficient protection to the PR. In conjunction with the power allocation, channel allocation can be employed to select a particular channel to be either in FD or HD mode with the objective of enhancing the achievable data rate [117].

VI. Tradeoff Analysis of FD-based Sensing and Communications in 5G DSS Networks

In this section, we first describe the traditional PST and CST schemes and then propose a novel transmission strategy for the FD-CR. Subsequently, we carry out the performance analysis of the proposed scheme and compare its performance with the traditional approaches. In our analysis,

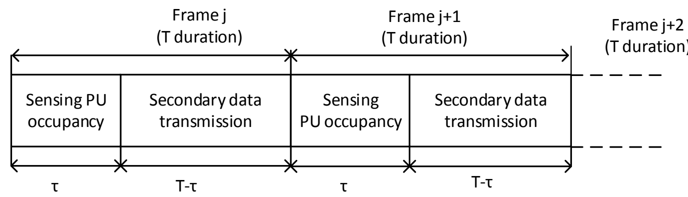


Fig. 6. Secondary frame structure for Periodic Sensing and Transmission (PST)

we assume ON/OFF PU traffic model ('ON' indicating the presence and 'OFF' indicating the absence of the PU in a specific channel). Furthermore, for the simplicity of analysis, we consider the static nature of the PU, i.e., channel occupancy state does not change during the sensing duration.

A. Transmission Frame Structures

1) Periodic Sensing and Transmission (PST): The frame structure of a CR with the PST scheme is shown in Fig. 6. In this conventional sensing approach, the CR operates in a time-slotted mode, i.e., the CR sensing module performs SS for a short duration, which is denoted by τ and transmits data for the remaining $(T-\tau)$ duration, T being the duration of a frame [22]. Since the SUs do not perform sensing and data transmission simultaneously, this scheme can also be referred as an HD SS scheme. The assumption here is that the PU status remains constant over each frame duration. Furthermore, SUs are not able to monitor the PU's status when they are transmitting, hence causing interference to the PR. In this frame structure, there exists an inherent tradeoff between sensing time and the secondary throughput as noted in various previous publications [22, 148, 149]. As the sensing time increases, the probability of detection increases and the probability of false alarm decreases, resulting in better PU protection and the improved utilization of the spectrum. On the other hand, the increase of sensing time causes a decrease in the data transmission time, hence resulting in the reduced throughput.

2) Concurrent Sensing and Transmission (CST): The frame structure of a CR with the CST method is shown in Fig. 7. Since continuous sensing can be achieved under this scheme, finding an optimal sensing time is no longer an issue. However, there exists the problem of strong SI which may degrade the sensing performance. In contrast to the periodic frame structure (Fig. 6) where the throughput increases with the power monotonously, there exists a power-

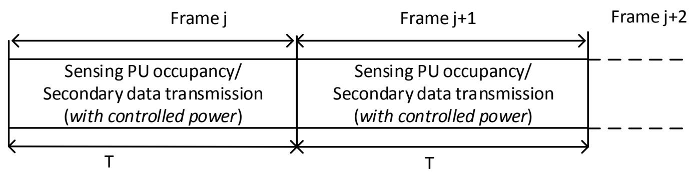


Fig. 7. Conventional secondary frame structure for Concurrent Sensing and Transmission (CST)

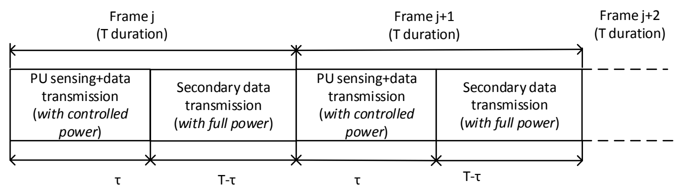


Fig. 8. Two-phase Concurrent Sensing and Transmission (2P-CST)

throughput tradeoff for the frame structure in Fig. 7, which creates a fundamental limitation in the performance of an FD-CR [25]. Authors in [25] showed that in the low-power region, the secondary throughput first increases and then decreases, and there is an optimal transmit power to achieve the maximum throughput, whereas in the high-power region, the secondary throughput increases monotonically with the power.

3) Two-Phase Concurrent Sensing and Transmission (2P-CST): Regarding the aforementioned power-throughput tradeoff problem in the CST method, the assumption in most of the related works is that the CR transmits with the controlled power over the entire frame duration. In this case, power control over the entire frame duration must be performed to mitigate the effect of SI on the sensing performance. To this end, we propose a novel Two-Phase CST (2P-CST) frame structure presented in Fig. 8 in which the transmission strategy can be described as follows: At the beginning of the frame, CR performs SS for a certain fraction of the frame duration and also transmits simultaneously with the controlled power and for the remaining fraction of the frame duration, the CR only transmits with the full power. In this context, our design objective is to optimize two parameters: sensing time, and the transmit power in the first slot, which result in the maximum secondary throughput.

B. Performance Metrics with Self-Interference

The commonly used metrics for evaluating the performance of a detector are probability of false alarm ($\mathcal{P}_f$) and probability of detection ($\mathcal{P}_d$). Subsequently, using these probabilities, the performance of a CR system can be characterized in terms of different tradeoffs such as sensing-throughput tradeoff and power-throughput tradeoff. As mentioned earlier, there exists a sensing-throughput tradeoff for an HD CR and a power-throughput tradeoff for an FD-CR. For the proposed frame structure in Fig. 8, there exist both aforementioned tradeoffs and we can characterize its performance in terms of the sensing-power-throughput tradeoff.

Let N be the number of samples collected within τ duration, i.e., $N = \lceil \tau f_s \rceil$, with f_s being the sampling frequency. Regarding the binary hypothesis testing problem in (2), the test statistic (D) for the ED technique is given by; $D = \frac{1}{N}\sum_{n=1}^{N}|r(n)|^2$, where D is a random variable and its Probability Density Function (PDF) under the H_0 hypothesis follows a Chi-squared distribution with $2N$ degrees of freedom for the complex valued case. For very large values of N, the PDF of D can be approximated by a Gaussian distribution with mean $\mu = \sigma_w^2$ and the variance $\sigma_0^2 = \frac{1}{N}[E[w(n)]^4 - \sigma_w^2]$ [22], where $E[.]$ denotes an expectation operator. The expressions for $\mathcal{P}_f$ and $\mathcal{P}_d$ can be computed by; $\mathcal{P}_f = \Pr(D > \lambda | H_0)$, $\mathcal{P}_d = \Pr(D > \lambda | H_1)$. where λ is the sensing threshold. For the circularly symmetric complex Gaussian noise case, $E[w(n)]^4 = 2\sigma_w^4$, thus $\sigma_0^2 = \frac{1}{N}\sigma_w^4$, the expression for $\mathcal{P}_f$ can be written as [22]

$$\mathcal{P}_f(\lambda, \tau) = Q\left(\left(\frac{\lambda}{\sigma_w^2} - 1\right)\sqrt{\tau f_s}\right), \tag{3}$$

where $Q(.)$ is the complementary distribution function of the standard Gaussian random variable. Similarly, under the H_1 hypothesis, the expression for $\mathcal{P}_d$ is given by

$$\mathcal{P}_d(\lambda, \tau) = Q\left(\left(\lambda/\sigma_w^2 - \gamma_p - 1\right)\sqrt{\frac{\tau f_s}{2\gamma_p + 1}}\right), \tag{4}$$

where γ_p is the PU SNR measured at the ST. Let $\bar{\mathcal{P}}_d$ be the target probability of detection to be respected by the detector based on the current radio regulations. Combining (3) and (4), $\mathcal{P}_f$ is related to $\bar{\mathcal{P}}_d$ as follows

$$\mathcal{P}_f = Q\left(\sqrt{(2\gamma_p + 1)}Q^{-1}(\bar{\mathcal{P}}_d) + \sqrt{\tau f_s}\gamma_p\right). \tag{5}$$

The main problems in the PST scheme illustrated in Fig. 6 are [25]: (i) an SU has to allocate a certain fraction of the frame duration for the sensing purpose, and transmission slot needs to be divided into small discontinuous time slots even if the spectrum opportunity is available for a long period, and (ii) during data transmission phase, SUs cannot monitor the changes of PUs states, which leads to the collision when the PUs become active and the spectrum opportunity is wasted when PUs become inactive. In the FD-CR, since the transmitted power level affects the SI and subsequently the sensing performance, one way of achieving desired sensing performance is to constrain the transmit power of the ST. However, this leads to the reduction in the achievable throughput of the secondary system.

The main problem with the CST strategy is that the node suffers from the SI due to its own transmitted signal, hence causing sensing errors. The expression for P_f for an FD transceiver depends on the following cases, namely, perfect and imperfect SI cancellation.

1. *Without Residual Self-Interference (Perfect SI Cancellation)*: For a target probability of detection $\bar{\mathcal{P}}_d$, $\mathcal{P}_f$ in (5) for the considered ED technique can be written as

$$\mathcal{P}_f(T) = Q\left(\sqrt{(2\gamma_p + 1)}Q^{-1}(\bar{\mathcal{P}}_d) + \sqrt{Tf_s}\gamma_p\right). \tag{6}$$

2. *With Residual Self-Interference (Imperfect SI Cancellation)*: Although several antenna-based, RF and digital interference mitigation techniques have been investigated in the literature to mitigate the SI [150, 151], there still remains its residual effect. The sensing-throughput tradeoff performance of the FD transceiver is affected by this residual interference which depends on the SI mitigation capability. This is due to the effect of residual SI on $\mathcal{P}_d$ and $\mathcal{P}_f$. Considering the residual SI mitigation factor η defined in Section III-A with $\eta \in \{0, 1\}$, the expressions for P_d and P_f can be written as [102]

$$\mathcal{P}_d(\lambda, \tau, \eta) = Q\left(\left(\frac{\lambda}{\sigma_{\mathrm{w}}^2} - \eta^2\gamma_{\mathrm{in}} - \gamma_{\mathrm{p}} - 1\right)\sqrt{\frac{Tf_s}{2\eta^2\gamma_{\mathrm{in}} + 2\eta^2\gamma_{\mathrm{in}}\gamma_{\mathrm{p}} + 2\gamma_{\mathrm{p}} + 1}}\right), \tag{7}$$

$$\mathcal{P}_f(\lambda, \tau, \eta) = Q\left(\left(\frac{\lambda}{\sigma_w^2} - \eta^2\gamma_{\mathrm{in}} - 1\right)\sqrt{\frac{Tf_s}{2\eta^2\gamma_{\mathrm{in}} + 1}}\right), \tag{8}$$

where γ_{in} denotes the ratio of the strength of the SI to the noise power, measured at the receiver of the same node. It can be noted that (7) and (8) reduce to (4) and (3), respectively, when $\eta = 0$, i.e., perfect cancellation of the SI. Combining (7) and (8), the expression for P_f for a target $\bar{\mathcal{P}}_d$ can be written as

$$\mathcal{P}_f = Q\left(\left(Q^{-1}(\bar{\mathcal{P}}_d)\sqrt{2\eta^2\gamma_{\text{in}} + 2\eta^2\gamma_{\text{in}}\gamma_{\text{p}} + 2\gamma_{\text{p}} + 1} + \gamma_{\text{p}}\sqrt{Tf_s}\right)\frac{1}{\sqrt{2\eta^2\gamma_{\text{in}} + 1}}\right). \quad (9)$$

As highlighted earlier in Section IV, power control is one important approach to control the SI and we consider this approach in this paper. The employed power control mechanisms are detailed in the following subsection.

C. *Tradeoff Analysis*

We denote the full secondary transmit power by P_{full}, the controlled secondary power by P_{cont}, and the PU transmit power by P_{p}. The expressions for the throughput of the secondary network in the absence (C_0) and the presence (C_1) of the active PU can be defined as:

$$\begin{aligned} C_0 &= \log_2(1+\gamma_s), \\ C_1 &= \log_2\left(1+\frac{\gamma_s}{1+\gamma_p}\right). \end{aligned} \quad (10)$$

Let $\mathcal{P}(H_0)$ denote the probability of the PU being inactive, and $\mathcal{P}(H_1)$ as the probability of the PU being active. For the conventional PST approach, the average throughput for the secondary network is given by

$$R_{\text{PST}}(\lambda,\tau) = R_0(\lambda,\tau) + R_1(\lambda,\tau), \quad (11)$$

where the values of $R_0(\lambda,\tau)$ and $R_1(\lambda,\tau)$ can be calculated using the following expressions

$$\begin{aligned} R_0(\lambda,\tau) &= \frac{T-\tau}{T}(1-\mathcal{P}_f(\lambda,\tau))\mathcal{P}(H_0)C_0, \\ R_1(\lambda,\tau) &= \frac{T-\tau}{T}(1-\mathcal{P}_d(\lambda,\tau))\mathcal{P}(H_1)C_1, \end{aligned} \quad (12)$$

where the values of C_0 and C_1 are obtained from (10), with $\gamma_{\text{s}} = \frac{P_{\text{full}}}{N_0}$, and $\gamma_{\text{p}} = \frac{P_{\text{p}}}{N_0}$, with N_0 being the noise power measured at the CR node.

For the CST approach, sensing duration is T instead of τ in the periodic SS approach. Therefore, the total throughput of the CST approach can be written as [107]

$$R_{\text{CST}}(\lambda,T) = R_0(\lambda,T) + R_1(\lambda,T), \quad (13)$$

where the values of $R_0(\lambda,T)$ and $R_1(\lambda,T)$ can be calculated using the following expressions: $R_0(\lambda,T) = (1-\mathcal{P}_f(\lambda,T))\mathcal{P}(H_0)C_0$, and $R_1(\lambda,T) = (1-\mathcal{P}_d(\lambda,T))\mathcal{P}(H_1)C_1$, where the values of C_0 and C_1 are obtained from (10), with $\gamma_s = \frac{P_{\text{cont}}}{N_0}$, and $\gamma_{\text{p}} = \frac{P_{\text{p}}}{N_0}$.

In the proposed scheme with the frame structure shown in Fig. 8, the total throughput will be contributed both from the controlled power and full power transmissions. In this context, the additional throughput, let us denote by R_2, is given by

$$R_2(\lambda,\tau) = \frac{\tau}{T}(1-\mathcal{P}_f(\lambda,\tau))\mathcal{P}(H_0)C_0 + \frac{\tau}{T}(1-\mathcal{P}_d(\lambda,\tau))\mathcal{P}(H_1)C_1, \tag{14}$$

where the values of C_0 and C_1 are obtained from (10), with $\gamma_s = \frac{P_{\rm cont}}{N_0}$, and $\gamma_{\rm p} = \frac{P_{\rm p}}{N_0}$.

In this scheme, we formulate the throughput optimization problem in two ways as follows:

i. **Approach 1**: In this scheme, the controlled power $P_{\rm cont}$ is calculated based on the SI mitigation capability η. Based on this model, the controlled power is calculated as

$$P_{\rm cont} = P_{\rm full}(1-\eta). \tag{15}$$

From (15), it is implied that since η varies from 0 and 1, $P_{\rm cont}$ varies from $P_{\rm full}$ to 0. The optimization problem for this approach can be written as

$$\max_{\tau} R(\tau) = R_0(\lambda,\tau) + R_1(\lambda,\tau) + R_2(\lambda,\tau),$$
$$\text{subject to } \mathcal{P}_d(\lambda,\tau) \geq \bar{\mathcal{P}}_d, \tag{16}$$

where $R_0(\lambda,\tau)$ and $R_1(\lambda,\tau)$ can be obtained using (12) and $R_2(\lambda,\tau)$ using (16). This approach allows us to make the fair comparison of the proposed approach with the CST approach.

ii. **Approach 2**: In this method, the controlled power is not based on the value of η and we optimize both parameters $P_{\rm cont}$ and τ. The secondary throughput optimization problem for this case can be formulated as

$$\max_{\tau, P_{\rm cont}} R(\tau) = R_0(\lambda,\tau) + R_1(\lambda,\tau) + R_2(\lambda,\tau),$$
$$\text{subject to } \mathcal{P}_d(\lambda,\tau) \geq \bar{\mathcal{P}}_d, \tag{17}$$

where $R_0(\lambda,\tau)$ and $R_1(\lambda,\tau)$ are obtained from (12) and $R_2(\lambda,\tau)$ from (14).

To solve the optimization problem (17), we take the following iterative approach:

1) For a fixed value of η, calculate the controlled power based on the first approach (Approach 1).
2) Based on the controlled power in step (1), calculate the optimum value of τ which provides the maximum throughput.

3) Increment the controlled power in step (1) by δ and calculate the value of total throughput R.
4) Repeat step (3) till the calculated throughput becomes less than or equal to the throughput in the previous iteration and note the corresponding controlled power as the optimum controlled power.
5) Using the optimum controlled power calculated in step (4), calculate R.

D. Analysis for Fading Channel

The aforementioned analysis does not include the effect of fading in the sensing channel. In this section, we include channel fading in the sensing channels while evaluating the optimization problems considered in Section VI-C. In this case, under the H_1 hypothesis, the expression for P_d without considering the effect of SI can be expressed as

$$\mathcal{P}_d(\lambda, \tau) = Q\left(\left(\lambda/\sigma_w^2 - |h|^2\gamma_p - 1\right)\sqrt{\frac{Tf_s}{2|h|^2\gamma_p + 1}}\right), \tag{18}$$

where h represents the zero-mean, unit variance complex Gaussian random variable. It can be noted that (18) reduces to (4) when $|h| = 1$, i.e., no channel fading. Similarly, considering the SI effect, the expression for P_d can be written as

$$\mathcal{P}_d(\lambda, \tau) = Q\left(\left(\frac{\lambda}{\sigma_{\mathrm{w}}^2} - \eta^2\gamma_{\mathrm{in}} - |h|^2\gamma_{\mathrm{p}} - 1\right)\sqrt{\frac{Tf_s}{2\eta^2\gamma_{\mathrm{in}} + 2\eta^2|h|^2\gamma_{\mathrm{in}}\gamma_{\mathrm{p}} + 2|h|^2\gamma_{\mathrm{p}} + 1}}\right). \tag{19}$$

Subsequently, the expressions for P_f in terms of the target P_d after considering the effect of SI can be written as

$$\mathcal{P}_f = Q\left(\left(Q^{-1}(\bar{\mathcal{P}}_d)\sqrt{2\eta^2\gamma_{\mathrm{in}} + 2\eta^2|h|^2\gamma_{\mathrm{in}}\gamma_{\mathrm{p}} + 2|h|^2\gamma_{\mathrm{p}} + 1} + |h|^2\gamma_{\mathrm{p}}\sqrt{Tf_s}\right)\frac{1}{\sqrt{2\eta^2\gamma_{\mathrm{in}} + 1}}\right). \tag{20}$$

Next, the analysis presented in Section VI-C is applied to obtain the corresponding throughput in the presence of channel fading. Then the results obtained with the optimization problems (16) and (17) while considering the effect of channel fading in throughput expressions are presented in Section VI-E.

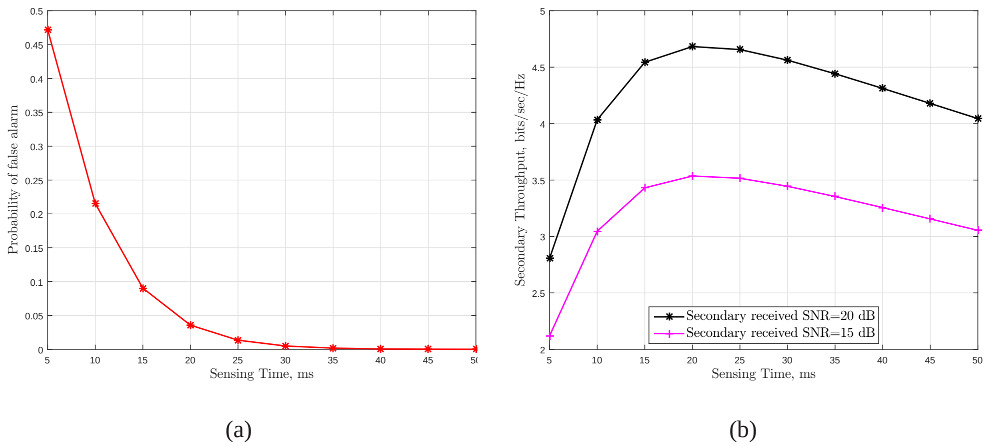


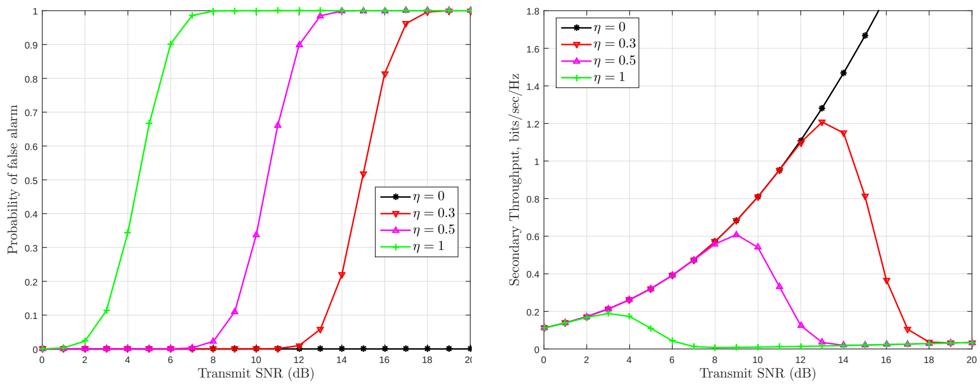
Fig. 9. (a) Probability of false alarm versus sensing time for the PST approach, primary received $\mathrm{SNR} = -20$ dB, (b) Sensing-throughput tradeoff for the PST approach, primary received $\mathrm{SNR} = -20$ dB.

E. Numerical Results

In this section, we present some numerical results for evaluating the performance of the conventional PST, CST and the proposed 2P-CST schemes. For this performance evaluation, we consider carrier bandwidth and sampling frequency to be 6 MHz. Let us consider $\mathcal{P}(H_1) = 0.2$ and the target detection probability be 0.95. In the presented simulation results, we consider a fixed channel attenuation of 10 dB for the channel between ST and the SR.

Figure 9(a) shows the probability of false alarm P_f versus sensing time τ for the conventional PST method. It can be observed that the value of P_f decreases with the increase in the value of sensing time and its value almost approaches zero at the value of $\tau = 35$ ms. In Fig. 9(b), we plot secondary throughput versus sensing time for the PST approach. From the figure, it can be noted that there exists a tradeoff between the secondary throughput and sensing time for the PST approach as noted in [22]. It can be further noted that the secondary throughput increases for the higher received power at the secondary receiver.

Figure 10(a) presents P_f versus transmit SNR for the CST approach for different levels of residual SI mitigation capability, i.e., η. It can be noted that when $\eta = 0$, P_f is almost zero for all values of the transmit SNR. However, for $\eta \neq 0$, P_f remains constant up to a certain value of SNR and then increases sharply with the increase in the transmit SNR, and this sharp increase occurs earlier (i.e., at lower values of the transmit SNR) for the higher values of η. This sharp



(a) (b)

Fig. 10. (a) Probability of false alarm versus transmit SNR for the CST method, primary received $\mathrm{SNR} = -20$ dB, $T = 0.2$s, (b) Power throughput tradeoff for CST method, primary received $\mathrm{SNR} = -20$ dB, $T = 0.2$s.

increase in the value of P_f after a certain value of the transmit SNR is due to the increase in the value of SI beyond the SI mitigation capability of the FD transceiver.

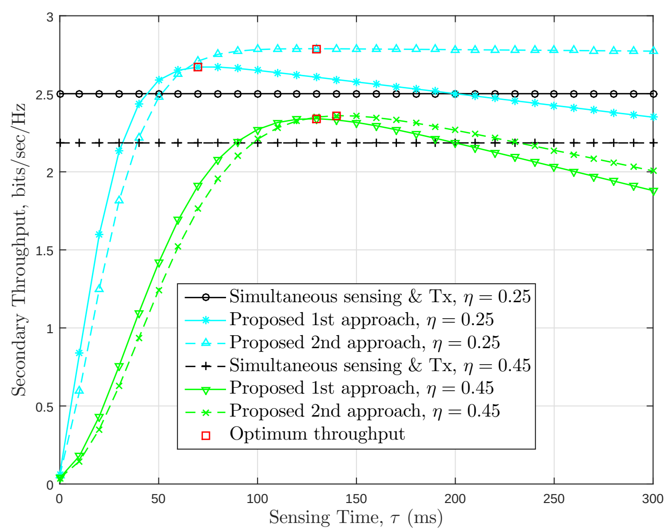


Fig. 11. Secondary throughput versus sensing time for the proposed methods, primary received $\mathrm{SNR} = -20$ dB, secondary transmit SNR (Full)$= 10$ dB, Frame duration $T = 0.2$s.

Figure 10(b) depicts the secondary throughput versus transmit SNR for the CST scheme for different values of η. It can be observed that for $\eta = 0$ i.e., perfect SI cancellation, the secondary throughput increases with the increase in the value of transmit SNR. However, in practice, it

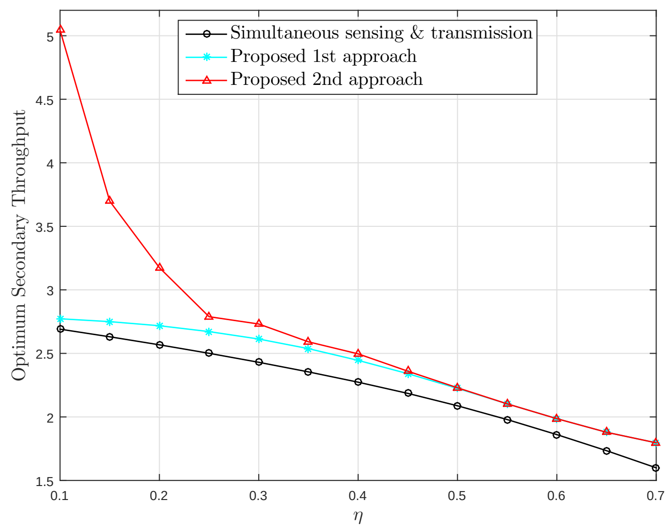


Fig. 12. Secondary throughput versus η for the proposed methods, primary received $\text{SNR} = -20$ dB, secondary transmit SNR (Full)$= 10$ dB, Frame duration $T = 0.2$s.

is impossible to completely suppress the SI and we need to take the residual SI into account. From Fig. 10(b), it can be noted that for $\eta \neq 0$, the secondary throughput first increases, reaches the maximum point and then decreases. As also illustrated in reference [25], this result clearly shows the tradeoff between transmit power and the secondary throughput in the presence of residual SI. With the increase in the value of η, the secondary throughput decreases due to the effect of SI and the optimal tradeoff point appears at lower values of SNR.

In order to analyze the performance of the proposed two approaches, we plot the secondary throughput versus sensing time in Fig. 11. It can be deduced that there exists a tradeoff between sensing time and the secondary throughput tradeoff as in the traditional PST approach. More importantly, the optimum value of throughput due to both approaches is higher than the throughput that can be obtained with the conventional sensing and transmission method. Furthermore, the optimum throughput for the second approach is higher than the optimum value of throughput with the first approach for the considered values of η.

In order to demonstrate the effect of η on the optimum throughput provided by the proposed two approaches and by the CST approach, we plot secondary throughput versus η in Fig. 12. From the figure, it can be noted that both approaches provide higher throughput than the conventional sensing and transmission approach. In particular, the proposed second approach provides higher optimum throughput than the first approach up to the value of $\eta = 0.5$ for the considered frame duration $T = 0.2$ s and beyond this value, the optimum throughput values of both approaches become the same. On the other hand, the first approach is simple and the second approach requires the iterative process to compute the controlled power. Thus, depending on the interference rejection capability of the FD transceiver and the complexity implementation requirement, we can make a suitable choice between the proposed techniques.

The above results were obtained without considering the effect of fading in the sensing channel. In order to analyze the performance of the proposed algorithms in fading channels, we generated a complex Gaussian sensing channel and then followed the analysis presented in Section VI-D to obtain the results shown in Figure 13. While comparing the cases without fading in Fig. 12 and with fading in Fig. 13, it can be noted that the trend of the curves is similar, however, the value of optimum secondary throughput is less in the presence of fading. Furthermore, it can be depicted that the gap between the achievable throughput with the simultaneous sensing and transmission approach and the proposed approach is larger in Fig. 13 than in Fig. 12, especially at the higher values of η.

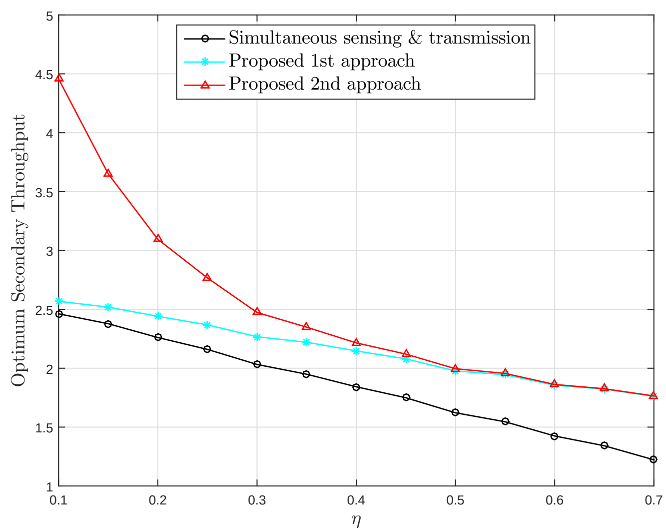


Fig. 13. Secondary throughput versus η for the proposed methods considering Rayleigh fading in the sensing channel, primary received SNR $= -20$ dB, secondary transmit SNR (Full)$= 10$ dB, Frame duration $T = 0.2$s.

VII. Research Issues and Future Directions

A. Primary Traffic Model

The performance of DSS networks operating in the opportunistic mode may degrade significantly due to the dynamicity of channel occupancy in the licensed channel since the PU may appear or leave a wireless channel at a random time. However, most of the FD-CR studies consider the scenario where sensing and transmission happen in one frame duration and the sensing result calculated in one frame is utilized to take the decision on the data transmission in the next frame. Therefore, the assumption that PU activity remains constant over the entire frame duration is required for this strategy, which may not be the case in practice. Although the frame duration can also be divided into small intervals and the decision can be applied more frequently, proper linkage with the realistic traffic model in the literature is missing. In the context of HD-CR, several existing works [152–154] studied the impact of dynamic PU traffic on the performance of a DSS network in various settings and have shown significant performance degradation in terms of achievable throughput and sensing efficiency. Besides, primary systems may carry different kinds of traffic such as bursty user traffic and more static backhaul traffic. In this context, it is crucial to have an accurate estimation of PU traffic/channel parameters and then to investigate the linkage between PU traffic distribution and the FD transmission strategies in such a way that available spectral opportunities can be utilized efficiently.

Acquiring spectrum occupancy information of the surrounding environment accurately within a required time frame is a critical challenge in opportunistic DSS networks. Although several existing works assume the prior knowledge about the spectrum occupancy information such as the state of a channel (idle/busy) and the received power, such a prior knowledge is difficult to acquire in practice and these parameters need to be estimated [97]. For modeling the PU activity, existing works mostly use ON/OFF models such as two state Markov model, Bernoulli and exponential models, and recently, the concept of using learning based PU modeling is getting attention in the literature [41, 155]. In practice, parameters related to the PU traffic/channel can be estimated by employing the following approaches: (i) statistical analysis of sensing measurements obtained from spectrum occupancy measurement campaigns [30], (ii) spectrum prediction models like hidden Markov model and Bayesian interference model [156], and (ii) Radio Environment Map (REM) which can be created either based on sensing information obtained from the sensor nodes or database information obtained from regulators/operators or both [32, 157].

In DSS networks, if SUs can acquire sufficient knowledge about the PUs' traffic distributions, various performance benefits can be obtained including the minimization of channel switching delay, interference minimization by predicting PUs' future behavior and also finding optimal PU channel sensing order [158]. Hence, the accurate estimation of the PUs' traffic by the SUs and fitting the estimated traffic into suitable probability distributions is crucial to enhance the efficiency of a DSS scheme. This traffic classification would also be beneficial to identify the strategy of individual licensees and to adapt the licensing rules accordingly in emerging LSA networks. Therefore, the combination of traffic estimation and classification with the FD approach is an interesting future research direction. Besides the variation in the PU channel state during the sensing period, the received energy at the SUs may change between adjacent observation windows due to the random arrival and departure of PU signals. In this regard, weighted spectrum sensing scheme [159], which uses larger weights to the new samples using a power function based on the corresponding sampling sequence as compared to the previous samples, seems promising for the FD CR to reduce the false probability and improve the energy efficiency.

B. Self-Interference Cancellation and Related Issues

As discussed earlier, the realization of FD-CR communications requires the combination of different types of SI mitigation techniques such as antenna cancellation, analog cancellation and digital cancellation, which usually require complex algorithms and costly hardware circuitry [21]. Furthermore, SI mitigation techniques should be able to operate efficiently for the scenarios involving high transmit power and wider bandwidth. In addition, the performance of digital SI cancellation techniques is constrained by the intermodulation distortion caused by a power amplifier, leading to the need of non-linear SI cancellation techniques [160]. The cancellation of non-linear components requires additional resources such as extra hardware, pilot overhead and higher computational power. In this regard, it is highly important to develop cost-efficient low-complexity SI mitigation algorithms to make FD-CR more realizable in practice.

In order to carry out SS with FD-CR having low SI rejection capability, it is crucial to distinguish the self-interfering signal from the PU signal to be detected. However, the simple and commonly studied ED technique cannot differentiate between a PU signal and a self-interfering signal. In this context, suitable waveform based techniques which can distinguish the PU signal characteristics from the self-interfering signal deserve further study. In addition, the consideration of real constellations is needed rather than the widely used assumption of Gaussian signalling [161]. Besides, multi-antenna based techniques such as spatial filtering can be investigated for distinguishing the two spatially separated transmissions. In addition, suitable training/calibration methods can be explored in order to have the proper modeling of the SI channels. Furthermore, one may exploit the spectral opportunities over a wideband spectrum to better distinguish the PU signal from the SI (for example, by learning the characteristics of the PU signal from the unused bands). Moreover, investigating the FD paradigm in the wideband context utilizing compressive sensing with the improved sidelobe suppression capability and adaptive power control is another interesting research direction. Furthermore, it should be noted that most of existing FD-based sensing works approximate self-interference as an additional noise but in order to find the detection performance accurately, one needs to model the distribution of SI by considering the SI channel effects. In addition, pilot signals utilized to estimate SI channel in the existing digital domain cancellation techniques will introduce delay and transmission overhead to the system [162]. In this direction, suitable SI channel estimation algorithms need to be developed by considering the aspects of delay and transmission overhead.

C. Energy-Efficient FD-DSS Systems

The FD-CR needs additional processing in order to combat the effect of SI, resulting in additional power requirement. Since the wireless terminal devices are limited in power, one of the requirements of the next generation wireless devices is to be as energy-efficient as possible. To this end, one may employ a CST scheme over the entire (or some part of the) frame duration and consider power control in order to limit the effect of SI. The main problem in this transmission strategy, however, is that the CR has to compromise its throughput due to the limitations in the power, leading to the power-throughput tradeoff where its optimal tradeoff solution is not known [25]. On the other hand, it could also be possible to utilize a multiple antenna FD-CR with separate arrays for transmission and reception with the use of appropriate beamforming/antenna selection strategies. Nevertheless, how to enable optimal single/multiple antenna FD energy-efficient transmission is an interesting future research direction.

Wireless energy harvesting from the surrounding RF environment is considered as a promising approach to enhance energy efficiency in 5G spectrum sharing networks [163]. In such energy harvesting based DSS networks, an SU can act as a relay for the PU and simultaneously harvest energy from the PU signals using an FD mechanism. Similarly, in the context of wireless powered communication network, FD can enable the hybrid access point to simultaneously broadcast wireless energy to the users in the downlink and to receive information from the users using time division multiple access in the uplink [164]. Moreover, it can also enable an RF energy harvesting-enabled wireless node to perform energy harvesting from the surrounding ambient environment and to perform uplink transmission at the same time. In this regard, it is an important research direction to study energy harvesting and simultaneous wireless and information transfer problems in combination with FD by considering the practical constraints such as energy storage capacity at the energy harvesting devices.

D. Imperfections in FD-DSS systems

As in the traditional HD CR, there can be several practical imperfections such as noise uncertainty, channel uncertainty, hardware imperfections, noise/channel correlation in the context of FD-CR communications [13]. The RF impairments occurring within the FD transceivers present one of the most significant challenges for the implementation of an FD-CR [130]. Various impairments such as phase noise in the local oscillators of the transmit and receive RF chains, power amplifier non-linearity, in-phase/quadrature imbalance and quantization noise limit the amount of active analog cancellation in the FD node. Out of these impairments, experiment results [165] have shown that the transmit and receive phase noise is the main bottleneck in achieving the desired level of SI cancellation at the FD node.

More specifically, these RF imperfections may impose limitations on the SI mitigation capability of the employed techniques. In the ideal scenario, it may be possible to estimate the linear channel experienced by the SI signal and then equalize the total received signal by generating a corresponding cancellation signal to be subtracted from the received signal [166]. However, practical impairments may prevent the usage of such a simple procedure, thus presenting a crucial challenge in achieving a sufficient level of SI mitigation. Furthermore, due to the large difference in the powers of the transmitted signal and the received signal of interest, especially when operating near to the sensitivity level of the receiver, even relatively mild distortion of the overall signal may lead to a drastic decrease in the final SINR. In this regard, practical imperfections including the hardware imperfections need to be taken into account while designing the FD-based systems. Furthermore, development of a common framework which can combat these imperfections requires further studies.

E. Coordination and Synchronization in Multiuser FD-DSS Networks

Most of the existing FD-DSS works in the literature consider a single SU scenario. However, in practical FD-DSS networks, multiple SUs need to share the detected vacant spectrum at a time in order to maximize the spectrum utilization efficiency. Moreover, DSS systems in practice should be operated based on the collective decision process since the decision coming from one node may not be reliable in practice. This operation requires effective coordination among various network nodes as well as between two networks. In this regard, how to enable coordination among the nodes of FD-DSS networks in making reliable decision about the dynamic spectrum utilization is one crucial to be considered in future research. Besides, if the transmissions of multiple SUs over a radio channel are not synchronized, the aggregate interference at the PR will be affected. Furthermore, there may arise interference at the FD cognitive receiver due to transmissions from other co-channel cognitive transmitters, thus reducing the overall achievable throughput of the secondary network. In this regard, it is crucial to investigate suitable cross-layer mechanisms and distributed solutions which can optimize sensing time, and the transmit power in order to minimize the aggregate interference at the PR as well as to minimize the collision probability with the transmissions from co-channel SUs while maximizing the overall secondary throughput. One potential approach to apply FD in multiuser wireless networks with minimum synchronization burden could be to employ it in more static-type of networks such as point to multi-point wireless backhaul networks.

F. FD-based Concurrent Sensing and Transmission

FD-based CST scheme can significantly enhance the sensing efficiency and the achievable secondary throughput of interweave DSS systems. However, several challenges need to be addressed in order to employ FD-based CST in practical DSS systems. The residual SI causes the problem in achieving the full capacity of FD-based CST and suitable SI mitigation techniques should be investigated for a particular DSS application scenario. Also, it is difficult to distinguish SI signal and PU signals at lower SNR values in practice using a simple energy statistics-based technique and hence suitable waveform-based techniques need to be developed. Furthermore, suitable beamforming and antenna selection techniques can be investigated to mitigate the effect of SI in practice.

Although no sensing-throughput exists in FD-based sensing, there exists a power-throughput tradeoff and suitable transmission strategies need to be investigated to balance this tradeoff. Furthermore, in dynamic environment with varying PU traffic statistics, FD-based sensing suffers from frequent sensing errors [81], and therefore, suitable sensing and transmission strategies should be investigated by taking PU traffic/channel statistics into account. For the case of sensing and transmission in separate antennas, the affect of SI will be reduced but it may create the problem of channel imbalance problem [109]. In addition, the performance of FD-based CST is also affected by hardware impairments such as I/Q imbalance and novel techniques need to investigated to compensate their effects.

G. *FD-based Concurrent Transmission and Reception*

As discussed in Section IV, FD-based CTS can provide significant advantages in underlay DSS systems and cooperative relaying systems. However, there are several challenges to incorporate FD-based CST schemes in practice. Similar to the CST case, the main limitation of FD arises due to residual SI, and suitable techniques need to be investigated to mitigate the impact of SI for enabling simultaneous transmission and reception in a single channel. Another challenge in underlay DSS application scenario is to provide sufficient protection to the PRs. For this purpose, primary interference constraint should be taken into account while applying resource allocation techniques, Also, learning interference channel gain between ST and PR and the interference constraint of the PRs is also another challenge to be addressed. One possible approach to learn interference channel is to employ a suitable probing scheme at the ST and to learn PU reverse link feedback by analyzing different parameters of the reverse PU link such as binary ACK/NACK packets and modulation and coding scheme [167].

Similarly, in the context of cooperative relaying system, residual SI and the cross-talk interference caused due to imperfect channel estimation may impact the performance of FD-based CTR. Furthermore, it is a crucial challenge to reduce cooperative overhead required in exchanging channel state information. Moreover, combatting additional interference caused by the FD operation at the relay and selecting the best relay to satisfy a certain performance metric are other challenges to be addressed. In this direction, future works should focus on developing low-complexity channel estimation algorithms, interference mitigation techniques and relay selection strategies in FD-based cooperative relaying systems.

H. *Efficient MAC Layer Protocols*

Although it may be possible to achieve almost double capacity gain for a single wireless link in theory, the additional interference and imperfect SI cancellation degrades the achievable throughput of a wireless system in practice. Furthermore, in large-scale networks, the benefits of FD are significantly affected due to various factors such as spatial frequency reuse and asynchronous contention [87]. Therefore, it is crucial to design efficient MAC protocols for FD systems by taking these aspects into account in order to be able to translate the physical layer capacity enhancement to the gain in the network level throughput. In this direction, one promising approach seems to design an adaptive MAC protocol which can allow a node to decide on its FD or HD mode of operation based on the surrounding interference with the objective of achieving some performance objective such as the overall network throughput [168]. Furthermore, in FD-DSS networks, the nodes can operate in different transmission modes such as CTS, CTR, SO, and CS as highlighted in Section II-D.1 and it is crucial to design an adaptive MAC which can select one of these modes based on channel conditions and PU traffic model.

Moreover, in FD-DSS scenarios, deafness caused due to directional antennas may result in the collision in the transmissions of two co-channel transmissions since other users will not be able to detect these transmissions. In this case, an efficient centralized MAC controller can be employed in order to avoid such collisions [49]. Another research channel in FD-enabled wireless networks to address the fairness caused due to non-uniform distribution of users in a coverage area and also the unbalanced traffic distribution. In this direction, efficient and fair MAC protocols need to be developed which can allocate the channel access opportunities to all the nodes in a coverage area in a fair manner [49].

VIII. Conclusions

One promising way of addressing spectrum scarcity problem in future wireless networks is to enable the dynamic sharing of the available spectrum among two or more wireless systems either in an opportunistic way, i.e., interweave or with interference avoidance approach, i.e., underlay. The level of spectrum utilization achieved with dynamic spectrum sharing mechanisms can be further enhanced using full-duplex technology. In this regard, starting with the main features of FD technology and its importance in 5G DSS wireless systems, this paper has provided an overview of the existing works which employed FD principles in DSS systems. Furthermore, the potential technologies which can enable FD operation in DSS systems by mitigating the effect of SI have been described. Subsequently, considering a power control mechanism as an important enabler, a novel 2P-CST transmission framework for the FD-based DSS system has been proposed and its performance analysis has been carried out in terms of the achievable secondary throughput. It has been concluded that the proposed 2P-CST FD transmission strategy provides better performance in terms of the achievable throughput than the conventional PST and CST techniques. Finally, some interesting open issues for further research have been discussed with the aim of accelerating future research activities in this domain.

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