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A–Z overview of the in-band full-duplex cognitive radio networks

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ABSTRACT

Wireless communications have gained huge attention over the past decades because of continuously increasing demands. The main goal of all wireless network designers is to utilize the spectrum efficiently. Many techniques have been introduced to tackle this. One of these techniques is Cognitive Radio Technology, which allows unlicensed users to utilize the neglected spectrum by operating alongside with the licensed users. In-Band Full-Duplex (IBFD) technology is another technology that has allowed wireless devices to communicate simultaneously in the same frequency band, which also efficiently increased the utilization of the spectrum. The implementation of these two technologies in unison has been attracting researchers' interests in recent years. The main concentration of this work is to survey IBFD Cognitive Radio Networks (IBFD–CRNs) from the perspective of each layer, namely the Physical (PHY), Medium Access Control (MAC) and network layers. The key objective of this work is to help the research community in understanding the big picture of this field, starting from the very basics of cognitive radios, then going through recent advances of IBFD communications with coverage of several Self Interference Cancelation techniques and finally ending with discussing the basic concepts of IBFD–CRNs along with providing some future research directions.

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1. Introduction

Wireless networks have grown tremendously over the past few years and are expected to continue to grow. Nowadays, wireless connections can be implemented anytime and anywhere with seamless mobility and coverage, i.e. users are able to remain connected while wandering between different networks. All of this was achieved due to the continuous development of wireless communication technologies [1,2]. Some of the advanced wireless communication technologies used in modern networks are Orthogonal Frequency Division Multiplexing/Orthogonal Frequency Division Multiple Access (OFDM/OFDMA), Multiple Antenna Systems and Massive Multiple Input Multiple Output (MIMO), Millimeter Wave Communication (a.k.a. Mm-wave communication), Relay Networks, femtocells, and Cognitive Radios (CR) [3–6].

Obviously, wireless communication systems used to be designed to operate with orthogonal resources, such as time, frequency or code (e.g., OFDM). Fascinatingly, system designers are shifting their interest towards new non-orthogonal transmission modes, such as Non-Orthogonal Multiple Access (NOMA), non-orthogonal Filter Bank Multi Carrier (FBMC) or In-Band Full-Duplex (IBFD). This is because the Self-Interference (SI) problem, that faces these modes, is now canceled with a reasonable performance. Remarkably, the SI caused in IBFD mode is lower than the SI caused in other non-orthogonal modes, therefore IBFD has gained much more interest.

The mix of IBFD and CR technologies is an interesting topic nowadays, because it can support internet-of-things and handle the spectrum scarcity problem. Specifically, CRs use dynamic spectrum allocation, which will allow the devices to connect without consuming the spectrum as in fixed spectrum allocation. Additionally, using IBFD–CRs in internet-of-things will double the spectrum utilization by operating in one spectrum band per device. Such advantages represent the motivation behind this work.

In general, a CR senses the spectrum, determines the vacant frequency bands, dynamically changes its operating parameters, and then uses the vacant bands to communicate with other CRs. Such capabilities allow the CR to operate in licensed and unlicensed bands. This therefore can help the CR to efficiently utilize the spectrum, i.e., it fills the holes of the spectrum without requiring an extra band to operate. Moreover, the unlicensed bands do not belong to any particular service or user, while the licensed bands refer to the spectrum bands registered to specific wireless services or applications.

IBFD technology allows the transmitting and receiving terminals of a device to operate instantaneously in the same frequency band. Therefore, theoretically, using IBFD would double the spectrum utilization, i.e., the same spectrum band will be used by each device, instead of two bands, so other vacancies will be left for other devices to use. However, the main challenge facing this technology is SI, which needs to be canceled in order to use IBFD technology.

SI-Cancelation (SIC) can be achieved using several passive and active techniques. Passive techniques are related to antenna design whereas active techniques operate inside the receiving terminal and they are divided into analog radio frequency (RF) cancelation (done before discretizing and digitizing the received signal) and digital cancelation (operates on the digital signals).

Furthermore, employing IBFD technology in Cognitive Radio Networks (CRNs) allows each unlicensed user to sense the spectrum while transmitting data or transmit and receive data instantaneously. Thus, in the first case, sensing errors will decrease and the spectrum will be efficiently utilized, particularly, reducing the false alarms in the sensing process will definitely allow the CR to use more of the vacant spectrum without letting it go to waste (cleared in Section 4.2.2). In the second case, the throughput of the CRN will increase.

IBFD–CRNs differ from other IBFD networks by the flexibility in the spectrum utilization, i.e., IBFD–CRNs dynamically use any vacant spectrum band for each device rather than allocating a specific band with no changes. This reduces the number of allocated spectrum bands in the long run and allows various devices to use the same spectrum band over and over.

To the best of our knowledge, there is no prior survey similar to ours. In particular, the amount of information provided in this work with this detail have not been surveyed in one place before. Additionally, the flow of this work is compatible for beginners, moderate, and professional readers. With that being said, the existing surveys related to specific subjects of this work are provided in each subject's sub-section.

The general structure of this work is summarized in Fig. 1. In Section 2, the basics of Cognitive Radios are explained in order to provide a solid understanding of how the whole cognitive radio concept works. Each important concept in Half-Duplex CRNs (HD-CRNs) is then discussed to help understand the connection between the old HD mode and the new IBFD mode of operation in CRNs. In Section 3, the motivation, advantages, applications and challenges of IBFD communications are discussed along with the SIC techniques used to overcome the main challenge of IBFD. Section 3 is going to answer the following questions: "What is IBFD?", "Why IBFD was not used before this point?" and "Why would IBFD be used in CRNs, especially now?" In Section 4, the concepts of IBFD–CRNs are covered from the perspective of each layer. In the Physical (PHY)-layer, SIC considerations in IBFD–CRNs are discussed, PHY layer spectrum management protocols and spectrum sensing techniques are then reviewed. Several spectrum access protocols in the Medium Access Control (MAC) layer are discussed. Additionally, a few considerations regarding the network layer in IBFD–CRNs are discussed. As a final point, Section 5 provides some recommendations for future research work. It cannot be missed out to be mentioned that all abbreviations used in this work are well-defined in Table 1.

2. Fundamentals of half-duplex cognitive radios

Regulatory bodies in different countries, such as the federal communications commission, have assigned a specific range of the radio spectrum for each wireless service. The users of each licensed wireless service are called licensed or Primary users (PUs). Due to ever-increasing demands on wireless services and applications, the ranges of the radio spectrum assigned to some of these applications are becoming very crowded with users. Spectrum ranges of other applications have few users [7,8]. Ironically, this led to the predicament that mobile users have no space in the spectrum to transmit, all the while some ranges of spectrum are not fully utilized. This spectral inefficiency was conquered with the use of cognitive radio technology, which was first introduced in 1999 [9,10]. It is worth mentioning that the first worldwide wireless standard based on cognitive radios using the TV spectrum was in 2005; the IEEE 802.22 [11].

Table 1
Abbreviations list and definitions.

Abbreviations	Definitions	Abbreviations	Definitions
5G	Fifth Generation	LBT	Listen-Before-Talk
ADC	Analog-to-Digital Converter	NOMA	Non-Orthogonal Multiple Access
AF	Amplify and Forward	MAC	Medium Access Control
AP	Access Point	MIMO	Multiple Input Multiple Output
ARQ	Automatic Repeat request	OFDM	Orthogonal Frequency Division Multiplexing
BS	Base Station	OFDMA	Orthogonal Frequency Division Multiple Access
CR	Cognitive Radio	PHY	Physical
CRNs	Cognitive Radio Networks	PU	Primary User
CSI	Channel State Information	QoS	Quality of Service
CSS	Cooperative Spectrum Sensing	RF	Radio Frequency
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance	RSI	Residual Self-Interference
DSA	Dynamic Spectrum Access	RTS/CTS	Request-To-Send / Clear-To-Send
FBMC	non-orthogonal Filter Bank Multi-Carrier	SDR	Software Defined Radio
FD	Full-Duplex	SI	Self-Interference
FDD	Frequency Division Duplexing	SIC	Self-Interference Cancelation
FDTR	Full-Duplex Transmit and Receive	SNR	Signal-to-Noise-Ratio
FDTS	Full-Duplex Transmit and Sense	SU	Secondary User
FFT	Fast Fourier Transform	TDD	Time Division Duplexing
HD	Half-Duplex	VoIP	Voice over Internet Protocol
IBFD	In-Band Full-Duplex	WLAN	Wireless Local Area Network
LAT	Listen-And-Talk	WSNs	Wireless Sensor Networks

A Cognitive radio can be described as an enhancement of the Software Defined Radio (SDR) concept [1]. An SDR system is a radio communication system which can change its operating parameters, i.e. it can tone to any frequency band and operate with any modulation across a large frequency spectrum. An SDR system is actually a programmable hardware that is controlled by a software.

2.1. Characteristics of cognitive radios

CR technology permits unlicensed (cognitive or secondary) users (SUs) to make use of the spectrum vacancies in a certain region and at a certain time, without or with limited interference with the PUs. Each cognitive user has a transceiver, which must include radio environment awareness and spectrum intelligence [7,8,12]. Spectrum intelligence is the ability to learn about the spectrum environment (a.k.a. cognitive capability) and adjust the transmission parameters accordingly (a.k.a. reconfigurability) [13].

Fig. 2 illustrates the typical CR duty cycle, which consists of four main processes [8]. They can be shortly described as the following:

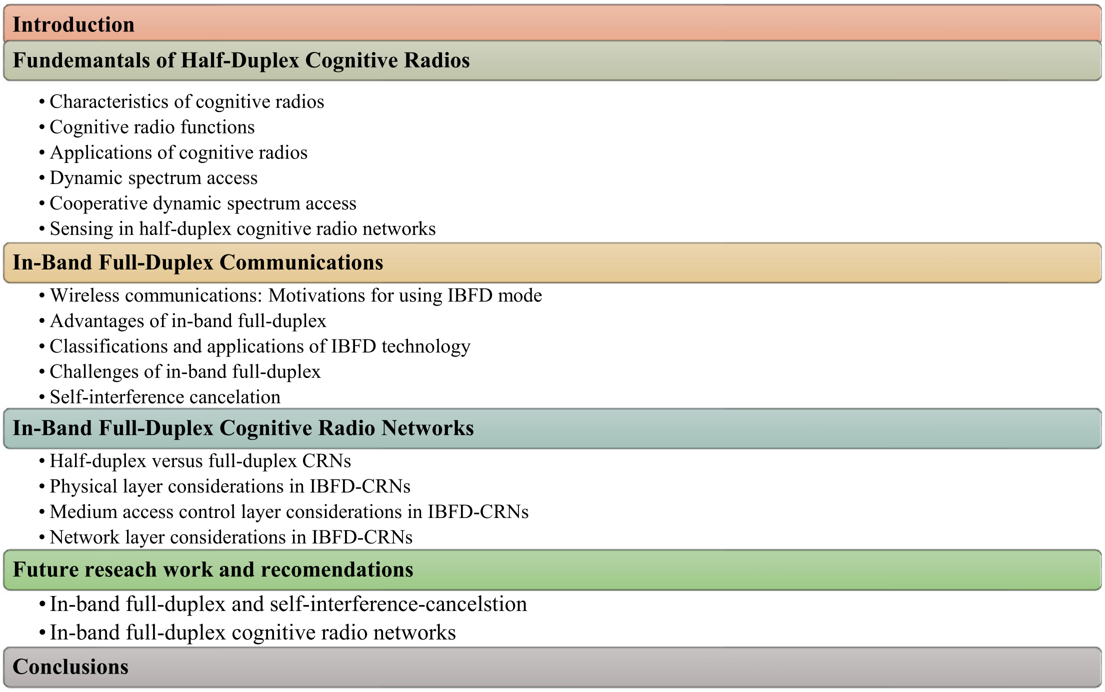

Fig. 1. The structure of this work.

(1) *The sensing process*
Detecting spectrum white spaces by monitoring the radio environment.
(2) *The analysis process*
Characterization of the radio environment.
(3) *The reasoning process*
The process in which the reaction strategy is determined.

- Selecting best new operating parameters, e.g. frequency, power, and modulation type.
- Finding when to use the spectrum and when to vacate it, e.g. some SUs leave the spectrum when the primary user is active.
- Coordinating with other users to access the spectrum.

(4) *The adaption process*
The process of transmitting to the new operating parameters.

2.2. *Cognitive radio functions*

There are functions that support the cognitive cycle, namely: Spectrum sensing and analysis, Spectrum management and handoff, and Spectrum allocation and sharing [8]. These functions are categorized from a different perspective, according to [2] and [14], as the following: spectrum sensing (finding spectrum white spaces), spectrum decision (selecting the best operating parameters), spectrum sharing (cooperating with other users), and spectrum mobility (leaving the spectrum or changing the operating parameters according to PU's activates).

In a given network, CR nodes may have different levels of cognitive capabilities or all of these nodes may have the same cognitive capability [15]. Therefore, designing a full cognitive radio network can be very challenging. That is because there are several system components that need to be considered when designing cognitive radio networks. Some of these system components are: PHY layer signal processing, MAC layer spectrum management, and network layer routing and statistical control. All of this has led to a different categorization of the CR functions according to which layer these functions are in; PHY, MAC, or network layer [15]. This classification is added to the processes of the cognitive cycle in Fig. 2. In addition, it is illustrated thoroughly in Fig. 3 as discussed in the following text.

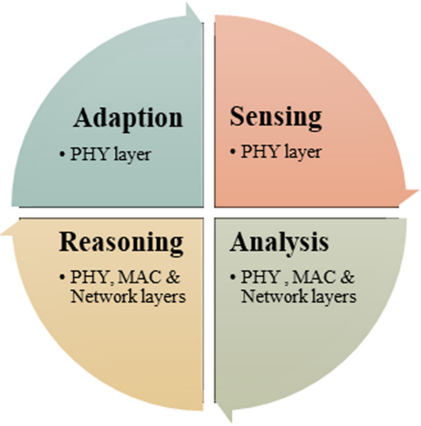

Fig. 2. Cognitive cycle from [8] with layered classification from [15].

2.2.1. *In the physical layer*

Spectrum sensing allows CR users to identify spectrum gaps (i.e. available channels), while environmental learning helps the CR users to get radio environment knowledge at a higher level, i.e. CR users will know the channel-state information (CSI) or the channel gain from the CR transmitter to the primary receiver [13]. These operations provide the basic information for the cognitive spectrum access that is carried out through the transceiver optimization and reconfiguration function.

2.2.2. *In the medium access control layer*

The sensing scheduling and the spectrum-aware access control functions are managed by the sensing-access coordinator. More specifically, the spectrum sensing scheduler manages the sensing operations, while the spectrum-aware access control manages access operations to the recognized spectrum gaps. The sensing-access coordinator manages

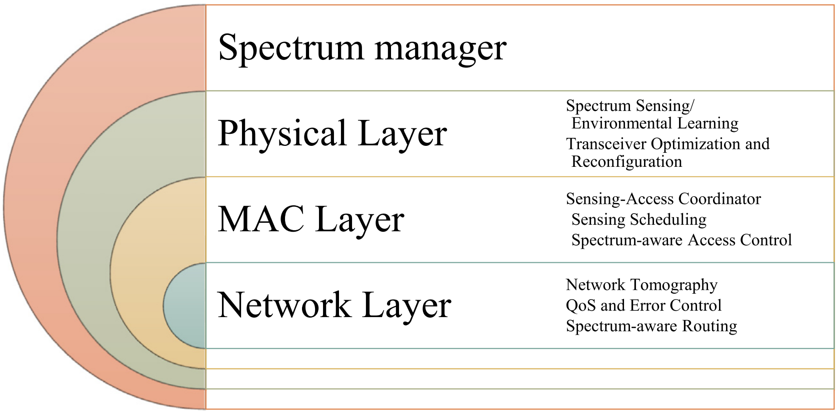

Fig. 3. Functions of the Cognitive Radio, classified based on the layers [15].

these operations in a timely basis by balancing between the sensing duty and the spectrum access opportunity that a CR user might get.

2.2.3. In the network layer

There are three important functions in the network layer. These functions are the network tomography, quality of service (QoS) and error control, and spectrum-aware routing [7,15].

The network tomography is the process of sensing traffic patterns of the primary and the coexisting networks; because traffic patterns are important to understand the utilization of the network from a packet-level point of view and they are important for the routing design.

QoS, error, congestion and topology controls are the main requisites for a successful CRN. Statistical controls can be used to handle these requisites over CRNs that have opportunistic links. Furthermore, the node-to-node availability statistics, the delay control [16] and the statistical QoS control [17] are the practical replacements of the end-to-end services in a CRN. Moreover, these statistical controls can be used to build the tomography of the CRN in order to obtain some information that is useful for routing [16]. For instance, cooperative relays are usually associated with node-to-node availability statistics, which can be measured by observing the history and the statistics of the successfully transported packets over a specific cooperative relay path. Additionally, since explicit propping packets or implicit traffic packets are always transmitted over multiple links in cooperative networks, a CRN tomography can be created using the node-to-node availability statistics. In summary, the tomography of a CRN and the statistical controls assist the source node in estimating the probability of successfully transmitting packets over a group of possible cooperative relay paths, based on the reception historical record of the destination node [15]. It is worth mentioning that optimization of lower levels and cross-layer processes in the viewpoint of QoS control have been studied in [18–20].

Generally, the spectrum-aware routing function has two problems to handle [15]. The first problem is finding out how to make the routing algorithms and protocols aware of the dynamically available spectrum gaps and how to make these algorithms adapt their operations accordingly. Consequently, the second problem is finding out how to make these algorithms interact with dynamic spectrum access routines in order to find routing paths with minimum interferences.

Ultimately, the spectrum manager function combines all three layers and handles accessing vacant spectrum dynamically and efficiently.

Other characterizations of the CR functions are also available in [7,21].

2.3. Applications of cognitive radios

CR technology can be used in many applications, depending on the network architecture and the spectrum access technique [21]. In general, CRN architectures can be categorized as infrastructure-based (i.e. centralized) networks or ad-hoc (i.e. distributed) networks [15, 22,23]. In addition, spectrum access techniques can be concurrent or opportunistic [1]. Some of the CR applications discussed in the literature are: smart grid networks [24–30], public safety networks [31], Wireless Sensor Networks (WSNs) [32–35], cellular networks [36–46], high-speed vehicle networks [47–52], unmanned aerial vehicles [53] and multimedia applications [54,55]. Each application focuses on some specific network resources such as transmission time slots, transmission power, spectrum white space, sensing nodes, sensing channels and the required throughput. The following text summarizes some of these applications.

Smart grid networks considered wireless communications to support the required transmission distance variance, as the customers are not all at the same distance from the power providing company. Furthermore, CRs were considered in such networks in order to efficiently utilize the spectrum in the customer's area.

Public safety networks use CRs to provide reliable and stable communications under any circumstance.

WSNs can employ CR technology to dynamically use the available spectrum, thus avoiding congestion and interference with other networks in the area.

In cellular networks, CR technology can be employed in the Base Stations (BSs) to collaborate with the TV network in order to access the vacant spectrum. Furthermore, CR technology alongside with OFDM can be used in relay-based cellular networks in order to increase the capacity and coverage of cells while efficiently utilizing the spectrum and increasing the throughput of the system.

High speed vehicle networks use CRs to cope with the rapidly changing channel availability.

Multimedia applications use CR technology in order to provide extra bandwidths to meet their huge demands. Additionally, multimedia applications have the ability to be supported by any CR-based network such as public safety, CR-WSNs, CR-cellular networks and others.

2.4. Dynamic spectrum access

Dynamic spectrum access (DSA) (or white space utilization as in [2]) can be defined as a technique in which the operating spectrum of a radio network can be selected dynamically from the existing spectrum [31,48]. DSA has been proposed as a policy to allow the SUs and the PUs to coexist in the same frequency band in order to utilize the valuable spectrum in a better way [9,56].

Generally, SUs access the spectrum dynamically by one of two methods [1], which are explained in the following text as seen in Fig. 4.

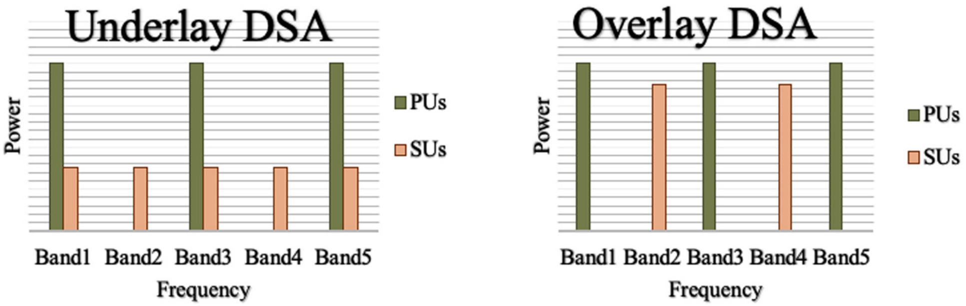

Fig. 4. Underlay and Overlay spectrum access, [1].

2.4.1. Spectrum underlay

In spectrum underlay [57], the SUs transmit in the spectrum band while PUs are active, but each SU's transmitter is governed by the PU's interference temperature limit (i.e. the noise tolerance level of the PU). This method of spectrum access is also called concurrent spectrum access as in [15], and spectrum sharing as in [16].

2.4.2. Spectrum overlay

In spectrum overlay [57,58] the SUs transmit only when the PUs are not transmitting in the spectrum band. Hence, there is no interference temperature limit applied on the SU's transmitter, but the SU definitely needs to sense the unused spectrum (i.e. spectrum holes) and reconfigure its transmission parameters accordingly to be able to transmit without any interference with the PUs. This method of spectrum access is also referred to as opportunistic spectrum access as in [15] and interweave model as in [59]. Furthermore, the pioneering work that proposed this approach of spectrum access can be found in [60] and [9], in which it was called spectrum pooling.

At this point, it is worth mentioning that [2] referred to the interweave model of DSA in IBFD–CRNs when the spectrum band is not used by any PU at a certain time. This model was used in the Listen-And-Talk (LAT) PHY-layer protocol [61] (see Section 4.2.2.2). Furthermore, the interweave model in [2] is said to be different from the aforementioned overlay model as it does not require the SUs to change their transmission parameters to avoid interfering with the PUs. Instead, the SUs have to suspend their transmissions while PUs are using the frequency band because the frequency band is the same for both primary and secondary networks (i.e. the separation between SUs and PUs is in time domain not in frequency domain).

2.5. Cooperative dynamic spectrum access

There are two types of cooperative networks for multiple SUs [15, 22]. Namely, the centralized and the distributed scenarios.

2.5.1. Centralized networks

In the centralized CRNs, an Access Point (AP) can be used as a central controller for all SUs [15]. The central controller is used to do the following:

- Sense the vacant spectrum or receive the sensing results from all SUs in the network, depending on the network's design.
- Decide which SU is allowed to use the spectrum and at what time it can use it.
- Assign the transmission properties for the SUs, e.g. the transmission power and frequency.

Compared to distributed networks, the centralized networks allow the SUs to have a high data rate. Besides, they guarantee that the sensing process is reliable because of the central controller. Therefore, the collisions can be avoided but they cannot allow the SUs to communicate directly without the central controller.

2.5.2. Distributed networks

In the distributed networks, all SUs in the system use the same spectrum and each SU senses the spectrum and tries to access the channel separately. Additionally, distributed networks do not have any central controller to manage the SUs channel access. This can result collisions to occur between SUs, therefore, multiple access protocols must be used to manage the spectrum access process for every SU. Multiple access protocols are known as MAC protocols to declare that the MAC layer is managing these protocols.

There are two classes of MAC protocols, the carrier-sense-based and the non-carrier-sense-based protocols. The former is denoted by the Carrier Sense Multiple Access (CSMA) protocol and the latter is denoted by the ALOHA and the Slotted ALOHA protocols [57].

The MAC protocols used in HD-CRNs have been surveyed thoroughly in the literature and therefore will not be discussed in this work, as the focus here is on IBFD–CRN. For more details about various MAC protocols used specifically in HD-CRNs, interested readers can refer to [15] and [9].

2.6. Sensing in half-duplex cognitive radio networks

Spectrum sensing is one of the most essential parts in CRNs. It is defined as the process that finds the available parts of the licensed spectrum band [21]. Sensing technique's performance can be measured in terms of many parameters such as sensing delay and throughput of SUs. The performance parameters are set based on the application requirement and the available bandwidth [54]. As an example, to achieve better performance in broadband (or high-speed) communications, sensing delay must be minimized in order to obtain higher SU throughput [21].

Each communication layer has specific duties concerned with the sensing process as cleared in [15], (see Section 2.2). Spectrum sensing in both the PHY and the data-link layers has been thoroughly studied in [62]. The following text provides a summarized discussion of the sensing process in the PHY and the Data-Link layers separately.

2.6.1. Physical layer sensing

Sensing in the PHY-layer focuses on recognizing the signals of PUs efficiently in order to detect their presence in the channel. The previously studied PHY-layer sensing methods are divided into narrowband and wideband sensing [63]. Narrow band sensing is widely common, and is divided into five methods: energy detection, matched filter, cyclostationary feature detection, covariance-based detection [64] and machine learning based sensing [65]. Some sequential narrowband spectrum sensing techniques were also studied in the literature. One of which is the sequential shifted chi-square test [66], which reduced the sensing delay by decreasing the average number of samples in each sensing period compared to the energy detection technique which has a fixed number of samples. Another technique that uses a sequential probability ratio test for cooperative sensing was proposed in [67].

Furthermore, some studies focused on providing sensing techniques that support multimedia applications [54]. For time critical applications, authors of [81] proposed a QoS-aware sensing technique. To

Table 2
A summary of recent advances in wide band spectrum sensing.

Category		Description	References	Main contribution
Nyquist-based sensing	Wavelet-based detection	Wavelet transform is used to categorize the edges of a received signal that occupies several bands. Then, sequentially, the irregularity structure of each band is found by wavelet transform after getting the power spectral density	[68]	Introducing an improved wavelet-based algorithm that relies on normalizing the power spectral density then scaling the wavelet transform coefficients using non-linear algorithms in order to increase the accuracy
			[69]	Considering low signal-to-noise-ratio values when performing wavelet-based spectrum sensing relying on finding the edges with continuous wavelet transform
	Multi-band joint detection	Jointly sensing several bands rather than one band at a time using an RF front end, serial to parallel converter and a bank of narrow band-pass filters. Then, energy detection is applied on all the bands together	[70]	Introducing the first multi-band joint detection which relies on exploiting the hidden convexity of the optimization problem that represents the sensing process
			[71]	Introducing a spatial-spectral joint detection technique that maximizes the throughput while considering constrains on the interference to the PUs and handling the channel fading problem with spatial diversity
	Filter bank detection	Sensing several bands by estimating the power spectral density of each band then using energy detection. The bands are separated using a poly-phase demonstration of a prototype filter that implements band-pass filters	[72]	Introducing a two-stage spectrum sensing technique that uses a finite impulse response filter and a frequency response masking filter to implement a cosine modulated filter bank
			[73]	A cosine modulated filter bank with spline function is designed for spectrum sensing using Kaiser window function to reduce the complexity and increase the accuracy compared to other wide-band sensing techniques
Compressive sensing		Compressive sensing recovers the sparse signal using few measurements. This is done by three main processes: sparse representation, measurement, and sparse recovery. The first process projects the signal on a suitable basis to make it sparse. The second process multiplies the signal by a measurement matrix. The last process recovers the sparse signal. Then, the sensing process is conducted on the recovered signal	[74]	An estimation of the sparsity order is presented, which uses a very small number of samples found by data fitting. This method is helpful for designing compressive samplers
			[75]	Introducing a compressed detector that senses the compressed measurements without reconstructing the sparse signal. It uses energy detection and handles the measurements with discrete cosine transform
			[76]	Reducing the computational complexity of compressive sensing by introducing an algorithm that works without reconstructing the entire signal
			[77]	Introducing a sensing method that is similar to filter bank detection but with a smaller number of ADCs. It exploits the statistical properties of the samples without reconstructing the signal
			[78]	Introducing an adaptive spectrum sensing algorithm that reconstructs the signal from sub-Nyquist samples, but it terminates the constructing process dynamically when the recovered parts are satisfactory
			[79]	Introducing a hybrid technique that combines compressive sensing with a geo-location database stored at each SU in a distributed CRN. They used an algorithm that reduces the computational complexity of wide-band sensing
			[80]	Adopting an algorithm for compressive sensing with a geo-location database, while ensuring accurate detection with the least number of measurements. They modified a subspace augmented greedy algorithm

support real-time applications, a cooperative energy-detection-based sensing technique was proposed in [82], (see Section 2.6.3).

Moreover, wideband sensing techniques are divided into two categories: Nyquist-based and compressive wideband sensing [63]. The first type contains three methods: wavelet-based [68,69], multi-band joint [70,71], and filter bank detection [72,73]. However, the second type [74–80] has two methods: blind and non-blind compressive sensing, based on the previous knowledge of the received signals parameters.

Wideband sensing is considered a promising topic, and many researchers are studying it nowadays. Specifically, compressive sensing; since it reduces the sensing delay and the number of samples required to efficiently detect the PUs, compared to Nyquist-based sensing. Previously, various wideband sensing techniques relied on dividing the wide band spectrum into multiple narrow bands and they performed the sensing process sequentially. However, this comes with the price of consuming more time for spectrum sensing. Fortunately, a summary of some recent wideband sensing techniques is provided in Table 2. As it is widely common in HD-CRNs, Narrow band sensing is not described in this context except in IBFD–CRNs. Interested readers can refer to [63].

A general classification of sensing techniques can be found in [2, 8,14,15]. In this classification, if the primary transmitter is being detected, then this type of sensing is called indirect sensing. However, if the primary receiver is being detected, then it is called direct sensing. Lastly, if the sensing process is concerned with the interference temperature limit of the PUs, then this type of sensing is called interference temperature management. Under this general classification, the aforementioned sensing techniques are considered as part of indirect sensing. These techniques were heavily studied and surveyed in the past literature [8,14,15,63], thus only the techniques used in IBFD–CRNs will be discussed in detail in Section 4.2.3. Nevertheless, direct sensing techniques have drawn a lot of interest lately because primary receivers are either passive most of the time (as in two-way communications) or even passive all the time (as in one-way communications, such as TVs) [15]. On one hand, the primary receiver's local oscillator leakage signal is detected in one-way communications [83]. On the other hand, in two-way communications proactive detection is used, which depends on sensing the primary transmitter's signal and understanding the hidden information about the primary receiver that exists within this signal.

Proactive detection is actually possible because of the link adaption between the primary transmitter and the primary receiver [15]. Usually, in order to achieve this link adaption, wireless systems utilize closed-loop control schemes [15,84], such as power control, adaptive coding (or modulation), and automatic repeat request (ARQ) operation. However, this link adaption requires an extra feedback channel to let the receiver inform the transmitter about the quality of the received signal, and accordingly, the transmitter will modify its transmission parameters to sustain a good quality report from its receiver [15].

Given that link adaption requires an extra feedback channel (unknown to the SUs) and allows the primary transmitter to proactively detect the primary receiver. This created an interesting problem for researchers, which led to the development of advanced sensing techniques that focus specifically on direct sensing [31]. A summary of these techniques is provided in the following text and in Table 3.

Table 3
A brief comparison between advanced sensing techniques.

Technique	Task	Notes
Region-based sensing	Primary receiver detection	Low implementation complexity, and no interference with PUs
Jamming-based probing	Primary receiver detection	Medium implementation complexity, and high interference with PUs
Relay-based probing	Cross-Ch. estimation	High implementation complexity, and low interference with PUs

2.6.1.1. *Region-based sensing.*

When the power of the primary transmitter's signal is measured, the SU can conclude the location of the primary receiver. Moreover, it is a passive technique, so it does not interfere with the primary receiver.

This type of sensing is used to know which type of DSA methods can be used. For example, in cognitive small cell networks, the use of overlay DSA is preferred only when the macro cells have enough empty channels to cover the requirements of the small cells [85,86] whereas the use of underlay DSA is preferred when the macro cells have a few empty bands [87–90]. The cognitive BS would know the number of used channels by detecting the primary receivers in the macro cell.

To clarify, macro cells provide large area coverage using high power cell towers and antennas but small cell networks divide the macro cells coverage into small areas. It is worth mentioning that small cells are used to increase the capacity of the network, decrease the effects of interference, decrease the power consumption, and increase the robustness of the system (because if one cell fails then only a small area will be affected). For more details, interested readers can refer to [91].

2.6.1.2. *Jamming-based probing.*

When the cognitive user sends a probing signal and observes the response in the primary transmitter's signal, it can detect the primary receiver. This method causes interference with the primary receiver but its detection is better than the region-based method. Additionally, this method can be used in cellular networks as suggested in [57].

2.6.1.3. *Relay-based probing.*

The cognitive user sends a probing signal and observes the reaction of the primary transmitter. It can then estimate the cross-channel information as proposed in [92–98]. This method causes low interference but its implementation complexity is very high.

The last two sensing techniques are considered part of the proactive detection techniques, and as a clarification, they operate in the following manner: a probing signal is sent by the cognitive user, which will affect the primary transmission. Consequently, the primary transmitter will automatically adjust its parameters to respond to the probing signal (because of the aforementioned link adaption). Therefore, the cognitive user will be able to observe the reaction of the primary signal and conclude information about the primary receiver [31].

2.6.2. *Medium access control-layer sensing*

As previously noted in Section 2.5, the MAC layer performs an important role in CR-based centralized networks, in which it handles the channels that the SUs should sense and access in order to obtain good performance and to avoid having several sensing nodes performing spectrum sensing for the same channel [15,21]. As for CR-based distributed networks, the MAC layer chooses how the SUs can access the spectrum in an efficient manner after the spectrum gaps are found by more than one SU [15].

To be more precise, the MAC layer is responsible for obtaining spectrum opportunities as quickly as possible by minimizing the sensing time and the intervals between sensing activities in order to have quick responses to the activities of PUs [15,21]. But this affects the SUs transmission. Additionally, the MAC layer enhances the sensing accuracy and avoids inter-user interference. This means ensuring that when spectrum sensing is carried out, all SUs communications are suspended. This task is called scheduling quiet sensing periods [15]. However, this scheduling task must be designed to maintain accurate spectrum sensing and quick responses to the activity changes of PUs while minimizing the negative effects of quiet sensing periods on the QoS of some applications, such as video streaming or voice-over-internet-protocol [15,54].

In conventional networks, the multiple access protocol is like a set of rules used to govern the behaviors of the nodes when accessing the channel. The definition is not different in CRNs, but it is a bit more complicated, as the operational parameters of each SU may vary, including the used channel. Therefore, a CRN-MAC protocol must consider allowing each SU to sense various channels and dynamically access the spectrum using either spectrum overlay, or spectrum underlay. Additionally, cooperation between SUs must be considered in order to avoid collisions in the vacant channels, especially in ad hoc CRNs, where SUs compete for the vacant spectrum.

In short, as seen in Sections 2.2.2 and 2.5, the MAC layer manages the time domain resources to serve the spectrum sensing and the spectrum access requirements; because in HD-CRNs both processes must happen separately in time domain. Accordingly, many studies worked on the MAC layer in order to provide medium access protocols and policies to help balance between sensing and access process in an energy efficient manner that guarantees limited interference with the PUs. For more details, interested readers can refer to [15,21,99–104].

2.6.3. *Cooperative spectrum sensing*

The performance of local sensing techniques is usually degraded due to noise uncertainty and channel fading [15]. For example, if an SU is separated from a PU by a wall (i.e. signals encounter shadowing) or by an object that scatters the signals (i.e. having multi-path fading), the SU will not be able to detect the presence of the PU. It might also access the licensed spectrum – thinking it is empty – resulting an interference with the PU's communication. In such situations, the detection error possibility can be reduced by Cooperative Spectrum Sensing (CSS), which means allowing multiple users to collaborate in spectrum sensing in a manner that guarantees spatial diversity to overcome the channel fading [15,105].

Lately, CSS has been greatly studied in CR-based centralized networks [57] since it overcomes the degradation of sensing performance created by multi-path fading and shadowing, as discussed in the previous example [15,21]. Another reason for this great interest in cooperative sensing is its ability to reduce the sensing time because additional sensing data can be obtained simultaneously from other SUs [15]. Furthermore, CSS in centralized networks allows each SU to send its row collected data to a combining user (or a fusion center) (see Section 2.5.1). If not, each SU may perform local spectrum sensing and then transmit its own binary decision or test statistics to the fusion center. Then, in order to achieve successful cooperation, the fusion center has to combine and process the samples received by all other SUs performing local spectrum sensing. Nevertheless, several diversity combination schemes, such as selective combining, maximal ratio combining, equal gain combining, and switch combining, are used before processing the received samples in the fusion center. These procedures are carried out in order to make a robust decision of whether the spectrum is used by PUs or not [2,15]. It is worth mentioning that these combination schemes and signal processing techniques are considered to be part of the PHY-layer functions.

According to [15], most CRNs prior to 2011 have been assumed to be centralized. Decentralized CRNs have been initially studied using relays in [106,107], where the amplify-and-forward (AF) cooperation protocol has been used to make each SU act as a relay for the other SU, then amplify and forward the received signal without any processing.

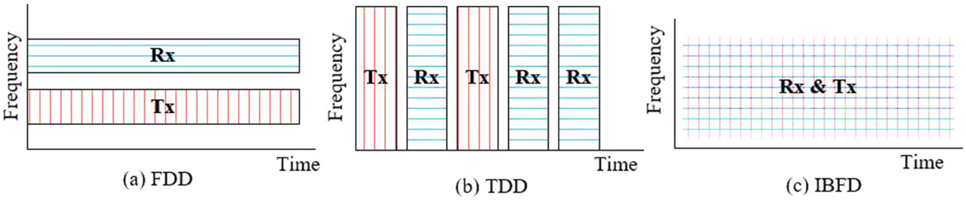

Fig. 5. FD in wireless communications per device, (a) FD using HD-FDD, (b) FD using HD-TDD, (c) FD using IBFD.

But, to achieve good performance of spectrum sensing using the AF protocol, an efficient pairing of cooperative SUs is needed. Therefore, many researchers have worked on creating efficient pairing algorithms to utilize the AF protocol. However, an algorithm that grants SUs with high throughput in the presence of PUs interference was proposed in [108]. In this study, the performance of OFDM underlay CRN was analyzed using full duplex relays. Moreover, a new two-phase support vector machine algorithm was used in [109] in order to achieve CSS.

The concept of cooperation started out as a PHY-layer protocol; because of the required combination and signal processing techniques. However, the design of other layers is greatly affected by cooperative transmission [1]. Correspondingly, as pointed out in [15,110], when thinking about CSS, three main questions arise:

- How much is gained from cooperation?
- How can SUs cooperate?
- What is the associated operating cost of cooperation?

To discuss these questions based on the functions of each layer, the following can be stated:

From the PHY-layer's perspective, the gain brought to the network by cooperation depends on the channel characteristics and the frequency band of interest [15,111,112].

As for the MAC layer design, it should focus on how to achieve cooperation and what operational costs are associated with this cooperation [15]. For illustration, authors of [113] studied how distributed SUs exchange sensing outcomes while maintaining acceptable sensing accuracy. Since each SU in distributed networks makes its individual sensing decision, some false alarms and misdetections will occur. The overhead in this scenario is that exchanging sensing data between distributed SUs would take significant time, which affects the network's performance. Other cooperation costs have been studied in several works as well. Interested readers can refer to [114,115].

At this point, the most important aspects of HD-CRNs have been discussed in substantial detail. This will provide basic information that will be built upon to clear the concepts of IBFD–CRNs. However, instead of considering IBFD–CRNs right away, we rather discuss the IBFD technology first. The following section is therefore going to highlight the interesting parts of this technology.

3. In-band full-duplex communications

3.1. Wireless communications: Motivations for using IBFD mode

Wireless communication systems can operate in HD or in Full-Duplex (FD) mode. Furthermore, HD communication systems can only allow data to flow in one direction at a time, while FD systems allow data to be transmitted and received simultaneously. Although wireless communications nowadays appear to be operating in FD mode, they are actually achieving this simultaneous transmission and reception by employing different orthogonal resources for each operation (i.e., resources that do not intersect with one another) [116]. Generally, wireless communications operate in HD mode using Time Division Duplexing (TDD) (i.e. orthogonal time slots) or using Frequency Division Duplexing (FDD) (i.e. orthogonal frequency bands) [1].

However, when it comes to spectrum efficiency, these duplexing modes are considered wasteful of this valuable resource. Specifically, FDD uses a dedicated spectrum band for each communication link and uses empty frequency guard bands to avoid interference between those links, as illustrated in Fig. 5(a), [116]. In addition, TDD uses the spectrum for transmission and reception in different time slots and uses guard intervals to allow the communicating devices to switch from transmit mode to receive mode, as demonstrated in Fig. 5(b) [116]. Nevertheless, TDD and FDD also suffer from other constraints, and these constraints are considered to be somehow the main motivation behind employing the "real FD" mode in wireless communications [116]. The following text will provide a summary of TDD and FDD constraints.

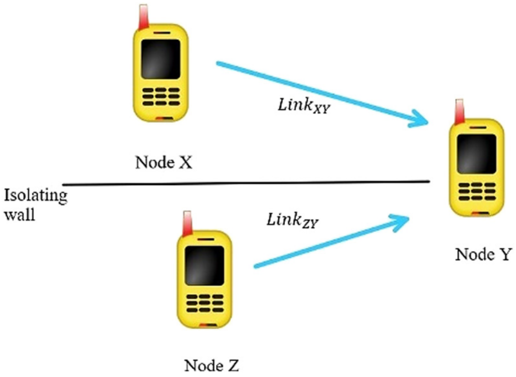

Fig. 6. An illustration of the hidden terminal problem.

3.1.1. Frequency division duplexing mode constraints

3.1.1.1. Quantization of the CSI at the transmitter. The receiver performs channel estimation to know the properties of its operating channel (i.e. the CSI). It then sends a quantized version of this CSI to the transmitter so that it can adapt its transmission to achieve a reliable communication. However, due to quantization noise, this quantized version of the CSI is different than the original CSI at the receiver side, which may affect the communication link's reliability [116].

3.1.1.2. Inflexible bandwidth allocation. In FDD, a fixed frequency band is used for each link and this band cannot be dynamically assigned based on the data traffic demand. This is not desirable because it means there is an inefficient spectrum utilization [116].

3.1.1.3. The guard frequency band between the links. In FDD, there exists an extra empty frequency band between each subsequent communicating links in order to avoid interference between those links. However, these guard bands can be considered a waste of the spectrum [116].

3.1.2. Time division duplexing mode constraints

Although TDD mode allows the capacity to be allocated dynamically based on the demand, it has other constraints such as:

3.1.2.1. Duplexing delay in the MAC layer. In TDD, the transmission and the reception operations alternate in time. Therefore, the received and the transmitted frames are delayed from each other. This delay is called duplexing delay and is inversely proportional to the frame's length [116].

3.1.2.2. Out-of-date CSI at the transmitter. Because of the duplexing delay, the CSI at the Transmitter may be out of date, especially when the channel states vary rapidly (i.e. in time-varying channels) [116].

3.1.2.3. The guard intervals between the links. In order to apply the transmit–receive mode switching, the TDD uses guard intervals. These intervals waste the time resource, and thus wasting the spectrum resource [116].

It was very common to say that terrestrial wireless communication systems, such as cellular and Wi-Fi, can only be designed to operate in HD mode using orthogonal resources such as time, frequency or code (e.g. TDD, FDD, OFDM and code division multiple access) [117,118]. Remarkably, this assumption was made because of the links interferences and most importantly, the SI problem, which occurs between the receiving and the transmitting terminals of a wireless device when using non-orthogonal resources [2,101,119,120]. Nonetheless, this assumption was changed when SIC methods evolved to reach a promising cancelation performance. Therefore, the modern non-orthogonal transmission modes are now considered in designing practical systems [2,61,119]. Out of which, NOMA [117,118], FBMC [121,122], and IBFD [1,2,61,119]. Curiously, the SI created by NOMA and FBMC modes can be higher than the SI created by IBFD mode. Hence, the IBFD mode has gained more interest compared to other non-orthogonal transmission modes. Moreover, it is noteworthy to mention that the term IBFD is used instead of just FD, in order to declare that the same frequency band is used, and no type of frequency or time duplexing is used to achieve FD communications, as illustrated in Fig. 5(c).

Impressively, by allowing simultaneous transmission and reception, the IBFD mode has shown its potential to double the spectral efficiency, which granted this technology great interest by researchers in both academic and industrial fields [1]. For this reason, the following subsection will provide some details about the advantages of using the IBFD mode in wireless communications.

3.2. Advantages of in-band full-duplex

From the PHY-layer's perspective, the IBFD technology can be used in order to almost double the spectral efficiency by allowing the transmitter and the receiver to communicate at once in the same frequency band.

However, from the MAC-layer's perspective, using the frame-level IBFD wireless technology guarantees that each terminal is allowed to reliably receive a frame while transmitting another frame at the same time (i.e. there is no duplexing delay as in TDD mode). This means that the terminals can now detect collisions, receive a CSI, or receive feedback about other terminals states while transmitting [61,119].

Interestingly, authors of [123] and [124] have hinted that the use of IBFD can increase the total throughput of an entire wireless network rather than just doubling the spectral efficiency of a point-to-point link. That is because in IBFD each terminal is allowed to transmit data to a second terminal and at the same time, it is allowed to receive data perhaps from a third terminal. This means there are no scheduling constraints as in HD wireless communications. It is noteworthy to mention that scheduling constraints are related to the MAC-layer protocols that are used to balance the transmission and reception times [15]. Besides, according to [124], employing IBFD can also provide a solution to the hidden terminal problem that used to exist in HD communications, as well as its resulting collisions and retransmissions.

As a clarification of the hidden terminal problem, the following scenario is considered [124]: There are three communicating HD nodes, X, Y, and Z. Suppose that nodes X and Z cannot see each other (i.e. they cannot communicate directly). Additionally, assume that both X and Z can directly communicate with node Y through $Link_{xy}$ and $Link_{zy}$ respectively, as seen in Fig. 6. Subsequently, if nodes X and Z decide to send signals to node Y at once, perhaps if the transmission power of X towards Y is lower than the detection threshold of Z, then X and Z's signals will collide, and a retransmission will be required. This scenario is handled differently when the three nodes are operating in IBFD mode. Now both nodes Y and X are allowed to have a bi-directional FD communication. Since the same frequency band is used, then node Z can now sense that the spectrum band is busy by detecting the signals transmitted from node Y. Accordingly, it would move its transmission to a different time-slot. It is worth mentioning that this scenario of interaction in IBFD mode depends on the adopted medium access protocol, but this example is used for illustration purposes only.

To sum up, the following text will provide a brief discussion of the advantages of employing IBFD mode in wireless communications [61].

3.2.1. Doubling the capacity

In view of the fact that the IBFD technology fully utilizes the time and the frequency resources, it is therefore theoretically capable of doubling the communication link's capacity.

3.2.2. Reducing feedback delay

Since feedback signals can be received at the same time as data transmission, the latency in the feedback information would be shortened (i.e. avoiding the duplexing delay) [61,125]. There are several examples of feedback signals, such as the CSI, control information, resource allocation, acknowledgment/negative acknowledgment (ACK/NACK), etc. [61].

3.2.3. Reducing the end-to-end delay

In relay systems, the IBFD relay nodes can receive data from the source node while transmitting data to the destination node. Therefore, the end-to-end-delay would be reduced [61,126,127].

3.2.4. Improving the network's secrecy

Seeing as each two communicating nodes use the same frequency for transmission and reception, then any eavesdropper will receive mixed signals. This will make the decoding process a very complex task for the eavesdropper [61,128–130]. Moreover, as proposed in [128,131], the secrecy of a point-to-point communication link can also be achieved by making the receiver transmit a jamming signal while receiving its desired signal. This will make it even more difficult for eavesdroppers to detect the useful signal.

3.2.5. Improving the efficiency of ad-hoc network protocols

Ad-hoc networks suffer from the hidden terminal problem. However, collisions can be avoided in the hidden terminal scenario when IBFD is being used, as clarified from Fig. 6. [61,132–135].

3.2.6. Increasing spectrum usage flexibility

Apart from using one type of transmission mode, the transceivers can be allowed to choose whether to operate in HD mode or in IBFD mode in order to use the spectrum more freely. This idea was introduced in [61,136–139]. More to the point, in IBFD mode, the bandwidth of each communication link can be dynamically assigned based on the link's traffic demands [116]. The idea here is supporting variable bandwidths for the links not supporting CR capability. Thus, the flexibility term has different definition than that in IBFD–CRNs.

It cannot be missed out that the first application of IBFD was the well-known continuous wave radar system in 1940 [2,61,119]. However, some key modern application scenarios of IBFD technology are discussed in the following sub-section [1,61].

3.3. Classifications and applications of IBFD technology

IBFD technology has the potential to be used in many communication scenarios such as: ad hoc networks, Wireless Local Area Networks (WLANs), satellite networks, vehicle communications, cellular networks and wireless powered networks e.g. WSNs [140]. However, these applications and others were described in the literature by means of some key scenarios. Therefore, the text below will provide a discussion of the IBFD applications in the same manner [1,2,61].

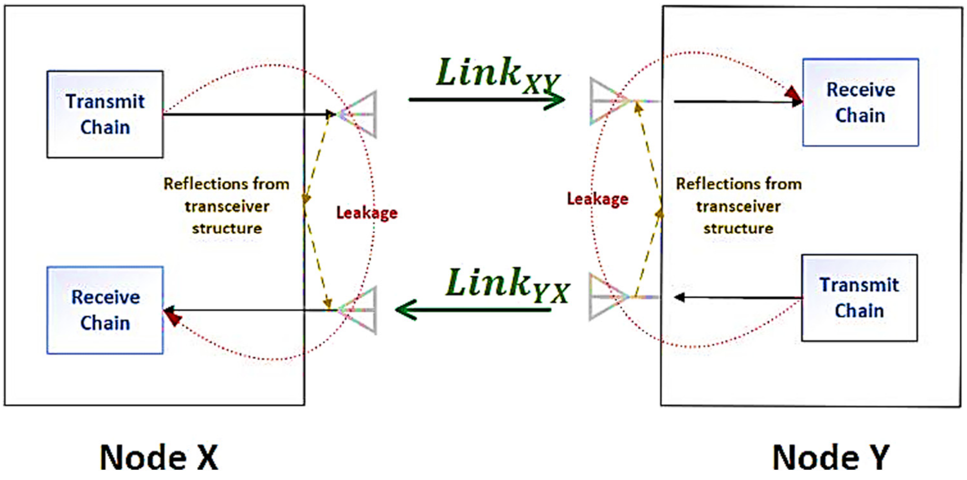

Fig. 7. Bi-directional In-Band Full-Duplex communication, [1].

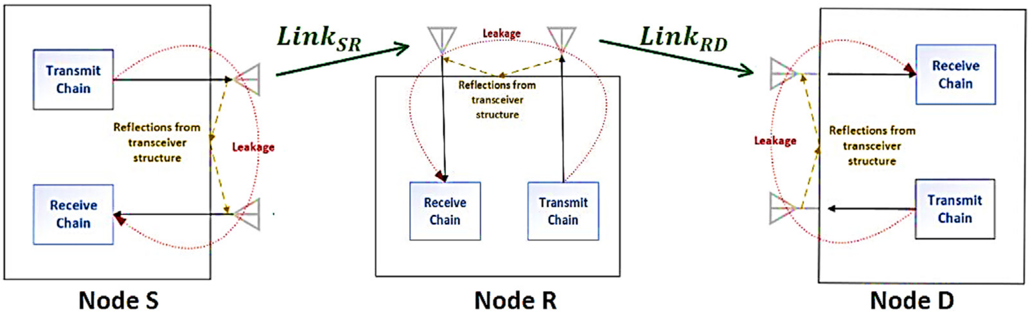

Fig. 8. IBFD cooperative communion: IBFD relaying [1,64].

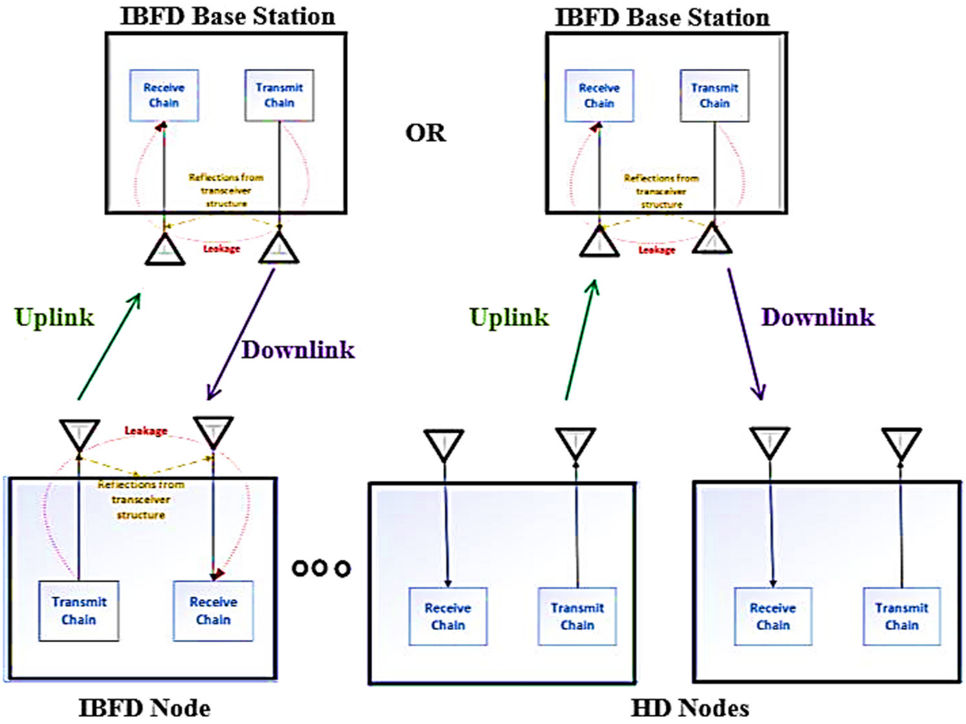

Fig. 9. The use of IBFD in cellular networks [61].

3.3.1. IBFD bidirectional communications

In this scenario, two IBFD transceivers are allowed to transmit and receive data to and from one another at the same time and in the same frequency band. This scenario is the basic representation of the IBFD concept. Fig. 7 illustrates the IBFD bi-directional communication between two nodes. From Fig. 7, it can be seen that both nodes X and Y have two antennas, one for transmission and one for reception (each node may have several antennas for transmission and reception, but the figure only shows two antennas for simplicity).

$Link_{XY}$ denotes transmission from node X to node Y, and $Link_{YX}$ signifies transmission from node Y to node X. Obviously, each node suffers from interference coming from its own transmitting antenna towards its receiving antenna. This interference is known as the SI [1]. In this FD scenario, if the SI is completely removed, the spectrum efficiency can be doubled compared to HD communications [1,61].

3.3.2. IBFD cooperative communication scenario

In this application, there exists three types of nodes: the source, the relay, and the destination nodes. The source node is supposed to transmit data to the destination node. The relay is used in order allow this transmission to be carried out from a longer distance. This means it is used to increase coverage of the source node by receiving the data from the source, amplifying it then retransmitting it towards the destination node. Fig. 8 shows how this cooperation can be achieved in IBFD mode. In the figure, the link from node S towards node R and the link from node R towards node D are represented by $Link_{SR}$ and $Link_{RD}$ respectively. Clearly, the signals are traveling from the source S to the destination D through the relay R. Subsequently, if IBFD mode is enabled by the relay node, then the transmission can be carried out between S and R and between R and D instantaneously. Therefore, IBFD can theoretically double the spectrum efficiency, but only by completely canceling the SI at the relay node [1,61]. Furthermore, IBFD relaying was compared with HD relaying in [119,123,141]. Then the results showed that IBFD relaying does not only increase the spectrum efficiency but also increase the data rate of the communication. It is worth mentioning that this application can be considered as an example of distributed cooperative networks (e.g., ad-hoc and WSNs).

3.3.3. Cellular networks

The IBFD technology can be supported by the BS in cellular networks, which allows it to instantaneously receive signals from a mobile device (i.e. uplink) and transmit signals towards another mobile device (i.e. downlink) [142–144]. Conversely, the mobile device can also support the IBFD technology, which means that the BS and the same mobile device can communicate in the uplink and the downlink directions instantaneously [1,61]. Fig. 9 shows how IBFD technology can be employed in cellular networks. Clearly, the use of IBFD mode in this application shows the potential of doubling the spectrum efficiency compared to the use of HD mode. Obviously, this application can be considered as an example of centralized cooperative networks.

3.3.4. In-band full-duplex cognitive radio networks

As previously mentioned, CRNs have unlicensed users (i.e. the SUs) that are allowed to access the licensed spectrum without harmfully interfering with the licensed users (i.e. the PUs). Correspondingly, the spectrum sensing process allows the SUs to find the spectrum gaps. Therefore, it is considered a key process in CRN. However, in conventional HD-CRNs, the SUs had to interrupt their transmissions to perform spectrum sensing, which wasted a lot of the valuable spectrum and introduced a delay in the responses for the state changes of the PUs. Fortunately, the employment of IBFD technology by the SUs in such networks, allows the SUs to perform spectrum sensing while transmitting. This particular scenario defers from other scenarios by the dynamicity of spectrum access (i.e., whenever the spectrum is empty, the devices will communicate). This application can have many advantages along with several challenges. A thorough discussion regarding this specific application is presented in Section 4.

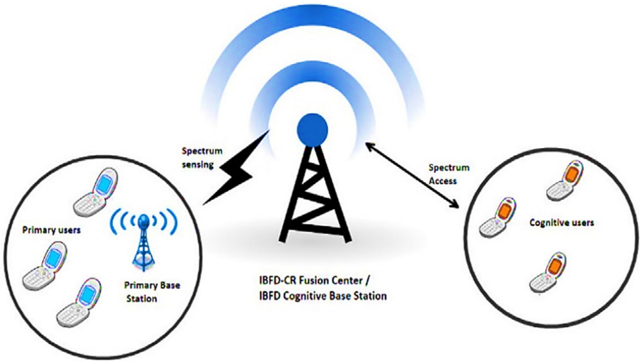

Fig. 10. Cellular IBFD–CR system, [62,145,146].

3.3.5. In-band full-duplex cognitive radio cellular networks

This scenario is considered as an example of centralized CRNs but in IBFD mode. Fig. 10 illustrates how the cellular IBFD–CRN operates based on the proposal of [145,146]. As previously mentioned, the fusion center (or the central controller) in normal centralized CRNs usually receives sensing data from the SUs in the network and then decides how the spectrum is going to be allocated. This scenario was used for IBFD–CR cellular networks in [147]. However, authors of [145,146] assumed that the central controller makes its decisions using its own sensing results when they worked on cellular IBFD–CRNs. Besides, such scenarios can enhance the spectrum utilization and the throughput of cellular networks compared to HD-CR cellular networks. Remarkably, researchers have considered the CR technology to help navigate through the entire radio spectrum range to achieve the critical requirements of the Fifth Generation (5G) mobile network such as wider-coverage, massive-capacity, massive-connectivity and low-latency [148]. This is because the spectrum range of the 5G will be widened to reach the so called "full spectrum era", which covers the range starting from 1 GHz to 100 GHz. In addition, the CR technology in IBFD mode was considered in [148] as one of the key-enabling technologies that can be used to meet the demands of 5G. For more details about how IBFD–CR can be used in cellular networks and specifically in 5G networks, interested readers can refer to [2,116,148,149].

At this point, the motivations, advantages and applications of IBFD were discussed. However, the following question is still worth asking: "why would we consider IBFD now?" Interestingly, according to [119], light has been shed on IBFD technology for two reasons: The first reason is that other traditional techniques used to increase the spectral efficiency have been already exhausted, such as the MIMO technology and the advances in modulation and coding schemes. The second reason is that communication system designers are shifting their interest towards short-range systems such as small cell systems and Wi-Fi; because the transmit power in such systems is lower than large-scale systems. This means that the difference between the transmit power and the receive power is reduced, and therefore, the SIC problems are much more controllable. This point can be explained by the following example [124]: If the distance between two cellular transceivers is 500 m, then the desired received signal will attenuate by approximately 120 dB (using the free space path loss equation and applying the cellular frequency range). This attenuation is definitely higher than the attenuation of a signal passing a shorter distance, which is approximately 250 m in small cell networks [150]. Accordingly, the low attenuation of small-scale networks means that the desired signal has higher power compared to large-scale networks. Therefore, the power of the desired signal in small-scale networks is much closer to the power of the self-interfering signal (i.e. the transmitted signal). More details about SIC techniques and how this power difference affects them are discussed in Section 3.5. Furthermore, researchers in [104,105,135,151–159] have worked on testing IBFD in small-scale wireless environments, such as Wi-Fi, along with improving the SIC techniques to the point where the IBFD can be considered feasible for Wi-Fi networks [119].

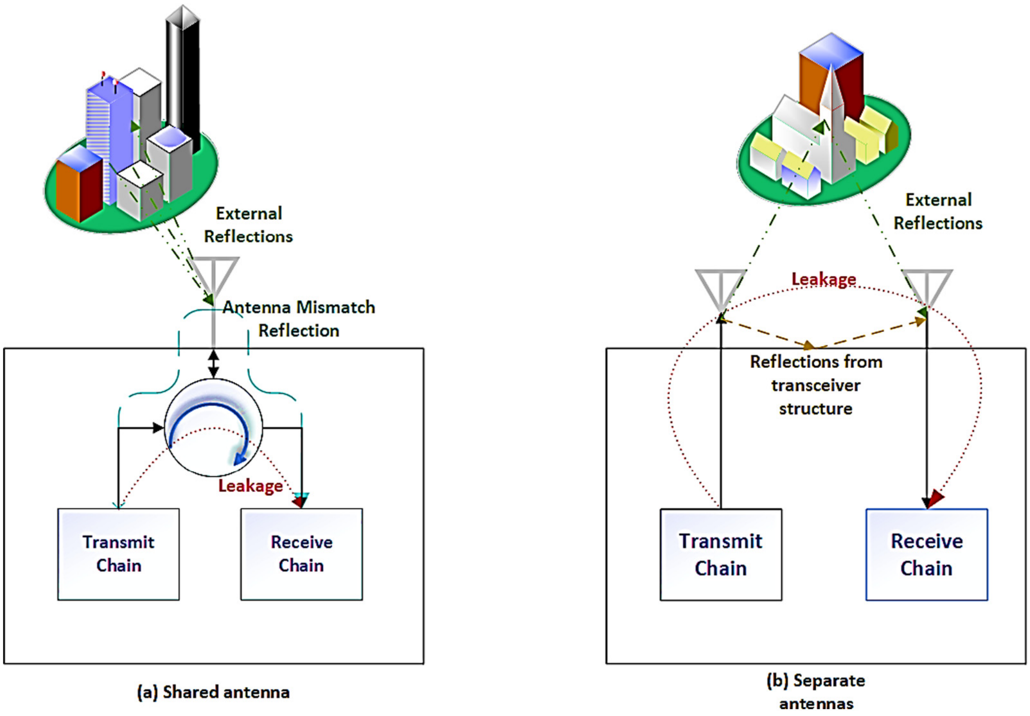

Fig. 11. Illustration of SI for (a) Shared antenna and (b) Separate antennas transceivers.

3.4. *Challenges of in-band full-duplex*

In spite of the striking advantages of using IBFD, it is still not widely used because of the unescapable SI problem [66]. Aside from this, it must also be understood that in order to get the full advantages of IBFD, network and communication system designers must carefully consider the Data-Link and the higher layer protocols because they are as important as the PHY-layer. Therefore, maybe the greatest challenge remains in building the foundations of a network design where all or some of the terminals are allowed to operate with IBFD capabilities [119]. On the other hand, the inter-user interference cannot be neglected because it can severely affect the network's performance. Additionally, employing IBFD will increase the hardware complexity of the nodes in the network, which will increase the power consumption.

Moreover, IBFD technology prototypes are still large in size, thus they cannot be fully utilized in practical environments. Aside from that, SIC techniques are still being tested on specific operating environments so they cannot be applied in real-time environments.

There are many challenges facing the SIC techniques, as they are required to support MIMO systems, time-varying channels, infrastructure-based networks, and small and portable devices. Obviously, many limitations can degrade the performance of SIC techniques. Out of which, there is the non-linear behavior of the RF hardware components, which increases the severity of the SI effects. Additionally, some estimation errors of the SI signal can occur during SIC. Such errors happen because of the external interferences and they might damage the SIC performance. To this extent, a summary of the challenges facing IBFD technology is provided in the text below.

3.4.1. *Self-interference*

SI means the interference that a transmitting FD terminal is causing to its own receiving terminal, forbidding it from properly receiving the desired signal [61,119]. As mentioned above, the power difference between the desired signal and the SI depends proportionally on the distance between the transceivers because of the attenuation that affects the desired signal. However, according to [61], this power difference increases exponentially as the distance increases. Additionally, the power of the SI can be 50–110 dB stronger than the power of the desired received signal [1]. Nevertheless, assuming that a reliable communication link requires at least 5 dB of signal-to-interference-ratio, then in the worst-case scenario the SI has to be reduced by 115 dB in order to provide a reliable link [61,132,135,160]. Moreover, nearby obstacles can reflect some parts of the transmitted signal producing the reflected interference signals (a.k.a. external reflections [124]) [61]. Fig. 11 illustrates the reflected and the self-interfering signals for two types of transceivers: (a) the shared antenna transceiver and (b) the separate antennas transceiver. It is obvious from Fig. 11(a) that one antenna is used to simultaneously transmit and receive signals with the help of a circulator to isolate the transmit and the receive paths as in radar systems [161]. In addition, the internal reflections are coming from the circulator leakage (i.e. when it fails to perfectly isolate the transmit and receive chains) and from the antenna impedance mismatch. Whereas, from Fig. 11(b) it can be seen that the transmission and the reception antennas are physically separated. Furthermore, the interfering signals are propagating directly from the transmit antenna to the receive antenna and the reflection of the transmitted signal from the transceiver's structure produce the internal reflections. It is worth mentioning that on one hand, the internal reflections depend on the transceiver's hardware design. For this reason, they are static. On the other hand, the external reflections that produce reflected copies of the transmitted signal are varying over time because the external obstacles are not necessarily fixed, especially if the transceiver is a mobile device.

3.4.2. *Limited interference cancelation*

In real life, the SI cannot be completely canceled for many reasons. Mainly, one reason is related to the fact that the development of SIC techniques is still going [2,61,132,154,160,162–164]. Another reason can relate to the nonlinearity of the RF chain hardware components, which creates a problem by producing high order harmonics of the transmitted signal. This indicates that the SI power will become greater than the tolerable range [61]. In addition, insufficient cancellation can result from estimation errors of the SI signal, which occurs because there are time-varying reflected interferences (i.e. external interferences) [61].

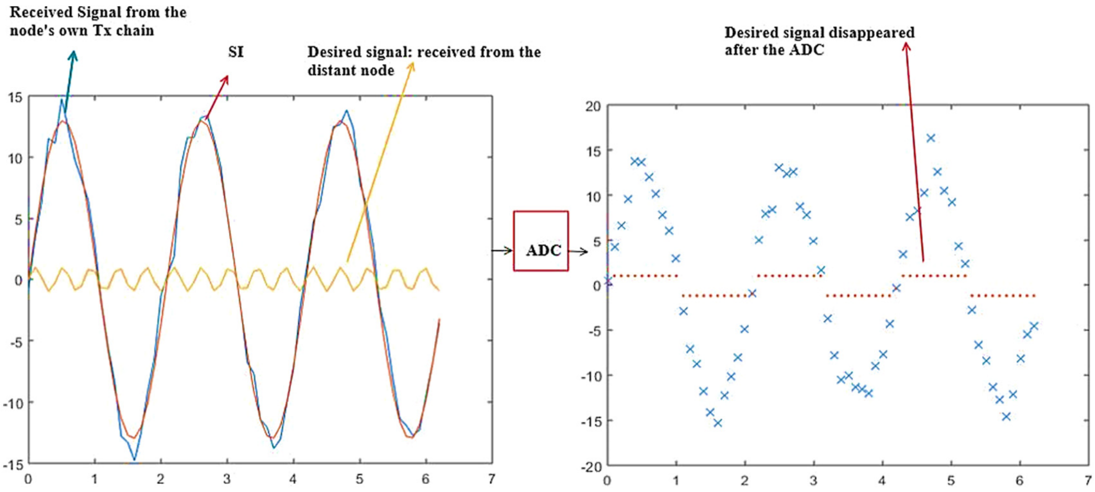

Fig. 12. SI compared to the desired signal before and after the ADC, as described in [1].

3.4.3. Higher inter-user interference

This interference is larger in IBFD networks compared to old wireless networks because all nearby nodes are transmitting simultaneously in the same frequency band [61,125,142,143,165–167]. As a clarification, inter-user interference on each node is caused by the transmissions of other neighboring nodes in the network.

3.4.4. Higher consumed power and higher complexity

Canceling all kinds of interferences (i.e. internal, external, and inter-user interferences) at each node in the network will require extra hardware components to be added to the node, which in turn consumes more power and resources [61,168].

3.5. Self-interference cancelation

Although it may seem easy to cancel the SI effect by simply subtracting the signal transmitted by the transmitting FD terminal (i.e. SI) from the entire received signal (i.e. desired signal and SI), this subtraction is not practically possible because the magnitude of the interfering signal is larger than the magnitude of the desired signal. This interfering signal's large magnitude leads to two problems. One of which is the receiver front-end saturation. In addition, if there is no saturation, another problem will appear at the Analog-to-Digital Converter (ADC), where there will be a high quantization noise that is even larger than the signal of interest (i.e. low signal-to-quantization-noise-ratio) [61,119]. To clear this point, Fig. 12 shows the SI signal compared to the desired signal before and after the ADC, in which it can be seen that the desired received signal's magnitude is much smaller than the SI signal's magnitude. However, the problem appears at the ADC, because the dynamic range is going to be set for the SI signal's amplitude, which means that the quantization level of the ADC is going to be larger than the desired signal's amplitude. Therefore, the desired signal will be hidden [1,61]. For interested readers, more details about ADC designs are available in [169–171].

There are several studies that thoroughly cover the advances in SIC techniques, such as, [61,119,124], and [172]. Therefore, this subsection will briefly cover the SIC techniques that can be used in IBFD transmission as described in [61,119]. SIC techniques can be categorized into three main types: passive propagation-domain SIC, active analog-circuit-domain SIC and active digital-domain SIC. To this extent, Fig. 13 shows where each type of SIC is used. The following text will provide some insights about each type of SIC techniques.

3.5.1. Antenna or propagation-domain SIC

This type of SIC methods is referred to as passive cancelation. It depends on electromagnetically isolating the transmit chain from the receive chain, which means canceling the SI before it can hit the receiving terminal's front end (i.e. before entering the receiver's RF chain [124]). This can be achieved by several approaches. Out of which, there are the path-loss-based techniques and the cross-polarization techniques. Hence, the following discussion will briefly describe each type of approaches.

3.5.1.1. Path-loss-based techniques. Some of these techniques depend on the isolation shield or the distance between antennas (i.e. antenna isolation, and separation techniques [135,173–175]). Other techniques depend on the placement of antennas (i.e. the placement of multiple transmit antennas in a manner that makes their transmitted signals cancel with each other to create a null space at the receive antenna [152,176]). Apart from that, some other techniques depend on using directional antennas (i.e. pointing the main beam of the antenna towards a desired direction). Interestingly, directional antennas have been experimentally tested and confirmed to be efficient for SI cancelation by [132,152,175,177,178]. Also, a reconfigurable directional antenna was proposed in [179].

To this extent, it is noteworthy to mention that in practical applications, physical constraints decide what technique can be used. For instance, antenna separation and isolation techniques are very unlikely to be used with small devices [124]. However, for more details, studies that focus on such techniques can be found in [135,177,178].

3.5.1.2. Cross-polarization techniques. These techniques can be used to passively cancel the SI with relatively small antennas. Such techniques might work by transmitting only horizontally polarized signals and receiving only vertically polarized signals. This specific situation was studied in [155,178].

It is worth mentioning at this point that in transceivers with a shared antenna, the circulator adapts a passive SIC technique to isolate the transmission chain from the reception chain (see Section 3.4.1, Fig. 11(a)). Moreover, commercial circulators typically achieve about 20 dB of isolation, according to [124].

3.5.2. Active analog-circuit-domain SIC

These methods rely on canceling SI in the RF circuit of the receiver (i.e. before the ADC). This cancelation can be done by subtracting an estimate of the SI from the total received signal [124]. Nonetheless, these techniques increase the circuit's complexity and the consumed power because they require adding extra hardware elements in the RF circuit, Furthermore, studies that worked on this type of cancellation techniques can be found in [154,156,180]. It is worth mentioning that,

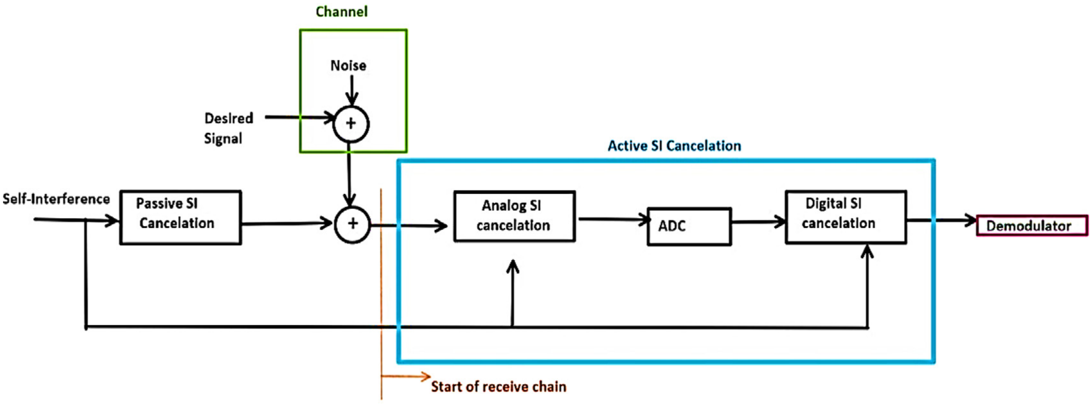

Fig. 13. An illustration of SIC methods at the receive chain of a transceiver, based on the categorization of [61].

on one hand, some studies focused on adding analog elements to the RF circuit [132,178,181] to cancel only the internal reflections by creating a replica of the transmitted signal [61,124]. On the other hand, other studies added digital components [151,154,160,182] to cancel out the random external reflections [124]. (internal and external reflections are parts of the SI, details were cleared in Section 3.4.1, Fig. 11).

3.5.3. Active digital-domain SIC

Such techniques act in the digital (baseband) domain after quantizing the received signal by the ADC. They apply complicated digital signal processing techniques to the received signals [153,183–185]. Although digital-domain SIC techniques avoid circuit complexity and power consumption, according to [119], they cannot suppress a high amount of SI. Therefore, they need the help of other SIC techniques to decrease the amount of SI effect. Moreover, another weakness of such techniques is that they require effective estimation or a previous knowledge of the transmitted (or SI) signal in order to work properly. For more details, interested readers can refer to [124].

To this end we would like to introduce the major challenges of SIC which are basically described as follows.

3.5.4. Challenges of self-interference-cancelation

After describing the SIC techniques, it is convenient now to talk about the challenges facing researchers when developing these techniques, in order to provide some intuitions about the open research areas. Therefore, the following text will provide a brief discussion of these challenges. Additionally, interested readers may refer to [61] and [124] for more details.

3.5.4.1. SIC in IBFD multi-input-multi-output systems. IBFD–MIMO systems differ from IBFD systems with a single antenna as IBFD–MIMO systems require extra powerful SIC. This comes from the fact that multiple transmitting antennas in MIMO systems produce several loopback (or interfering) signals combining at the receiving antennas rather than having only one interfering signal coming from the transmit chain to the receive chain [61]. Interestingly, some studies, such as [186], used some antennas of the MIMO system to perform path-loss-based SIC. However, according to [124], the proposal of [186] degraded the efficiency of MIMO systems by losing some data-transmitting antennas for the sake of SIC.

3.5.4.2. SIC in a time-varying channel. Several SIC techniques were studied under the constraint of having a static channel. However, mobile devices in realistic IBFD networks would normally have varying SI power. That is because mobile devices are constantly moving, which means there are a lot of changeable external interferences (see Section 3.4.1). That opens the door for developing adaptive analog and digital SIC techniques to handle the time-varying-channels [61]. Furthermore, interested readers can find more details about this in [124].

3.5.4.3. SIC for infrastructure-based systems. In centralized networks, such as cellular networks, the transmit power of the BS must be high enough to communicate with all cellular users. However, high transmission power in IBFD means high SI power, thus, the required level of SIC is high. In conclusion, SIC techniques face a great problem in such networks because their performance is still limited (as cleared in Section 3.4.2) [124,163,164]. For instance, according to [61] and [187], to use the IBFD in cellular networks SIC of more than 140 dB is required. This value is even higher than 110 dB, which is the best performance achieved by a combination of analog and digital SIC techniques proposed for Wi-Fi networks in [188].

3.5.4.4. Small-sized circuits for SIC. The need for smaller-size components raised from the fact that smaller and portable devices, such as laptop computers, cellular phones, etc., are becoming more desirable by most people [61].

To this extent, the IBFD technology has been discussed from various point of view, such as motivations, advantages and challenges. However, we will not stop to this extent. Rather, we are going to discuss the application of IBFD technology in CRNs in the following section.

4. In-band full-duplex cognitive radio networks

Impressively, when allowing the SUs in CRNs to operate in IBFD mode, they will simultaneously sense the spectrum while transmitting data. This means continuous transmission is sustained and smaller interference to PUs is caused. This mix allows the network to be smart and consume little portions of the spectrum for its entire operation. For instance, IBFD technology allows the network to handle its demands using the least number of channels (frequency bands), just to avoid inter-user interference, by using one channel for both links (transmission and reception) instead of two, or it gives the nodes in the network the ability to sense the spectrum band while transmitting over it. However, CR technology will allow the devices in the network to be fixable in using the spectrum whenever it is empty. It should be noted that the availability of each channel is varying in CRNs, thus being able to sense the channel while transmitting is very helpful to avoid collisions with PUs. Accordingly, researchers became very interested in this field. For example, researchers of [61,119,172,189,190] have proposed surveys that focused on IBFD communications and they have emphasized on the possibility of using IBFD for CRNs. Moreover, researchers of [2] have provided a comprehensive survey in FD-CRNs. However, in this part, IBFD–CRNs are going to be discussed from the perspective of the PHY, MAC, and network layers. Additionally, the following sub-section will provide some insights about the differences between HD-CRNs and IBFD–CRNs.

4.1. Half-duplex versus in-band full-duplex CRNs

4.1.1. From the viewpoint of spectrum sensing

- In IBFD–CRNs, the sensing process is continuous, but the problem arises when the sensing antenna gets interfered by the Residual Self-Interference (RSI) (i.e. the reminder of the SI after passive cancelation). This means the signal-to-interference-plus-noise-ratio in the sensing process will decrease.
- In HD-CRNs, the sensing process is done alternatingly and periodically (see Section 2.6.2). The RSI is not a problem here. However, the problem lies in the deficient number of samples used to make the sensing decision, which means that the sensing process is unreliable in such networks.

4.1.2. From the viewpoint of data transmission

- In IBFD–CRNs, while the PU is not using the spectrum, the SU can transmit continuously which improves the data rate. However, each SU will be constrained by a transmission power limit. This power limit is set because of the RSI, as it degrades the sensing performance.
- In HD-CRNs, each SU can use the free spectrum for data transmission after the sensing duration is over [62]. Additionally, the SUs will access the spectrum according to the suitable DSA method (see Sections 2.4 & 2.5).

4.1.3. From the perspective of harvesting energy

- In IBFD–CRNs, the SUs can harvest energy from an external source while transmitting data and performing spectrum sensing [2,191].
- In HD-CRNs, the SUs must suspend the spectrum sensing process and the data transmission operation in order to harvest energy [2].

To this extent, a general comparison between HD- and IBFD–CRNs was introduced. However, the following sub-sections will provide further details about IBFD–CRNs accompanied by clear comparisons with HD-CRNs.

4.2. Physical layer considerations in IBFD-CRNs

As aforementioned in Section 2, the PHY-layer in a CR is responsible for detecting the presence of PUs in the channel by the spectrum sensing process, learning some information about the channel by the environmental learning process and accessing the spectrum cognitively by the transceiver optimization and reconfiguration function. However, the PHY-layer is definitely concerned with the SI and its cancelation techniques in IBFD–CRNs. Therefore, the following text will provide some insights about IBFD–CRNs from the viewpoint of SI.

4.2.1. Self-interference-cancelation in IBFD-CRNs

After the proposed discussion of SIC techniques in Section 3.5, it is only convenient at this point to briefly talk about what needs to be considered when performing SIC specifically in IBFD–CRNs. Thus, according to [2], these considerations are summarized in the following text:

- SIC techniques should not interfere with the inter-user interference Cancelation techniques.
- Passive antenna separation SIC techniques must carefully find the optimal antenna separating distance in order to avoid the RSI that degrades the sensing performance.
- The type of SIC used in the design of IBFD–CRNs should be chosen carefully in order to address the interferences created in such networks; as this choice critically affects the performance of the network.
- In passive SIC, the transmit power of SUs in IBFD–CRNs should be controlled to avoid the SI's negative effects on the CRN's performance. The most important of which are the resulting poor sensing performance of SUs and the low throughput of the CRN. The SI negatively affects the communications of the network nodes which decreases the overall throughput. In short, there is a tradeoff between the transmit power and the throughput of the IBFD–CRN.

Interestingly, the processes in the PHY-layer of a CR are very harmonious with the MAC-layer processes. Therefore, some spectrum management protocols were introduced to handle the required cognitive processes in both of these layers together. Fortunately, to clear this point out, the following text will discuss the two major spectrum management protocols in HD-CRNs and IBFD–CRNs in a decent detail.

4.2.2. Major spectrum management protocols

The spectrum management function controls several cognitive processes in all three layers (i.e. PHY, MAC and network layers) and the most important process in the PHY-layer is the sensing process, which practically starts the CR cycle. However, spectrum management in CRNs is widely implemented by several protocols in the PHY and the MAC layers. Out of these protocols, the LAT Protocol is considered an important PHY-layer protocol that supports IBFD in CRNs. Nevertheless, in order to discuss the LAT protocol and show its advantages the Listen-Before-Talk (LBT) MAC-layer Protocol needs to be addressed. Therefore, the following text will discuss the LBT MAC-layer protocol then the LAT PHY-layer protocol.

4.2.2.1. Listen-before-talk protocol. It has been very common to depend on the LBT Protocol in HD-CRNs [101,192–195]. Fig. 14 illustrates how the LBT protocol works over one channel. The SU senses the channel periodically and only starts transmitting when it detects a spectrum hole. Interestingly, the sensing duration (the periodic squares in Fig. 14) and the sensing interval (the distance between the squares) are the most important parameters in the design of this protocol. The sensing duration means the period of time in which the sensing process is carried out and the sensing interval means the period of time between two consequent sensing activities. Accordingly, accurate sensing takes long sensing time and short sensing interval. However, this means having low throughput and low spectrum efficiency [192,194,196]. Therefore, researchers in [197] suggested using adaptive sensing and transmission durations to achieve higher spectrum efficiency in HD-CRNs.

Remarkably, the LBT protocol has proven its ability to handle overlay DSA just fine but it suffers from two main problems that can be summarized in the following text [193].

- SUs must give some of their transmission time for spectrum sensing. For illustration, it can be seen in Fig. 14 that even when the spectrum hole is continuous in time, the data transmission must be done in separate discontinuous fractions, which leads to inefficient spectrum usage.
- While an SU is transmitting, it cannot sense the change in the PU's state, which may lead to severe interference with the PU's communications. Additionally, when a PU quits the channel, the SU may not be able to transmit instantly, which also leads to inefficient spectrum usage.

Although, the LBT protocol has the advantage of requiring little infrastructure support and is considered effective, but it can only support HD communications. In other words, the LBT protocol requires employing orthogonal resources (e.g. TDD or FDD) in order to properly use the spectrum with little waste in FD communications (see Section 3.1) [193]. On the contrary, the LAT protocol was designed specifically for IBFD communications, thus, it does not require orthogonal resources to function well. Intriguingly, this is not the only concept that needs to be examined. Therefore, the following text will discuss further details about the LAT spectrum management protocol.

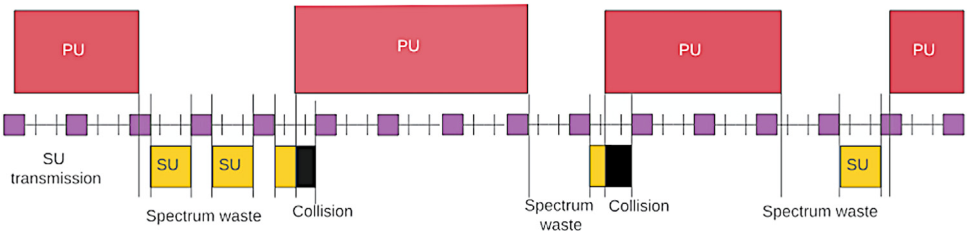

Fig. 14. The Listen before talk protocol, [198,199].

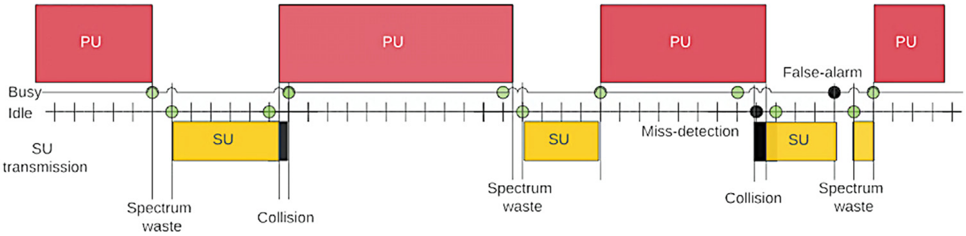

Fig. 15. The LAT protocol, [198,199].

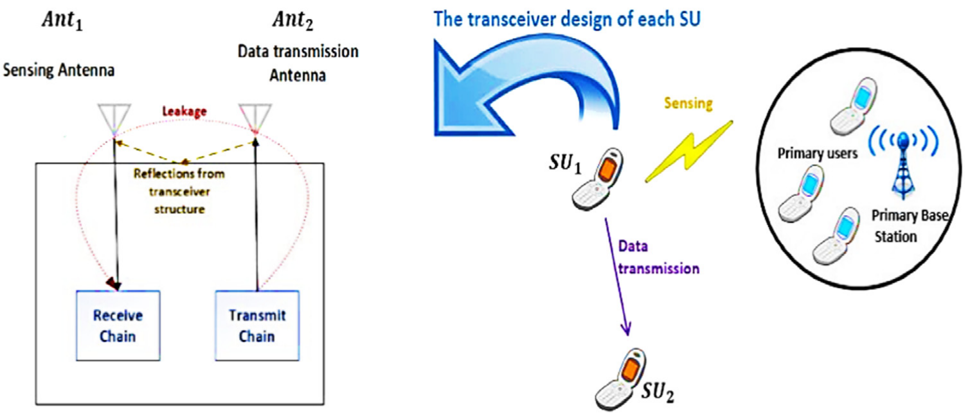

Fig. 16. LAT protocol system model, [198,199].

4.2.2.2. Listen-and-talk protocol. IBFD communication mode has shown its capability of receiving while transmitting in the same frequency band. Therefore, authors of [198,199] presented the LAT protocol, which conquered the limitations of the LBT protocol. Furthermore, as illustrated in Fig. 16, the system model of the LAT protocol assumes that each SU has two antennas. Typically, at any instance an SU (say SU_1) employs the first antenna Ant_1 for sensing while the second antenna Ant_2 is used for transmitting data to another SU instantaneously (say SU_2 which receives through its first antenna Ant_1). Specifically, Ant_1 of SU_1 senses the spectrum for a time slot τ before making the decision about the PUs states. The sensing process during τ time slot is done with a sampling rate of f_s.

Interestingly, for illustration and comparison purposes, Fig. 15 shows how the LAT protocol works. The circles and the intersections on the line represent the decision-making points of the SU after each time slot τ. It is noteworthy to mention that an SU can only transmit in the next time slot $(\tau + 1)$ when the PU is not around for the current time slot τ (see the interweave DSA in Section 2.4). Correspondingly, it is obvious that the most important parameters in this protocol are the sampling rate f_s and the time τ needed to make the decision.

It can be deduced from Fig. 15 that there are four states of spectrum usage and these states are abbreviated as the following:

- Only the PU is using the spectrum while the SU is silent.
- The PU is silent and only the SU is using the spectrum.
- Both the PU and the SU are using the spectrum (i.e. collision).
- Both the PU and the SU are silent (i.e. spectrum waste).

The last two states can occur for the following reasons:

- The PU changes its state while the SU is still collecting sensing samples (i.e. during time slot τ).
- Sensing Error (i.e. miss detection or false alarm).

To this extent, a summary of the advantages of the LAT protocol over the LBT is provided in the points below:

- SUs do not have to suspend the sensing process while transmitting.
- SUs do not have to adopt orthogonal resources to achieve FD communications.
- SUs can respond quicker to changes in PUs states compared with LBT. This depends on τ, the minimum slot length required to make a reliable decision in LAT protocol, compared to the blind duration (the sensing interval) in LBT protocol.

We do not stop to this extent but rather we are going to use the throughput of the CRN as a parameter to evaluate the LBT and the LAT protocols in the following paragraph.

As previously stated, increasing the transmission power of SUs in IBFD–CRNs will decrease the throughput of the CRN due to SI effects. Unfortunately, this means the LAT may encounter lower throughput values compared to the LBT protocol. To tackle this, the authors of

[198] and [199] provided a method that switches between the LAT and the LBT protocols to improve the throughput of the network. However, to clear this idea, a comparison between cooperative and non-cooperative sensing of both the LAT and the LBT protocols in terms of maximum throughput achieved is provided in the following text:

- When the average sensed Signal-to-Noise-Ratio (SNR) is small, cooperative sensing of both protocols perform better compared to non-cooperative sensing. However, apart from cooperation, the LAT protocol performs better than the LBT protocol, as it has fewer sensing errors due to continuous sensing.
- Under perfect sensing conditions, i.e. when the sensed SNR is large enough, cooperation does not change the performance of both protocols.

It is noteworthy to mention that some researchers in [200] have introduced an adaptive system model for FD-communications in non-time slotted CRNs to avoid collisions with PUs and eventually increase the throughput of the CRN. This model has three modes of operation; CSS, FD Transmit and Sense (FDTS), and in-band FD Transmit and Receive (FDTR) with asynchronous SUs transmissions. Predictably, in the CSS mode, a new MAC protocol is used to cooperatively detect the presence of PUs and set the spectrum access mode in the consequent spectrum hole. Interestingly, the mode adaption decision is done based on two energy thresholds used to evaluate the channel's condition. This decision determines whether to use FDTS or FDTR. Furthermore, simulations were conducted under imperfect SIC conditions to evaluate this model based on various metrics such as probability of collision, average collision duration, cumulative collision duration and the average throughput of the CRN. The results showed that this model outperforms the old LBT protocol and the FDTR mode with synchronous SUs transmissions by means of average collision duration and average CRN throughput.

It can be noticed from [200] that IBFD–CRs can represent SUs capable of sensing while transmitting (e.g., the LAT protocol) or capable of transmitting while receiving over the same channel without sensing. Therefore, both definitions will be referred to in the following part of this work by the same name (i.e. IBFD–CRs).

Additionally, since SIC techniques are still imperfect, the performance of IBFD systems is strongly affected by the SI and the external interferences of fading channels. Fortunately, for this reason, the authors of [201] have also considered an adaptive scheme for solar energy-harvesting-powered CRNs that changes the operational mode between HD and FD in order to achieve the best long-term throughput.

A detailed discussion of the most important concepts related to the comparison between HD- and IBFD–CRNs has been deliberately provided so far in this work. The following part will focus on IBFD–CRNs from the perspective of each layer without considering a detailed discussion of the HD counterparts of each concept. Some sensing, allocation and routing techniques used in the general FD-CRNs (i.e. HD-CRNs with a duplexing scheme like FDD) will be considered in this work because they may be helpful for understanding the requirements of IBFD–CRNs.

A comprehensive survey that studied spectrum sensing techniques in IBFD–CRNs is provided in [2] and a tutorial about blind sensing (i.e. detecting PUs without prior knowledge of their signal's characteristics) is provided in [202]. Sections 4.2.3, 4.2.4, 4.2.5 and 4.2.6 in this work will provide some insights on how the sensing process is done. Mainly, by considering the used sensing techniques in IBFD–CRNs, then discussing cooperative sensing, non-cooperative sensing and ON/OFF model sensing. Curiously, it was noticed that only energy detection-based techniques have been studied thoroughly in past literature. Obviously, this means the doors are open for further investigation of other sensing techniques for FD-CRNs and specifically for IBFD–CRNs [2,193].

In order to show the important role of signal processing in the sensing process, all types of spectrum sensing will be reviewed in the PHY-layer section of this work (i.e. in the following text) [15].

4.2.3. *Spectrum sensing techniques*

Robust spectrum sensing in IBFD–CRNs requires high sampling rates, large ADC dynamic range and high-speed processors [2]. The hardware components of the SUs in IBFD–CRNs must be designed to sense a wide range of the spectrum and to support efficient SIC methods, in order to realize high network throughput compared to HD-CRNs [2]. Remarkably, the existing spectrum sensing techniques only use primary transmitter detection, i.e. indirect sensing (see Section 2.6.1). A summary of the existing IBFD–CR sensing techniques is provided in the following text and in Table 4.

4.2.3.1. Cyclostationary spectrum sensing. The term cyclostationary refers to some features of the signal such as periodicity, mean and autocorrelation [14]. The transmissions of the PUs can be detected in this sensing technique by analyzing the cyclostationary features of the signals received by the SU, [14,203,204]. This analysis is done by calculating the cyclic autocorrelation of the received signals. Considering that, in wireless communications the transmitted signals are periodic as they are modulated and coupled with cyclic prefixes, pulse trains or sinusoidal wave carriers, while the additive noise signals are generally wide sense stationary with zero autocorrelation. Accordingly, if the cyclic autocorrelation was zero then there is no PU transmission (H_0), otherwise, it is an indication that PUs are occupying the channel (H_1) [8,14]. The model of the received signal can be represented mathematically by [63]:

$$H_0 : \; y(t) = \eta(t) \tag{1}$$

$$H_1 : \; y(t) = \eta(t) + hx(t) \tag{2}$$

where $y(t)$ is the received signal, $\eta(t)$ is a white Gaussian noise with zero mean and σ^2 variance, while $x(t)$ is the transmitted signal from the PU, h is the channel gain, and t is the sensing time.

The mathematical expression of $y(t)$ if it was cyclostationary (i.e., has periodic autocorrelation and mean) is represented by:

$$m_y(t) = E\{y(t)\} = m_y\left(t + T_0\right) \tag{3}$$

$$R_y(t, \tau) = R_y\left((t + T_0), \tau\right) \tag{4}$$

where T_0 is the period of the signal $y(t)$, τ is the time offset, E is the expectation operator, and R_y is the autocorrelation function of $y(t)$ and is calculated by:

$$R_y(\tau) = E\{y(t+\tau)y^*(t-\tau)e^{j2\pi\alpha t}\} \tag{5}$$

where α is the cyclic frequency, and * denotes the complex conjugate.

The practical concept of this sensing technique can be summarized in the following procedures and in Fig. 17 [63]:

- Digitizing the received analog signal $y(t)$ by the ADC.
- Computing the N-point Fast Fourier Transform (FFT) of the digital signal.
- Correlating these FFT values with themselves.
- Averaging the number of samples over N.
- Detecting the features of the average outcome to get the sensing decision (is there a correlation or not).

Cyclostationary sensing is robust against noise uncertainty and can differentiate between different types of primary systems. However, it requires information about the primary signals' characteristics, and requires very complex computations. This means the hardware devices of the SUs require high processing power capabilities; thus, the implementation cost of this sensing technique is going to be high [14]. Cyclostationary spectrum sensing was first proposed in [225] and utilized in IBFD–CRNs by [205–207]. On one hand, authors of [205] studied the effect of SI on the performance of IBFD–CR-enabled LTE networks and WLANs in the unlicensed 5-GHz band. In their study, they used active SIC techniques and evaluated the effect of SI on the detection probability of SUs performing cyclostationary sensing. The authors

Fig. 17. The practical block diagram of cyclo-stationary spectrum sensing [63].

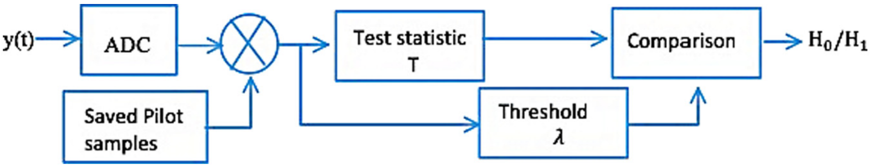

Fig. 18. The block diagram of coherent detector with pilot tones, [63].

of [206] considered an OFDM system with IBFD–CRs performing simultaneous transmission and spectrum sensing. They studied the impact of the cyclic feature of the secondary signals on the SIC techniques by altering the cyclic prefix of the OFDM signals. More to the point, authors of [207] proposed a method for conducting cyclostationary sensing without prior knowledge of the primary signal's characteristics. They calculated the probability of detecting the PUs for different values of SNR. They were able to prove that their method can differentiate between various OFDM signals.

4.2.3.2. Waveform-based sensing. Waveform-based sensing (a.k.a. coherent detection [8]) depends on previous knowledge of the PU's activity patterns. However, unlike matched filtering, it does not require perfect knowledge of the entire PU's activity patterns to operate, such that if any specific PU pattern was found in the signals received by the SU, then coherent detection can be utilized to determine whether the PU is occupying the spectrum (H_1) or not (H_0) [8,226]. This is done by projecting the received signal in the direction of a specified PU pattern. Remarkably, this is possible because there are particular patterns for most wireless communication systems such as pilot tones, spreading codes, preambles, midambles, and etc., that are used for control, synchronization, or equalization. Accordingly, the PU's signals will be characterized by these patterns based on the design of the primary wireless communication system.

An example of using coherent detection with pilot tone is provided in the following text [8].

The idle and the occupied channel states can be represented in coherent detection by:

$$H_0: \; y(t) = \eta(t) \tag{6}$$

$$H_1: \; y(t) = \eta(t) + \sqrt{\epsilon} x_p(t) + \sqrt{1-\epsilon}\, x(t) \tag{7}$$

where $x_p(t)$ is the pilot tone (known and transmitted by the PU), $\eta(t)$ is the white Gaussian noise, $x(t)$ is the desired signal (transmitted by the PU and assumed to be orthogonal on the pilot tone), and ϵ is the energy allocated to the pilot tone.

To clarify, signals are said to be orthogonal if their inner product is zero, i.e.

$$\langle x(t), x_p(t)\rangle = \int_{-\infty}^{\infty} x(t) . x_p(t)\, dt = 0 \tag{8}$$

As mentioned before, the test statistic of the coherent detection is done by taking the projection of the received signal in the pilot tone's direction,

$$T = \frac{1}{N}\sum_{t=1}^{N} y(t)\, \hat{x}_p(t) \tag{9}$$

where $\hat{x}_p(t)$ is a normalized unit vector in the pilot tone's direction (in practice it is a pilot sample). When the test statistic's value T increases it gets closer to the H_1 hypothesis (i.e., when it exceeds the threshold value then the channel is occupied).

The practical concept of coherent detection with pilots can be summarized in the following procedures and in Fig. 18 [63]:

- Digitizing the analog signal $y(t)$ using the ADC.
- Multiplying the digital signal with the predefined pilot samples.
- Evaluating the test statistic T.
- Comparing the test statistic's value with the predefined threshold and making the sensing decision.

Interestingly, coherent detection is robust against noise uncertainty and requires short time to achieve low probability of false alarm and miss detection. However, this technique requires exact information about certain primary signal's patterns, which increases the complexity of the system. Curiously however, the waveform-based sensing was used in IBFD–CRNs by [208] and [209]. Specifically, in [208] the waveform-based spectrum sensing was used to analyze the performance of the proposed adaptive transmission–reception–sensing strategy. The spectrum-awareness/efficiency tradeoff was handled by allowing the SUs to adaptively switch modes depending on the PUs activity. This strategy was able to double the throughput of the secondary system and decrease the collision probability with PUs to the half compared to its counterpart in HD-mode. Accordingly, the strategy proposed in [208] was tested again in [209] but with some modifications, as a centralized IBFD–CRN topology with overlay DSA has been adopted. Moreover, two antennas were used in [208] with the help of a hybrid SIC technique (i.e. both active and passive SIC) to ensure an acceptable SIC capability. Additionally, an underlay DSA model was adopted in [208] in order to optimize the transmission powers of the SUs that maximize the total throughput of the links under the PU's outage constraint (i.e. they wanted to find the maximum transmission power allowed by the SUs without cutting the PUs communications).

4.2.3.3. Energy detection-based sensing. In this type of sensing, the energy of the signal received by the SU is measured in a given bandwidth and time interval and then compared with a threshold to determine the presence or absence of the PU's signals [31]. To clarify, the energy detector test statistic T is defined as the average energy of N sensed samples [8],

$$T = \frac{1}{N}\sum_{t=1}^{N} |y(t)|^2 \tag{10}$$

The value of the test statistic is then compared to a predetermined threshold λ. H_1 is detected if $T > \lambda$, and H_0 is detected if $T < \lambda$.

The practical concept of the energy detection technique can be summarized by the following procedures and in Fig. 19 [63]:

- Digitization of the received analog signal $y(t)$ by the ADC.
- Computing the N-point FFT of the digital signal.
- Calculating the squared magnitude of the FFT values (i.e., computing the energy).
- Averaging the FFT squared values over N (number of samples).
- Making the sensing decision depending on the threshold λ.

This sensing technique is commonly used because it has low implementation cost, as it does not require estimates of the channel gain or any

Table 4
Summary of spectrum sensing techniques in the literature.

Sensing technique	Description of the sensing technique	Reference	Notes		
			Key category	Contribution	Methodology
Cyclostationary-based spectrum sensing	Tests the received signal's cyclic autocorrelation function, or its general characteristics and matches them with the already known PU signals characteristics	[205]	LTE networks and WLANs with IBFD capability	Measuring the effect of SI on the cyclostationary sensing performance	Analog and digital active SIC has been considered then the detection probability for SUs has been evaluated
		[206]	OFDM based IBFD–CRNs.	Studying the impact of the cyclic feature of the SU signals on the SIC techniques	The cyclic prefix of the OFDM signals has been altered for the SUs then the performance of the SIC techniques has been evaluated
		[207]	OFDM based IBFD–CRNs	Conducting cyclostationary sensing without prior knowledge of the primary signal's characteristics	The probability of detecting the PUs for different values of SNR was calculated
Waveform-based sensing (coherent detection)	Detects the presence of PUs by projecting the received signal in the direction of a specified PU waveform pattern	[208]	Underlay DSA	Introducing a transmission–reception–sensing strategy	Sensing decisions were made using the waveform-based spectrum sensing to analyze the performance of the proposed adaptive strategy, they maximized the throughput of the links under the PU's outage constraint
		[209]	Centralized IBFD -CRN topology (overlay DSA)	Testing the adaption strategy proposed in [208] in a practical network model	
Energy detection-based sensing	Measures the energy of the received signal then compares it with a threshold to determine the presence or absence of the PU's signals	[147]	Centralized CSS	Exploiting white spaces of cellular CRNs with IBFD capability using CSS, and a passive SIC technique	
		[210]		Deriving expressions to analyze the detection and the false alarm probabilities for Rayleigh fading channels.	
		[211]		Testing a proposed CSS technique that reduces SI, improves detection probability and archives robustness against malicious nodes	
		[147]	Distributed CSS	Proposing and examining a distributed CSS technique for IBFD–CRN that operates with the LAT protocol, using a digital SIC technique	
		[200]		Proposing an adaptive FD-communications for CRNs while employing two energy detection thresholds	
		[212]		Proposing a distributed CSS technique for IBFD enabled relaying CRNs, where unsuccessful primary packets were relayed to increase the throughput of both primary and secondary networks	
		[213]		Examining a non-time slotted IBFD–CRN with CSS that reduces the collision and the outage probabilities for SUs	
		[214]		Introducing a cross-layer optimal design for multi-hop IBFD–CRNs with derivation of CSS expressions	
		[146]	Non-cooperative spectrum sensing	Introducing a sensing approach that supports centralized and distributed networks and considers the power-throughput tradeoff	
		[215]		Introducing a joint spectrum sensing and power allocation scheme for IBFD cellular CRNs	
		[216]		Introducing a sensing technique to suppress the residual interference in a distributed network, with a propagation-based SIC technique	
		[217]		Introducing a non-CSS approach for decentralized IBFD–CRNs, with passive, analog and digital SIC techniques	
		[218]		Achieving synchronization between the SUs in a non-time slotted IBFD–CRN, with hybrid SIC	
		[219]		Proposing a novel sensing approach for IBFD–CRNs that finds the probability of white space detection, then estimates the channel utilization	
		[220]		Allowing each SU to sense the spectrum separately and work as a relay by forwarding the PU packets in order to gain extra bandwidth in return	
		[221]		Introducing a technique that considers multiple channels and analyzes their utilization to support non-time slotted IBFD–CRNs without the need for synchronization between SUs and PUs	
		[222]		Modeling imperfect sensing and studying the effect of sensing frequency on the energy efficiency, the average throughput, and the collision probability	
		[223]		maximizing the capacity of IBFD–CRNs while having non-time-slotted PU activity	
		[224]		Introducing a new spatial and temporal spectrum sensing technique for heterogeneous network environments	

other parameter. However, its performance depends on the channel's condition; such that, high noise uncertainty and high background interference can severely drop the performance [227]. Furthermore, energy detection cannot classify the source of the signal (i.e. PU signals cannot be distinguished from other signals in the spectrum). For illustration, in the scope of FD-communications, authors of [228] have studied the influences of residual RF impairments and channel fading on the classical energy detection performance. In their study, they assumed Nakagami-m fading channels and they proved that the environmental conditions must be considered when energy detection-based techniques are used.

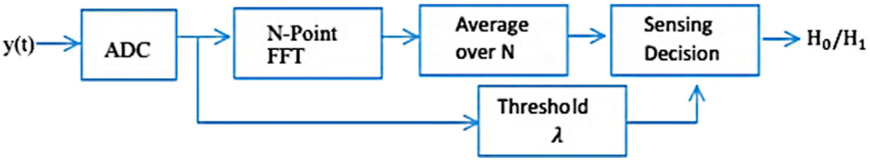

Fig. 19. The practical block diagram of energy detection, [63].

We do not stop to this extent but rather we are going to discuss various applications of energy detection-based sensing in the following parts of this work, as it has been studied thoroughly in the past literature.

4.2.4. Cooperative spectrum sensing

CSS improves the detection reliability, but it is considered an overhead because it adds extra transmission costs, sensing time, end-to-end delay, energy and computational costs, as it uses extra resources (e.g. spectrum bands) to send the sensing results between the nodes in distributed networks or towards the fusion center in centralized networks [2]. Furthermore, in cooperative sensing for both HD- and IBFD–CRNs, the PHY-layer is responsible for performing signal processing in order to analyze and combine the sensing results, while the MAC layer manages the spectrum sensing and the spectrum access operations in order to figure out how to achieve cooperation (see Section 2.6.3). Moreover, the energy detection-based sensing technique was used in IBFD–CRNs with centralized spectrum sensing and they are examined in [147,210] and [211]. Furthermore, distributed spectrum sensing techniques in IBFD–CRNs are studied in [145,200,212,213], and [214].

The available white spaces of cellular CRNs with IBFD capability were exploited with a centralized CSS method in [147]. The transmit limitations were addressed using beamforming and a passive propagation-based SIC technique was used. Nevertheless, in [210], IBFD–CRNs with synchronous and non-synchronous centralized primary and secondary networks were analyzed. In their analysis, expressions of the detection and the false alarm probabilities were derived for Rayleigh fading channels. Additionally, the receiver operating characteristics and the total error rates were also analyzed while employing the energy detection technique. Furthermore, in IBFD–CRNs, a centralized CSS technique that keeps robustness against malicious nodes has been studied in [211]. The proposed technique also reduces SI and improves the detection probability by using a confidence-only report rule and a weighted majority fusion rule [211].

As for distributed CSS techniques, authors of [145] proposed and examined a distributed CSS for IBFD–CRN that operates with the LAT protocol. In this technique, each SU used two antennas with a digital SIC method [145]. The achieved throughput by this technique was improved compared with the LBT protocol [145]. Furthermore, authors of [200] adopted a cooperative energy detection criterion with two thresholds. One of which is for detecting active PUs and the other is for choosing the operational mode for the SUs in the next time slot. Moreover, in IBFD enabled relaying CRNs, a distributed CSS technique has been proposed and investigated in [212]. In this technique, the unsuccessfully transmitted PU packets were relayed and the throughput of the secondary and the primary networks were increased compared to HD-CRNs [212]. Besides, in [213] a non-time slotted IBFD–CRN with CSS has been examined. The collision and the outage probabilities were reduced for SUs while having PUs that randomly change their transmission activities. Authors of [214] Investigated a cross-layer optimal design of a multi-hop ad hoc IBFD–CRN. Particularly, they derived the analytical expressions of CSS in different fading environments. Then, they presented a multi-objective optimization model to maximize the opportunistic throughput and minimize the transmit power of CRs.

4.2.5. Non-cooperative spectrum sensing

The reason behind studying non-CSS techniques in IBFD–CRNs rather than cooperative sensing is that they do not require extra resources to sense the spectrum and make the decision for spectrum access [2]. Therefore, each node in the network can make its spectrum access decision on its own.

Moreover, the PHY-layer examines the sensing results while the MAC layer manages the sensing and the access operations (see Section 2.6). Several studies have considered using non-CSS in IBFD–CRNs such as [146,215–224]. In [146], a sensing approach that supports centralized and distributed networks has been introduced. This technique was compared with the old sensing approaches. In this approach, the power-throughput tradeoff was considered to cancel the SI and increase the throughput [146]. Nevertheless, authors of [215] studied a joint spectrum sensing and power allocation scheme for IBFD cellular CRNs and they handled the power-throughput tradeoff using this method. Additionally, the proposed approach in [215] allows the secondary BSs to operate in IBFD mode where they can sense the spectrum while transmitting. On the other hand, authors of [216] considered suppressing the residual interference using energy-detection based spectrum sensing in a distributed network and they used a passive propagation-based SIC technique. Moreover, Authors of [217] Introduced a non-CSS approach for decentralized IBFD–CRNs, with passive, analog and digital SIC techniques. The method proposed in [217] reduced the packet loss probability compared to HD-CRNs.

Since synchronization between the SUs is important in the design of IBFD–CRNs, authors of [218] managed the synchronization between the SUs in a non-time slotted IBFD–CRN using non-CSS. The proposed technique showed its effectiveness in combination with hybrid (passive and active) SIC [218]. Moreover, in [219] a novel sensing approach for IBFD–CRNs was proposed. The probability of white space detection was found, and the channel utilization was then estimated. The theoretical and the simulation results showed that the proposed method has an advanced performance compared to older spectrum sensing techniques.

In cooperative IBFD–CRNs, each SU can sense the spectrum individually (i.e. non-CSS), therefore, authors of [220] have chosen to make the SUs sense the spectrum separately and work as relays to forward the PU packets in order to gain extra bandwidth in return. This method increases the throughput and supports the decentralized network topology. Furthermore, authors of [221] proposed a non-CSS technique for non-time slotted IBFD–CRNs that considers multiple channels and analyzes their utilization. This approach allows each SU to select a single channel based on the results of its own FD spectrum sensing, therefore, it does not require synchronization between SUs and PUs. The results showed that the proposed method maximized the channel utilization and enhanced the throughput of the PUs. More to the point, authors of [222] modeled and analyzed a CRN with imperfect FD spectrum sensing (i.e. with errors and asynchronous with primary traffic) using impeded Markov chain. Specifically, the authors studied the effect of sensing frequency on the energy efficiency, the average throughput, and on the collision probability with PUs. The results were examined compared to the HD counterpart of the modeled network. On the other hand, the authors of [223] considered maximizing the capacity of IBFD–CRNs while having non-time-slotted PU activity. They first derived the formulas of the sensing probabilities. Then, for active and silent SUs, the operating parameters were jointly optimized. The numerical results showed that the proposed optimization method in

[223] provides higher capacity and lower computational cost compared to IBFD–CRNs with time-slotted PU activities. Authors of [224] have addressed the challenges of spectrum sharing in high density small-cell internet-of-things situations, where PUs and IBFD–CRs (particularly FDTS) exist. The main challenge is the heterogeneous environment created because of the dense and random distribution of IBFD–CRs, where there are time and space varying spectrum opportunities. In this study, the authors considered the traffic variations of PUs in time and space, and they introduced a new spatial and temporal spectrum sensing technique for such heterogeneous environments.

4.2.6. ON/OFF model-based sensing

This periodic sensing model can be used with any sensing technique to sense and access the spectrum in IBFD–CRNs. However, this ON/OFF model was initially used with energy detection-based sensing in [229]. It was shown that adopting this model along with having adaptive SUs operational modes (i.e. switching between transmit–receive and Transmit–Sense modes) can enhance the throughput of IBFD–CRNs and decrease the collision probability in comparison with HD-CRNs. Moreover, the LAT protocol used this periodic ON/OFF spectrum sensing model with energy detection-based sensing in [198,199] (see Section 4.2.2.2). On the other hand, the waveform-based sensing was used with this model in [209].

Excitingly, the following sub-section will focus on the MAC layer protocols for IBFD-networks and for IBFD–CRN.

4.3. Medium access control layer considerations in IBFD-CRNs

The main difference between the MAC layer protocols in HD mode and in IBFD mode is deduced from the fact that terminals operating in IBFD mode use simultaneous transmission and reception [124,151,160]. This means that HD-based MAC protocols will not be able to acquire the advantages of IBFD communications because they only support transmission and reception of frames in different time spans. Accordingly, different FD-based MAC protocols need to be designed in order to handle this situation.

It is worth mentioning at this point that according to [119], even if the terminals are HD in the PHY-layer, the advantages of full duplexing can be retained as long as the terminals are FD in the MAC layer (i.e. at the frame level). This scenario can be called virtual IBFD. Moreover, this conclusion was proposed by authors of [119] because having HD PHY-layer terminals avoids the infeasible SIC that occurs when the power difference between the transmitted and the received signals is too large to handle. Furthermore, researchers in [230] have proposed a signaling technique to achieve virtual IBFD by creating off-slots inside each frame of a terminal in the frequency or in the time domain. Through these off-slots, the terminal can collect useful signals without worrying about the SI. In addition, researchers have studied the advantages of using the virtual IBFD from several perspectives related to the overall network performance, such as neighbor discovery as in [231], localization and ranging as in [232], and mutual broadcasting as in [233], which can be used for exchanging network state information.

4.3.1. IBFD medium access control protocols

IBFD based MAC protocols have the potential to increase the throughput and the fairness of the network by resolving the hidden terminal problem and employing a scheduling algorithm (see Section 3.2). Fortunately, in [61], a survey that discussed IBFD-MAC protocols was proposed. The following text will provide a brief discussion of some of the proposed IBFD-MAC protocols. This is to understand what needs to be considered when designing such protocols for both IBFD and IBFD–CR networks.

4.3.1.1. MAC protocols for centralized IBFD networks. IBFD-MAC protocols in centralized networks suffer from several problems such as hidden terminal, node starvation, and inter-user interference. The following discussion provides a summary of each problem and how it was handled by the proposed MAC protocol.

- *Problems of IBFD centralized MAC protocols: Hidden terminal problem*

Theoretically, two IBFD nodes are allowed to transmit and receive packets at the same time. However, in asymmetric network environments one node may not have data to transmit to the other node. In this situation, the hidden terminal problem may arise if the apparent node had no data to transmit (see Section 3.2). Therefore, a centralized MAC protocol was proposed in [151] to solve the hidden terminal problem in such asymmetric networks. This MAC protocol permits the node that is receiving data but has no data to transmit a busy tone until its reception ends.

- *Problems of IBFD Centralized MAC protocols: Node starvation problem*

If two IBFD nodes are simultaneously communicating with data and ACK packets that have headers to maintain this transmission opportunity, then the channel will be occupied only for this transmission and other nodes may suffer from starvation (i.e. not being able to use the spectrum for their communications). Therefore, a centralized IBFD-MAC protocol that redesigned the frame structure of the IEEE 802.11 MAC protocol was proposed in [152]. The name of this protocol is FD-MAC, it allows the Access Point AP (i.e. the central controller) to switch between IBFD and HD modes to ensure that all nodes have the opportunity to transmit. Three new elements were added to the standard IEEE 802.11 Packet structure. They are the virtual contention resolution (a.k.a. virtual back-offs [2]), the header snooping, and the shared random back-offs. Packets are prioritized inside the buffers in the IEEE 802.11 standard; hence, the virtual back-offs allow the AP to prioritize the packets before initiating the IBFD mode. Moreover, the header snooping allows the AP to estimate the network topology by analyzing every packet that needs to be transmitted. Using this topology, the AP will know when to switch its operating mode (either HD or IBFD mode). Furthermore, the shared random back-offs SRB field avoids having collisions and interferences when two nodes are transmitting packets at the same time by allowing the nodes to share information about their packets. Additionally, for addressing the node starvation problem in IBFD–MIMO systems, another centralized MAC protocol was proposed in [234], in which, spatial resources were allocated to the IBFD nodes to increase their transmission opportunity.

- *Problems of In-Band Full Duplex Centralized Medium Access Control protocols: Inter-user interference Problem*

The main challenge facing network designers when implementing a centralized IBFD-MAC is the inter-user interference that occurs when the central controller communicates with multiple nodes simultaneously and degrades the performance of the network. This problem was not addressed in the aforementioned MAC protocols. Therefore, a centralized IBFD-MAC protocol which considers the existence of a certain amount of inter-user interference was proposed in [235]. This protocol schedules the transmission mode (HD or IBFD) of the AP in a manner that reduces collisions by controlling the timing and the rate of packet transmission.

4.3.1.2. MAC protocols for distributed IBFD networks. IBFD distributed MAC protocols have been considered in several studies. Each study focused on handling a specific problem such as collisions, hidden terminals, and inter-node interference. Therefore, the following text provides a brief description of the main contributions of the distributed IBFD-MAC protocols.

- *Problems of IBFD Distributed MAC protocols: Collisions and hidden terminal problems*

IBFD distributed MAC protocols such as [160,236] can be used to prevent collisions and the hidden terminal problem without requiring the handshaking procedure. This handshaking procedure used to exist in conventional HD MAC protocols and reduced the throughput of the network. However, if the data traffic of the network was asymmetric then the hidden terminal problem will appear again [61]. This situation was handled by the proposed MAC protocol in [237] which uses the CSMA/Collision Avoidance (CSMA/CA) with Request To Send/Clear To Send (RTS/CTS) mechanism in IBFD mode along with allowing each receiving node to transmit a busy tone when it does not have data packets to transmit. Nonetheless, according to [61,237,238], a busy tone is considered to be wasting the node's energy. Therefore, a MAC protocol with RTS/full-duplex CTS was proposed in [239] to solve the hidden terminal problem for ad-hoc networks while avoiding this busy tone. Furthermore, unlike the normal RTS/CTS, the RTS/full-duplex CTS grants the transmitting node the permission to send the full-duplex CTS message to its own neighbors. That way, the coverage range of the broadcasted full-duplex CTS will be larger than regular CTS messages [61].

- *Problems of IBFD Distributed MAC Protocols: Inter-node interference*

In distributed networks, if three nodes decide to simultaneously communicate as in IBFD-relay scenario (Section 3.3.2), then all nodes will experience additional interference at their receiving antennas due to inter-node interference. Therefore, IBFD-MAC protocols need to address this situation by scheduling the nodes transmission especially in asymmetric data traffic environment. Consequently, a distributed MAC protocol was proposed in [240], which depends on contention resolution to handle the inter-node interference. This protocol supports a newly designed FD ACK and a transmission flag fields. The FD ACK is used to negotiate the transmission mode (HD or FD) between each two communicating nodes and the transmission flag is used as a reply to allow or deny the simultaneous transmission and reception before the two nodes start sending their data packets.

- *Problems of IBFD Distributed MAC protocols: Energy consumption*

Many MAC protocols focused on enhancing the throughput of the network, however, the work of [239] can be considered as an energy efficient protocol because it does not have the power consuming busy tone. Nevertheless, a new energy efficient MAC protocol for IBFD devices was proposed in [241]. The energy consumption problem was handled by allowing SUs to adaptively change their modes of operation using three types of control frames. Additionally, the protocol proposed in [241] was tested analytically and proven to be energy and throughput efficient compared to the literature.

4.3.2. Medium access control protocols for IBFD-CRNs

For cognitive radio networks, the use of IBFD mode allows the SUs to sense the traffic while transmitting [124,242]. Therefore, there is no need for quiet sensing periods scheduling, which used to be a task of the MAC layer in HD mode, and was referred to as sensing-access tradeoff by [15] (see Section 2.6.2).

The MAC layer protocols for IBFD–CRNs have been surveyed in [2]. Nevertheless, the following text provides a discussion of the MAC layer protocols studied so far based on each study's contribution.

4.3.2.1. Problems of IBFD-CRNs MAC protocols: Unexpected appearance of PUs. When a PU appears suddenly while an SU is using the spectrum, it regains its right to use the spectrum so the SU will suspend its transmission. This raises a challenge for the MAC layer design of SUs because if the transmission was suspended while a packet was still being transmitted, then the packet will be dropped. Therefore, a MAC protocol that fragments the packets was introduced in [165] to address this problem by reducing the number of dropped packets. Additionally, another MAC protocol was proposed in [235], which supports packet/frame fragmentation and relies on the IEEE 802.11 standard back-off mechanism.

4.3.2.2. Problems of IBFD-CRNs MAC protocols: Cooperative spectrum sensing. The LAT protocol-based CSS MAC protocols were tested in [145,198,199]. The advantages of using CSS with the LAT protocol are summarized in Section 4.2.2.2. In short, these MAC protocols can double the spectrum efficiency if the SU's transmission power was optimally controlled. Furthermore, another MAC protocol that supports cooperative IBFD–CRNs is proposed in [243], where separate queues for SUs and PUs are utilized along with using an error-free ACK/NACK packet to decrypt the PU's activity packets to achieve cooperation between PUs and SUs in the network. Additionally, authors of [244] have proposed a cooperative repeat request method ARQ for FD-CRNs. The performance parameters were the primary and the secondary users' throughputs along with the MAC layer's packet error rate. These parameters were evaluated for ARQ and hybrid ARQ modes and the results showed no effect of SUs on PUs network in ARQ mode, while an improvement on the performance of PUs network was proven in hybrid ARQ mode.

4.3.2.3. Problems of IBFD-CRNs MAC protocols: Collisions. Collisions between SUs and collision durations were reduced in the MAC protocol proposed in [213]. This protocol estimates the spectrum usage and the collision ratios along with estimating the contention window size. This offers the SUs the ability to make intelligent decisions in order to select only the idle channels for their transmission.

4.3.2.4. Problems of IBFD-CRNs MAC protocols: Synchronization between SUs. A MAC protocol was proposed in [245] to avoid the overhead that comes with synchronizing SUs. This protocol was called FD cognitive MAC protocol. It does not require any synchronization between SUs. The operation of this protocol is divided into two stages; the first stage allows the SUs to operate in IBFD mode to perform channel contention and the second stage allows the SUs to perform spectrum sensing and transmit data.

4.3.2.5. Problems of IBFD-CRNs MAC protocols: Handling multi-channels. Flexibility with multi-channels is required especially when dealing with multi-hop CR networks, therefore, a MAC protocol was proposed in [246] that allows the SUs to change their operating channel without needing to wait for a specific channel to become idle. This means providing each SU with the flexibility to find idle channels and switch its transmission and reception to them. Plus, this protocol can operate without a control channel. Moreover, other MAC protocols that support using multi-channel are proposed in [247] and [221]. In [247], a randomized channel selection and a standard back-off mechanism were considered to develop the MAC protocol proposed in [245]. The randomized channel selection helps the SUs to handle multi-channels and the standard back-off mechanism is used to handle the channel contention. This protocol can achieve load balancing and improve the sensing and transmission performance. The authors of [221] proposed a MAC protocol that supports multiple channels in non-time slotted IBFD–CRNs. In this protocol, each SU uses FD sensing to detect PUs re-activation in order to avoid collisions [221].

4.3.2.6. Problems of IBFD-CRNs MAC protocols: Enhancing the throughput. Authors of [248] considered a non-time-slotted CRN with SUs capable of sensing while transmitting and PUs operating at any time. The throughput per frame for the SUs was calculated to find the best SU's frame duration with the absence of PUs activity and while considering the PU's temperature limit.

To this point, various MAC protocols were considered from their contraption's viewpoint in order to help grasping the main idea behind each protocol. Additionally, a summary of these protocols is provided in Table 5.

4.4. Network layer considerations in IBFD-CRNs

From the network layer perspective, advantages of IBFD can be achieved when the routing algorithms begin to use intersecting routes, which may reduce the route's length and the overall interference and may increase the system's throughput [119]. This can happen if the terminals in each route are allowed to jointly process bidirectional flows which may be done by developing network coding techniques [217,249,250].

In the following text, the available routing algorithms in IBFD and in IBFD–CRNs are discussed.

Table 5
Summary of IBFD MAC protocols in the literature.

Network type		Main contribution	Reference	Notes
IBFD networks	Centralized	Handling the hidden terminal problem	[151]	In asymmetric communications, the receiving node can transmit a busy tone until its reception ends
		Handling the node starvation problem	[152]	A modification of the IEEE 802.11 frame structure is done to ensure that all nodes have the opportunity to transmit by allowing the AP to switch between IBFD and HD modes
			[234]	In IBFD–MIMO systems, spatial resources are allocated to the IBFD nodes to increase their transmission opportunity
		Handling the inter-user interference problem	[235]	For the AP, IBFD and HD modes are scheduled to reduce collisions in the network, while considering the existence of a certain amount of interference
	Distributed	Handling collisions and hidden terminals	[160,236]	IBFD-MAC protocols are introduced to prevent collisions and the hidden terminals without requiring the handshaking procedure
			[237]	CSMA/CA with RTS/CTS is used in IBFD mode and each receiving node is allowed to transmit a busy tone when it does not have data packets to transmit
			[239]	CSMA/CA with RTS/full-duplex CTS (FCTS) is introduced to avoid using the busy tone
		Handling the inter-node interference	[240]	A newly designed FD ACK (FDA) and a Transmission Flag (TF) fields are used to set the transmission mode between nodes before transmitting data
		Handling energy consumption	[241]	SUs are allowed to adaptively change their modes of operation using three types of control frames
IBFD–CRNs		Handling the unexpected appearance of PUs	[165]	SUs packets are fragmented to avoid dropping the packets being transmitted
			[235]	Packets and frames are fragmented, and the standard IEEE 802.11 back-off mechanism is used
		Considering CSS	[145]	LAT protocol-based CSS MAC protocols are examined
			[243]	Separate queues for SUs and PUs, and an error-free ACK/NACK packet for PU's activities are used to achieve cooperation between the PUs and the SUs
			[244]	A cooperative repeat request method ARQ for FD-CRNs, with evaluation of the primary and the secondary users' throughputs along with the MAC layer's packet error rate PER
		Handling collisions	[213]	The protocol estimates the spectrum usage and the collision ratios along with estimating the contention window size
		Handling the synchronization between SUs	[245]	Avoids synchronization between SUs by allowing each SU to work in two stages, one is operating in IBFD mode to do channel contention, and the other is performing spectrum sensing and transmitting data.
		Providing flexibility with multi-channels	[246]	SUs are allowed to change their operating channel without waiting for a certain channel to become idle, and the protocol can operate without a control channel
			[247]	A randomized channel selection and a standard back-off mechanism were considered to develop the MAC protocol introduced in [245]
			[221]	The MAC protocol supports multiple channels in non-time slotted IBFD–CRNs
		Enhancing the throughput	[248]	A protocol for a non-time-slotted CRN with SUs capable of sensing while transmitting, along with evaluation of the throughput per frame to find the best frame duration

4.4.1. *Routing in IBFD multi-hop networks*

In Multi-hop wireless networks, the routing protocol is a very important component that is used to satisfy certain performance metrics in the network, such as increasing the end-to-end throughput. Therefore, for IBFD multi-hop networks a modification of the Dijkstra's routing algorithm was proposed in [251]. This routing protocol considered the residual SI and solved the joint routing and the power allocation problems in order to maximize the end-to-end throughput. It is worth noting that the Dijkstra algorithm starts at the source node and looks for the shortest path until it reaches the destination node. Furthermore, a new routing algorithm was proposed in [252] which also considered the joint routing and the power allocation problems with residual SI for IBFD wireless networks.

4.4.2. *Routing in in-band full-duplex cognitive radio networks*

In HD ad-hoc CRNs, the nodes cannot transmit packets while sensing which means that the spectrum is not efficiently utilized. Moreover, routing protocols obtain the optimal paths depending on the results of periodic spectrum sensing, which is performed in the PHY-layer to find the available channels at each node in the network. However, this comes with the price of consuming extra energy and time to perform these sensing operations. Furthermore, more time is required for the process of switching between different channels to sense them. However, if IBFD technology was applied to ad-hoc CRNs, the nodes would be able to transmit packets while performing spectrum sensing. Thus, the required time to find the available channels will not affect the transmission. Fortunately, authors of [253] have discussed the problems of non-time slotted multi-channel CR ad-hoc networks. Specifically, they discussed the reactivation failure, the frequently unexpected handoffs, the non-real-time aggregation, the inefficient power allocation and the frequent reroute problems. Interestingly, they introduced a FD framework to address these problems.

Beyond all that, routing in FD-CRNs has only been considered in two studies so far [254] and [255]. Interestingly, the routing algorithm proposed in [254] assumes that each SU can have simultaneous transmission and reception over different channels. Additionally, each SU is assumed to be capable of suppressing the SI. Furthermore, the feasibility of conducting simultaneous transmission and reception over different channels FD communications between SUs was examined by employing a "path Capacity" metric. This metric considers maximizing the number of links that can be simultaneously activated across a given path while using the minimum number of distinct channels. Accordingly, the routing algorithm chooses the best path and assigns the channels in order to achieve the highest capacity possible. However, in [255], the researchers continued their study to include SUs capable of transmitting and receiving over the same channel (i.e. IBFD). They analytically studied the channel assignment and the path selection problems while enhancing the "path capacity" metric.

Excitingly, routing in IBFD–CRNs is still an open field for further research in the future.

5. Future research work and recommendations

5.1. In-band full-duplex and self-interference-cancelation

IBFD technology and SIC techniques should be more mature in order for them to be added in a new wireless standard. This maturity is in different aspects; such as handling network and MAC layer, demonstrating the SIC techniques in different operating environments, and applying IBFD and SIC techniques in practical sized devices rather than having large prototypes.

5.2. In-band full-duplex cognitive radio networks

5.2.1. Sensing and analysis processes

The PHY components of IBFD–CRs must be able to sense a wide range of the spectrum. This can be done in the future by applying wideband sensing techniques in IBFD–CRNs.

Energy detection has been studied extensively in the past literature, however, this technique cannot detect weak signals. Moreover, waveform-based detection and cyclo-stationary feature detection consume considerable power because of their complexity. Therefore, efforts should be made to reduce the complexity of such techniques in order to use them in real-life application. It is noteworthy to mention that wide-band spectrum sensing techniques require high sampling rates, thus, they need high-speed signal processors and high-resolution ADCs. This means the design of accurate and reliable wide-band spectrum sensing techniques with low complexity is quite challenging. However, this is still a growing field and is very likely for such challenges to be handled in the near future. Furthermore, wide-band sensing techniques have been studied and analyzed through simulations in the literature. Thus, the physical implementation of such sensing techniques should be studied in the future for both HD and IBFD modes.

5.2.2. Reasoning process (spectrum sharing)

DSA in IBFD–CRNs has been considered in relay networks and there is one study that considered a multi-hop network in various fading environments [214]. Thus, there is a need to study overlay networks, multi-hop networks, and different networks in fading environments.

5.2.3. Adaptation process

The available channels and hence, the operating parameters of CRs in the network will vary depending on the positions of CRs and PUs. Varying the positions of PUs have been studied only in [224]. Therefore, varying SUs and PUs positions should be considered in the future to get closer to real-life applications.

5.2.4. General recommendations about IBFD-CRNs

Many studies about IBFD–CRNs can be extended in the future by considering more complicated network scenarios, such as using multiple PU transmitters (e.g., [224]). This will increase the maturity of IBFD–CR technologies, such that they can have a specific wireless standard to be used in real-life applications.

Creating practical devices that support adaptive FD–HD and FDTR–FDTS–CSS modes of operation is encouraged; since such adaptive models will avoid collisions with PUs and increase the throughput of CRN.

IBFD–CRNs have been secured in the PHY-layer using SIC techniques [256] and by allowing the SUs to transmit jamming signals while sensing or while receiving data (or energy) packets to avoid eavesdropper's attacks [2]. However, PHY-layer security has not been studied for overlay and interweave DSA models, and it needs further investigation in underlay models; as it has been studied only when PUs are the eavesdroppers [2,257]. Additionally, other CRN threats such as PU emulation attacks [258], jamming attacks, denial-of-service attack, spectrum sensing data falsification attacks and others [259] have not been considered for IBFD–CRNs. Furthermore, the effects of spectrum sensing techniques on the security of IBFD–CRNs have not been examined in detail in the past literature [2].

6. Conclusions

A review of the cognitive radio networks, the IBFD communications, and the IBFD–CRNs is presented in this work from the perspective of each network layer. It has been shown that IBFD–CRNs can offer higher spectrum utilization, data rates, and energy-efficiency, compared to HD-CRNs. However, this comes with a price, as the IBFD–CRNs require new signal processing methods (in the PHY-layer), new resource allocation algorithms (in the MAC layer), and new network-layer routing protocols. The most important aspects that need to be considered when designing an IBFD–CRN are: the used SIC technique, the used sensing technique, the used spectrum access mechanism, the network architecture, the used routing protocol and the metrics that need to be optimized (i.e. throughput, QoS, energy efficiency and spectrum utilization).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Lingyang Song, Beijing, Risto Wichman, Yonghui Li, Zhu Han, Full-Duplex Communications and Networks, Cambridge University Press, 2017.

[2] Amjad Muhammad, Fayaz Akhtar, Mubashir Husain Rehmani, Martin Reisslein, Full-duplex communication in cognitive radio networks: A survey, IEEE Commun. Surv. Tutor. 19 (4) (2017) 2158–2191.

[3] K.G. Shin, H. Kim, A.W. Min, A. Kumar, Cognitive radios for dynamic spectrum access: From concept to reality, IEEE Wirel. Commun. Mag. 17 (6) (2010) 64–74.

[4] S. Bhattarai, J.-M.J. Park, B. Gao, K. Bian, W. Lehr, An overview of dynamic spectrum sharing: Ongoing initiatives, challenges, and a roadmap for future research, IEEE Trans. Cognit. Commun. Netw. 2 (2) (2016) 110–128.

[5] B. Rashid, M.H. Rehmani, A. Ahmad, Broadcasting strategies for cognitive radio networks: Taxonomy, issues, and open challenges, Comput. Electr. Eng. 52 (2016) 349–361.

[6] B. Sharif, M. Hassibi, On the Capacity of MIMO broadcast channels with partial side information, IEEE Trans. Inform. Theory 51 (2) (2005) 506–522.

[7] I.F. Akyildiz, W.-Y. Lee, M.C. Vuran, S. Mohanty, Next generation/dynamic spectrum access/cognitive radio wireless networks: A survey, Comput. Netw. 50 (2006) 2127–2159.

[8] Wang Beibei, K.J. Ray Liu, Advances in cognitive radio networks: A survey, IEEE J. Sel. Top. Signal Process. 5 (1) (2011) 5–23.

[9] J. Mitola, G.Q. Maguire, Cognitive radio: making software radios more personal, IEEE Pers. Commun. 6 (4) (1999) 13–18.

[10] J. Mitola, Cognitive Radio—an Integrated Agent Architecture for Software-Defined Radio (Ph.D. dissertation), Roy. Inst. Technol., Stockholm, Sweden, 2000.

[11] C. Cordeiro, K. Challapali, D. Birru, S. Shankar, IEEE 802.22: the first worldwide wireless standard based on cognitive radios, Proceedings of New Frontiers in Dynamic Spectrum Access Networks (2005) 328–337.

[12] Paul Kolodzy, Spectrum policy task force, Federal Commun. Comm. Washington, DC, Rep. ET Docket 40 (4) (2002) 147-158.

[13] S. Haykin, Cognitive radio: Brain-empowered wireless communications, IEEE J. Sel. Areas Commun. 23 (2) (2005) 201–220.

[14] D.M. Alias, Cognitive radio networks: A survey, in: Proceedings of Wireless Communications, Signal Processing and Networking (WISPNET), International Conference, IEEE, Chennai, India, 2016, pp. 1981–1986.

[15] Y.C. Liang, K.C. Chen, G.Y. Li, P. Mahonen, Cognitive radio networking and communications: An overview, IEEE Trans. Veh. Technol. 60 (7) (2011) 386–407.

[16] K.-C. Chen, S.-Y. Tu, C.-K. Yu, Statistical inference in cognitive radio networks, in: Proceedings of 2009 IEEE China Com, Xian, China, 2009, pp. 1–10.

[17] S.-Y. Lien, N. Prasad, K.-C. Chen, C.-W. Su, Providing statistical quality-of-service guarantee in cognitive radio networks with cooperation, in: Proceedings of 2nd Int. Workshop CogART, Aalborg, Denmark, 2009, pp. 6–11.

[18] Y. Zhao, L. Morales, J. Gaeddert, K.K. Bae, J.-S. Um, J.H. Reed, Applying radio environment maps to cognitive wireless regional area networks, in: Proceedings of 2nd IEEE Int. Symp. DySPAN, Dublin, Ireland, 2007, pp. 115–118.

[19] R.W. Thomas, D.H. Friend, L.A. Dasilva, A.B. Mackenzie, Cognitive networks: Adaptation and learning to achieve end-to-end performance objectives, IEEE Commun. Mag. 44 (12) (2006) 51–57.

[20] Mähönen Petri, Marina Petrova, Janne Riihijärvi, Matthias Wellens, Cognitive wireless networks: Your network just became a teenager, in: Proceedings of the INFOCOM, 2006, pp. 23–29.

[21] T. Jiang, Z. Wang, Y. Cao, Cognitive Radio Networks: Efficient Resource Allocation in Cooperative Sensing, Cellular Communications, High-Speed Vehicles, and Smart Grid, CRC Press, 2015.

[22] F. Akyildiz, W.-Y. Lee, K.R. Chowdhury, CRAHNS: Cognitive radio ad hoc networks, Ad Hoc Netw. 7 (5) (2009) 810–836.

[23] T. Luo, T. Jiang, W. Xiang, H.-H. Chen, A subcarriers allocation scheme for cognitive radio systems based on multi-carrier modulation, IEEE Trans. Wirel. Commun. 7 (9) (2008) 3335–3340.

[24] O. Fatemieh, R. Chandra, C.A. Gunter, Low cost and secure smart meter communications using the TV white spaces, in: Proceedings of International Symposium on Resilient Control Systems, Idaho Falls, ID, USA, 2010, pp. 37–42.

[25] A. Ghassemi, S. Bavarian, L. Lampe, Cognitive radio for smart grid communications, in: Proceedings of IEEE International Conference on Smart Grid Communications, Gaithersburg, MD, USA, 2010, pp. 297–302.

[26] M. Brew, F. Darbari, L.H. Crockett, M.B. Waddell, M. Fitch, S. Weiss, R.W. Stewart, UHF White space network for rural smart grid communications, in: Proceedings of IEEE International Conference on Smart Grid Communications, Brussels, Belgium, 2011, pp. 138–142.

[27] K. Nagothu, B. Kelley, M. Jamshidi, A. Rajaee, Persistent net—AMI for microgrid infrastructure using cognitive radio on cloud data centers, IEEE Syst. J. 6 (1) (2012) 4–15.

[28] R. Yu, Y. Zhang, S. Gjessing, C. Yuen, S. Xie, M. Guizani, Cognitive radio-based hierarchical communications infrastructure for smart grid, IEEE Netw. 25 (5) (2011) 6–14.

[29] Q.D. Vo, J.-P. Choi, H.M. Chang, W.C. Lee, Green perspective cognitive radio-based M2M communications for smart meters, in: Proceedings of International Conference on Information and Communication Technology Convergence (ICTC), Jeju, South Korea, 2010, pp. 382–383.

[30] S. Gong, H. Li, Dynamic spectrum allocation for power load prediction via wireless metering in smart grid, in: Proceedings of Annual Conference on Information Sciences and Systems, Baltimore, MD, USA, 2011, pp. 1–6.

[31] Atapattu Saman, Chintha Tellambura, Hai Jiang, Energy Detection for Spectrum Sensing in Cognitive Radio, Springer, New York, NY, USA, 2014.

[32] Ozgur B. Akan, Osman B. Karli, Ozgur Ergul, Cognitive radio sensor networks, IEEE Netw. 23 (4) (2009).

[33] Song Gao, Lijun Qian, Dhadesugoor R. Vaman, Qi Qu, Energy efficient adaptive modulation in wireless cognitive radio sensor networks, in: Proceedings of IEEE International Conference on Communications (ICC'07), Glasgow, UK, 2007, pp. 3980–3986.

[34] S. Byun, I. Balasingham, X. Liang, Dynamic spectrum allocation in wireless cognitive sensor networks: Improving fairness and energy efficiency, in: Proceedings of 2008 IEEE Vehicular Technology Conference VTC, Calgary, BC, Canada, 2008, pp. 1–5.

[35] S. Gao, L. Qian, D.R. Vaman, Distributed energy efficient spectrum access in wireless cognitive radio sensor networks, in: Proceedings of 2008 IEEE Wireless Communications and Networking Conference WCNC, Las Vegas, NV, USA, 2008, pp. 1442–1447.

[36] J. Sachs, I. Mari, A. Goldsmith, Cognitive cellular networks within the TV spectrum, in: Proceedings of 2010 IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, Singapore, Singapore, 2010, pp. 1–8.

[37] Y. Yang, H. Hu, J. Xu, G. Mao, Relay technologies for WiMAX and LTE advanced mobile systems, IEEE Commun. Mag. 47 (10) (2009) 100–105.

[38] S. Kadloor, R. Adve, Relay selection and power allocation in cooperative cellular networks, IEEE Trans. Wirel. Commun. 9 (5) (2010) 1676–1685.

[39] T. Ng, W. Yu, Joint optimization of relay strategies and resource allocations in cooperative cellular networks, IEEE J. Sel. Areas Commun. 25 (2) (2007) 328–339.

[40] W. Nam, W. Chang, S.-Y. Chung, Y. Lee, Transmit optimization for relay based cellular OFDMA systems, in: Proceedings of IEEE International Conference on Communications, 2007, pp. 5714–5719.

[41] M. Kim, H. Lee, Radio resource management for a two-hop OFDMA relay system in downlink, in: Proceedings of IEEE Symposium on Computers and Communications, Las Vegas, NV, USA, 2007, pp. 25–31.

[42] S. Kim, X. Wang, M. Madihian, Optimal resource allocation in multi-hop OFDMA wireless networks with cooperative relay, IEEE Trans. Wirel. Commun. 7 (5) (2008) 1833–1838.

[43] X. Li, T. Jiang, S. Cui, J. An, Q. Zhang, Cooperative communications based on rate-less network coding in distributed MIMO systems, IEEE Wirel. Commun. Mag. 17 (3) (2010) 60–67.

[44] S. Kim, W. Choi, Y. Choi, J. Lee, Y. Han, I. Lee, Downlink performance analysis of cognitive radio-based cellular relay networks, in: Proceedings of International Conference on Cognitive Radio Oriented Wireless Networks and Communications, Singapore, Singapore, 2008, pp. 1–6.

[45] R. Wang, V. Lau, Y. Cui, Decentralized fair scheduling in two-hop relay assisted cognitive OFDMA systems, IEEE J. Sel. Top. Sign. Proces. 5 (1) (2011) 171–181.

[46] J. Jia, J. Zhang, Q. Zhang, Cooperative relay for cognitive radio networks, in: Proceedings of IEEE INFOCOM, Rio de Janeiro, Brazil, 2009, pp. 2304–2312.

[47] M. Fitch, M. Nekovee, S. Kawade, K. Briggs, R. Mackenzie, Wireless service provision in TV white space with cognitive radio technology: A telecom operator's perspective and experience, IEEE Commun. Mag. 49 (3) (2011) 64–73.

[48] J. Yao, S. Kanhere, M. Hassan, Improving QoS in high-speed mobility using bandwidth maps, IEEE Trans. Mob. Comput. 11 (4) (2012) 603–617.

[49] R. Murty, R. Chandra, T. Moscibroda, P. Bahl, Sense-Less: A database driven white spaces network, IEEE Trans. Mob. Comput. 11 (2) (2012) 189–203.

[50] W. Wang, X. Liu, List-coloring based channel allocation for open spectrum wireless networks, in: Proceedings of IEEE Vehicular Technology Conference, 2005, pp. 690–694.

[51] H. Zheng, C. Peng, Collaboration and fairness in opportunistic spectrum access, in: Proceedings of IEEE International Conference on Communications, 2005, pp. 3132–3136.

[52] K. Yang, X. Wang, Cross-layer network planning for multi-radio multichannel cognitive wireless networks, IEEE Trans. Commun. 56 (10) (2008) 1705–1714.

[53] G.M.D. Santana, R.S. Cristo, C. Dezan, J.P. Diguet, D.P. Osorio, K.R. Branco, Cognitive radio for UAV communications: Opportunities and future challenges, in: Proceedings of 2018 International Conference on Unmanned Aircraft Systems (ICUAS), IEEE, Dallas, TX, USA, 2018, pp. 760–768.

[54] Amjad Muhammad, Mubashir Husain Rehmani, Shiwen Mao, Wireless multimedia cognitive radio networks: A comprehensive survey, IEEE Commun. Surv. Tutor. 20 (2) (2018) 1056–1103.

[55] C. An, H. Ji, P. Si, Dynamic spectrum access with QoS provisioning in cognitive radio networks, in: Proceedings of 2010 IEEE Global Telecommunications Conference (GLOBECOM), Miami, FL, USA, 2010), pp. 1–5.

[56] http://standards.ieee.org/findstds/standard/1900.1-2008.html (last accessed in Nov. 2018).

[57] Zhang Ning, Hao Liang, Nan Cheng, Yujie Tang, Jon W. Mark, Xuemin Sherman Shen, Dynamic spectrum access in multi-channel cognitive radio networks, IEEE J. Sel. Areas Commun. 32 (11) (2014) 2053–2064.

[58] Q. Zhao, B.M. Sadler, A survey of dynamic spectrum access, IEEE Signal Process. Mag. 24 (3) (2007) 79–89.

[59] W. Lehr, J. Crowcroft, Managing shared access to a spectrum common, in: Proceedings of 1st IEEE Int. Symp. DySPAN, Baltimore, MD, 2005, pp. 420–444.

[60] A. Goldsmith, S.A. Jafar, I. Maric, S. Srinivasa, Breaking Spectrum Gridlock with Cognitive Radios: An Information-Theoretic Perspective, Vol. 97 (5), IEEE, 2009, pp. 894–914.

[61] Y. Liao, L. Song, Z. Han, Listen and Talk: Full-Duplex Cognitive Radio Networks, Springer, 2016.

[62] Kim Dongkyu, Haesoon Lee, Daesik Hong, A survey of in-band full-duplex transmission: From the perspective of PHY and MAC layers, IEEE Commun. Surv. Tutor. 17 (4) (2015) 2017–2046.

[63] A. Youness, N. Kaabouch, A comprehensive survey on spectrum sensing in cognitive radio networks: Recent advances, new challenges, and future research directions, Sensors 19 (1) (2019) 126.

[64] K.S. Kumar, R. Saravanan, R. Muthaiah, Cognitive radio spectrum sensing algorithms based on eigenvalue and covariance methods, Int. J. Eng. Technol. 5 (2013) 595–601.

[65] B. Khalfi, A. Zaid, B. Hamdaoui, When machine learning meets compressive sampling for wideband spectrum sensing, in: Proceedings of the International Wireless Communications and Mobile Computing Conference, Vol. 26, Valencia, Spain, 2017, pp. 1120–1125, (30).

[66] S. Enserink, D. Cochran, A cyclostationary feature detector, in: Proceedings of Asilomar Conference on Signals, Systems, and Computers, 1994, pp. 806–810.

[67] Y. Xin, H. Zhang, S. Rangarajan, SSCT: A simple sequential spectrum sensing scheme for cognitive radio, in: Proceedings of IEEE Global Telecommunications Conference, Honolulu, HI, USA, 2009, pp. 1–6.

[68] A. Kumar, S. Saha, R. Bhattacharya, Improved wavelet transform based edge detection for wide band spectrum sensing in cognitive radio, in: Proceedings of the USNC-URSI Radio Science Meeting, Fajardo, Puerto Rico, 2016, pp. 21–22.

[69] D. Capriglione, G. Cerro, L. Ferrigno, G. Miele, Analysis and implementation of a wavelet-based spectrum sensing method for low SNR scenarios, in: Proceedings of the International Symposium on a World of Wireless, Mobile, and Multimedia Networks, Coimbra, Portugal, 2016, pp. 1–6.

[70] Z. Quan, S. Cui, A.H. Sayed, H.V. Poor, Wideband spectrum sensing in cognitive radio networks, in: Proceedings of the International Conference on Communications, Beijing, China, 2008, pp. 901–906.

[71] Y. Zhi Quan, Y.-C. Shuguang Cui, A.H. Sayed, H.V. Poor, Y. Zeng, K. Kua, Optimal multiband joint detection for spectrum sensing in cognitive radio networks, IEEE Trans. Signal Process. (2009) 1128–1140.

[72] I. Raghu, S.S. Chowdary, E. Elias, Efficient spectrum sensing for cognitive radio using cosine modulated filter banks, in: Proceedings of the IEEE Region 10 Conference, Singapore, 2016, pp. 2086–2089.

[73] K. Sharma, A. Sharma, Design of cosine modulated filter banks exploiting spline function for spectrum sensing in cognitive radio applications, in: Proceedings of the International Conference on Power Electronics, Intelligent Control, and Energy Systems, Delhi, India, 2016, pp. 1–5.

[74] Y. Wang, Z. Tian, C. Feng, Sparsity order estimation and its application in compressive spectrum sensing for cognitive radios, IEEE Trans. Wirel. Commun. (2012) 2116–2125.

[75] T.A. Khalaf, M.Y. Abdelsadek, M. Farrag, Compressed measurements based spectrum sensing for wideband cognitive radio systems, Int. J. Antennas Propag. (2015) 1–7.

[76] S. Hong, Direct spectrum sensing from compressed measurements, in: Proceedings of the Military Communications Conference, San Jose, CA, USA, 2010, pp. 1187–1192.

[77] C.-P. Yen, Y. Tsai, X. Wang, Wideband spectrum sensing based on sub-nyquist sampling, IEEE Trans. Signal Process. (2013) 3028–3040.

[78] H. Sun, W.-Y. Chiu, A. Nallanathan, Adaptive compressive spectrum sensing for wideband cognitive radios, IEEE Commun. Lett. (2012) 1812–1815.

[79] Z. Qin, Y. Gao, G.G. Parini, Data-assisted low complexity compressive spectrum sensing on real-time signals under sub-nyquist rate, IEEE Trans. Wirel. Commun. (2016) 1174–1185.

[80] Y. Ma, X. Zhang, Y.G.Q. Mary, An efficient joint sub-nyquist spectrum sensing scheme with geolocation database over TV white space, in: Proceedings of the International Conference on Communications, Paris, France, 2017, pp. 1–6.

[81] J.-K. Choi, K.-H. Kwon, S.-J. Yoo, QoS-Aware channel sensing scheduling in cognitive radio networks, in: Roceedings of Ninth IEEE International Conference on Computer and Information Technology (CIT), Vol. 2, Xiamen, China, 2009, pp. 63–68.

[82] X. Sun, T. Zhang, D.H. Tsang, Optimal energy-efficient cooperative sensing scheduling for cognitive radio networks with QoS guarantee, in: Proceedings of 7th International Wireless Communications and Mobile Computing Conference, Istanbul, Turkey, 2011, pp. 1825–1830.

[83] Y. Shei, Y.T. Su, A sequential test-based cooperative spectrum sensing scheme for cognitive radios, in: Proceedings of IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Cannes, France, 2008, pp. 1–5.

[84] B. Wild, K. Ramchandran, Detecting primary receivers for cognitive radio applications, in: Proceedings of IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2005), Baltimore, 2005, pp. 124–130.

[85] J. Ma, G.Y. Li, B.H. Juang, Signal Processing in Cognitive Radio, Vol. 97, IEEE, 2010, pp. 805–823, no. 5.

[86] D. Lopez, A. Valcarce, G. Roche, J. Zhang, OFDMA Femtocells: A road map on interference avoidance, IEEE Commun. Mag. 47 (9) (2009) 41–48.

[87] D. Lopez, I. Guvenc, G. Roche, M. Kountouris, T. Quek, J. Zhang, Enhanced inter-cell interference coordination challenges in heterogeneous networks, IEEE Wirel. Commun. 18 (3) (2011) 22–30.

[88] W. Cheung, T. Quek, M. Kountouris, Throughput optimization spectrum allocation and access control in two-tier femtocell networks, IEEE J. Sel. Areas Commun. 30 (3) (2012) 561–574.

[89] S. Akoum, M. Kountouris, R. Heath, On imperfect CSI for the downlink of a two-tier network, in: Proceedings of IEEE International Symposium on Information Theory (ISIT 2011), St. Petersburg, Russia, 2011, pp. 553–557.

[90] S. Mukherjee, Distribution of downlink SINR in heterogeneous cellular networks, IEEE J. Sel. Areas Commun. 30 (3) (2012) 575–585.

[91] J.H. Schiller, Mobile Communications, Pearson education, 2003.

[92] J. Andrews, F. Baccelli, R. Ganti, A tractable approach to coverage and rate in cellular networks, IEEE Trans. Commun. 59 (11) (2011) 3122–3134.

[93] R. Zhang, Y. Liang, Exploiting hidden power-feedback loops for cognitive radio, in: Proceedings of IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2008), Chicago, 2008, pp. 1–5.

[94] G. Zhao, Y. Li, C. Yang, Proactive detection of spectrum holes in cognitive radio, in: Proceedings of IEEE International Conference on Communications (ICC 2009), Dresden, Germany, 2019, pp. 1–5.

[95] R. Zhang, On active learning and supervised transmission of spectrum sharing based cognitive radios by exploiting hidden primary radio feedback, IEEE Trans. Commun. 58 (10) (2010) 2960–2970.

[96] I. Bajaj, Y. Gong, Cross-channel estimation using supervised probing and sensing in cognitive radio networks, in: Proceedings of IEEE International Communications Conference (ICC 2011), Kyoto, Japan, 2011, pp. 1–5.

[97] Y. Noam, A. Goldsmith, Blind null-space learning for MIMO underlay cognitive radio with primary user interference adaptation, IEEE Trans. Wirel. Commun. 12 (4) (2013) 1722–1734.

[98] F. Yuan, G. Villardi, F. Kojima, K. Yano, Channel direction information probing for multi-antenna cognitive radio system, in: Proceedings of IEICE Society Conference, Akashi, Japan, 2015, pp. 39–44.

[99] Q. Zhao, L. Tong, A. Swami, Y. Chen, Decentralized cognitive MAC for opportunistic spectrum access in ad hoc networks: A POMDP framework, IEEE J. Sel. Areas Commun. 25 (3) (2007) 589–600.

[100] Y. Chen, Q. Zhao, A. Swami, Joint design and separation principle for opportunistic spectrum access in the presence of sensing errors, IEEE Trans. Inform. Theory 54 (5) (2008) 2053–2071.

[101] A.T. Hoang, Y.C. Liang, Y. Zeng, Adaptive joint scheduling of spectrum sensing and data transmission in cognitive radio networks, IEEE Trans. Commun. 58 (1) (2010) 235–246.

[102] H. Kim, K.G. Shin, Fast discovery of spectrum opportunities in cognitive radio networks, in: Proceedings of IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, Chicago, IL, USA, 2008, pp. 1–12.

[103] S.J. Kim, G.B. Giannakis, Sequential and cooperative sensing for multichannel cognitive radios, IEEE Trans. Signal Process. 58 (8) (2010) 4239–4253.

[104] J. Oksanen, J. Lunden, V. Koivunen, Reinforcement learning based sensing policy optimization for energy efficient cognitive radio networks, Neuro-Computing 80 (2012) 102–110.

[105] A. Ghasemi, E.S. Sousa, Collaborative spectrum sensing for opportunistic access in fading environments, in: Proceedings of the 1st IEEE Int. Symposium DySPAN, Baltimore, MD, 2005, pp. 131–136.

[106] G. Ganesan, G.Y. Li, Cooperative spectrum sensing in cognitive radio—Part I: Two user networks, IEEE Trans. Wirel. Commun. 6 (6) (2007) 2204–2213.

[107] G. Ganesan, G.Y. Li, Cooperative spectrum sensing in cognitive radio—Part II: Multiuser networks, IEEE Trans. Wirel. Commun. 6 (6) (2007) 2214–2222.

[108] S. Rajkumar, J.S., Thiruvengadam outage analysis of OFDM based cognitive radio network with full duplex relay selection, IET Signal Process. 10 (8) (2016) 865–872.

[109] E. Ghazizadeh, D. Abbasi-moghadam, H. Nezamabadi-pour, An enhanced two-phase SVM algorithm for cooperative spectrum sensing in cognitive radio networks, Int. J. Commun. Syst. 32 (2) (2019).

[110] D. Cabric, S.M. Mishra, R.W. Brodersen, Implementation issues in spectrum sensing for cognitive radios, in: Proceedings of Asilomar Conf. Signals, Syst., Comput., Vol. 1, Pacific Grove, CA, 2004, pp. 772–776.

[111] M. Wellens, J. Riihijarvi, M. Gordziel, P. Mähönen, Evaluation of cooperative spectrum sensing based on large-scale measurements, in: Proceedings of the 3rd IEEE Int. Symp. DySPAN, Chicago, 2008, pp. 1–12.

[112] M. Wellens, J. Riihijärvi, P. Mähönen, Empirical time- and frequency-domain models of spectrum use, Phys. Commun. 2 (1/2) (2009) 10–32.

[113] A.K. Kattepur, A.T. Hoang, Y.-C. Liang, M.J. Er, Data and decision fusion for distributed spectrum sensing in cognitive radio networks, in: Proceedings of IEEE ICICS, Singapore, 2007, pp. 1–5.

[114] L. Law, J. Huang, M. Liu, S. Li, Price of anarchy for cognitive MAC games, in: Proceedings of IEEE GLOBECOM, Honolulu, HI, USA, 2009, pp. 1–7.

[115] R. Thomas, L. DaSilva, M. Marathe, K. Wood, Critical design decisions for cognitive networks, in: Proceedings of IEEE ICC, Glasgow, U.K, 2007, pp. 3993–3998.

[116] X. Zhang, W. Cheng, H. Zhang, Full-duplex transmission in PHY and MAC layers for 5G mobile wireless networks, IEEE Wirel. Commun. 22 (5) (2015) 112–121.

[117] B. Kim, S. Lim, H. Kim, S. Suh, J. Kwun, S. Choi, D. Hong, Non-orthogonal multiple access in a downlink multiuser beamforming system, in: Proceedings of IEEE Mil. Commun. Conf., San Diego, CA, USA, 2013, pp. 1278–1283.

[118] J. Choi, Non-orthogonal multiple access in downlink coordinated two-point systems, IEEE Commun. Lett. 18 (2) (2014) 313–316.

[119] A. Sabharwal, P. Schniter, D. Guo, D.W. Bliss, S. Rangarajan, R. Wichman, In-band full-duplex wireless: Challenges and opportunities, IEEE J. Sel. Areas Commun. 32 (9) (2014) 1637–1652.

[120] A. Goldsmith, Wireless Communications, Cambridge University Press, Cambridge, U.K, 2005.

[121] C.X. Wang, F. Haider, X. Gao, X.H. You, Y. Yang, D. Yuan, H. Aggoune, H. Haas, S. Fletcher, E. Hepsaydir, Cellular architecture and key technologies for 5G wireless communication networks, IEEE Commun. Mag. 52 (2) (2014) 122–130.

[122] G. Wunder, M. Kasparick, S. ten Brink, F. Schaich, T. Wild, I. Gaspar, E. Ohlmer, S. Krone, N. Michailow, A. Navarro, G. Fettweis, 5GNOW: Challenging the LTE design paradigms of orthogonality and synchronicity, in: Proceedings of IEEE Veh. Technol. Conf. (VTC Spring), Dresden, Germany, 2013, pp. 1–5.

[123] N. Li, Y. Li, T. Wang, M. Peng, W. Wang, Full-duplex based spectrum sharing in cognitive two-way relay networks, in: Proceedings of IEEE Int. Symp. Pers. Indoor Mobile Radio Commun. (PIMRC), Hong Kong, 2015, pp. 997–1001.

[124] T. Le-Ngoc, A. Masmoudi, Full-Duplex Wireless Communications Systems: Self-Interference Cancellation, Springer, 2017.

[125] D. Kim, S. Park, H. Ju, D. Hong, Transmission capacity of fullduplex based two-way ad-hoc networks with ARQ protocol, IEEE Trans. Veh. Technol. 63 (7) (2014) 3167–3183.

[126] H. Ju, E. Oh, D. Hong, Catching resource devouring worms in next generation wireless relay systems: Two-way relay and full-duplex relay, IEEE Commun. Mag. 47 (9) (2009) 58–65.

[127] H. Ju, S. Lim, D. Kim, H.V. Poor, D. Hong, Full duplexity in beamforming-based multi-hop relay networks, IEEE J. Sel. Areas Commun. 30 (8) (2012) 1554–1565.

[128] G. Zheng, I. Krikidis, J. Li, A.P. Petropulu, B. Ottersten, Improving physical layer secrecy using full-duplex jamming receivers, IEEE Trans. Signal Process. 61 (20) (2013) 4962–4974.

[129] http://arxiv.org/abs/1311.3918 (last accessed in Nov. 2018).

[130] O. Cepheli, S. Tedik, G. Kurt, A high data rate wireless communication system with improved secrecy: Full duplex beamforming, IEEE Commun. Lett. 18 (6) (2014) 1075–1078.

[131] S. Parsaeefard, T. Le-Ngoc, Improving wireless secrecy rate via full-duplex relay-assisted protocols, IEEE Trans. Inf. Forensics Secur. 10 (10) (2015) 2095–2107.

[132] M. Duarte, A. Sabharwal, V. Aggarwal, R. Jana, K.K. Ramakrishnan, C.W. Rice, N.K. Shankaranarayanan, Design and characterization of a full-duplex multiantenna system for Wi-Fi networks, IEEE Trans. Veh. Technol. 63 (3) (2014) 1160–1177.

[133] W. Zhou, K. Srinivasan, P. Sinha, RCTC: Rapid concurrent transmission coordination in full-duplex wireless networks, in: Proceedings of the 21st Int. Conf. of Netw. Protocols, Goettingen, Germany, 2013, pp. 1–6.

[134] Y.-S. Choi, H. Shirani-Mehr, Simultaneous transmission and reception: Algorithm, design and system level performance, IEEE Trans. Wirel. Commun. 12 (12) (2013) 5992–6010.

[135] A. Sahai, G. Patel, A. Sabharwal, Pushing the limits of full-duplex: Design and real-time implementation. arXiv preprint arXiv:1107.0607 Jul. 2011.

[136] T. Riihonen, S. Werner, R. Wichman, Hybrid full-duplex/half-duplex relaying with transmit power adaptation, IEEE Trans. Wirel. Commun. 10 (9) (2011) 3074–3085.

[137] T. Riihonen, S. Werner, R. Wichman, Transmit power optimization for multiantenna decode-and-forward relays with loopback self-interference from full-duplex operation, in: Proceedings of the 45th Asilomar Conf. Signals, Syst. Comput., Pacific Grove, CA, USA, 2011, pp. 1408–1412.

[138] X. Rui, J. Hou, L. Zhou, On the performance of full-duplex relaying with relay selection, Electron. Lett. 46 (25) (2010) 1674–1676.

[139] I. Krikidis, H.A. Suraweera, P.J. Smith, C. Yuen, Full-duplex relay selection for amplify-and-forward cooperative networks, IEEE Trans. Wirel. Commun. 11 (12) (2012) 4381–4393.

[140] H. Ju, R. Zhang, Optimal resource allocation in full-duplex wireless-powered communication network, IEEE Trans. Commun. 62 (10) (2014) 3528–3540.

[141] L. Liu, Y. Zhang, S. Liu, Z. Zhang, Power allocation optimization for D2D communication underlaying cognitive full duplex relay networks, in: Proceedings of Int. Conf. Wireless Commun. Netw. Mobile Comput. (WiCOM), Shanghai, China, 2015, pp. 1–6.

[142] J. Bai, A. Sabharwal, Decode-and-cancel for interference cancellation in a three-node full-duplex network, in: Proceedings of 2012 Conference Record of the Forty Sixth Asilomar Conference on Signals, Systems and Computers (ASILOMAR), Pacific Grove, CA, USA, 2012, pp. 1285–1289.

[143] J. Bai, A. Sabharwal, Distributed full-duplex via wireless side channels: Bounds and protocols, IEEE Trans. Wirel. Commun. 12 (8) (2013) 4162–4173.

[144] https://cordis.europa.eu/docs/projects/cnect/9/316369/080/deliverables/001-316369DUPLOD412renditionDownload.pdf (last accessed Jul. 2018).

[145] Y. Liao, T. Wang, L. Song, B. Jiao, Cooperative spectrum sensing for full-duplex cognitive radio networks, in: Proceedings of IEEE Global Communication Conferences (ICCS), Macau, China, 2014.

[146] T. Wang, Y. Liao, B. Zhang, L. Song, Joint spectrum access and power allocation in full-duplex cognitive cellular networks, in: Proceedings of IEEE International Conference on Communications (ICC), London, UK, 2015.

[147] G. Zheng, I. Krikidis, B. Ottersten, Full-duplex cooperative cognitive radio with transmit imperfections, IEEE Trans. Wirel. Commun. 12 (5) (2013) 2498–2511.

[148] Hu Feng, Bing Chen, Kun Zhu, Full spectrum sharing in cognitive radio networks toward 5G: A survey, IEEE Access 6 (2018) 15754–15776.

[149] Z. Zhang, X. Chai, K. Long, A.V. Vasilakos, L. Hanzo, Full duplex techniques for 5g networks: Self-interference cancellation, protocol design, and relay selection, IEEE Commun. Mag. 53 (5) (2015) 128–137.

[150] https://spectrum.ieee.org/video/telecom/wireless/everything-you-need-to-know-about-5g (last accessed Apr. 2018).

[151] M. Jain, J.I. Choi, T. Kim, D. Bharadia, S. Seth, K. Srinivasan, P. Levis, S. Katti, P. Sinha, Practical, real-time, full duplex wireless, in: Proceedings of ACM MobiCom 2011, New York, NY, 2011.

[152] M.A. Khojastepour, K. Sundaresan, S. Rangarajan, X. Zhang, S. Barghi, The case for antenna cancellation for scalable full-duplex wireless communications, in: Proceedings of the 10th ACM Workshop on Hot Nets, Cambridge, Massachusetts, 2011.

[153] D.W. Bliss, P.A. Parker, A.R. Margetts, Simultaneous transmission and reception for improved wireless network performance, in: Proceedings of the IEEE Statistical Signal Processing Workshop, Madison, WI, USA, 2007.

[154] M. Duarte, C. Dick, A. Sabharwal, Experiment-driven characterization of full-duplex wireless systems, IEEE Trans. Wirel. Commun. 11 (12) (2012) 4296–4307.

[155] E. Aryafar, M. Khojastepour, K. Sundaresan, S. Rangarajan, M. Chiang, MIDU: Enabling MIMO full duplex, in: Proceedings of ACM MobiCom, Istanbul, Turkey, 2012.

[156] Duarte Melissa, Ashutosh Sabharwal, Vaneet Aggarwal, Rittwik Jana, K.K. Ramakrishnan, Christopher W. Rice, N.K. Shankaranarayanan, Design and characterization of a full-duplex multiantenna system for wifi networks, IEEE Trans. Veh. Technol. 63 (3) (2014) 1160–1177.

[157] Amir Keyvan Khandani, Methods for spatial multiplexing of wireless two-way channels, U.S. Patent 7, 817, 641, issued October 19, 2010.

[158] B. Radunovic, D. Gunawardena, P. Key, A.P.N. Singh, V. Balan, G. Dejean, Rethinking Indoor Wireless: Low Power, Low Frequency, Full Duplex, Technical Report, Microsoft Research, 2009.

[159] M. Duarte, Full-duplex.Wireless:. Design, Full-Duplex Wireless: Design Implementation and Characterization (Ph.D. thesis), Rice University, 2012.

[160] J.I. Choi, M. Jain, K. Srinivasan, P. Levis, S. Katti, Achieving single channel, full duplex wireless communication, in: Proceedings of the 16th Annul Int. Conf. Mobile Comput. Netw, Chicago, Illinois, USA, 2010, pp. 1–12.

[161] J.F. O'Hara, G.M. Moore, A high performance CW receiver using feed thru nulling, Microw. J. 6 (9) (1963) 63–71.

[162] H. Ju, X. Shang, H.V. Poor, D. Hong, Rate improvement of beamforming systems via bi-directional use of spatial resources, in: Proceedings of IEEE Global Telecommun. Conf., Kathmandu, Nepal, 2011, pp. 1–5.

[163] B.P. Day, A.R. Margetts, D.W. Bliss, P. Schniter, Full-duplex bidirectional MIMO: Achievable rates under limited dynamic range, IEEE Trans. Signal Process. 60 (7) (2012) 3702–3713.

[164] T.M. Kim, H.J. Yang, A.J. Paulraj, Distributed sum-rate optimization for full-duplex MIMO system under limited dynamic range, IEEE Signal Process. Lett. 20 (6) (2013) 555–558.

[165] H. Ju, D. Kim, H.V. Poor, D. Hong, Bi-directional beamforming and its capacity scaling in pairwise two-way communications, IEEE Trans. Wirel. Commun. 11 (1) (2012) 346–357.

[166] D. Kim, H. Ju, D. Hong, Transmission capacity of bi-directional beamforming in ad-hoc networks, in: Proceedings of 27th Int. Tech. Conf. Circuits/Syst. Comput. Commun, 2012, pp. 1–3.

[167] A. Sahai, S. Diggavi, A. Sabharwal, On uplink/downlink full-duplex networks, in: Proceedings of 48th Annu. Conf. Inf. Sci. Syst, Pacific Grove, CA, USA, 2013, pp. 14–18.

[168] E. Ahmed, A.M. Eltawil, A. Sabharwal, Self-interference cancellation with phase noise induced ICI suppression for full-duplex systems, in: Proceedings of IEEE Global Commun. Conf, Atlanta, GA, USA, 2013, pp. 3384–3388.

[169] R.H. Walden, Analog-to-digital converter survey and analysis, IEEE J. Sel. Areas Commun. 17 (4) (1999) 539–550.

[170] P. Angeletti, G. Gallinaro, L. Hili, X. Maufroid, Evolution of analog to digital conversion technology for wideband space applications, in: Proceedings of the 23rd AIAA International Communications Satellite Systems Conference (ICSSC 2005), Rome, Italy, 2005, pp. 25–28.

[171] http://www.analog.com/en/index.html (last accessed Nov. 2018).

[172] K.E. Kolodziej, B.T. Perry, J.S. Herd, In-band full-duplex technology: Techniques and systems survey, IEEE Trans. Microw. Theory Tech. (2019).

[173] Achaleshwar Sahai, Gaurav Patel, Ashutosh Sabharwal, Asynchronous full-duplex wireless, in: Proceedings of IEEE Fourth International Conference on Communication Systems and Networks (COMSNETS), Bangalore, India, 2012.

[174] C.R. Anderson, S. Krishnamoorthy, C.G. Ranson, T.J. Lemon, W.G. Newhall, T. Kummetz, J.H. Reed, Antenna isolation, wideband multipath propagation measurements, and interference mitigation for on-frequency repeaters, in: Proceedings of IEEE Southeast Con, Greensboro, North Carolina, USA, 2004.

[175] K. Haneda, E. Kahra, S. Wyne, C. Icheln, P. Vainikainen, Measurement of loop-back interference channels for outdoor-to-indoor full-duplex radio relays, in: Proceedings of the Fourth European Conference on Antennas and Propagation (EuCAP), Barcelona, Spain, 2010.

[176] J.I. Choi, S.-K. Hong, M. Jain, S. Katti, P. Levis, J. Mehlman, Beyond full duplex wireless, in: Proceedings of ASILOMAR Signals, Syst. Comput, Pacific Frove, California, USA, 2012.

[177] Melissa Duarte, Ashutosh Sabharwal, Full-duplex wireless communications using off-the-shelf radios: Feasibility and first results, in: Signals, Systems and Computers (ASILOMAR), 2010 Conference Record of the Forty Fourth Asilomar Conference, IEEE, Pacific Grove, CA, USA, 2010, pp. 1558–1562.

[178] E. Everett, A. Sahai, A. Sabharwal, Passive self-interference suppression for full-duplex infrastructure nodes, IEEE Trans. Wirel. Commun. 13 (2) (2014) 680–694.

[179] E. Ahmed, A.M. Eltawil, Z. Li, B.A. Cetiner, Full-duplex systems using multi-reconfigurable antennas, IEEE Trans. Wireless Commun. 14 (11) (2015) 5971–5983.

[180] A. Sahai, G. Patel, C. Dick, A. Sabharwal, On the impact of phase noise on active Cancelation in wireless full-duplex, IEEE Trans. Veh. Technol. 62 (9) (2013) 4494–4510.

[181] E. Everett, M. Duarte, C. Dick, A. Sabharwal, Empowering full-duplex wireless communication by exploiting directional diversity, in: Proceedings ASILOMAR Signals, Syst. Comput., Pacific Frove, California, USA, 2011.

[182] Ahmed Masmoudi, Tho Le-Ngoc, Joint radio-frequency/baseband self-interference cancellation methods and systems, U.S. Patent Application 14/675, 278, filed Oct. 2016.

[183] J. Sangiamwong, T. Asai, J. Hagiwara, Y. Okumura, T. Ohya, Joint multi-filter design for full-duplex MU-MIMO relaying, in: Proceedings of IEEE Vehicular Technology Conference, VTC Spring 2009, Barcelona, Spain, 2009, pp. 1–5.

[184] P. Lioliou, M. Viberg, M. Coldrey, F. Athley, Self-interference suppression in full-duplex MIMO relays, in: Processing of Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, USA, 2010, pp. 658–662.

[185] T. Riihonen, A. Balakrishnan, K. Haneda, S. Wyne, S. Werner, R. Wichman, Optimal eigen beam forming for suppressing self-interference in full-duplex MIMO relays, in: Proceedings of 45th Annual Conference on Information Sciences and Systems (CISS), IEEE, Baltimore, MD, USA, 2011, pp. 1–6.

[186] T. Riihonen, S. Werner, R. Wichman, Mitigation of loopback self-interference in full-duplex MIMO relays, IEEE Trans. Signal Process. 59 (12) (2011) 5983–5993.

[187] B. Yin, M. Wu, C. Studer, J.R. Cavallaro, J. Lilleberg, Full-duplex in large-scale wireless systems, in: Proceedings of 48th Annu. Conf.Inf. Sci. Syst, Pacific Grove, CA, USA, 2013, pp. 1623–1627.

[188] D. Bharadia, E. McMilin, S. Katti, Full duplex radios, in: Proceedings of ACM SIGCOMM, Hong Kong, China, 2013, pp. 375–386.

[189] G. Liu, F.R. Yu, H. Ji, V.C.M. Leung, X. Li, In-band full-duplex relaying: A survey, research issues and challenges, IEEE Commun. Surv. Tutor. 17 (2) (2015) 500–524, 2nd Quart..

[190] Z. Zhang, K. Long, A.V. Vasilakos, L. Hanzo, Full-Duplex Wireless Communications: Challenges, Solutions, and Future Research Directions, Vol. 104 (7), IEEE, 2016, pp. 1369–1409.

[191] M.-L. Ku, W. Li, Y. Chen, K.J.R. Liu, Advances in energy harvesting communications: Past, present, and future challenges, IEEE Commun. Surv. Tutor. 18 (2) (2016) 1384–1412, 2nd Quart.

[192] Y.C. Liang, Y. Zeng, E.C.Y. Peh, A.T. Hoang, Sensing-throughput tradeoff for cognitive radio networks, IEEE Trans. Wireless Commun. 7 (4) (2008) 1326–1337.

[193] T. Yucek, H. Arslan, A survey of spectrum sensing algorithms for cognitive radio applications, IEEE Commun. Surv. Tutor. 11 (1) (2009) 116–130.

[194] S. Huang, X. Liu, Z. Ding, Short paper: On optimal sensing and transmission strategies for dynamic spectrum access, in: Proceedings of IEEE DySPAN, Chicago, IL, 2008.

[195] S. Huang, X. Liu, Z. Ding, Opportunistic spectrum access in cognitive radio networks, in: Proceedings of IEEE INFOCOM 2009, Rio de Janeiro, Brazil, 2009.

[196] Q. Zhao, S. Geirhofer, L. Tong, B.M. Sadler, Optimal dynamic spectrum access via periodic channel sensing, in: IEEE Wireless Comm. and Networking Conf (WCNC) 2007, Hongkong, China, 2007, pp. 33–37.

[197] W. Afifi, A. Sultan, M. Nafie, Adaptive sensing and transmission durations for cognitive radios, in: Proceedings of IEEE Int'l Symp. on Dynamic Spectrum Access Networks (DySPAN), Aachen, Germany, 2011, pp. 380–388.

[198] Y. Liao, T. Wang, L. Song, Z. Han, Listen-and-Talk: Full-Duplex Cognitive Radio, Springer, Cham, 2014.

[199] Y. Liao, L. Song, Z. Han, Y. Li, Full-duplex cognitive radio: A new design paradigm for enhancing spectrum usage, IEEE Commun. Mag. 53 (5) (2015) 138–145.

[200] Towhidlou Vahid, Mohammad Shikh-Bahaei, Adaptive full-duplex communications in cognitive radio networks, IEEE Trans. Veh. Technol. 67 (9) (2018) 8386–8395.

[201] Nhut Khai Hoan, Tran, Hiep Vu-Van, Insoo Koo, Joint full-duplex/half-duplex transmission-switching scheduling and transmission-energy allocation in cognitive radio networks with energy harvesting, Sensors 18 (7) (2018) 2295.

[202] Faroq Awin, Esam Abdel-Raheem, Kemal Tepe, Blind spectrum sensing approaches for interweaved cognitive radio system: A tutorial and short course, IEEE Commun. Surv. Tutor. 21 (1) (2018) 238–259.

[203] Akhila Asokan, R. AyyapaDas, Survey on cognitive radio and cognitive radio sensor networks, in: Proceedings of IEEE Conference on Electronics and Communication Systems, Coimbatore, India, 2014, pp. 1–7.

[204] I.F. Akyildiz, W.Y.L. Lee, M.C. Vuran, S. Mohanty, A survey on spectrum management in cognitive radio networks, IEEE Commun. Mag. 46 (4) (2008) 40–48.

[205] V. Syrjala, M. Valkama, Coexistence of LTE and WLAN in unlicensed bands: Full-duplex spectrum sensing, in: Proceedings of Int. Conf. Cogn. Radio Orient. Wireless Netw, Doha, Qatar, 2015, pp. 725–734.

[206] V. Syrjala, M. Valkama, M. Allén, K. Yamamoto, Simultaneous transmission and spectrum sensing in OFDM systems using full-duplex radios, in: Proceedings of IEEE Veh. Technol. Conf. (VTC Fall), Boston, MA, USA, 2015, pp. 1–6.

[207] P. Vijayakumar, George Jeswin, S. Malarvizhi, A. Sriram, Analysis and Implementation of Reliable Spectrum Sensing in OFDM Based Cognitive Radio, Smart Computing and Informatics Book, Springer, Singapore, 2018, pp. 565–572.

[208] W. Afifi, M. Krunz, Adaptive transmission-reception-sensing strategy for cognitive radios with full-duplex capabilities, in: Proceedings of IEEE Int. Symp. Dyn. Spectr. Access Netw. (DYSPAN), McLean, VA, USA, 2014, pp. 149–160.

[209] W. Afifi, M. Krunz, Incorporating self-interference suppression for full-duplex operation in opportunistic spectrum access systems, IEEE Trans. Wirel. Commun. 14 (4) (2015) 2180–2191.

[210] Santoshkumar Sabat, Abhay Gandhi, Prabhat Kumar Sharma, Cooperative spectrum sensing in full-duplex CRN with primary user activity, in: Proceedings IEEE 10th International Conference on Communication Systems & Networks (COMSNETS), Bengaluru, India, 2018.

[211] Y. Liao, K. Bian, L. Ma, L. Song, Robust cooperative spectrum sensing in full-duplex cognitive radio networks, in: Proceedings of Int. Conf. Ubiquitous Future Netw, Sapporo, Japan, 2015, pp. 66–68.

[212] S. Ha, W. Lee, J. Kang, Cooperative spectrum sensing in non-time-slotted full duplex cognitive radio networks, in: Proceedings of IEEE Consum. Commun. Netw. Conf. (CCNC), Las Vegas, NV, USA, 2016, pp. 820–823.

[213] Y. Liao, T. Wang, K. Bian, L. Song, Z. Han, Decentralized dynamic spectrum access in full-duplex cognitive radio networks, in: Proceedings of IEEE Int. Conf. Commun, London, U.K, 2015, pp. 7552–7557.

[214] H. Li, C. Liu, Cross-layer optimization for full-duplex cognitive radio network with cooperative spectrum sensing, Int. J. Commun. Syst. 32 (5) (2019).

[215] Y. Liao, L. Song, Z. Han, Y. Li, Full duplex cognitive radio: A new design paradigm for enhancing spectrum usage, IEEE Commun. Mag. 53 (5) (2015) 138–145.

[216] Riihonen, R. Wichman, Energy detection in full-duplex cognitive radios under residual self-interference, in: Proceedings of Int. Conf. Cogn. Radio Orient. Wireless Netw. Commun, Oulu, Finland, 2014, pp. 57–60.

[217] W. Cheng, X. Zhang, H. Zhang, Full duplex wireless communications for cognitive radio networks, arXiv preprint arXiv:1105.0034, 2011.

[218] W. Cheng, X. Zhang, H. Zhang, Full duplex spectrum sensing in non-time-slotted cognitive radio networks, in: Procedings of IEEE Mil. Commun. Conf., Baltimore, MD, USA, 2011, pp. 1029–1034.

[219] Y. Lu, D. Wang, M. Fattouche, Novel spectrum sensing scheme in cognitive radio by simultaneously sensing/transmitting at fullduplex Tx and BER measurements at Rx, in: Proceedings of IEEE Int. Symp. Pers. Indoor Mobile Radio Commun, Washington, DC, USA, 2014, pp. 638–642.

[220] A.E. Shafie, T. Khattab, Energy-efficient cooperative relaying protocol for full-duplex cognitive radio users and delay-aware primary users, in: Proceedings of IEEE Int. Conf. Comput. Netw. Commun., Garden Grove, CA, USA, 2015, pp. 207–213.

[221] W. Cheng, S.X. Zhang, H. Zhang, Full-duplex spectrum-sensing and MAC-protocol for multichannel non-time-slotted cognitive radio networks, IEEE J. Sel. Areas Commun. 33 (5) (2015) 820–831.

[222] Ali Bayat, Sonia Aïssa, Full-duplex cognitive radio with asynchronous energy-efficient sensing, IEEE Trans. Wirel. Commun. 17 (2) (2018) 1066–1080.

[223] Wenjun Xu, Jiji Tang, Zhen Wang, Li Guo, Capacity maximization in full-duplex cognitive radio systems with non-slotted primary user state change, IEEE Commun. Lett. 22 (9) (2018) 1890–1893.

[224] K. Waqas, H. Yu, Spatial–temporal sensing and utilization in full duplex spectrum-heterogeneous cognitive radio networks for the internet of things, Sensors 19 (6) (2019).

[225] W.Gardner, Signal interception: A unifying theoretical framework for feature detection, IEEE Trans. Commun. 36 (8) (1988) 897–906.

[226] A. Sahai, R. Tandra, S. Mishra, N. Hoven, Fundamental design tradeoffs in cognitive radio systems, in: Proceedings of the 1st Int. Workshop Technol. Policy for Accessing Spectrum, 2006.

[227] A. Mariani, A. Giorgetti, M. Chiani, SNR Wall for energy detection with noise power estimation, in: Proceedings of IEEE International Conference on Communications (ICC), Kyoto, 2011.

[228] Alexandros-Apostolos A. Boulogeorgos, George K. Karagiannidis, Energy detection in full-duplex systems with residual RF impairments over fading channels, IEEE Wirel. Commun. Lett. 7 (2) (2018) 246–249.

[229] W. Afifi, M. Krunz, Exploiting self-interference suppression for improved spectrum awareness/efficiency in cognitive radio systems, in: Proceedings of IEEE INFOCOM, Turin, Italy, 2013, pp. 1258–1266.

[230] D. Guo, L. Zhang, Virtual full-duplex wireless communications via rapid on-off-division duplex, in: Proceedings of Allerton Conference on Communications, Control and Computing, Allerton, IL, USA, 2010.

[231] L. Zhang, J. Luo, D. Guo, Neighbor discovery for wireless networks via compressed sensing, Perform. Eval. 70 (2013) 457–471.

[232] M. Gan, D. Guo, X. Dai, Distributed ranging and localization for wireless networks via compressed sensing, arXiv preprint arXiv:1308.3548, 2013.

[233] L. Zhang, D. Guo, Virtual full-duplex wireless broadcasting via compressed sensing, IEEE/ACM Trans. Netw. 22 (5) (2014) 1659–1671.

[234] M. Fukumoto, M. Bandai, MIMO Full-duplex wireless: Node architecture and medium access control protocol, in: Proceedings of 7th Int. Conf. Mobile Comput. Ubiquitous Network, Singapore, Singapore, 2014, pp. 76–77.

[235] J.Y. Kim, O. Mashayekhi, H. Qu, M. Kazadiieva, P. Levis, Janus: A novel MAC protocol for full-duplex radio, in: Proceedings of CSTR, 2013, pp. 1–12.

[236] K. Miura, M. Bandai, Node architecture and MAC protocol for full duplex wireless and directional antennas, in: Proceedings of IEEE 23rd Int. Symp. PIMRC, Sydney, NSW, Australia, 2012, pp. 369–374.

[237] B. Radunovic, D. Gunawardena, A. Proutiere, N. Singh, V. Balan, P. Key, Efficiency and fairness in distributed wireless networks through self-interference cancellation and scheduling, Microsoft Research, Cambridge, U.K. Tech. Rep. MSR-TR-(2009) 2009-27.

[238] S. Kim, W.E. Stark, On the performance of full duplex wireless networks, in: Proceedings of 47th Annual CISS, Baltimore, MD, USA, 2013, pp. 1–6.

[239] W. Cheng, X. Zhang, H. Zhang, RTS/FCTS mechanism based fullduplex MAC protocol for wireless networks, in: Proceedings of IEEE Global Commun. Conf., Atlanta, GA, USA, 2013, pp. 5017–5022.

[240] S. Goyal, P. Liu, O. Gurbuz, E. Erkip, S. Panwar, A distributed MAC protocol for full duplex radio, in: Proceedings of Asilomar Conf. Signals, Syst. Comput., Pacific Grove, CA, USA, 2013, pp. 788–792.

[241] Yu Song, Wangdong Qi, Wenchi Cheng, Energy efficient MAC protocol for wireless full-duplex networks, China Commun. 15 (1) (2018) 35–44.

[242] D. Datla, A.M. Wyglinski, G.J. Minden, A spectrum surveying framework for dynamic spectrum access networks, IEEE Trans. Veh. Technol. 58 (8) (2009) 4158–4168.

[243] Sherif ElAzzouni, Ozgur Ercetin, Amr El-Keyi, Tamer ElBatt, Mohammed Nafie, Full-duplex cooperative cognitive radio networks, in: Proceedings of Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), 13th International Symposium, IEEE, Mumbai, India, 2015, pp. 475–482.

[244] Vahid Towhidlou, Mohammad Shikh-Bahaei, Improved cognitive networking through full duplex cooperative ARQ and HARQ, IEEE Wirel. Commun. Lett. 7 (2) (2018) 218–221.

[245] L.T. Tan, L.B. Le, Design and optimal configuration of fullduplex MAC protocol for cognitive radio networks considering self-interference, IEEE Access 3 (2015) 2715–2729.

[246] N. Choi, M. Patel, S. Venkatesan, A full duplex multi-channel MAC protocol for multi-hop cognitive radio networks, in: Oceedings of IEEE Int. Conf. Cogn. Radio Orient. Wireless Netw. Commun, Mykonos Island, Greece, 2006, pp. 1–5.

[247] L.T. Tan, L.B. Le, Multi-channel MAC protocol for full-duplex cognitive radio networks with optimized access control and load balancing, in: Proceedings of IEEE Int. Conf. Commun. (ICC), Kuala Lumpur, Malaysia, 2016, pp. 1–6.

[248] Jingwen Zhang, Wang Fanggang, Zhangdui Zhong, Throughput analysis for full-duplex sensing in non-time-slotted cognitive radio network, in: Proceedings of the 14th International Wireless Communications & Mobile Computing Conference (IWCMC), IEEE, Limassol, Cyprus, 2018.

[249] J. Bai, A. Sabharwal, Distributed full-duplex via wireless side-channels: Bounds and protocols, IEEE Trans. Wirel. Commun. 12 (8) (2013) 4162–4173.

[250] W. Schacherbauer, A. Springer, T. Ostertag, C. Ruppel, R. Weigel, A flexible multiband frontend for software radios using high IF and active interference cancellation, in: Proceedings of IEEE International Microwave Symposium, Phoenix, AZ, USA, 2001.

[251] D. Ramirez, B. Aazhang, Optimal routing and power allocation for wireless networks with imperfect full-duplex nodes, IEEE Trans. Wirel. Commun. 12 (9) (2013) 4692–4704.

[252] K. Kato, M. Bandai, Routing protocol for directional full-duplex wireless, in: Proceedings of IEEE 24th Int. Symp. PIMRC, London, UK, 2013, pp. 3239–3243.

[253] W. Cheng, W. Zhang, L. Liang, H. Zhang, Full-duplex for multi-channel cognitive radio ad hoc networks, IEEE Netw. 99 (2018) 1–7.

[254] R. El-Khatib, H. Bany-Salameh, A routing scheme for cognitive radio networks with self-interference suppression capabilities, in: Proceedings of IEEE Fourth International Software Defined Systems (SDS) Conference, Valencia, Spain, 2017, pp. 20–25.

[255] H. Bany-Salameh, R. El-Khatib, Spectrum-aware routing in full-duplex cognitive radio networks: An optimization framework, IEEE Syst. J. 13 (1) (2018) 183–191.

[256] F. Zhu, F. Gao, T. Zhang, K. Sun, M. Yao, Physical-layer security for full duplex communications with self-interference mitigation, IEEE Trans. Wirel. Commun. (2015) 329–340.

[257] Q. Xu, P. Ren, Q. Du, L. Sun, Secure secondary communications with curious primary users in cognitive underlay networks, in: 2016 IEEE 83rd Vehicular Technology Conference, 2016, pp. 1–5.

[258] H. Li, Z. Han, Dogfight in spectrum: Combating primary user emulation attacks in cognitive radio systems—Part II: Unknown channel statistics, IEEE Trans. Wirel. Commun. (2010) 274–283.

[259] L. Zhang, G. Ding, Q. Wu, Y. Zou, Z. Han, J. Wang, Byzantine attack and defense in cognitive radio networks: A survey, IEEE Commun. Surv. Tutor. 17 (3) (2015) 1342–1363.