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 SURVEY

Spectrum Sensing Using Software Defined Radio for Cognitive Radio Networks: A Survey

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ABSTRACT Cognitive radio (CR) network has emerged as a potential solution to the under-utilization problem of the allocated radio spectrum, where spectrum sensing (SS) plays a key role to enable the coexistence between primary and secondary users. It has attracted research interests, and several works have been reported in the literature. Nevertheless, the assumptions and simplifications introduced during the modeling of the communication system often yield misleading conclusions each time relevant aspects of their implementation on a testbed are omitted. Hence, prototypes are built to study their behaviour under real-world conditions, therefore software defined radio (SDR) has emerged as an ideal vehicle to allow researchers to experiment with prototypes of these CR approaches. In this survey, we provide an overview of the latest works in CR networks related to the spectrum awareness approaches and taking into account their implementation on testbeds. These approaches are classified from a practical point of view, where a detailed review of the existing works for each category is provided. A review of the existing SDR platforms is also exposed highlighting the main components and features of current architectures employed for experimental evaluation of CR approaches. Next, the challenges to implement current spectrum awareness approaches on SDR platforms are detailed. Finally, at the light of these reviews, research challenges and open issues are identified for future research directions.

INDEX TERMS Cognitive radio, spectrum sensing, SDR platforms, hardware impairments.

I. INTRODUCTION

With the increasing demand of broadband wireless spectrum due to the incorporation of wireless devices requiring higher data rates, the allocation of spectrum has been carried out inefficiently, and its provision has been limited by the segmentation of the spectrum, and the allocated frequencies of standardized wireless systems.

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This shortage of the spectrum has motivated the conception of CR networks as a potential candidate to perform a complete dynamic spectrum access (DSA) by exploiting the available frequency bands called spectrum holes or white spaces [1]. It incorporates various techniques enabling the coexistence of licensed and unlicensed systems over the same spectrum, where primary users (PUs), also known as licensed or incumbents users, are defined as the users who have higher priority or legacy rights for using a specific part of the spectrum, while secondary users (SUs), also called cognitive users, exploit the spectrum in such a way that they do not

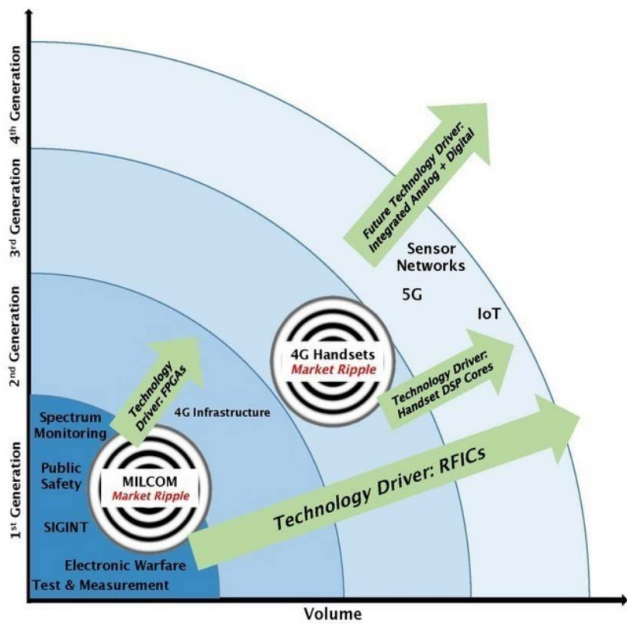


FIGURE 1. SDR: past, present, and future. Evolution of SDR through successive generation and its adoption as a de facto industry standard for radios [3].

cause harmful interference to the normal operation of the license PUs.

Although numerous approaches have been conceived for CR networks over the last decades, and despite of the significant efforts carried out by research institutions, regulatory and industrialization bodies, the final adoption of this technology is still facing numerous challenges [2]. For that end, the research of practical solutions towards a realistic implementation has become critical for the actual system deployment.

SDR has been a supporting technology that facilitates the assessment of novel approaches under more realistic environment. It allows to implement radio communication systems by shifting a hardware design to systems where most functional components are defined in software, as conceived by Joseph Mitola III [1]. Since its conception, different cognitive radio capabilities have been implemented, so that CR devices can acquire information from their operating environments and adapt their radio parameters autonomously in order to exploit the underutilized parts of the spectrum. In this way, the feasibility and validation of the novel approaches can be assessed through exhaustive experimental evaluations that can corroborate the expected results.

During the last years, the SDR adoption has been evident allowing the markets to move from hardware radio architectures (e.g. military communications) to SDR architectures, as it is depicted in Fig. 1. The advancement of radio frequency integrated circuits (RFICs) and programmable devices (Field-programmable gate array - FPGAs, DSP, system on a chip - SoC, etc.) has enabled it to become the dominant industry standard in 4G networks, and the current

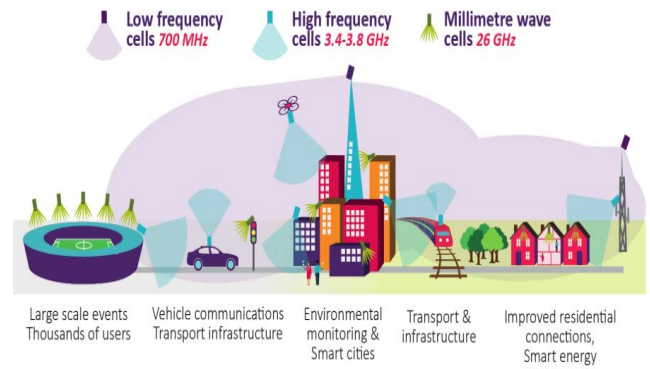


FIGURE 2. 5G technology enables diverse services and applications requiring access to different spectrum bands [7].

development of the wireless communications demands the validation of CR approaches.

In cellular networks, long term evolution (LTE) developed by third generation partnership project (3GPP) has extended its usage to WiFi unlicensed bands [4], where coexistence strategies using the sensing capabilities of the LTE network have been conceived. For instance LTE introduces a licensed-assisted access (LAA) feature to leverage the use of the unlicensed spectrum. It relies on different channel access procedures based on sensing the channel before transmissions. In fact, this mechanism known as listen-before-talk (LBT) is studied and validated on a SDR platform addressing the coexistence between LTE-LAA systems and wireless local area networks (WLAN) [5]. Moreover, it is also considered for 5G services such as the ultra-reliable and low latency communication (URLLC) [6], thus the incorporation of more advanced features to the current SDR-based platforms is required for the adoption and standardization of unlicensed communication systems.

5G networks have also introduced a massive MIMO technology, where a higher number of antennas at the base station provides a new dimension for opportunistic transmissions in addition to the time-frequency dimension, i.e. the spatial dimension. Hence, spectrum sensing techniques related to this dimension have been conceived and evaluated through multi-antenna SDR platforms [8]. Furthermore, with the increasing number of applications demanding higher data rate, higher spectral resources are required. Conventional narrowband SS schemes are not enough to explore the wide frequency bands, and wideband spectrum sensing (WSS) techniques are explored [9]. It is portrayed in Fig. 2, where the access to different frequency bands from lower frequencies to higher frequencies with large bandwidths are required by several applications/services. Nevertheless it imposes several challenges at the hardware level, along with a higher complexity for its implementation on current SDR platforms, as well as new challenges for the incorporation of reconfigurable antennas to handheld transceivers.

Last but not least, IoT networks are taking part of numerous applications such as monitoring purpose, e-health

TABLE 1. List of abbreviations in alphabetical order.

Acronym	Explanation
ADC	Analog-to-digital converter
AIR-T	Artificial intelligence radio - transceiver
AWGN	Additive white Gaussian noise
CAF	Cyclic autocorrelation function
CR	Cognitive radio
CSS	Cooperative spectrum sensing
CUDA	Compute unified device architecture
DAC	Digital-to-analog converter
DCR	Direct-conversion receiver
DDC	Digital down converter
DSA	Dynamic spectrum allocation
DSP	Digital signal processing
ED	Energy detector
FC	Fusion center
FPGA	Field-programmable gate array
GPP	General purpose processor
GPSDO	GPS disciplined oscillator
GPU	Graphic processing unit
HDL	Hardware description level
HLS	High level synthesis
IQ	In-phase and quadrature
LNA	Low noise amplifier
LO	Local oscillator
LTE	Long term evolution
MF	Matched filter
ML	Machine learning
NF	Noise figure
NI	National instrument
OFDM	Orthogonal frequency-division multiplexing
PA	Power amplifier
PAPR	Peak-to-average power ratio
PPS	Pulse-per-second
PU	Primary user
RF	Radio frequency
RTL	Register transfer level
SDR	Software defined radio
SNR	Signal-to-noise ratio
SoC	System on a chip
SS	Spectrum sensing
SU	Secondary user
URLLC	Ultra-reliable and low latency communication
USRP	Universal software radio peripheral
VGA	Variable gain amplifier
WLAN	Wireless local area network
WPAN	Wireless personal area networks
WSS	Wideband spectrum sensing
3GPP	Third generation partnership project

applications, smart homes, agriculture, among others giving rise to a high demand on spectral resources [10], [11]. Once more numerous SS mechanisms are being adapted and evaluated addressing their challenging implementation on large-scale testbeds. Thus highlighting the urgent need for the standardization of CR SS approaches.

A. RELATED WORKS

In Table 2, we cite the works related to the implementation and evaluation of SS techniques on SDR platforms. A brief review is provided along with their limitations in relation to the present survey.

In the upper part of the Table, the works concerning SS techniques are reported. In [12], the existing spectrum

occupancy models based on measurement campaigns are investigated, without addressing the detection performance based on these models. Spectrum prediction algorithms based on occupancy models are reported in [14], remaining their assessment and validation on SDR platforms. Several spectrum algorithms are surveyed in [13], and practical considerations for their implementations are provided, however these are very barely covered for an energy detector without addressing SDR implementations and experimental evaluations. More recently, the authors in [15] focus on particular aspects such as full duplex and cooperative spectrum sensing (CSS), and in a similar way in [11] the recent narrowband/wideband SS techniques are reviewed. Nevertheless, the main scope of these latest works relies mainly on the mathematical models supporting the SS metrics.

On the other hand, SDR architectures have also been surveyed to cover in general the hardware needs for radio communication [22]. The second part of Table 2 is devoted to these works. In [16], different multi-core processor architectures are explored for the increasing complexity of new generation of mobile terminals, where SS is not covered but foreseen to require higher levels of dynamism and complexity. SDR and CR introduce new classes of security threats which are considered in [17], but they are out of the scope for SS approaches. In [18], the authors highlight the employment of radio software to provide a more flexible usage of the current heterogeneous hardware architectures suitable for CR. Nevertheless, it does not cover the challenges regarding the implementation of SS approaches. Moreover, in [19], [20], and [21] the implementation of CR mechanisms are not considered. In [19], the transmitter/receiver radio chain for a particular SDR board is studied, identifying the main bottlenecks when connecting a SDR board to a host PC via Ethernet. Wyglinski et al. [20] present some case studies about the employability of SDR platforms, while some SDR enhancements are reported in [21]. Finally, a comprehensive survey in [22] concerning the architecture, state-of-the-art, and challenges is reported, while covering only general requirements for SDR platforms.

B. SCOPE AND OBJECTIVES OF THE SURVEY

The increasing amount of works reported in these surveys has also propitiated a vast amount of work assessing their performance in more realistic environments with the employment of SDR platforms.

In this survey, we provide an overview of the latest developments for CR approaches related to the SS while highlighting their practical implementation aspects on current SDR platforms. The most relevant functions for the successful deployment of CR networks are identified and studied. Consequently, a classification of these approaches from this perspective is portrayed, along with a review of the experimental evaluations carried out to validate them on a SDR testbed.

Unlike, the aforementioned SDR surveys and magazine articles, current platforms are examined based on CR

TABLE 2. A brief summary of existing surveys and magazines along with their limitations in relation to the current survey.

Surveys & Magazines	Year	Brief summary of survey/magazine	Limitation
Spectrum sensing			
Yunfei Chen et al. [12]	2016	Brief review of spectrum occupancy models based on measurements campaigns, and spectrum occupancy prediction	SS approaches, and SDR implementation not addressed
Abdelmohsen Ali et al. [13]	2017	Review of spectrum sensing algorithms: narrowband/wideband/cooperative spectrum sensing, and practical implementation considerations.	SDR implementation not examined
Guoru Ding et al. [14]	2018	Comprehensive survey and tutorial on the recent advances in spectrum prediction algorithms.	Focused on spectrum inference algorithms
Youness Arjoune et al. [11]	2021	Brief review of full duplex and cooperative spectrum sensing, and spectrum sensing for IoT and 5G networks	Based only on SS algorithms
Abbass Nasser et al. [15]	2021	Brief review of full-duplex spectrum sensing, and spectrum sensing applications for IoT, 5G networks and beyond.	Review of SS algorithms
SDR			
Palkovic et al. [16]	2010	An overview of multicore architectures for future SDR platforms.	Limited to the requirements of an SDR transceiver
G. Baldini et al. [17]	2012	Survey of security aspects in SDR and CR, overview of the security threats and related protection techniques.	Review of SDR aspects not related to SS
C. Moy and J. Palicot [18]	2015	Evolution of SDR technology for the employment of complex and heterogeneous hardware architectures.	Centered on software radio
R. Machado & A. Wyglinski [19]	2015	Evolution of SDR technology and case study related to the development of a SDR platform	Limited to the deployment of an SDR platform, CR mechanisms not addressed
A. Wyglinski [20]	2016	Some case studies are presented to highlight the employability of SDR platforms for the industry and academy.	Illustrative examples using an SDR platform, CR mechanisms not addressed
S. Singh et al. [21]	2017	Enhancements for building a more efficient and flexible SDR technology.	Improvements not directly related to CR and SS
R. Akeela & B. Dezfouli [22]	2018	Survey of SDR platforms, overview of SDR architecture, design trends and development tools.	Exhaustive review of SDR platforms

requirements to alleviate the deployment of this technology. It is worth highlighting that the SDR implementation of each class of SS techniques faces different challenges in hardware and software aspects, which are addressed, and discussed.

Furthermore, an overview of the development tools along with the existing SDR architectures tailored for CR networks is exposed, by describing their main analog and digital components. Finally, future research directions and SDR enhancements are provided and discussed. Hence the ultimate goal of this article is to provide a bridge between the latest researchers tailored for SS concepts, and their deployment using SDR platforms.

C. CONTRIBUTIONS OF THE SURVEY

Hence the main key contributions distinguishing our paper can be outlined as follows:

- A survey of SS techniques concerning their practical implementation, i.e. taking into account hardware impairments and limitations.
- Review of SDR platforms tailored for CR approaches, main components for a completed functional CR platform are identified and detailed.

- Deployment of SS approaches on current SDR platforms, where we highlight the main challenges for a real-time prototyping.
- Open research issues remained for the conception of CR approaches, and future SDR developments.

To the best of our knowledge, it is the first time that spectrum sensing approaches are reviewed taking into account the challenges of their implementation, i.e. hardware impairments, as well as advantages and weakness of current SDR platforms.

Related surveys have provided partial answers from a theoretical and practical point of view when conceiving a CR approach. On the other hand, SDR architectures have been reviewed considering general requirements for the implementation of radio protocols. In this regard, this article aims to fill this gap by providing an up-to-date survey of current efforts for the deployment and adoption of this technology.

D. ORGANIZATION OF THE SURVEY

The content of this article is organized as follows: In Section II, SS algorithms are reviewed and discussed taking

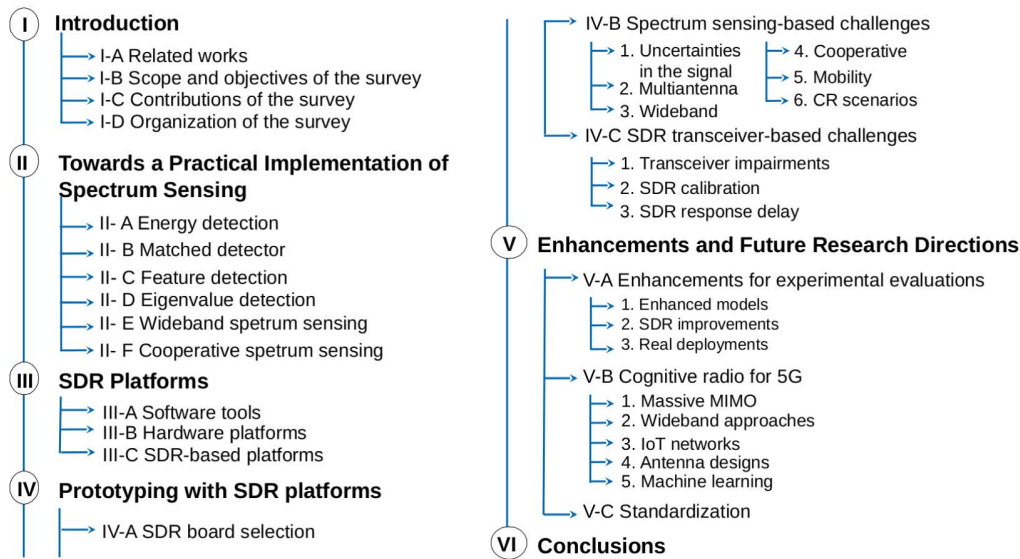


FIGURE 3. Overall organization of the survey.

into account the aspects of their implementations. The existing SDR tools are provided in Section III, where the current hardware, software and SDR platforms are reviewed. Later, Section IV exposes and discusses the identified challenges related to the SDR implementation of SS approaches. Next, research challenges and future research directions for CR are given in Section V. Finally, our conclusions are presented in Section VI. The overall organization of this article can be depicted in Fig. 3.

II. TOWARDS A PRACTICAL IMPLEMENTATION OF SPECTRUM SENSING

The scope of this survey can be depicted in Fig. 4, where PUs and SUs coexist, and a SDR platform is used to emulate a SU in order to assess its performance under more realistic conditions. We briefly review the fundamental concepts when addressing the implementation of SS approaches on SDR platforms that will be employed as background to expose and discuss the reported works in the literature.

CR is a potential candidate to exploit the white spaces, where SS is probably the most employed mechanism for acquiring information about the spectrum occupancy. It enables the SUs to detect the presence or absent of the PU over a frequency channel of interest,¹ and it is often formulated as a hypothesis test, while evaluated based on the detection and false alarm probabilities P_D and P_{FA} [23], respectively.

Each of these spectrum sensing approaches face different challenges when addressing their performance employing real measurements that can deviate from what is reported P_D

¹It is worth recalling that in the sequel of the present paper, we are interested to address interweave techniques, quite often reported in the literature.

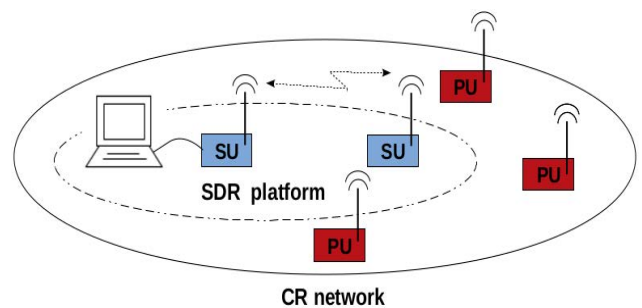


FIGURE 4. SDR platform for SS in a CR network.

and P_{FA} . In doing so, some detection problems are formulated by incorporating practical aspects to the signal model, so that a degradation of the performance, can be avoided or at least mitigated. Some of them have been studied resorting to computer-based simulations, while others are validated through experimental evaluations.

For that end, it is important to highlight the main concerns regarding the implementation of sensing mechanisms. It can be clarified with a description of the main components in a SDR receiver. In Fig. 5, it is depicted and is composed of two main parts: a digital and a radio frequency (RF) front end. The digital front end part is basically composed of a digital down converter (DDC), sample rate conversion (decimation) and low-pass filters, digital oscillators, among others. It is in charge of the rate adaptation, and channelization to operate between a wideband multichannel digital signal and independent baseband channels. On the other hand, RF front end is composed of elements such as low noise amplifiers (LNA), mixers, variable gain amplifiers (VGA), and automatic gain controller (AGC), where it carries out analog operations such as the down conversion from the operating RF signal to

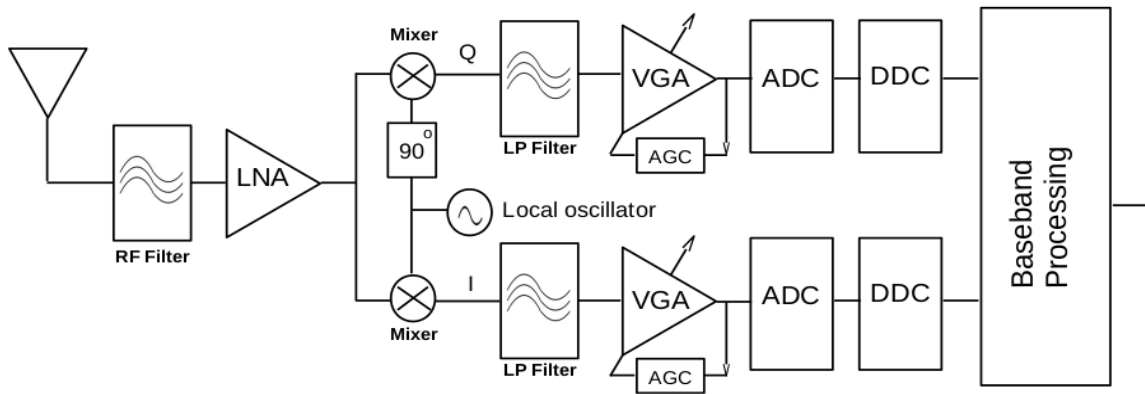


FIGURE 5. SDR receiver: main components of a radio chain.

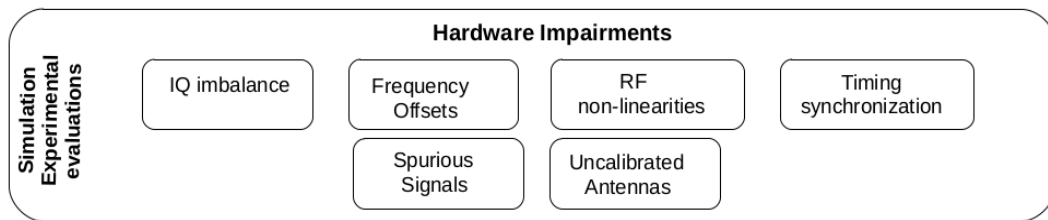


FIGURE 6. Overview of SS techniques and hardware impairments.

the baseband signal.² When a RF signal is received, first it is downconverted to a baseband signal, and the analog-to-digital converter (ADC) provides digital samples to the DDC. To sum up, an SDR receiver is then composed of a RF, a digital front end, and finally a baseband signal processing.

SS approaches reported in previous classifications have been examined considering missing aspects of their implementation. It has been portrayed in Fig. 6, where main hardware impairments are described. Then, mathematical models overlooking these aspects prevent from obtaining analytical expressions, and thus resorting to experimental evaluations. Hence, SS approaches are surveyed regarding:

- Signal uncertainties: noise uncertainty, non-Gaussian noise, time-varying noise floor.
- Hardware impairments: in-phase and quadrature (IQ) imbalance, frequency offset, timing synchronization, RF non-linearities, uncalibrated antennas.

A. ENERGY DETECTION

An energy detector (ED) does not need prior information about the PU signals, and has the lowest computational complexity among other methods [23]. It has been exhaustively studied and analyzed, under ideal assumptions, such as additive white Gaussian noise (AWGN) or known noise power. However, more realistic scenarios, where the noise uncertainty, a realistic wireless channel, and hardware

²Note that a zero-IF architecture, also-known as direct-conversion architecture, is described as it has been quite adopted for SDR platforms.

impairments of a radio receiver limit its performance, or make it infeasible for some applications [24], [25], [26], [27], [28], [29], [30], [31], [32].

The required number of samples for detecting signals that span over a short period of time is studied in [28]. The noise uncertainty and non-Gaussian noise are taken into account in [26] and [27] to assess the performance of an ED. This uncertainty makes it challenging to compute a threshold in order to meet the detection requirements in CR networks. Furthermore, the time-varying noise floor in practical CR scenarios has motivated the proposal of adaptive mechanism for the threshold selection, where the estimation of noise power and the computation of signal-to-noise (SNR) ratio are required [29], [33]. Some of these aspects are depicted in Fig. 7, where the received baseband signal composed of a PU signal, an spurious and noise floor in time domain are plotted. Energy values are outlined showing the challenge to detect a PU signal under spurious signal, while the Gaussian/Laplacian noise distribution are common assumptions found in the literature.

On the other hand, the importance of modeling hardware impairments is exposed and addressed in [25], for accurate energy-based SS. In Fig. 8, some sources of these impairments are depicted for a direct-conversion receiver (DCR). The LNA, for instance, introduces signal distortions, while phase noise and frequency offsets come from the local oscillator (LO). IQ impairments comprising timing/quadrature skews and gain imbalance are also described, where probably IQ gain imbalance is the most cited in

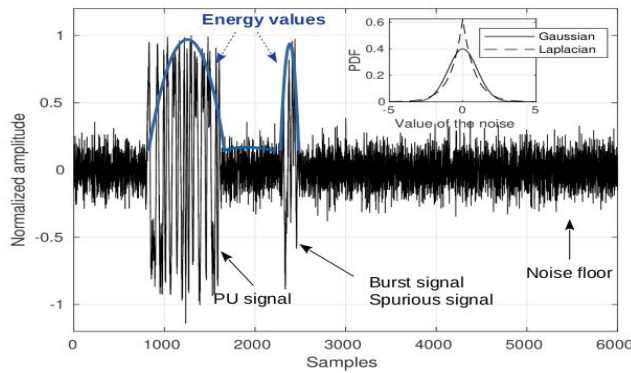


FIGURE 7. Capture of a received baseband signal containing a PU and a spurious signal in time domain, with the noise floor along with common assumptions about its distribution reported in the literature.

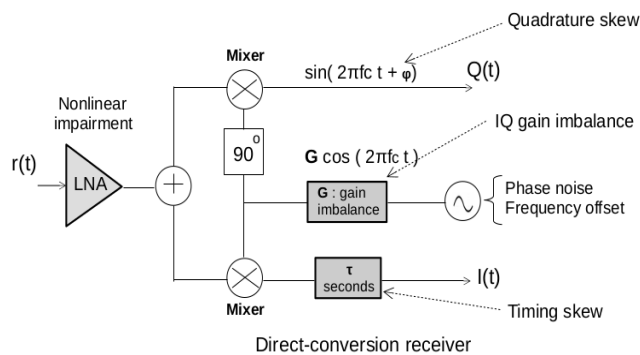


FIGURE 8. Some of sources of impairments at the receiver side. Non-linear impairments, and IQ impairments composed by timing/quadrature skews and IQ gain imbalance, phase noise and frequency offsets because of the LO.

the literature. Moreover, it is worth noticing that the joint of these impairments are present in a SDR board, and their impact on the detection performance appeals for their study. In this regard, the LNA non-linearities, IQ imbalance, and phase noise, are analyzed in [31] and [32], while assuming flat fading Rayleigh channels. Real measurements have been considered to validate the underlying assumption when conceiving a novel approach. In [26], the authors study the performance of an improved ED under noise uncertainty, that later is validated through experimental validations in [30].

B. MATCHED DETECTOR

A matched filter (MF) is implemented by the cross-correlation between the known transmitted signal and the receiver one. Under a low SNR regime, it has reported a robust and better performance than an ED, at the expense of higher computational complexity. Commonly, the MF performance has been employed as benchmarking to assess the obtained gain of a novel approach [34] through computer-based simulations. In addition, it has been proposed to assist an ED in [35], and some mechanisms for a dynamic threshold selection have been conceived in [36].

Although, the assumptions about full knowledge of the signal can be hard to meet in practice. For instance, due to aspects such as non-Gaussian noise, proper timing, hardware impairments, or real fading channel, that degrade the cross-correlation. It is also reported for purposes of experimental comparisons, as it is shown in [37] comparing a matched and ED using a common SDR platform.

C. FEATURE DETECTION

Specific signatures of the PU signal can be identified in most practical communication systems, such as preambles, pilots, cyclic prefix, second-order statistics, etc. Among these features, it is worth highlighting the periodicity of the second-order statistics. This feature is exhibited in digital modulated PU signals due to the symbol rate, chip rate, channel code or cyclic prefix, for which its detection is quite useful and popular in CR networks reporting numerous cyclostationarity-based detectors in the literature. This detector is based on the cyclic autocorrelation function (CAF) [23], and it has shown to be reliable at low SNR. However, it has a higher complexity, and requires a large sensing interval. Simulation-based results are often employed to validate novel approaches, and a simple variant based on symmetry property of CAF has been introduced in [38] and with a low complexity.

Its performance has been studied under noise uncertainty [39], while offsets in frequency and sampling clock are considered on the detection performance in [40], where P_D and P_{FA} expressions are provided. In fact, frequency offsets has reported a noticeable degradation in the detection performance, and it can occur because of LO drifts. It has been characterized for a SDR board in [41] that we reproduce in Fig. 9. An evident lack of accuracy and stability for a given carrier frequency is observed, for which the latest SDR implementations address the problem.

The computational complexity is also reported in [39] for different cyclostationarity-based detectors, and the cost of its implementation in FPGA boards [42]. Furthermore, measurements campaigns have been carried out employing SDR platforms in [38], [43], and [33] showing that the use of theoretical models may result in detection errors under real conditions, where the detector in [38] shows to be insensitive to the problem of local oscillator drift.

D. EIGENVALUE-BASED TECHNIQUES

Eigenvalue-based spectrum sensing can make detection by capturing correlation features in space, time and frequency domains, and probably the spatial domain is the one that have received more attention. In fact, multiple antenna detectors have been reported in a significant number of works in the literature, thus being addressed in this section.

These detectors are based on the sample covariance matrix of the received signal. They exploit the fact that under the null hypothesis the signals received at the different antennas are spatially uncorrelated, whereas the presence of a PU induces some correlation and/or additional structure in

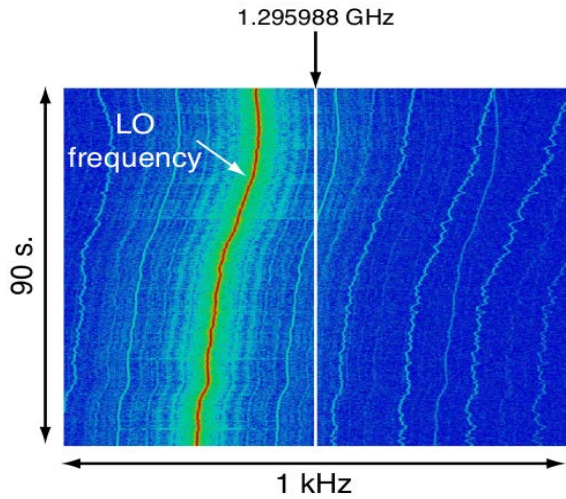


FIGURE 9. LO drift of an off-the-shelf SDR board. It causes frequency mismatches at the receiver side degrading the performance of cyclostationarity-based detectors [41].

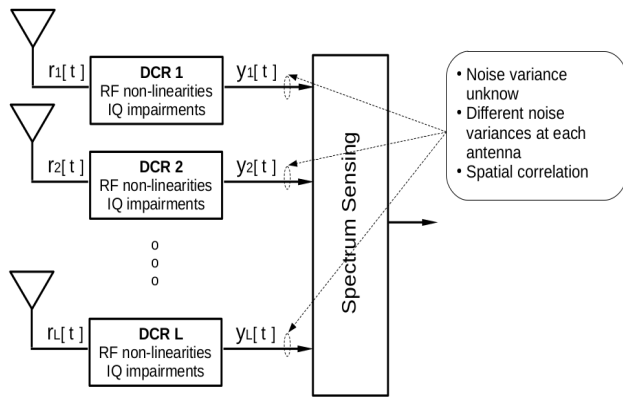


FIGURE 10. Multiantenna detection with uncalibrated antennas. Different noise variances can be measured at the output of each DCR for each antenna.

the spatial covariance matrix. Among these methods, the eigenvalues of the covariance matrix, have been so far explored [44], [45], [46].

However, in more practical scenarios, the detection performance is degraded due to the uncalibrated antennas. It has been described in Fig 10, where each DCR at each antenna has different RF and IQ impairments, and the noise variances measured at the input to the SS approach are different. IQ imbalance [47] has been considered for the proposal of novel detectors in [48] and [46], while the improperity of the received complex-value signals due to the IQ imbalance has also been addressed in [49], where a constant false alarm rate detection is reported. The multi-antenna signal detection has also been studied under PU-signal correlation due to oversampling [44], and novel detectors under interference are also conceived in [50].

Efficient implementations on FPGA boards for its incorporation to SDR platforms have been reported in [51], and

several comparisons of eigenvalue-based detectors using real measurements have been presented in [52] and under time-selective channels. In addition, some covariance-based detectors tailored for uncalibrated antennas are assessed in [53].

E. WIDEBAND SPECTRUM SENSING

WSS techniques aim to determine the available channels in a wide range of frequency, and one of the key requirements is the higher sampling rate, as it can be appreciated with the numerous works found in the literature classified as Nyquist or Sub-Nyquist WSS.

Nyquist approaches require a high computational complexity due to the high sampling rate, for which Sub-Nyquist techniques have attracted research interest. It employs sampling rates lower than the Nyquist rate, while detecting spectral opportunities using partial measurements, thus suitable for being evaluated using SDR boards. However, wideband RF front-end circuits introduces impairments into the received signal. For instance, the nonlinear components, LNA and mixer, produce intermodulation terms, while the ADC converter introduces spurious signals, thus making the detection of unoccupied bands more difficult and degrading the detection performance if not mitigated [54]. It can be observed in Fig. 11, where spurious frequencies appear in occupied and non-occupied sub-bands and are more likely to occur as a large bandwidth is sensed. Moreover, the noise floor may vary across all sub-bands, and it has been studied under non-gaussian, and impulsive noise in [55].

The validation of Sub-Nyquist approaches has been addressed through experimental validations [56], [57], and compressive sensing is incorporated to reduce the computational complexity in [57]. In [58] a tunable WSS detector is implemented on a FPGA board. It operates in the frequency range 70 MHz-6 GHz with a bandwidth of 30.72 MHz, and incorporates a pipeline architecture to reduce the latencies. Thus, allowing to characterize the time-varying PU traffic.

The availability of SDR platforms has motivated the experimental validations under different impairments [9], [59], [60]. A novel WSS detection under colored noised and partial spectral overlap is evaluated in [9]. A calibration method to estimate the actual transfer function of a Sub-Nyquist sampling architecture (concretely a modulated wideband converter [61]) is conceived in [59]. Recently, analytical and experimental results for a cyclostationarity WSS detector at a 5G frequency band (3.5 GHz and 100 MHz) is studied in [60], where a degradation in the P_D is observed. Fig. 12 summarizes the main sources impairments and detectors for WSS.

F. COOPERATIVE SPECTRUM SENSING

Unreliable and miss-detection rate of a single SU is often caused by fading, shadowing, hidden terminals. To mitigate these issues, CSS strategies are adopted to exploit the spatial diversity among the observations of SUs. It motivates the deployment of testbeds emulating these scenarios, as well as

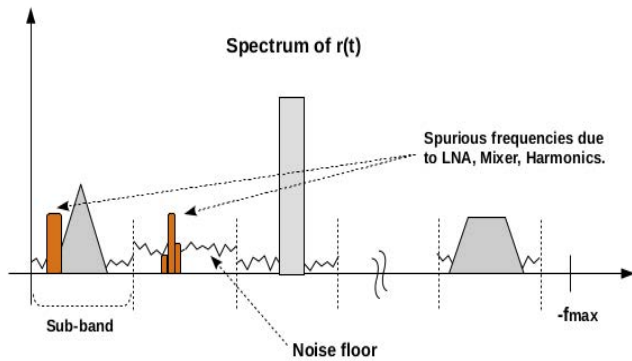


FIGURE 11. Wide monitored bandwidth composed of several sub-bands. Spurious signals and different noise floor degrade the detection performance of spectrum sensing approaches.

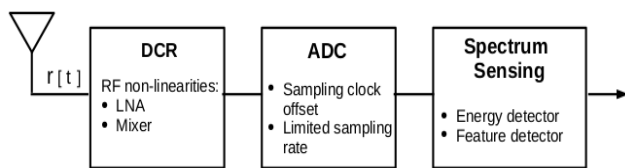


FIGURE 12. RF impairments at the DCR and ADC, and common detectors employed for WSS.

campaigns of experimental evaluations to assess the performance of CSS approaches. Nevertheless, in addition to the DCR impairments already exposed, the implementation of these strategies might be affected by other impairments such as timing inaccuracies among the SUs for simultaneous local sensing, the different sensing capabilities of SUs, heterogeneous SNRs at each SU, the presence of external interference coming from other wireless networks, among others [62], [63], [64], [65].

In a CSS detection, cooperative users report their local measurements to a fusion center (FC) for making a decision, where the entire measurements are reported (soft combination scheme) or one-bit decision (hard combination scheme). A soft-combining decision rule for cooperative prediction is proposed and assessed employing real-world WiFi signals on a SDR platform [62]. In addition, the problem of soft-decision schemes perfectly matches the matching learning (ML) paradigm [65]. ML has been employed to mitigate the presence of narrowband external interference, and it has been validated by means of experimental evaluations [63].

Furthermore, the hidden terminal problem that provokes a miss-classification of spectrum occupancy by some SUs has also been addressed in [67]. In this work, the authors propose a strategy to place SUs, so that the whole area of the PUs can be covered. With this methodology, the performance of a ML based CSS scheme can be guaranteed, which is confirmed by resorting to experimental evaluations. Finally, the detection performance is also analysed when applying an energy detector under non-Gaussian noise in [66], which is validated by experimental measurements.

G. SPECTRUM SENSING AND SDR IMPAIRMENTS

In Table 3, we summarize the different SS techniques along with the addressed HW impairment. Some of them are more relevant for a particular type of SS such as the frequency offsets and RF-non linearities for cyclostationarity and WSS detectors respectively. Furthermore, it is also worth mentioning that these approaches take into account the mentioned impairments by modeling them, thus conceiving novel approaches. Nevertheless many of them are not validated through experimental evaluations confirming the attained performance in more realistic environments.

III. SDR PLATFORMS

The implementation of CR approaches follow designs that typically employ programming languages at low-level and/or at high-level. At low-level, hardware description languages (HDL), such as Verilog or VHSIC Hardware description language (VHDL), aim at designing the digital logic of the system with register-transfer level (RTL) abstractions, where the exchange of data between registers can be designed. The employment of HDL allows the implementation of low-level architectures providing more control in the design of its components. Nevertheless, it entails a large time in acquiring expertise to implement at low-level. In this regard FPGA-based SDR platforms can use dynamic partial reconfiguration in order to reduce reconfiguration time.

On the other hand, the time of implementation at low-level can be avoided by generating HDL from programming language at high-level. For instance, high-level synthesis (HLS) processes are incorporated to convert designs described by programming languages at high-level (C/C++, Python, etc) to HDL. In this way, it allows the researchers to address targeted design by just providing algorithmic specifications.

A. SOFTWARE TOOLS

The selection of the software corresponds to the general requirements of a CR implementation. Next, we list the most employed tools:

1) MATLAB AND SIMULINK

MATLAB and Simulink have become very common and widely adopted for most designers that start employing SDR tools [68]. The high-level of language and block diagram environment, named Simulink, alleviates the task for the design and experimental evaluation of wireless transmissions. It is able to work with hardware platforms such as universal software radio peripheral (USRP) [68], RTL-SDR [69], ADALM-PLUTO [70], Zynq SDR, among others.

On the other hand, the provided high-level tools may not be enough to the needs of our design. For instance, the implementation of more complex scenarios working in real-time, scalable designs and the lack of open-source code. In fact, it is often used for offline processing prohibiting its employment to more sophisticated emulations.

TABLE 3. Summary of HW impairments addressed for spectrum sensing.

Detectors	Ref.	HW impairment	Validation	Remarks
Energy	[26]	SDR transceiver	Real measurements with different radio technologies	Impact of noise uncertainty and energy patterns in measurements are studied
	[27]	Not addressed	Exhaustive simulations	Laplacian noise and impact of noise uncertainty are explored
	[31]	IQ imbalance: amplitude and phase	Exhaustive simulations	Impairments of a wideband RF front-end are considered
Feature	[40]	Frequency and sample offsets	Simulations under AWGN for BPSK, MSK and QAM signals	Impact of frequency offsets is studied for cyclostationary detectors
	[39]	Frequency offset	Numerical results under AWGN & flat-fading channel	A Femtocell LTE-A scenario and noise uncertainty are considered
	[38]	SDR is employed	Real measurements using FM, 8PSK, GMSK signals	Cyclostationary-based detector performance
Multiantenna	[44]	Uncalibrated antennas	Simulations using QPSK signal	Correlated PU signals are considered
	[45]	Uncalibrated antennas	Simulations and comparisons	Correlated signals are considered and under noise uncertainty
	[46]	IQ imbalance: amplitude and phase Uncalibrated antennas	Simulations and comparisons under several IQ mismatches	Evaluated for a SIMO configuration, and CFAR property is assessed
	[49]	IQ imbalance: amplitude and phase	Numerical simulations using 8-QAM, BPSK	Improperly of signal is studied and CFAR property evaluated
Wideband	[54]	RF non-linearities: LNA and mixer intermodulation terms	Numerical simulations	Study of HW impairments on detection performance
	[55]	Not addressed	Numerical simulations BPSK signal	Non-Gaussian and weakly correlated noise
	[9]	SDR receiver is employed	Experimental measurements	Colored noise and spectral overlapping channels are considered
Cooperative	[63]	SDR receiver is employed	Experimental measurements employing OFDM signals	CSS under external interference resorting to ML techniques
	[66]	SDR receiver is employed	Numerical and experimental measurements using FM, GSM, among other signals	Non-Gaussian noise is also considered
	[67]	SDR receiver is employed	Experimental measurements employing 802.11 devices	The hidden node problem is addressed

2) GNU RADIO

GNU Radio is a set of open tools aiming to implement SDR systems [71]. It provides signal-processing blocks that are interconnected to form a flow graph representing the implemented transceiver in software. Basically, these blocks consist of source blocks (data files, audio files, etc), processing blocks (modulators, filters, multipliers and amplifiers), and sink blocks (FFT sink, constellation sink, oscilloscope sink). One of the main advantages is the capacity to define and add new blocks by employing C++ or Python. It is carried out by using a gr-modtool [72] script that allows to create our digital processing block. Besides, an intuitive graphical user interface (GUI) called GNU Radio Companion (GRC) is provided to alleviate the task of designing a new transceiver. Moreover, GNU Radio can be used with an external RF hardware (e.g. USRP [73], LimeSDR [74], RTL-SDR [69], ADALM-PLUTO [70]) or without it in a simulation-like environment.

Unlike Matlab, it allows the implementation of real-time radio system. However, it requires some expertise and knowledge to be more familiar with the developing tools. Moreover, although there exists a large number of projects available on the web, compatibility issues and a lack of updates prevent a rapid prototyping.

3) LabVIEW

National Instruments (NI) also offers a tool for the development of a SDR platform [75]. Likewise, GNU radio and Simulink, the design can be constructed schematically by connecting a chain of various blocks together in a visual programming environment. The different blocks of the system can be implemented using high-level languages such as C or MATLAB, and it is compatible with USRPs.

In addition, it provides application frameworks tailored for LTE and 802.11 implementations among others to easily get a real-time prototyping. Thus, allowing researchers to focus on radio aspects of their interest. Nevertheless, the products and licenses are not free, and the price for them could be not affordable.

4) XILINX VIVADO HLS

The Xilinx Vivado HLS tool [76] is a software suite produced by Xilinx. It provides a design environment for HLS that is widely employed on numerous Xilinx FPGA boards, where C, C++ and SystemC programs can be directly used into Xilinx devices avoiding the need to manually create RTL.

However, its usage is limited by the expertise and knowledge of the researcher about low-level languages and hardware architectures. For that end, it is often utilized when

the radio design can not be addressed with the current high-level tools.

B. HARDWARE PLATFORMS

The hardware of a SDR transceiver usually contains components such as a general purpose processor (GPP), digital signal processing (DSP), and FPGAs. The current SDR platforms are implemented employing a mixture of them, and the SDR-based prototypes require to review briefly some of these components.

GPPs are the preferable hardware platform by researchers in academia, since it can be used for several purposes. For instance generic x86/64 computer microprocessors, ARM architectures, and boards such as USRP [73] and LimeSDR [74]. However, the sequential processing of its instruction set (e.g. arithmetic and logic unit - ALU, data transfer, and I/O operations) limits its performance for real-time operations, where high-throughput and low latency are often required.

This limitation is overcoming with the incorporation of co-processors, such as the graphic processing unit (GPU), that are designed to process large blocks of streaming data in parallel for signal processing algorithms.

On the other hand, FPGA is an integrated circuit designed to be configured by a customer or a designer after manufacturing. It contains an array of programmable logic blocks, that can be configured using HDL. During the last years, it has significantly advanced and become more powerful computationally playing a remarkable role in embedded system development. However, the required prior knowledge about the FPGA hardware architecture can be time consuming for an efficient SDR implementation, and HLS tools have shown (e.g. Xilinx Vivado HLS) to alleviate this work.

C. SDR-BASED PLATFORMS FOR SPECTRUM SENSING

Next, we describe the current SDR platforms employed for CR networks.

1) USRP

USRPs are probably the most adopted and popular hardware platform. This board is generally composed of an RF front-end, ADC/DAC, and an FPGA, where the majority of operations (baseband processing) are offloaded to a GPP (host computer) via either USB, Ethernet, or peripheral component interconnect express (PCI-Express) connection. In addition, an embedded series comes with an internal GPP to operate in a standalone mode.

On the other hand, due to the fact that SDR tools such as GNU Radio, LabVIEW, and MATLAB Simulink support these boards, it is often reported in several research experiments motivating even more its employment. Nevertheless, USRP-based testbeds do not necessarily meet the requirements of communication standards. The bandwidth of the RF front-end, the data streams with a host processor, latencies, and the hardware impairments, are common aspects that usually affects the throughput and timing characteristics of the

platform. For that end, each released product provides more advance features to overcome these concerns. For instance, the employment of SoC integrating an ARM processor with the hardware programmability of an FPGA (e.g. Zynq-7000 family), as well as supplementary accessories (e.g. GPS disciplined oscillator - GPSDO). An example of a SoC-based SDR platform is the portable stand-alone USRP E310 embedded SDR that does not need a host computer, thus being suitable for field deployments.

2) LimeSDR

A low cost option and open source SDR, LimeSDR, is also available on the market, it has a similar architecture to the USRPs, and is comprised of a field programmable RF transceiver, an Intel FPGA, and a microcontroller. Moreover, it is connected to a GPP via USB 3.0, where the transceiver has the task to transmit/receive the wireless data, while the GPP generates the data and process the incoming signal. LimeSDR comes with LimeSuite software including source code, firmware, and schematics, and it is also supported by GNU radio.

3) ADALM-PLUTO

ADALM-PLUTO is an active learning module aiming to introduce the fundamentals of SDR. It is composed of a Xilinx Zynq-7000 SoC, and an analog-device-based RF front-end. Like previous architectures, it is connected to a GPP via USB, and a variety of software can be utilized such as MATLAB, Simulink, GNU Radio, or custom applications (C/C++,C#,Python). Although, it has been designed for teaching purposes and has some limitations such as the RF coverage, the number of antennas, and bandwidth frequency 20 MHz, it has been used for experimental evaluations whenever it fulfills the requirements.

4) RTL-SDR

RTL-SDR is the cheapest SDR receiver available today. It can be used as a based radio scanner for receiving radio signals covering a wide range of frequencies, it provides a custom driver to do some acquisitions and it is also supported by GNU radio.

5) bladeRF

bladeRF [77] is a promising powerful waveform development platform. It provides a 2×2 MIMO SDR, covering a large frequency range up to 6GHz, and connected to a GPP via USB. Supported by GNU radio and Matlab/Simulink, a HDL platform is also provided for the implementation of VHDL modem on FPGA meeting low latency and timing control required for the modulation/demodulation of 802.11 packets.

6) HackRF

HackRF One [78] is another SDR platform operating within a wide range of frequencies (1 MHz to 6 GHz). It is connected to a GPP via USB connector or programmed for stand-alone operation, and is compatible with GNU Radio.

7) BB60C

BB60C is a real-time RF spectrum analyzer covering a frequency range from 9 kHz to 6 GHz, with 27 MHz of instantaneous bandwidth [79]. This super-heterodyne receiver is connected to a GPP via USB. It provides a calibrated streaming suitable for accurate measurements, and a kit of development tools for custom applications. Moreover it is also supported by GNU Radio.

8) AIR-T

Artificial intelligence radio transceiver (AIR-T) is a high-performance SDR [80]. It incorporates an Nvidia GPU, a Xilinx FPGA and a multi-core CPU tailored for developing autonomous applications based on artificial intelligence and machine learning. A 2×2 MIMO SDR covering a frequency range from 300 MHz to 6GHz can be implemented employed embedded or edge series. This SDR can also be connected to a GPP via USB or Ethernet, and provides development tools to integrate deep learning into SDR systems, such as Anaconda [81] for ML, a compute unified device architecture (CUDA) [82] platform, and is also supported by GNURadio.

IV. PROTOTYPING WITH SDR PLATFORMS

A first step towards the implementation of a SDR-based testbed is the understanding of the general requirements. Different types of applications may lead to totally different requirements related to the hardware and software components. Some of these aspects can be, for instance, the number of nodes (transceivers), the processing capabilities at each node, single or multi-antenna nodes, the network topology (cooperative schemes), stationary/non-stationary environments (scenarios), among others. For that end, these prototyping challenges hindering the implementation of SS are reviewed in this section.

A. SDR BOARD SELECTION

The technical specifications related to each SDR board are reviewed when selecting a SDR board. The frequency range and bandwidth are some of these parameters. For instance, if a board covers the ISM frequency bands and wider bandwidths are required. Moreover the receiver sensitivity turns out to be relevant for the detection of low-power signals, where the noise figure (NF) of the RF front-end allows us to determine the noise floor, thus establishing minimum detectable signals.

A higher accuracy of a LO allows a proper downconversion of the RF signal and sampling at the ADC, for which the accuracy of the clock (i.e. the LO) is also examined. It is expressed in terms of its frequency variation, i.e. in parts per million (ppm) or parts per billion (ppb) and reported in the datasheets of SDR boards. Furthermore, phase noise specifications can also be extracted from the manufacturers. Nevertheless, a better characterization of these features can be carried out through experimental measurements [83]. This is often the case to determine the spectral purity of the receiver. A clean spectrum without strong DC and image components

as well as spurious signals is desirable, otherwise it will suggest us to apply some calibrations.

Each SDR board incorporates different hardware components, and the characterization of the receiver related to the aforementioned features becomes relevant for the assessment of the detection algorithms. In Table 4 we have reported some of these specifications in order to assist the selection of a SDR board.

B. SPECTRUM SENSING-BASED CHALLENGES

So far, we have addressed different SS techniques concerning their complexity, multi-antenna, bandwidth, and collaborative aspects. In this subsection, we discuss some of the challenges concerning the implementation of these approaches on a SDR platform, while reporting current efforts aligned to these aspects.

1) NOISE UNCERTAINTY

Noise uncertainty may come from several sources, internal components of a receiver chain and the external environment. Despite of common assumptions such as the stationary white Gaussian noise with zero mean, the distribution of this undesirable random process is not accurately known. Then, the noise variance has to be estimated in practice.

For instance in an ED, the threshold calculation depends on noise variance. Besides, it has been assumed to be constant over time and frequency domain. Furthermore, variations in the noise power levels across the spectrum may occur. Experimental evaluations employing a fixed threshold confirm the degradation on the detection performance, and some adaptive schemes have been proposed in [84] and [29], where a benchmarking performance of an ED is provided. A real-time computation of the threshold shows to obtain significant gains in terms of detection and false alarm probabilities [29], and under low SNR conditions [84].

2) MULTIAN TENNA

The experimental evaluations assessing the detection performance of multiantenna-based detectors have to deal with ignored problems in simulation-based environments. For instance, the transmission or acquisition of data streams through a given number of antenna requires to be executed simultaneously at the same time, while most available SDR boards are limited by the number of antennas. It has motivated the implementation of multi-antenna testbeds integrating several SDR boards [85], [86], [87]. In doing so, a synchronization module for sharing reference signals is incorporated. A timing synchronization for the transmission/reception of several aligned data streams is achieved by triggering the execution of transmissions/receptions at the same time at each SDR board. A clock signal is also shared among them, so that the LO can be obtained from a common source for all boards. An scheme of this synchronization among SDR boards is described in Fig. 13, where a central controller is also included for the parameter settings of the boards, storage of sensed data, among others. Some examples of these multiantenna

TABLE 4. SDR board parameters.

SDR board		Frequency range	Bandwidth	Remarks	Price
Ettus USRP	N210	up to 6GHz	40 MHz with daughterboards UBX, WBX, SBX, CBX	<ul style="list-style-type: none"> NF less than 8 dB (with WBX) Clock frequency stability 2.5 ppm 14 bits ADC 2x2 MIMO capability 	≈ \$3063
	B210	70 MHz – 6 GHz	56MHz	<ul style="list-style-type: none"> NF less than 8 dB Clock frequency accuracy ±2.0 ppm 12 bits ADC 2x2 MIMO capability 	≈ \$1918
	E310	70 MHz – 6 GHz	56MHz	<ul style="list-style-type: none"> NF less than 8 dB Clock frequency accuracy ±2.0 ppm 12 bits ADC 2x2 MIMO capability 	≈ \$4815
	X310	up to 6GHz	160 MHz with wideband daughterboards UBX, WBX, SBX, CBX	<ul style="list-style-type: none"> NF less than 8 dB (with SBX-120) Clock frequency accuracy 2.5 ppm 14 bits ADC 2x2 MIMO capability 	≈ \$8541
Lime micro-systems	LimeSDR	100 kHz – 3.8 GHz	61.44 MHz	<ul style="list-style-type: none"> NF, LO drifts and phase noise measurements specified in the LMS7002M IC datasheet 12 bits ADC 2x2 MIMO capability 	≈ \$468
Nuand	bladeRF 2.0 micro xA4	47 MHz - 6 GHz	56 MHz	<ul style="list-style-type: none"> NF and phase noise specifications in the AD9361 IC datasheet 12-bit ADC 2x2 MIMO capability 	≈ \$540
Analog devices	ADALM-PLUTO (PlutoSDR)	325 MHz - 3.8 GHz	20 MHz	<ul style="list-style-type: none"> NF less than 3.5 dB, clock frequency accuracy 25ppm. Phase noise measurements reported in AD9363 IC datasheet 12 bits ADC 	≈ \$235
Great Scott Gadgets	HackRF One	1 MHz - 6 GHz	20 MHz	<ul style="list-style-type: none"> NF reported in MAX2837 IC datasheet 8 bit ADC 	≈ \$301
RTL-SDR	Tuner Rafael Micro R820T/2/R860	24 – 1766 MHz	2.56 MHz	<ul style="list-style-type: none"> NF reported in the R820T tuner datasheet Clock frequency accuracy 30 - 150 ppm 8 bits ADC 	≈ \$39

SDR platforms can be found in [85] and [86], where the timing synchronization is carried out by sharing a pulse-per-second (PPS) signal provided by the Octoclock, and a NI module (XLe-6674T [88]) is employed to generate a clock signal, crystal oscillator (10 MHz), that later is amplified and distributed by the Octoclock, [89].

3) WIDEBAND

The implementation of larger WSS schemes on SDR platforms imposes other challenging aspects. For instance, any SDR architecture requiring a connection to a GPP via Ethernet cable (e.g. 1 GbE), will be limited to stream up to 25 Msps (for 16-bit samples), thus creating a bottleneck for larger values of Msps and consequently for larger bandwidths. This is the case in [87], where the authors require a sustainable signal acquisition at very high sampling rates, and consequently high data rate throughput and storage (e.g. 400 Msps covering a bandwidth of 320 MHz). In this regard, a radio frequency network on chip (RFNoC) development framework provided by Ettus Research enables the FPGA processing in USRP devices (e.g. X310), so that data streaming between the FPGA and the host PC is used to implement an acquisition platform for off-line processing.

4) COOPERATIVE

The implementation of cooperative approaches requires a degree of synchronization among the nodes being deployed. In CSS, it is expected to have synchronized measurements among SUs, so that the activity of a PU in a given band can be detected simultaneously, for instance, in nonstationary environments. In this regard, a triggering signal is implemented using PPS or GPS signals, as well as network time protocols. Quite often, these approaches are reported for indoor environments where a CSS scenario emulates a real world scenario with a limited number of nodes [63], [67], as it is depicted in Fig. 14, while outdoor measurements require the deployment of several nodes monitored using GPS signals and network time protocols for the synchronization of the experiments [90].

5) MOBILITY

The mobility of PUs causes changes to the set of available channels for SUs transmissions. Even more SUs may change their physical locations modifying the vacant channels of SUs neighbors. On the other hand, it is also challenging to recreate these scenarios in a testbed, where a limited number of PUs

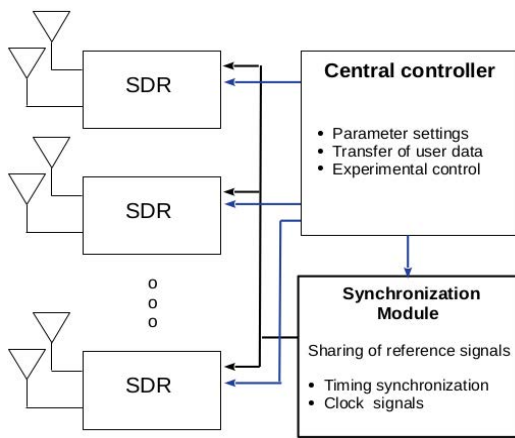


FIGURE 13. Implementation of a multi-antenna receiver employing SDR boards. A synchronization module allows the streaming data of each SDR board to be aligned by sharing reference signals.

and SUs can be tested, and emulations help to recreate such scenarios [52].

6) CR SCENARIOS

A testbed to recreate a CR scenario is also required to validate an approach. For instance, a real-time testbed to evaluate the impact of the interference on the detection performance is implemented in [91]. A CR scenario may also require the deployment of a large number of nodes, and emulations are one of these approaches to recreate a large-scale scenario (e.g. using a USRP node to emulate several users by transmitting continuously packets). However, it overlooks other factors such as multipath, path loss, hidden node problems. In this regard, some efforts in building large-scale testbeds [92], aim to provide external users a virtual space to deploy their own approaches (e.g using Docker containers and GNUradio in [92]). In fact, we can expect in future to have an online platform where all approaches can be compared under the same conditions avoiding users to face prototyping challenges.

C. SDR TRANSCEIVERS-BASED CHALLENGES

The imperfections of a SDR transceiver degrades and limits the performance of a CR system.

1) TRANSCEIVER IMPAIRMENTS

The non-linearities of the power amplifier (PA) due to the saturation region introduce non-linear distortions provoking a regrowth of the output signal resulting in adjacent channel interference (ACI). This problem is more evident with the multicarrier distortion faced by the transmission of orthogonal frequency-division multiplexing (OFDM) waveforms. The multiple parallel data flows transmitted on different subcarriers cause a large variation of amplitude in the time domain that requires to have an enough dynamic range of the PA. Several methods to reduce this variation (also known as peak-to-average power ratio - PAPR) have been proposed, In [93], the authors proposed a method based on a filtering

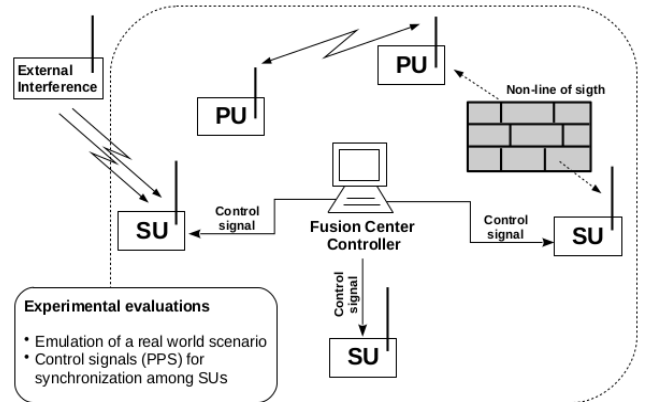


FIGURE 14. Emulation of a CSS scenario for a more real world experimentation. Real wireless channel, obstacles and interference are considered, while the FC is also emulated by a PC for controllability and repeatability of the experimental evaluation.

and clipping of the OFDM transmissions to improve the PAPR which is evaluated by modeling the PA, and eventually resorting to experimental evaluations on a SDR platform. In a similar way, a digital pre-distortion is designed and evaluated experimentally to compensate for PA impairments [94].

Although, the conversion of an analog RF signal to the digital form introduces some quantization errors at the ADCs, it does not deviate significantly the obtained performance from that obtained with infinite precision. In fact, the ADC resolution (e.g 12 bits) is set by default with the board and similarly for the ADC sampling frequency (sample rate per second). Despite of it, an interesting approach related to the ADC resolution is reported in [95]. The authors show the feasibility for the simultaneous acquisition of two signals with different powers, where an intra-quantum signal is acquire due to the contribution of a strong transmission when it crosses the quantization levels of the ADC, which is corroborated using one the latest SDR boards.

In practice several types of synchronization errors in frequency, time, phase drifts, introduce offsets degrading the performance of spectrum awareness approaches. A common source of LO is employed to provide these signals, and consequently its frequency stability turns out to be relevant. For instance a quartz oscillator with an output frequency of 1 MHz and 5 ppm will have a variation in frequency of 5 Hz. This problem is more evident for some approaches such as a cyclostationarity detector very sensitive to the mismatch of the cyclic frequency offsets due to these drifts. What is more, some applications (e.g. multiantenna approaches) require to have a common source of oscillator among the different RF receive chains of each antenna.

2) SDR CALIBRATION

Calibration of the RF hardware is often required when doing measurements since imperfections caused by e.g. the PA, LNA, the filtering and filter transients, can cause the measured values to differ throughout the deployed nodes. This

calibration can be done in the software by correcting the values of the received or transmitted signal based on a table of measured corrections factors. A simple calibration procedure can be made by connecting a signal generator directly to the board, and set up the corresponding gains. Some calibration procedures have been reported in [32] and [59]. However, the fact of having reconfigurable SDR and the different parameters related to CR approaches can be difficult to comprehensively and cost-effectively test with traditional methods. It is motivating the development of software defined synthetic instrument (SDSI) [97] to automatize the test and validation of SDR transceiver, even enabling the intermediate steps within the radio chain.

3) SDR RESPONSE DELAYS

High and unpredictable delays are commonly found in SDR platforms, and several studies have been carried out for its characterization [62], [98]. In this way, and with a better understanding of the SDR latencies, novel approaches can be conceived meeting the requirements of the targeted application. It is related to the time a frame takes to be transmitted or received when it goes through the transceiver chain. These latencies are often grouped and identified as: transceiver latency, communication link latency and host latency, as it is shown in Fig. 15, where significant delays have been reported concerning the communication link and host.

They have been measured and analyzed for the exposed platforms, such as GNU Radio [99], [100], employing USRPs and LimeSDR boards. Moreover, the integration of CR principles in spectrum access schemes, has been studied taking into the introduced latencies by the SDR platforms, as it is depicted in Fig. 15b. In this spectrum accesses scheme, the time after a sensing period and the transmission of packet (after determined that the channel is vacant) T_p is described, as well as the time to start receiving an ACK packet from a SU, T_w , both of them including SDR latencies.

In [62], the authors aim to assess the performance of a hidden markov model (HMM)-based prediction approach, for which the delay response of the SDR platform for packet transmissions after a previous sensing period slots turns out to be critical. This time between the end of the time slot for SS and the beginning of a time slot for a transmission is reported T_p , and the approach validated using real WiFi signals. More recently, the authors in [98], report long and variable delays when waiting for an ACK packet, T_w , after a packet transmission, for which a new sense-transmit scheme is proposed.

D. PROTOTYPING CHALLENGES AND EXPERIMENTAL VALIDATIONS

The implementation of an SDR-based testbed faces several prototyping challenges. In table 5, we summarize them when targeting the implementation of multiantenna, wideband, and cooperative SS on SDR-based testbeds. In addition, the corresponding approaches found in the literature are described.

It is worth highlighting that the validation of an SS technique aims to validate the proposal employing real measurements. In doing so, a main obstacle for some of these SS proposals is the implementation on an SDR platform, while for others it is straightforward allowing, in any case, the study of these approaches under different conditions. In Table 6, we show the numerous efforts for several SS techniques along with the employed SDR platform, implementation aspects and the validation addressed.

V. ENHANCEMENTS AND FUTURE RESEARCH DIRECTIONS

In this section we will discuss the enhancements that can be considered for the experimental evaluation of reported works, as well as the research gaps found to address for the support of the future generation of wireless communication networks.

A. ENHANCEMENTS FOR THE EXPERIMENTAL EVALUATIONS

At the light of exposed review, and with the current development of SDR platforms, novel approaches require to address more challenging CR scenarios under realistic conditions.

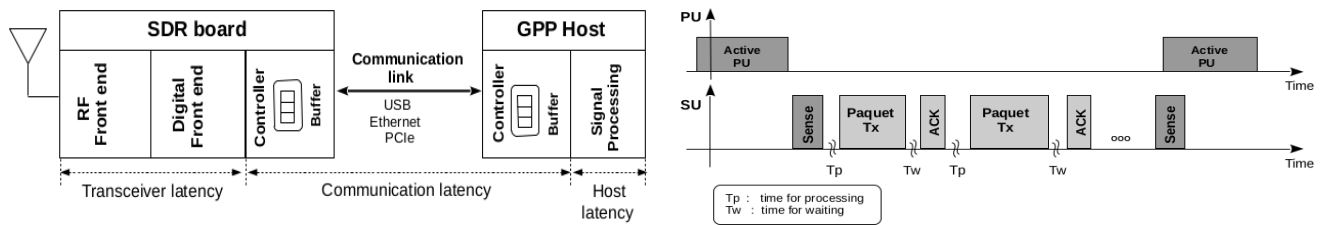
1) ENHANCED MODELS

Exhaustive measurement campaigns based on SDR platforms have been carried out to extract different statistical features of the spectrum occupancy. It has enabled the conception of several spectrum occupancy models that can be used to improve the accuracy of SS approaches. Nevertheless, these models have not been employed with the current experimental evaluations based on collecting noise or signal.

In addition, a perfect synchronization between the SU and PU has been so far assumed, so that two assumptions regarding the presence of a PU is only considered, i.e. under a null and alternative hypotheses. This assumption, however, is very hard to satisfy in a real word environment, where an asynchronous traffic of a PU is expected to be sensed by a SU. In this context, its impact on the sensing performance has been, for instance, addressed in [103], thus motivating the detection performance of SS approaches through more realistic experimental evaluations.

2) SDR IMPROVEMENTS

One of the challenges for GPP-based SDRs is to provide a generic runtime environment (e.g. to meet the performance for 5G Networks), for which low latencies and high throughput are among the desirable enhanced features of SDRs. Although, the new generation of SDR platforms is incorporating advanced features such as LabVIEW FPGA module and RF Network on Chip (RFNoc), the advantage of this computational power is still underused. An interesting work is the employment of these tools to provided an embedded solution (e.g. using RF Network on Chip). In this way, it allows to introduce our designs into the SDR boards instead of implementing them on the host PC, thus mitigating the communication bottlenecks between the SDR board



(a) Latencies of a SDR platform given by the transceiver, the communication link and the host latencies, occurring during the transmission or reception of data packets. (b) The implementation of an spectrum access scheme where SDR delays such as T_p and T_w are introduced.

FIGURE 15. SDR latencies and a spectrum access scheme.

TABLE 5. SDR implementation challenges and approaches for multiantenna, wideband and cooperative spectrum sensing.

SDR Implementation	Challenges	Approaches	Ref.	Remarks
Multiantenna	1. Time alignment of data streams	1. Synchronization in time and frequency	[89]	External source for synchronization
	2. Number of antennas limited by the SDR board	2. Employment of several SDR boards	[96]	Up to 128 antennas using two-antennas SDR boards
			[8]	4 × 64 massive MIMO system
	3. Data transfer and latencies requirements	3. Hierarchical architecture composed of centralized and distributed processing, high speed processing units	[86] [96]	Co-processors to help the CPU process, and switches to deliver data between co-processors and SDR boards
4. Reconfigurability	4. Central controller	[85]	Parameter settings of each SDR board	
Wideband	1. Higher sampling rate	1. Limited by the SDR board	[87]	Bandwidth up to 320 MHz and frequencies up to 6 GHz
	2. GPP host supporting higher sampling rate of SDR board	2. Introduction of adapters for high-speed network connectivity	[73]	PCI-Express, 10 Gigabit Ethernet for higher processing capabilities
	3. Storage capacity, latency	3. Methodology to deal with a large amount data	[85]	Short captures at higher rates,
[87]			Samples pre-stored at SDR board to meet latency requirements	
Cooperative	1. Synchronization among sensors	1. External triggering signal: GPS signal, network time protocols	[43] [90]	Tailored for field measurements in outdoor scenarios
	2. Scalability and reconfigurability	2. Low cost SDR and implementation of a control system	[90]	For the deployment of IoT applications

and host PC, for achieving lower latencies and/or higher throughput.

In addition, the adaptability of CR devices using the reconfiguration of radio parameters has been barely studied. For instance, modulation, coding schemes, power control, the operating carrier frequency, and bandwidth among others requires to be adaptive in real-time. Although, some of the software tools (e.g GNU Radio) incorporate this ability, it is still missing for other platforms limiting most of the experimental evaluations to off-line assessments.

3) REAL DEPLOYMENTS

A complete spectrum management framework showing its operability, while coexisting with other communication technologies, is not quite often reported in the literature. Although, there exists open platforms providing a full implementation of the protocol stack such as OAI [104], and srsRAN [105], these platforms require more efforts to learn its usage and key features. On the other hand, the incorporation of communication system components into the SDR platform is facilitating the deployment of more realistic testbeds. For instance, modules and toolboxes specifically

TABLE 6. Experimental validations reported in the literature: platform and implementation aspects.

Detection method	Ref.	Proposal	Platform		Implementation remarks & experimental evaluations addressed
			Hardware	Software	
Energy	[30]	Improved ED	N210 USRP	GNU Radio	<ul style="list-style-type: none"> SDR board captures real E-GSM 900 signals, to validate reported theoretical performance
	[29]	Adaptive threshold	PlutoSDR X310 USRP	GNU Radio	<ul style="list-style-type: none"> SDR-based transmitter and receiver for designing a real-time adaptive threshold
	[32]	Energy detection performance	Vector signal generator E310 USRP	MATLAB	<ul style="list-style-type: none"> Characterization of SDR board to determine the performance gap between simulations and real tests
Matching	[37]	Evaluation of matched detector	N210 USRP	GNU Radio	<ul style="list-style-type: none"> SDR testbed for performance comparisons
Feature	[38]	Cyclostationarity-based detector	N210 USRP	GNU Radio	<ul style="list-style-type: none"> SDR-based transmitter and receiver for performance evaluation under real HW impairments, indoor transmissions.
	[43]	Cyclostationary-based detector using field measurements	Commercial radio frequency integrate circuit (RFIC)		<ul style="list-style-type: none"> SDR board for capturing real DVB-T signals, and under mobility of SUs. A reported gap between experimental and theoretical results
	[33]	Cyclostationary and energy experimental evaluation	USRP2	GNU Radio	<ul style="list-style-type: none"> Practical implementation on an SDR board. Empirical estimation of cyclic frequency parameters, detection performance evaluation under limited mobility
Multiantenna	[101]	Evaluation of angle-of-arrival (AoA) algorithms	USRP 2920	LabVIEW	<ul style="list-style-type: none"> MIMO implementation, data streams aligned in time, frequency and phase. To assess the effectiveness of AoA algorithms
	[102]	Evaluation of 2-D spectrum sensing algorithms	RTL-SDR	MATLAB	<ul style="list-style-type: none"> Implementation of an four-antenna receiver using low-cost SDR to assess effectiveness of SS approaches
	[52]	Comparison of eigenvalue -based detectors	NI-USRP2954R	MATLAB	<ul style="list-style-type: none"> 1x2 MIMO implementation for detection performance comparisons considering the same RF impairments and mobility conditions
	[53]	Covariance-based detectors	N210 USRP	Not reported	<ul style="list-style-type: none"> A four-antenna receiver where the antenna space, uncalibrated antennas and mobility aspects are considered to assess their impact on detection performance
Wideband	[57]	Compressive sensing (CS) based detector	A commercial RFeye receiver	RFeye application	<ul style="list-style-type: none"> SDR board for the capture of real DVB-T signals and validation of CS-based approach to avoid higher sampling rates
	[56]	Sub-Nyquist sampling approach using an online learning	NI-USRP 2922	LabVIEW	<ul style="list-style-type: none"> The limited bandwidth and HW resources addressed by learning vacant frequency bands. Approach implemented and tested on SDR board
	[58]	Wideband spectrum sensing implementation	AD9361 RFIC Xilinx KC705	MATLAB	<ul style="list-style-type: none"> Reduction of latency for a continuous SS. Pipeline architecture to provide spectrum occupancy results in the order of 1-100ms for 30.72MHz of bandwidth
	[9]	Detection of signals with partial spectral overlap	N210 USRP	GNU Radio	<ul style="list-style-type: none"> SDR validation to detect frequency bands occupied by nearby transmitters in the 2.4GHz ISM band (e.g Bluetooth). HW impairments (colored noise, DC offset) are considered
Cooperative	[63]	Experimental validation of ML detection	N210 USRP	C++ & MATLAB	<ul style="list-style-type: none"> SDR boards synchronized in time to emulate a CSS scenario, SUs and PUs are controlled to study the detection under external interference
	[43]	Outdoor performance evaluation	Commercial radio frequency integrate circuit (RFIC)		<ul style="list-style-type: none"> Field measurements for CSS, asynchronous detection among 16 sensors is considered for practical measurements, fixed and mobile scenarios are evaluated
	[64]	New method for sensing TV white spaces	USRP 2952R	Not reported	<ul style="list-style-type: none"> Implementation of testbed to verify the fulfilment of IEEE 802.22 requirements
	[67]	Spectrum sensing coverage	NI USRP-2921	MATLAB	<ul style="list-style-type: none"> Data distribution is studied to improve the PU detection performance, real measurements obtained by several boards are required for designing new approaches

designed for cellular GSM, LTE, or Wi-Fi enable a rapid prototyping that can be considered for assessing the reported SS approaches.

B. COGNITIVE RADIO FOR 5G

5G networks will bring higher bandwidth and download speeds (in the order of multi gigabits per second), and several

underlying technologies for the radio access technology (5G NR) are expected to support them. Aiming to this goal, several gaps are expected to be addressed for the deployment of this technology.

1) MASSIVE MIMO

The effectiveness of current algorithms tailored for exploiting the diversity for massive MIMO networks will require to be re-examined. Massive MIMO incorporates a large number of antennas increasing its complexity, as well as the hardware cost. Although low-cost components enable the deployment of this technology, it comes with an increase of HW impairments. SDR platforms bring the ideal tool to assess the impact of these impairments in order to mitigate them. For instance, with the introduction of new signal models (as it has been exposed in this article), as well as with the design of compensation algorithms.

Exhaustive measurement campaigns not only for indoor, but also for outdoor environments require to be carried out to assess the massive MIMO performance. These measurements can allow to evaluate the viability of these systems in shared spectrum scenarios, so that new rules concerning the coexistence between PUs and SUs can be conceived. Nevertheless, these testbeds are not still quite reported due to the complexity of their prototyping with the current limitations of SDR boards.

2) WIDEBAND APPROACHES

The emerging bandwidth-hungry applications will be supported by WSS approaches. Nevertheless, wideband channel impairments such as frequency-selective fading, interference from close frequency bands, nearby transmitters, colored noise, or fast large-scale channel effects require to be taken into account on the sensing performance.

This evident gap can be fulfilled with the employment of SDR platforms where calibration methods for HW impairments related to wideband RF front-end (e.g. for millimeter waves) need to be addressed. In addition, the complexity of the digital front-end to deliver a higher throughput meeting lower latencies require more efforts for its rapid prototyping, and experimental evaluation with large volumes of data.

3) IoT NETWORKS

IoT over 5G cellular networks is one of the technologies considered for massive connectivity and better efficiency. Nevertheless, the evaluation of novel approaches (such as CSS) has been barely assessed in large-scale scenarios. In fact, the performance of these solutions is typically evaluated for indoor environments and generalized for large-scale scenarios leading, for instance, to an inefficient spectrum reuse.

The employment of empirical channel models fills the lack of accuracy of theoretical models, so as to improve the accuracy of a detection approach, for example taking into account the mobility of sensors. The main limitation to fill this gap, is the cost and manpower to deploy these networks at

large scale. In this regard, a promising prototype overcoming all these challenges is described in [106], where a cheap SDR board, composed by an FPGA board and a microcontroller, is configured over the air, while having common features of an IoT mote such as low power sleep modes.

4) MACHINE LEARNING

ML techniques have been successfully employed in cognitive radio networks, where SS can be formulated as a classification problem [107]. Deep learning is one of these classes of ML algorithms that using multiple layers extract relevant features from the raw data and it is reporting significant gains in comparison to conventional approaches based on model assumptions [108].

These approaches based their performance on the ability to learn the spatial and temporal features of the PU signal such as the energy-correlation features, or PU activity patterns. Nevertheless, the reported gains have not been experimentally verified. A gap to be covered should address the learning of these features using real measurements introducing spurious signals due to the HW impairments. Moreover, we can expect to validate and conceive more realistic DL-based approaches for MIMO, wideband and cooperative approaches.

On the other hand, the introduction of GPU-based SDR platforms promises a rapid prototyping. An interesting initiative is the development of AIR-T, that is specifically designed for high-performance computing applications. Concretely, the creation of ML-based wireless systems whose feasibility can be examined for spectrum sharing services in 5G networks.

5) ANTENNA DESIGNS

The design of antennas constitutes an important part in the development of new wireless devices. For instance, new frequency bands, wider channel bandwidths, higher antenna gains, and more antennas for MIMO systems are required for the 5G technology [109].

In massive MIMO, a realistic performance assessment requires to consider the features of a large antenna array (e.g. shape and size), so that it can capture the 3D propagation environment. Conventionally, patch antennas, omnidirectional dipoles, or 2D planar arrays have been employed for testbeds suitable for beamforming applications, and it is not clear which antenna pattern provides the best performance.

For massive IoT applications, the employment of compact antenna arrays along with the digital control of radiation pattern more directive, allows us to validate novel approaches when scanning surrounding sources. For instance, the accuracy for determining PU beams can be assessed dealing with multipath propagation, and under hardware imperfections (such as non-calibrated arrays or phase synchronization) due to the low-cost SDR boards.

We expect to have more antennas for millimeter-wave frequencies simplifying the deployment of large array of antennas (unlike the size for those arrays working below 5GHz),

thus allowing the assessment of adaptive approaches [110] in new frequency bands and with wide tuning capabilities.

C. STANDARDIZATION

Many standardization groups are working on incorporating CR technologies to communication system such as WLAN, ZigBee, and wireless personal area networks (WPAN), to exploit TV white spaces. In this regard, the experimental works provide accuracy channel models that later can be employed to assess system-level and link-level performances of advanced signal processing techniques for standardization purposes. The proof of concepts and experiments, part of the standardization phases, can be supported by the development of SDR-based platforms. Finally, different standards can be evaluated to decide with one is the most suitable for a given application.

VI. CONCLUSION

The scarcity of the radio spectrum has motivated the development of CR networks attracting research interests and reporting numerous approaches. Nevertheless the adoption of this technology is still facing several challenges. In this survey, we provide an overview of the latest works in CR networks, while taking into account relevant aspects of their implementation. Current SDR platforms have been reviewed and surveyed, and the main challenges for the deployment of CR approaches have been identified on SDR platforms. Finally, potential research directions as well as open issues are provided.

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