Cognitive Radio in Low Power Wide Area Network for IoT Applications: Recent Approaches, Benefits and Challenges

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***Abstract*—Some recent survey statistics suggest that low power wide area networks (LPWANs) are fast becoming the most prevalent communication platform used in many applications of the Internet of things (IoT). However, because most LPWANs are generally deployed in the presently congested industrial, scientific, and medical bands, they are invariably plagued by problems associated with spectral congestion, such as increased interference, reduced data rates, and spectra inefficiency. These problems are solvable by integrating cognitive radio (CR) technologies in LPWAN (termed CR-LPWAN), for which some pioneering solutions now exist in the literature. Consequently, the present paper takes an early look at some of these pioneering efforts pertaining to the development of CR-LPWAN systems. We discuss a general network architecture and a physical layer front-end model suitable for CR-LPWAN systems. Then, some notable state-of-the-art approaches for CR-LPWAN systems are discussed. Potential advantages of CR-LPWAN systems for IoT-based applications are also presented, and the paper closes with a few research challenges and future research directions in this regard. This paper aims to serve as a starting point for most budding researchers who may be interested in the development of effective and efficient CR-LPWAN systems for the enhancement of different IoT-based applications.**

***Index Terms*—Cognitive Radio, Industrial, Internet of Things, LPWAN, Survey**

I. INTRODUCTION

A wide range of recent applications of the Internet of things (IoT), for example smart industries, smart metering, and smart city architectures, often depend on devices that should be characterized by long battery lifetime, long range communication, low deployment cost, and large network scalability [1]. However, these requirements are difficult, if not impossible, to realize using existing cellular (3G and 4G) technologies, which are designed for more data-driven and power-demanding applications. Consequently, more suitable technologies such as the low power wide area network (LPWAN) are now widely deployed for such IoT-based applications. This is because LPWAN technologies provide relatively long single-hop transmission, low power consumption rates, simplified network topology, low cost, and straightforward deployment schemes, albeit at low data rates. [2], [3]. In fact, owing to the current wide-spread use of LPWAN technologies, recent statistics now suggest that LPWAN standards may connect over 700 million IoT devices by 2021 [4].

Nevertheless, because most LPWAN technologies operate in the relatively congested industrial, scientific, and medical (ISM) band, they are invariably prone to problems such as spectra congestion, which causes interference, reduced transmission range, limited scalability, and spectra inefficiency. Thus, in recent times, some pioneering researchers and developers alike, are tackling these problems based on the integration of cognitive radio (CR) technologies in LPWAN (termed CR-LPWAN).

In this regard, CR refers to a radio technology that can automatically detect unused channels (white spaces) and then change its transmission parameters to improve the communication performance of end nodes [5]. The development of CR has gained full consideration under new IEEE standards such as the IEEE 802.22, IEEE 802.15.2, IEEE standards coordinating committee (SCC) 41 [6] and it is now being widely used in many wireless communication applications, for example, towards improving the quality of service (QoS) in wireless sensor network (WSN)-based smart grid applications [7], [8]. Other works have used CR to minimise the level of interference in industrial WSNs (IWSNs) with benefits such as improved timely transmission, reduced latency, lower frame losses, as well as to improve dynamic spectrum allocation in IWSNs [9]. Furthermore, some recent papers have shown that CR can be used to minimise delay routing in time-critical industrial applications [10], and provide fast convergence for dynamic spectrum access in IWSNs. CR has also been applied in some industrial IoT (IIoT) applications towards safeguarding end-nodes from security threats in cyberphysical systems (CPS) and towards enhancing spectral access in cloud-based big data infrastructures.

However, the deployment of CR in LPWAN has only begun to suffice as a potential research area within the LPWAN research community. In fact, because of its potential, it is generally known that Sigfox, a popular LPWAN technology developer, presently integrates CR in some of its base stations, thus enabling their networks to attain very high capacities (now connecting over 3 Million devices) [11]. It is believed that such capacity-based benefits, enjoyed by Sigfox, may greatly motivate other LPWAN developers towards investing

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in the development of CR-LPWAN systems. Notably, the academic community has taken an early lead in this regard, and a number of pioneering articles are fast appearing in the literature with regards to the realization of CR-LPWAN systems. It is thus beneficial at the moment to present an early overview of these efforts. The present paper makes such an early attempt to discuss the different CR-LPWAN concepts, their pros and cons, towards the benefit of budding researchers who may be interested in this area of study. We discuss the different schemes that support the effective integration of CR in LPWAN. A network architecture and physical (PHY) layer front-end model are presented for CR-LPWAN systems. State-of-the-art approaches for CR-LPWAN systems are summarized, in addition to highlighting some advantages of CR-LPWAN systems. We close with a few research challenges and future research directions concerning the development of CR-LPWAN systems. Based on these efforts, the present paper posits the following contributions:

1) In addition to being different from existing works (see Section II), we present key insights concerning the use of CR in LPWAN, particularly emphasising CR as a potential solution to some known LPWAN problems.
2) We present a potential framework that integrates CR and LPWAN modules via a functional PHY layer unit. Our framework describes only the PHY front end of a generic CR-LPWAN system, as well as highlighting how each module may support effective CR-LPWAN systems.
3) We highlight specific challenges that may limit the functionality of CR-LPWAN systems. Specifically, we discuss new insights concerning the use of adaptive CR technologies in LPWAN transceivers.

It is worthy to mention that the present paper follows on our earlier work in [12] in a more substantive manner, with the following major differences: the present paper provides in-depth details concerning the various components of the PHY layer front-end model, which was missing in [12]. Four new sections were added in the present paper with regards to the potential benefits, research challenges and future directions concerning CR-LPWAN systems, which were not presented in [12]. Finally, different from [12], here, we discuss state-of-the-art approaches related to the realization of CR-LPWAN systems.

II. RELATED SURVEY PAPERS

In this section, we review related survey articles towards establishing the uniqueness of the present paper. We begin by mentioning the survey article of Wang *et al.*, [13] in which a number of open research challenges were identified and considered pertinent with regards to the development of effective control and management systems for LPWAN in IoT networks. Similarly, authors in [1] reviewed the opportunities, challenges and future directions for LPWAN technologies. Particularly, they studied challenges that relate to the development of LPWAN technologies such as spectrum limitation, coexistence issues, mobility management and scalability. Raza *et al.*, in [3] provided an extensive overview of LPWAN with focus on the design goals and techniques exploited in different LPWAN technologies. Importantly, Raza *et al.*, noted that most LPWAN standards are directed towards solving issues at the PHY and MAC layers, which indicates why our present paper considers to a greater extent PHY layer problems and their related solutions. Some other surveys in [13]–[16] focused on describing LPWAN enabling technologies, their limitations, potentials and future research directions.

With regards to the use of CR in IoT-based applications, the survey of Alam *et al.* in [17] explored methods regarding the use of CR in smart grid communication networks (SGCN). They discussed communication network requirements, their underlying technologies, and the provision of a suitable architecture for CR-SGCN. In a different paper, Khan *et al.*, discussed the use of CR in IoT with focus on applications, architectures, spectrum related issues and future research directions [18].

Essentially, even though the study of LPWAN technologies and IoT applications may seem quite exhaustive, nevertheless, our paper differs from the above-mentioned survey articles by presenting a unique overview of CR in LPWAN. We note that although the pioneering survey in [19] discusses networking over TV white spaces, nevertheless, our present paper specifically covers the subject of CR-LPWAN in more details, thus further emphasizing the uniqueness of our paper.

III. OVERVIEW OF LPWAN AND CR

We present a brief overview of LPWAN and CR as follows:

A. *LPWAN*

LPWAN refers to a new class of wireless communication technologies that provide low power consumption rates (i.e long battery lifetime), low device/deployment cost, long transmission range, at low data rates [3]. LPWAN is widely used in many IoT-based applications that consist of relatively small-sized sensors, which depend on tiny battery power supply units, and communicate by sending only small amount of data intermittently.

Following the present wide-spread interest in different IoT applications, the development of LPWAN technologies has gained greater patronage among a number of developers. Examples of some popular LPWAN developers include Sigfox, LoRa, Weightless, Wi-SUN, Telensa, and Qowiso. These different LPWAN developers produce different technologies with different performance characteristics, which are tailored specifically for unique IoT-based applications. Consequently, the choice of a specific LPWAN technology may depend on the particular IoT application of interest. Greater details, comparative analyses, advantages and disadvantages of these technologies can be found in classic articles, such as in [3], [18]. However, because different proprietary LPWAN technologies are produced by different developers, a highly competitive market exists, which seemingly stifles the standardization process between these different technologies [3].

Nevertheless, a few standard development organizations (SDOs) have been created with the aim to ensure interoperability between different LPWAN vendors. Examples of these SDOs include the European Telecommunications Standard Institute (ETSI) [20], the 3GPP group [1], Institute of Electrical and Electronics Engineers (IEEE) [21], and the Internet Engineering Task Force (IETF) [22]. The ETSI drives standards such as the low throughput network (LTN), which focuses on standardizing the type of modulation techniques used in LTN. The IEEE group controls standards such as the 802.15.4 and 802.11af standards, with specific focus on range extension and reduction in the power consumption rate of LPWAN devices. The 3GPP group drives standards based on cellular technologies, such as enabling the long term evolution (LTE) standards for narrow-band IoT (NB-IoT). The IETF, on the other hand, drives standards such as IPv6 for low power wireless personal networks (6LoWPAN). IETF focuses on making lightweight IP stacks for LPWAN operation.

There are also special interest groups (SIGs), which consist of individual industrial alliances, such as the LoRa Alliance, Weightless SIG, DASH7 Alliance, IQRF Alliance, Wi-SUN Alliance, and the IoT World Alliance. These efforts for standardization by SDOs and SIGs cover different areas of focus, consist of specific compliant LPWAN technologies, as well as comprising of different number of participating members/organizations.

B. Cognitive Radio

CR is defined by the Federal Communications Commission (FCC) as: "A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets" [5]. This definition points to a few characteristics that a CR device should possess: A CR device must provide adaptive and autonomous spectral awareness (spectrum sensing), detect available channels (spectrum decision making), be able to dynamically adjust its radio operating parameters (spectrum mobility), and conduct concurrent communication (spectrum sharing). These basic functions are briefly described as follows:

1) Spectrum Sensing (SS): A typical CR device scans (senses) its immediate electromagnetic environment for the presence/absence of primary user (PU) signals. Here, PU refers to the licensed owner of the spectrum. There are different approaches for SS including the use of the energy detector (ED), matched filters, cyclostationary detector (CDs), the Eigenvalue-based method, covariance method and the prediction-based approaches. Alternatively, the geolocation database approach can also be used to determine the presence of white spaces for use by CR devices [20]. In any case, a CR device may use either SS or the geolocation database approach to identity white spaces for opportunistic communication on a non-interference basis.

2) Spectrum Decision Making: Decision making by a CR device involves declaring whether a channel is free or not. When only the signal's energy values are known, the ED suffices as the most suitable detector for use. In this regard, decision is made as to the presence or absence of PU signals as a function of whether the received energy exceeds a specified threshold value or not, respectively. However, in cases where some specific characteristics are known about the PU signal, for example the signal's cyclic frequency, then the CD can be used to improve accuracy, albeit at the expense of complexity and long processing times.

3) Spectrum Access: Spectrum access is executed at the media access control (MAC) layer of the CR device. It involves using the information obtained from the PHY layer with regards to the absence/presence of PU signals in a band in order to adjust the transmission parameters of the CR device. Greater details in this regard can be found in [23].

4) Spectrum Mobility: Spectrum mobility involves the seamless hand-off from an occupied channel to a free one. It ensures that any ongoing communication between CR devices is conducted on a non-interference basis to the PU, and at relatively high data rates towards maintaining the quality of service experienced by CR users.

5) Spectrum Sharing: Spectrum sharing is concerned with the coexistence of CR devices within the same or adjacent channel of a PU transceiver. This involves operating the CR at below some interference levels.

At this point, we note that this section only briefly introduces the general concept of CR, however, interested readers may confer with other classic papers such as in [5], [23] towards gleaning greater details about the concept and development of CR.

IV. LPWAN: THE NEED AND DRIVE TO INTEGRATE CR

This section discusses why we need to integrate CR in LPWAN technologies, as well as providing an appraisal of the drive by LPWAN developers towards the integration of CR in their respective designs. There are three main problems that typically plague LPWAN technologies namely, interference, coexistence, and scalability problems. These problems stem from the fact that LPWAN technologies are mostly deployed in the presently congested ISM bands. For example, concerning the problem of scalability, it is known that the performance of some LoRa technologies often drops considerably as the number of end-nodes grow [2]. This is caused by the limited bandwidth experienced in the ISM band. By integrating CR in LPWAN, it is envisaged that CR-LPWAN technologies may greatly increase the scalability of LPWAN technologies. This has been demonstrated already in [24] and it will be further discussed in Section VI.

By being deployed in the now congested ISM band, LPWAN technologies typically experience increased interference. The ability to coexist with many other technologies while managing interference remains a major challenge for LPWAN developers [2]. Interference from spectra overcrowding further reduces the throughput of LPWAN technologies, limits their transmission range, and increases their latency levels. CR promises to address these problems by ensuring that LPWAN technologies easily migrate from ISM bands to free licensed bands towards enhancing communication performance, as well as vacating occupied bands quickly enough to avoid interference.

TABLE I: Different LPWAN technologies and factors that support the integration of CR technology in their designs

S/N	LPWAN Technology	Licensed Band Operation	Unlicensed Band Operation	Transceiver supports Adaptive Threshold	Supports Multiple Channels	Currently Supports CR	Considering future CR deployment
1	Weightless-W	✓	✓	?	✓	✓	✓
2	Sigfox	×	✓	?	✓	✓	✓
3	Nwave (Weightless-N)	×	✓	?	✓	✓	✓
4	LoRa	×	✓	✓	✓	×	✓
5	Symphony Link	×	✓	?	✓	×	✓
6	Amber Wireless	×	✓	?	✓	×	×
7	IQRF	×	✓	?	✓	×	×
8	LTE-M	✓	×	?	✓	×	×
9	NB-IoT	✓	×	?	✓	×	×
10	Starfish	×	✓	?	✓	×	×
11	Telensa	×	✓	?	✓	×	×
12	Wi-SUN	×	✓	?	✓	×	×
13	Qowisio	×	✓	?	×	×	×
14	Ingenu	×	✓	?	×	×	×

Labels:|✓ - Yes| |x - No| |? - Unknown|

Indeed, many LPWAN developers are aware of the benefits of integrating CR in LPWAN and these interest levels are appraised. To conduct our appraisal, we studied major LPWAN technologies/developers and appraised them based on some key CR factors that may indicate their support for CR. Table I lists these different LPWAN technologies based on whether they employ CR in their respective technologies or plan to support CR. In this regard, we considered six different metrics in Table I, where the question mark symbol (?) indicates that the required information was unknown at the time of this writing, due to the closed and proprietary nature of most LPWAN technologies. The factors considered in our appraisal include the bands of operation of each LPWAN technology, their current support for CR, the use of multiple channels, and the use of adaptive threshold techniques in their respective transceiver modules. Major LPWAN technologies are sorted based on the number of ”ticks” in Table I and they are ranked accordingly. Thus, on a scale of six factors (see Table I), the following technologies belonging to Weightless-W, Nwave (Weightless-N), Sigfox, LoRa, and Symphony are considered to have significantly included CR technologies in their design. This group accounts for 30% of the LPWAN technologies in Table I that have 4 - 6 ticks. About 50% may have partially included CR technologies in their design (see those with 2 - 3 ticks in Table I), while only 20% seem to have weakly considered CR technologies in their design (those with less than two ticks in Table I). Primarily, our appraisal suggests that many LPWAN developers seek to integrate CR in their several LPWAN technologies in order to solve problems such as increased interference being experienced in the ISM band, spectral congestion, and limited transmission range.

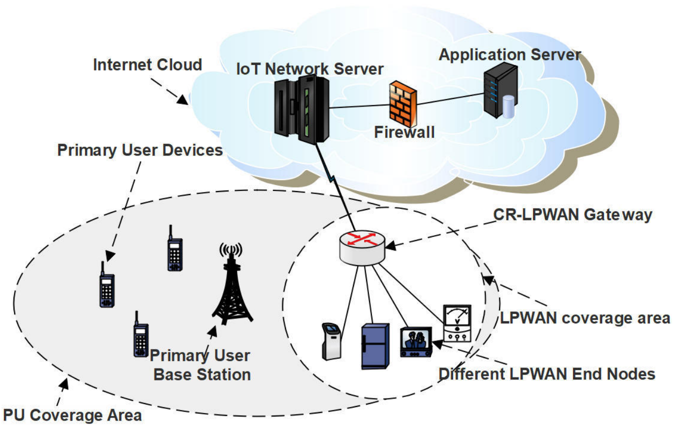

Fig. 1: A generic network architecture depicting a CR-LPWAN gateway

V. CR-LPWAN: NETWORK ARCHITECTURE AND PHY LAYER MODEL

In this section, we discuss a possible network architecture and PHY layer front-end model suitable for the development/deployment of CR-LPWAN systems.

A. *CR-LPWAN Network Architecture*

It is expected that every CR-LPWAN system should be deployed within a suitable network architecture in order to guarantee effective and efficient system performance. Essentially, such an architecture should ensure that resources are effectively managed, energy is conserved, and scalability is guaranteed for the participating CR-LPWAN systems. Thus, one possibility that describes such an architecture is illustrated in Fig. 1. The scenario in Fig. 1 depicts a possible set of different IoT-based end nodes, which depend on LPWAN to communicate, which may include energy meters (in smart metering), home appliances (in smart homes), or traffic lights (in smart cities). These end nodes communicate directly to a CR-LPWAN gateway (GW) via the LPWAN network. The coverage area of the CR-LPWAN network may typically reside within the coverage area of a primary user (PU) transceiver as depicted in Fig. 1. Such a PU network may belong either to a TV station or a typical cellular network. The CR-LPWAN GW then operates within the PU's coverage area by determining white spaces and transmitting opportunistically over such white spaces on a non-interference basis. Data arriving from the end nodes via such white spaces are forwarded by the CR-LPWAN GW to a typical IoT network server, which resides within the Internet. A geolocation database as well as other specific application servers can then be accessed by the CR-LPWAN GW via a typical firewall to determine the availability of white spaces as well as to render application-specific commands, respectively.

The network architecture of Fig. 1 is considered to be a general model since it is difficult at the moment to establish a unified network architecture for all LPWAN technologies [3]. Such a unified network architecture remains under consideration within the confines of the different SDOs and SIGs, and they may only begin to suffice within the nearest future. Thus, at the moment, we have considered only a few well-known elements within our network architecture simply to illustrate the possibility for the future deployment of CR-LPWAN systems, as well as to guarantee easier compatibility with existing proprietary LPWAN architectures.

We note that contemporary CR-LPWAN designs often suggest that CR technologies should be deployed at the LPWAN GW instead of at the end nodes [11]. This idea serves to minimize design complexities and to conserve the energy consumption rates of end nodes, which are typically resource constrained. Furthermore, it is often appealing to deploy CR technologies at the GW since most GWs are typically more computationally and memory robust than end nodes, in addition to being often connected to utility power supply. Consequently, our architecture in Fig. 1 considers CR as deployed at the GW, termed the CR-LPWAN GW.

Essentially, when in operation, the CR-LPWAN GW typically consults a geolocation database towards determining the presence of white spaces within its physical location [25]. In addition to the geolocation database, our design further supplements the CR-LPWAN GW with the use of spectrum sensing (SS) technique, which conforms to the requirement posed by the FCC with regards to the deployment of CR systems [26]. In using SS, the CR-LPWAN GW scans its surrounding local electromagnetic environment in order to detect the presence of white spaces for opportunistic use. In this regard, SS can be realized using the popular energy detector (ED) [5]. The ED is considered by many CR designers to be the most viable detector for use since it suffices as the simplest, cheapest, fastest, and least-energy consuming detector among others [5]. Consequently, in our subsequent discussion, we shall focus on the use of the ED as the front-end model in the CR-LPWAN GW.

If a channel is identified as free by the CR-LPWAN GW based on the ED, then such a free channel will typically be communicated to the LPWAN end nodes to be used for onward data transmission. However, it is noted as well that network signalling will typically take place between end-nodes and the GW before convergence may occur on the candidate white space. This is technically referred to as Rendezvous [27]. After channel convergence occurs, the GW then continues to forward any collected data from the end nodes to a defined IoT network server through a firewall to different application servers. The type of application server will often depend on the specific IoT application under consideration. Summarily, the CR-LPWAN network architecture discussed herewith is presented only as an insight to spur further innovative ideas towards the development of effective CR-LPWAN systems. Such ideas, as discussed here may be leveraged for the effective and efficient design of CR-LPWAN systems.

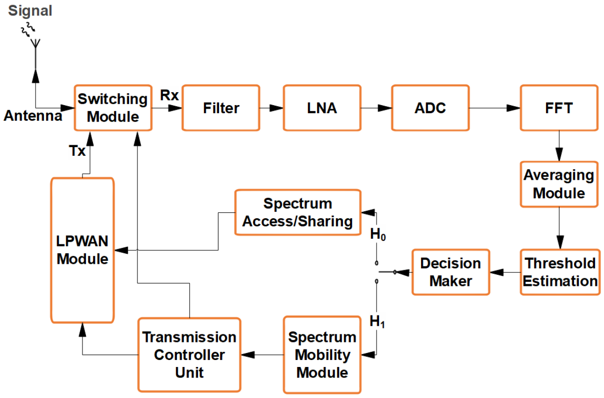

Fig. 2: A generic PHY Layer model of a CR-LPWAN front-end

B. *PHY Layer Sensing Front-end Model*

A general PHY layer front-end model is presented in Fig. 2, which integrates many well-known CR functions along with a LPWAN module to cater for the proprietary functions of different LPWAN developers. This PHY layer front-end model is typically embedded at the CR-LPWAN GW, which decides whether the band is occupied (H_1) by, or free (H_0) from PU signals. Thus, in the case where the model of Fig. 2 determines H_0 to be true, then the CR-LPWAN GW activates the spectrum access/sharing module towards preparing for LPWAN communication via the LPWAN module. However, if the sensing outcome turns out to be H_1, then the CR-LPWAN GW activates the spectrum mobility module towards expediting withdrawal from the band. This command is then fed to the transmission controller towards disengaging any on-going transmission process in the LPWAN module. The CR-LPWAN GW then simultaneously activates the switching module in order to recommence the sensing process (i.e it returns to the receiving mode) instead of the transmit mode. However, if the H_0 case persists, then the LPWAN module remains active to guarantee continuous transmission.

The realization of the key components of this model is briefly discussed as follows:

1) Switching Module: The switching module (SM) will typically be a Duplexer that enables bidirectional transmission over a single path. Its function is to separate the receiving path from the transmitting path while ensuring that a common antenna is usable by the CR-LPWAN GW for both transmission and reception purposes. This design is well elaborated and prototyped in [24], [25]. Nevertheless, a few LPWAN designs still suggest that the half duplex can also be used [3], [34], [35], however, most LoRaWAN technologies popularly opt for the use of the full duplex mode. Most importantly, we presume that the choice of either the half or full duplex mode will typically depend upon the developer's choice of application.

2) Low Noise Amplifier: The LNA amplifies the received RF signal in order to improve the signal-to-noise ratio (SNR) observed at the front-end of the CR-LPWAN system. There are

TABLE II: Comparison of notable state-of-the-art approaches for CR-LPWAN

	CR-LPWAN Approaches						
	SNOW [24]	**OpenChirp Architecture [28]**	**C-LPWAN [29]**	**WALDO [30]**	**FIWEX [31]**	**SenseLess [32]**	**WISER [33]**
PHY Solution	Yes	Yes	No	Yes	Yes	Yes	Yes
MAC Solution	Yes	Yes: Uses LoRaWAN	Yes	No	No	No	No
Session Solution	No	Yes	No	No	No	No	No
Application Solution	No	Yes	Yes	No	No	No	No
Local Sensing	No	No	N/A	Yes	Yes	No	Yes
Consults TV Database	Yes	Yes	N/A	Yes	Yes	Yes	Yes
Location Aware	No	Yes	No	No	No	No	Yes
Has a specific network Architecture	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Coverage Range	8km	≈3km	Depends on LPWAN technology	N/A	Indoor	N/A	Indoor
Topology	Star	Star	Star	Star	Star	Star	Star
Duplex Mode duplex	Single half Full duplex	N/A	N/A	N/A	N/A	N/A	
Battery lifetime	N/A	10 years	N/A	N/A	N/A	N/A	N/A
Operating Band	70 - 6000 MHz	137 - 1020 MHz	Depends on LPWAN technology	VHF-UHF	UHF	VHF-UHF	VHF-UHF
Scalability	Highly Scalable	Limited Scalability	N/A	N/A	N/A	N/A	N/A

several available low cost LNA modules that can be used in typical CR-LPWAN designs towards minimizing energy consumption rates. For example, a duplex current-reused CMOS LNA with complementary derivative superposition technique can be used, such as proposed in [36].

3) Filtering and Down Conversion: It is essential to filter and down-convert the input signal frequencies to their respective intermediate frequencies (IF). This process can be achieved by using a mixer to obtain the in-phase and quadrature components at the IF. Further processing of the signal can be done at both the IF and baseband level towards reducing the design complexities of CR-LPWAN GW.

4) Analogue to Digital Converter: The ADC converts the input signal to its digital form in order to present a fully digitized front end model for CR-LPWAN systems. Typically, a pair of readily available Sigma Delta ADCs can be used to perform data conversion since they possess minimal energy consumption rates. For interested readers, further details in this regard can be gleaned from classic materials such as in [37].

5) Fast Fourier Transformation (FFT) Module: The FFT module computes the energy content of the input signal. This can be readily achieved using commonly available modules such as the FFT LogiCORE IP core module, which implements the Cooley-Tukey FFT algorithm in a particularly efficient manner [38].

6) Threshold Estimator: The threshold estimation module computes a threshold value towards determining the presence/absence of PU signals in the band of interest. This is often a function of the noise floor, which depends further on the gain of the receiver, the matching filter, and the bandwidth. Thus, simple, yet effective approaches, such as the peak and average threshold techniques, can be considered in CR-LPWAN systems towards reducing design complexities. [39].

7) LPWAN Module: The LPWAN module is introduced in Fig. 2 in order to carter for the different, yet specific LPWAN PHY layer technologies of different developers. This module is aimed at handling other PHY layer characteristics such as the modulation type, band of operation, number of channels, link symmetry, adaptive data rates, payload length, and MAC layer operations such as forward error correction, handover, authentication and encryption. In this regard, each LPWAN developer can easily adopt their different proprietary LPWAN PHY layer parameters and easily adapt to the SS front-end system. For example, LoRa technologies typically adopt chirp spread spectrum (CSS) modulation scheme integrated with forward error correction (FEC) [40], which allows for longer transmission range as compared to using the frequency shift keying (FSK) technique adopted by Telensa [3]. These techniques can be easily adapted within the LPWAN module in Fig. 2.

The above details are provided only as an overview of a typical PHY layer front-end model, with the aim of spurring future research efforts in this regard.

VI. CR-LPWAN: STATE-OF-THE-ART APPROACHES

This section discusses notable pioneering efforts with regards to the development of CR-LPWAN systems. These approaches are categorized into dedicated and general approaches. By dedicated approaches, we refer to those specialized and well developed CR-LPWAN systems, which have been substantially tested in the literature for CR-LPWAN purposes. Whereas, general approaches refer to those well-known PHY layer CR techniques that are not necessarily designed for LPWAN purposes, nevertheless considered to be potentially useful for future LPWAN systems. A comparative summary of these approaches is provided in Table II. Each category and their complying approaches are further discussed as follows:

A. Dedicated Approaches

1) SNOW: Sensor Network over White Spaces: Saifullah *et al.,* in [24] provided a pioneering effort concerning the concept of sensor network over white spaces (SNOW). In particular, they extended SNOW to LPWAN over white spaces in [25] towards guaranteeing several advantages for LPWAN, such as concurrent data transmission, per-transmission acknowledgements, and mitigation of hidden terminal effects. These advantages were achieved following an innovative PHY layer design based on distributed orthogonal frequency-division multiplexing (D-OFDM). In particular, D-OFDM enables SNOW to address the problem of scalability even in dense network deployment scenarios. SNOW guarantees asynchronous, bidirectional and massively concurrent communication between end-nodes and the GW. SNOW adopts a star topology network architecture having a single half duplex transceiver at the end-nodes with narrowband radios. However, at the moment, SNOW supports only the use of geolocation database technology for its TVWS discovery, thus, future research works may leverage our generic PHY layer to include the use of spectrum sensing techniques. It is worth mentioning that SNOW has also been greatly improved towards enhancing its practicality and usage [41].

Advantages: 1. Increased Scalability. 2. SNOW enables asynchronous, directional and massively concurrent communication. 3. It mitigates hidden terminal effects. 4. SNOW has a lightweight MAC. 5. It enables transmission acknowledgement

Disadvantages: 1. SNOW does not support spectrum sensing at the moment. 2. It does not support localization

2) OpenChirp Architecture: Dongare *et al.,* in [28] proposed a LPWAN architecture termed OpenChirp for use in different IoT-based applications. OpenChirp is based on LoRaWAN (long range wide area network), with services made available at higher layers. OpenChirp provides a gateway that is designed with software defined radio (SDR) capabilities for the future exploration of white spaces. It provides a software architecture that allows users to register their devices, describe their transducer properties, and to transfer data and retrieve historical values. At the session layer, OpenChirp provides basic encoding and syntax to raw data streams. It also introduces an open source LoRaBug hardware platform at the PHY layer, which enables customized transducers to interact with Bluetooth low-energy (BLE) devices. The current LoRaBug solution based on OpenChirp can communicate using frequencies between 137 - 1020 MHz, which covers a large portion of the TVWS [28]. Based on the above mentioned characteristics of OpenChirp, we envisage that OpenChirp may become potentially useful for future CR-LPWAN systems.

Advantages: 1. OpenChirp allows users to customize its transducer properties, which makes it flexible for use. 2. It enables the transfer of data and the retrieval of historical values towards improving network management. 3. It encodes and provides syntax to raw data streams. 4. It provides an open source LoRaBug hardware that enables easy interaction with BLE devices.

Disadvantages: 1. It has limited scalability. 2. Its spectrum efficiency capability can be improved upon. 3. Security is still an open challenge in the OpenChirp design.

3) C-LPWAN: Cognitive-LPWAN: Chen *et al.,* in [29] proposed cognitive-LPWAN (C-LPWAN) based on an artificial intelligence (AI)-enabled cognitive engine. C-LPWAN suffices as both a MAC and an Application layer solution for LPWAN. Here, authors presented a robust C-LPWAN architecture that performs better than some known LPWAN technologies such as LoRa, NB-IoT, and LTE-M, particularly in terms of its reduced delay and minimal energy consumption rates.

Essentially, the C-LPWAN architecture integrates different LPWAN technologies in order to use the best option per time and per application. While serving as a higher layer solution, C-LPWAN adopts other existing LPWAN technologies such as LoRa, NB-IoT, and LTE-M to provide connectivity at the PHY layer. Primarily, the cognitive engine in the C-LPWAN architecture uses high precision calculations, in-depth data analysis, and distributed cloud support to select the best LPWAN technology to be used per time.

Advantages: 1. Has very high throughput rates, 2. Its able to select the best LPWAN technology per time, 3. Achieves lower latency compared to some well-known LPWAN technologies

Disadvantages: 1. It can be prone to security breaches 2. It suffers from increased complexity, particularly for real-time operation, 3. It may be more expensive to deploy and develop than existing approaches.

B. General Approaches

1) WALDO: White Space Adaptive Local DetectOr: WALDO was proposed in [30] as a general approach that can be used by low-cost devices to exploit white spaces. It consists of a BS and end nodes. End nodes typically conduct local spectrum sensing and the results obtained are forwarded to the BS, which employs fusion techniques to determine white spaces. WALDO uses local sensing at end nodes, which may not be beneficial for resource-constrained LPWAN end nodes. However, its fusion techniques can be adopted in future CR-LPWAN BS.

2) FIWEX: Cost-eFficient Indoor White space EXploration: FIWEX is an indoor solution for determining the presence of white spaces [31]. It measures the UHF TV channels and exploits the location and channel dependence of TV spectrum in indoor environments. FIWEX is a general approach that can be used by any application intending to use white spaces. It may be more beneficial for short range IoT applications. Nevertheless, its spatial and spectral feature based methods can be employed by CR-LPWAN BSs to improve white space detection.

3) SenseLess: SenseLess is an infrastructure based approach that employs a newly proposed SenseLess service to determine white spaces [32]. It boasts of a database in which information is stored pertaining to the location, channel, height, and transmit power of local TV stations, microphones and end nodes. It combines these information with terrain elevation data to determine white spaces. This approach can be greatly beneficial to future CR-LPWAN systems deployed at the BS for accurate detection of white spaces.

4) WISER: White Space Indoor Spectrum EnhanceR: WISER is an indoor approach that uses a realtime sensing module, database, and indoor positioning module to exploit whitespaces [33]. It uses sensing methods to report on the availability of white spaces to a database. It uses indoor positioning methods to determine its location towards consulting a database for a map of potential white spaces. This approach enhances the detection accuracy of white spaces, which can be greatly beneficial for the future design of CR-LPWAN BSs.

5) Dynamic Spectrum Access for CR-LPWAN: Moon in [42] proposed dynamic spectrum access (DSA) strategy for CR-LPWAN to maximize spectrum capacity. Moon showed via numerical analytics that CR-LPWAN achieves good blocking probability.

In summary, the above approaches reviewed in this section are mentioned to inspire future research efforts pertaining to the development of CR-LPWAN systems for IIoT and other general IoT-based applications.

VII. CR-LPWAN: BENEFITS FOR IOT APPLICATIONS

We discuss some benefits of CR-LPWAN systems pertaining to different IoT applications as follows:

1) Smart Industries and Factories: Smart industries and factories, envisaged under the Industry 4.0 concept, consist of machines that are augmented with wireless connectivity and sensors. They consist of distributed sensors, which are connected over wide coverage areas to a central system where visualization and decision is made towards improving network performance. These networks are often delay sensitive and require larger bandwidths. In this regard, existing networks will benefit from CR-LPWAN systems, which will provide opportunistic communication services to improve spectrum utilization for smart factory applications. The use of CR-LPWAN systems will enable these industrial networks to use white spaces that guarantee longer transmission distances, less interference, and improved duty cycle constraints.

2) Smart Agriculture: In recent agricultural practices, foraging animals are often tagged with sensors in order to monitor and keep track of their movement and health conditions. These land and marine animals often transverse long distances, requiring the need to conserve transmission power towards prolonging the battery lifetime of sensor nodes. CR-LPWAN systems can be beneficial in this regard, by exploiting white space transmission to achieve longer range transmission at low power rates and wider bandwidths. They will guarantee less interference, which will improve communication and better tracking of nomadic land and marine animals.

3) Smart Utility Applications: Smart utility applications may include the effective and efficient management of electricity, crude oil, natural gas, water and sewage. In these applications, sensors are planted along pipes for monitoring purposes. Energy meters are deployed in networks, which communicate over long distances to utility companies for better effective management practices. These applications will directly benefit from CR-LPWAN systems, since longer range transmission will be guaranteed at less interference. Most importantly, these applications can be easily deployed without incurring license fees, thus reducing investment costs by utility companies.

4) Smart City Applications: Smart city applications may include intelligent traffic control, city security services and emergency reporting services. For traffic control and management services, infrastructures can be deployed to use SDRs in CR-LPWAN systems, thus reducing their development and validation cost [43]. The ability to switch easily between different bands and change radio operating parameters seamlessly with minimal hardware involvement may repress the cost of developing and deploying smart city services.

Other general benefits that may apply across the above, and many other applications are summarized as follows:

5) Low Network Deployment Cost: The use of CR-LPWAN may ensure that licensed bands are used without interference to PUs and at no cost to the LPWAN operators. Essentially, this will enable more bandwidth to be used at little or no cost, further expediting the deployment rate of IoT networks.

6) Increased Scalability: The ability to seamlessly switch bands will enable more end nodes to exist and transmit in IIoT-based LPWAN. In fact, Sigfox networks are known to service up to 1 million end nodes per gateway [44] because they use CR in their LPWAN technologies. This scalability can be achieved by other developers by adopting CR-LPWAN technologies.

7) Better Reliability: With less hardware involvement and more SDR usage for CR purposes, CR-LPWAN technologies will provide better reliable network operation. Channel conditions will be better with more free bands to use and less interference than in ISM bands.

VIII. CR-LPWAN: CHALLENGES FOR FUTURE RESEARCH WORKS

This section discusses some CR-based problems, which may typically limit the early deployment of effective CR-LPWAN systems. These are mentioned as follows:

1) Rendezvous: CR-LPWAN systems will be confronted with the rendezvous problem, which relates to the realization of a common control channel (CCC) for control messaging between network elements. In practice, it will remain a challenge for CR-LPWAN BS and end nodes to simultaneously agree on a free CCC for coordinating network communication. Existing rendezvous algorithms in this regard are also quite complex, and simpler ones will be required for fast, simple and energy efficient CR-LPWAN systems.

2) Long range Interference: Since CR-LPWAN systems will be used for long range transmission, there will be a greater potential to interfere with faraway located PU transceivers [19]. It may not be straightforward to limit the transmit power of CR-LPWAN systems since this will invariably degrade their communication performance. Consequently, new adaptive-based ideas will be required to create a fair balance between transmit power and range, while avoiding interference.

3) Spectrum Sensing: Existing spectrum sensing (SS) approaches are either prone to errors (e.g the ED), complex or slow (such as cyclostationary detectors). Since CR-LPWAN systems are often lightweight devices, they will require fast, simple and effective SS methods, with low computational cost and minimal processing requirements. If the ED is used, simple effective and efficient threshold estimation techniques will also be required [45]. These are typical CR-based problems that require further research efforts towards developing effective CR-LPWAN systems.

4) Security: Every wireless network will be typically prone to security challenges, and CR-LPWANs are not exempted. In particular, signals are propagated to far areas, where they become prone to malicious attackers. Heavy encryption techniques may incur increased power consumption rates, increase cost and design complexities. Consequently, new research ideas are required in CR-LPWAN systems to guarantee improved security protocols with reduced complexities.

5) Energy Consumption: Recent CR-LPWAN designs are often prototyped using universal software radio peripheral (USRP) devices, which typically suffer from large form factors. They also adopt OFDM designs, such as in [24], which leads to high peak-to-average-power (PAPR) values. Such SDR hardware platforms will incur high energy consumption rates for CR-LPWAN systems. Consequently, improved designs and hardware platforms will be required for practical CR-LPWAN deployment purposes. Such designs are already under consideration, such as in [41].

6) Spectrum Mobility: Spectrum mobility refers to the ability to migrate seamlessly from an occupied channel to a free band with minimal communication loss. A major challenge pertains to the minimization of communication breaks during such handover processes. In CR-LPWAN networks, this challenge may be severe since GWs may be responsible for white space detection. Consequently, this may cause long network downtime during the detection/spectrum handover period. Thus, future research works are required in this regard towards ensuring seamless spectrum migration.

7) Channel State Information (CSI): CSI estimation is an important function in long range transmission such as in CR-LPWAN systems. Without CSI estimation, the overall reliability and communication can be undermined. However, because CR-LPWAN systems may need to transmit over asymmetric bandwidth requirements over different white spaces, there may be need for compliant CSI techniques towards guaranteeing effective communication.

8) Carrier Frequency Offset (CFO): CFO is a major problem with some low-cost devices, which leads to severe inter-carrier interference (ICI). ICI may decrease the overall bit rate of CR-LPWAN systems. Further research may be required in this regard.

These challenges require future research efforts towards the effective development and deployment of CR-LPWAN based networks.

IX. CONCLUSION

In this paper, we have briefly summarized present state-of-the-art approaches, along with a network architecture and PHY layer model suitable for the integration of CR in LPWAN (termed CR-LPWAN). To begin, we established how the present paper differs from other existing survey papers. An overview of LPWAN and CR was then presented as a background towards the integration of CR in LPWAN. Essentially, our discussion posits that several advantages may spin off from using CR-LPWAN systems such as improved spectra utilization, reduced transmit power constraints, longer transmission ranges, low device development and network deployment cost. However, a few limitations are existent, which are mainly CR-based problems, concisely related to CR-LPWAN systems under areas such as rendezvous in Ad hoc CR-LPWAN systems, spectrum sensing, spectrum mobility, adaptive CR technologies, interoperability and security issues. With some major developers, such as Sigfox being fully involved in the use of CR-LPWAN systems, and with great benefits to show, it is believed that the nearest future will experience greater investments in CR-LPWAN systems. Thus, this paper serves as an early lead in this regard by providing a summary of a number of research efforts geared towards the realization of effective CR-LPWAN systems. It is believed that such a summary will benefit the budding researcher who may be interested in the development of improved CR-LPWAN systems for IoT and IIoT-based applications.

REFERENCES

[1] D. Ismail, M. Rahman, and A. Saifullah, “Low-Power Wide-Area Networks : Opportunities , Challenges , and Directions,” *International Conference on Distributed Computing and Networking*, 2018.

[2] F. Adelantado, X. Vilajosana, P. Tuset-Peiro, B. Martinez, J. Melia-Segui, and T. Watteyne, “Understanding the Limits of LoRaWAN,” *IEEE Communications Magazine*, vol. 55, no. 9, pp. 34–40, 2017.

[3] U. Raza, P. Kulkarni, and M. Sooriyabandara, “Low Power Wide Area Networks: An Overview,” *IEEE Communications Surveys and Tutorials*, vol. 19, no. 2, pp. 855–873, 2017. [Online]. Available: http://ieeexplore.ieee.org/document/7815384/

[4] B. I. Insider, Business, “Ericsson just took a significant step toward delivering cellular-based IoT.” [Online]. Available: http://uk.businessinsider.com/ericsson-just-took-a-significant-step-toward-delivering-cellular-based-iot-2016-11

[5] T. Yucek and H. Arslan, “A survey of spectrum sensing algorithms for cognitive radio applications,” *IEEE communications surveys & tutorials*, vol. 11, no. 1, pp. 116–130, 2009.

[6] M. Sherman, A. N. Mody, R. Martinez, C. Rodriguez, and R. Reddy, “Ieee standards supporting cognitive radio and networks, dynamic spectrum access, and coexistence,” *IEEE Communications Magazine*, vol. 46, no. 7, pp. 72–79, 2008.

[7] G. A. Shah, V. C. Gungor, and O. B. Akan, “A cross-layer qos-aware communication framework in cognitive radio sensor networks for smart grid applications,” *IEEE Transactions on Industrial Informatics*, vol. 9, no. 3, pp. 1477–1485, 2013.

[8] A. A. Khan, M. H. Rehmani, and M. Reisslein, “Cognitive radio for smart grids: Survey of architectures, spectrum sensing mechanisms, and networking protocols,” *IEEE Communications Surveys & Tutorials*, vol. 18, no. 1, pp. 860–898, 2016.

[9] P. K. Sahoo, S. Mohapatra, and J.-P. Sheu, “Dynamic spectrum allocation algorithms for industrial cognitive radio networks,” *IEEE Transactions on Industrial Informatics*, vol. 14, no. 7, pp. 3031–3043, 2018.

[10] F. Tang, C. Tang, Y. Yang, L. T. Yang, T. Zhou, J. Li, and M. Guo, “Delay-minimized routing in mobile cognitive networks for time-critical applications,” *IEEE Transactions on Industrial Informatics*, vol. 13, no. 3, pp. 1398–1409, 2017.

[11] K. Mekki, E. Bajic, F. Chaxel, and F. Meyer, “A comparative study of LPWAN technologies for large-scale IoT deployment,” *ICT Express*, 2018. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S2405959517302953

[12] A. J. Onumanyi, A. M. Abu-Mahfouz, and G. P. Hancke, “Towards cognitive radio in low power wide area network for industrial IoT applications,” in *proceedings of the IEEE International Conference on Industrial Informatics (INDIN)*, Helsinki-Espoo, Finland, Jul. 2019.

[13] H. Wang and A. O. Fapojuwo, “A Survey of Enabling Technologies of Low Power and Long Range Machine-to-Machine Communications,” *IEEE Communications Surveys and Tutorials*, vol. 19, no. 4, pp. 2621–2639, 2017.

[14] R. S. Sinha, Y. Wei, and S. H. Hwang, “A survey on LPWA technology: LoRa and NB-IoT,” *ICT Express*, vol. 3, no. 1, pp. 14–21, 2017. [Online]. Available: http://dx.doi.org/10.1016/j.icte.2017.03.004

[15] A. Lavric and V. Popa, “Internet of Things and LoRa$^{\text{TM}}$ Low-Power Wide-Area Networks: A survey,” *ISSCS 2017 - International Symposium on Signals, Circuits and Systems*, 2017.

[16] D. Bankov, E. Khorov, and A. Lyakhov, “On the limits of LoRaWAN channel access,” *Proceedings - 2016 International Conference on Engineering and Telecommunication, EnT 2016*, pp. 10–14, 2017.

[17] S. Alam, M. F. Sohail, S. A. Ghauri, I. M. Qureshi, and N. Aqdas, “Cognitive radio based Smart Grid Communication Network,” *Renewable and Sustainable Energy Reviews*, vol. 72, no. December 2016, pp. 535–548, 2017. [Online]. Available: http://dx.doi.org/10.1016/j.rser.2017.01.086

[18] A. A. Khan, M. H. Rehmani, and A. Rachedi, “Cognitive-Radio-Based Internet of Things: Applications, Architectures, Spectrum Related Functionalities, and Future Research Directions,” *IEEE Wireless Communications*, vol. 24, no. 3, pp. 17–25, 2017.

[19] M. Rahman and A. Saifullah, “A comprehensive survey on networking over tv white spaces,” *arXiv preprint arXiv:1810.07120*, 2018.

[20] P. Rawat, K. D. Singh, and J. M. Bonnin, “Cognitive radio for M2M and Internet of Things: A survey,” *Computer Communications*, vol. 94, pp. 1–29, 2016. [Online]. Available: http://dx.doi.org/10.1016/j.comcom.2016.07.012

[21] U. Noreen, A. Bounceur, and L. Clavier, “A study of LoRa low power and wide area network technology,” *2017 International Conference on Advanced Technologies for Signal and Image Processing (ATSIP)*, pp. 1–6, 2017. [Online]. Available: http://ieeexplore.ieee.org/document/8075570/

[22] P. Thubert, A. Pelov, and S. Krishnan, “Low-Power Wide-Area Networks at the IETF,” *IEEE Communications Standards Magazine*, vol. 1, no. 1, pp. 76–79, 2017. [Online]. Available: http://ieeexplore.ieee.org/document/7885244/

[23] I. F. Akyildiz, W. Y. Lee, M. C. Vuran, and S. Mohanty, “NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey,” *Computer Networks*, vol. 50, pp. 2127–2159, 2006.

[24] A. Saifullah, M. Rahman, D. Ismail, C. Lu, R. Chandra, and J. Liu, “Snow: Sensor network over white spaces,” in *Proceedings of the 14th ACM Conference on Embedded Network Sensor Systems CD-ROM*. ACM, 2016, pp. 272–285.

[25] A. Saifullah, M. Rahman, D. Ismail, C. Lu, J. Liu, and R. Chandra, “Low-power wide-area network over white spaces,” *IEEE/ACM Transactions on Networking*, vol. 26, no. 4, pp. 1893–1906, 2018.

[26] IEEE802.22, “Enabling broadband wireless access using cognitive radio technology and spectrum sharing in white spaces,” *IEEE 802.22 Working Group on Wireless Regional Area Networks*, 2011.

[27] H. Ohize and M. Dlodlo, “A Channel Hopping Algorithm for Guaranteed Rendezvous in Cognitive Radio Ad Hoc Networks Using Swarm Intelligence,” *Wireless Personal Communications*, vol. 96, no. 1, pp. 879–893, 2017.

[28] A. Dongare and A. Rowe, “OpenChirp : A Low-Power Wide-Area Networking Architecture,” in *In 2017 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops),*, 2017, pp. 569 – 574.

[29] M. Chen, Y. Miao, X. Jian, X. Wang, and I. Humar, “Cognitive-LPWAN: Towards intelligent wireless services in hybrid low power wide area networks,” *IEEE Transactions on Green Communications and Networking*, 2018.

[30] A. Saeed, K. A. Harras, E. Zegura, and M. Ammar, “Local and low-cost white space detection,” in *2017 IEEE 37th International Conference on Distributed Computing Systems (ICDCS)*. IEEE, 2017, pp. 503–516.

[31] F. Wu, D. Liu, Z. Wu, Y. Zhang, and G. Chen, “Cost-efficient indoor white space exploration through compressive sensing,” *IEEE/ACM Transactions on Networking (TON)*, vol. 25, no. 3, pp. 1686–1702, 2017.

[32] R. Murty, R. Chandra, T. Moscibroda, and P. Bahl, “Senseless: A database-driven white spaces network,” *IEEE Transactions on Mobile Computing*, vol. 11, no. 2, pp. 189–203, 2011.

[33] X. Ying, J. Zhang, L. Yan, Y. Chen, G. Zhang, M. Chen, and R. Chandra, “Exploring indoor white spaces in metropolises,” *ACM Transactions on Intelligent Systems and Technology (TIST)*, vol. 9, no. 1, p. 9, 2017.

[34] N. Accettura, S. Medjiah, B. Prabhu, and T. Monteil, “Low power radiolocation through long range wide area networks: A performance study,” in *2017 IEEE 13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, oct 2017, pp. 1–8.

[35] T. Thomas, “LoRa, LoRaWAN, and the challenges of long-range networking in shared spectrum,” *Cognitive Radio Platform NL*, no. december, pp. 1–10, 2015. [Online]. Available: https://www.kivi.nl/uploads/media/584e9180f3822/cr-platform-lora-workshop-shared.pdf

[36] R. Dai, Y. Zheng, J. He, W. Kong, and S. Zou, “A duplex current-reused cmos lna with complementary derivative superposition technique,” *International Journal of Circuit Theory and Applications*, vol. 45, no. 1, pp. 110–119, 2017.

[37] R. H. Walden, “Analog-to-digital converter survey and analysis,” *IEEE Journal on selected areas in communications*, vol. 17, no. 4, pp. 539–550, 1999.

[38] D. S. Vivado, “Logicore ip fast fourier transform v9. 0,” *LogiCORE IP Product Guide, Xilinx*, pp. 1 – 99, Oct. 2017.

[39] Semtech, *LoRa: SX1276/77/78/79- 137 MHz to 1020 MHz Low Power Long Range Transceiver*, Semtech, Wireless, Sensing,&Timing, Aug. 2016.

[40] S. M. Jacob and S. Nandan, “Performance analysis of different spectrum sensing techniques in cognitive radio under different fading channels,” *International Journal of Advanced Research in Computer and Communication Engineering*, vol. 4, no. 6, 2015.

[41] M. Rahman, D. Ismail, V. P. Modekurthy, and A. Saifullah, “Implementation of LPWAN over white spaces for practical deployment.” 2019, pp. 178 – 189.

[42] B. Moon, “Dynamic Spectrum Access for Internet of Things Service in Cognitive Radio-Enabled LPWANs,” *Sensors*, vol. 17, no. 12, p. 2818, 2017. [Online]. Available: http://www.mdpi.com/1424-8220/17/12/2818

[43] W. H. Tuttlebee, “Software-defined radio: facets of a developing technology,” *IEEE Personal Communications*, vol. 6, no. 2, pp. 38–44, 1999.

[44] B. Manz, “Standardizing IoT Connectivity by the Kilometer: SIGFOX, LoRa®, or LTE?” [Online]. Available: https://eu.mouser.com/applications/sigfox-lora-lte/

[45] A. J. Onumanyi, A. M. Abu-Mahfouz, and G. P. Hancke, “A comparative analysis of local and global adaptive threshold estimation techniques for energy detection in cognitive radio,” *Physical Communication*, vol. 29, no. C, pp. 1–11, Apr. 2018.