IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received July 6, 2019, accepted July 15, 2019, date of publication July 19, 2019, date of current version August 6, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2929915

Technical Issues on Cognitive Radio-Based Internet of Things Systems: A Survey

FAROQ A. AWIN[1,2], (Member, IEEE), YASSER M. ALGINAHI[1], (Senior Member, IEEE), ESAM ABDEL-RAHEEM[1], (Senior Member, IEEE), AND KEMAL TEPE[1]

[1]Department of Electrical and Computer Engineering, University of Windsor, Windsor, ON N9B3P4, Canada
[2]Department of Electrical and Electronic Engineering, University of Tripoli, Tripoli 13555, Libya

Corresponding author: Faroq A. Awin (awin@ uwindsor.ca)

This work was supported by the Natural Science and Engineering Research Council of Canada (NSERC).

ABSTRACT Cognitive radio (CR)-based Internet of Things (IoT) system is an effective step toward a world of smart technology. Many frameworks have been proposed to build CR-based IoT systems. The CR-based IoT frameworks are the key points on which this survey focuses. Efficient spectrum sensing and sharing are the main functional components of the CR-based IoT. Reviews of recent SS and sharing approaches are presented in this survey. This survey classifies the SS and sharing approaches and discusses the merits and limitations of those approaches. Moreover, this survey discusses the design factors of the CR-based IoT and the criteria by which the proper SS and access approaches are selected. Furthermore, the survey explores the integration of newly emerging technologies with the CR-based IoT systems. Finally, the survey highlights some emerging challenges and concludes with suggesting future research directions and open issues.

INDEX TERMS Cognitive radio, spectrum sensing, IoT, MAC, spectrum accessing, spectrum sharing, spectrum management, security, data privacy, blockchain, machine learning.

I. INTRODUCTION

The advancement in technology has caused an explosion in the number of devices connected to the Internet. Intel is projecting that the number of connected devices would reach 200 billion by 2020 from the 2 billion devices in 2006 [1]. Also, according to Business Insiders, it is predicted that by 2020, 75% of vehicles will come with built-in Internet of Things (IoT) connectivity [2]. Therefore, with the unprecedented growth in the number of devices connected to the Internet, i.e., IoT, more and more challenges are emerging everyday. Nowadays, IoT applications are seen everywhere. In the last few years, many new terms associated with IoT has popped up, such as, but not limited to, smart health, smart cities, smart homes, smart transportation, smart agriculture and smart industry. Hence, the deployment of IoT systems will provide significant savings and revenues in many areas, in particular in providing monitoring and maintenance solutions. Therefore, this growth has forced businesses to adopt different strategies to cope with this exponential growth and the challenges associated with them, such as allocating sufficient spectrum bands in IoT applications. That includes transmission performance degeneration, spectrum scarcity, spectrum sharing, interference among devices, etc. Recently, the adaptation of Cognitive Radio Networks (CRNs) in IoT has shown equivalent or better performance than currently used networks such as Wi-Fi, WiMAX, Bluetooth, etc. Hence, opportunistic approaches for Radio Frequency (RF) spectrum control and management to optimize the scare spectrum resources is emerging as one of the main challenges.

With the recent unprecedented increase of wireless communication systems, applications and their users limits spectrum resources and make connectivity between their interconnected objects a crucial task. Therefore, the demands for smart devices that can manage and configure its transmission parameters based on the spectrum availability in spatio-temporal dimensions are remarkably increased. Cognitive Radio (CR) is the best candidate technology; it is defined as an adaptive, intelligent radio and network technology that automatically detects available channels in a wireless spectrum and changes transmission parameters enabling more communications to run concurrently and also improves radio operating behavior [3]. The benefits of CR systems would be to [4]:

- relieve spectrum scarcity by broadcasting on unused spectrum and avoiding interference with primary licensee,

The associate editor coordinating the review of this manuscript and approving it for publication was Hayder Al-Hraishawi.

- avoid radio jamming and interference based on the selected Spectrum Sensing (SS) approach,
- support switch to power saving protocol,
- improve communication quality by using higher bandwidth services, and
- improve Quality of Service (QoS), since the availability, suitability and reliability will be enhanced.

New spectrum resources can be gained by allowing non-licensee users, i. e., Secondary Users (SUs), to share a licensee users, i.e., Primary User (PU), bands such that PUs should be always protected from SUs interference. Therefore, CR users must consider protecting the PUs over any other interest. There are three CR paradigms (i.e., schemes) by which a SU can share a PU's spectrum band, these are: overlay, underlay and interweave. For overlay and underlay schemes, a SU can coexist with the PU without interference or with a minimum interference, since in underlay scheme transmission power of the SU should never exceed some limit, while in overlay scheme there is no such constraint; however, the SU should have a full knowledge about the PU's signal, so that the SU can generate an orthogonal signal to the PU's signal to eliminate interference. In the interweave scheme, a SU is allowed to transmit if and only if a PU is not utilizing its spectrum band; nevertheless, if the PU resumes its activity, the SU should leave the spectrum band by either switching to another band or by ceasing its activity if no vacancy exists.

The CR works through a cognition cycle with four functional phases which are sensing, decision, sharing, and mobility. The cognition cycle begins with SS phase through which the available spectrum resources are detected over the selected spectrum band using different SS approaches. Based on the detection results, the decision is made to concurrently share the band, or to cease transmission in that band. Once a CR decides to exploit the band, a proper Medium Access Control (MAC) protocol is employed and power allocation should be considered to satisfy the PU protection. Finally, switching from band to another is performed through the mobility phase. This work initially discusses the main design factors of CR-based IoT systems. Moreover, the work reviews the most recent research works related to SS and spectrum sharing approaches, classifies the approaches, discusses their IoT applications, and introduces the criteria of selecting the most appropriate SS approach and MAC protocol for the CR-based IoT system. Furthermore, this work reviews and compares the applicable MAC protocols employed in this area. In addition, this work discusses the integration of emerging technologies with CR-based IoT systems. Finally, this work considers the challenges and possible future research directions and open issues.

The contributions of this survey paper are:

- reviewing the recent existing works on the field of SS and sharing for CR-based IoT,
- discussing the design factors of CR-based IoT system and its main components,
- presenting and categorizing the SS approaches for IoT applications,
- identifying the main requirements for SS phase for IoT CR networks,
- developing the selection criteria of proper SS and sharing approaches for a proper CR-based IoT applications,
- discussing the integration of emerging technologies with CR-based IoT system, and
- providing the future research directions and challenges.

A list of acronyms used throughout this paper is provided in Table 1, while the remaining part of this paper is organized as follows; Section II describes the recent related works, Section III discusses the design factors of CR-based IoT, Section IV presents CR-based IoT design flow, Section V discusses the integration of emerging technologies with CR-based IoT systems, Section VI addresses some future research directions and open issues, and finally, Section VII provides the conclusions.

II. RELATED WORKS

A limited number of papers surveyed CR-based IoT and have discussed this topic from different perspectives. The survey in [5] briefly discusses the principle of IoT technology; moreover, it describes how CR system works, its applications, and challenges of implementing CR system in reality. Despite that the survey mentions the possibility of incorporating CR and IoT for smart applications; it does not describe how to achieve this goal and challenges that might be faced.

The authors in [6] classified IoT technologies based on their orientations. Furthermore, they described the types of enabling technologies for IoT and discuss the IoT applications. Moreover, the authors explained the importance of adding cognitive capabilities to the IoT device for smart purposes. In addition, the authors considered the challenges of adopting CR capabilities in IoT and the SS paradigms for CR-based IoT. The survey did not cover how to incorporate different types of SS approaches and their IoT applications; the benefits of employing CRNs for IoT applications were not discussed either.

The basis of the CR-based IoT is thoroughly explained in [7] where the principles of adopting CR in IoT applications were explained, as well as, possible architectures and frameworks were described. Moreover, the survey classified the frameworks based on features such as context awareness, scalablity, configurability and volume of data. The survey also considered real-world scenarios of CR-based IoT systems and the challenges that might be faced. Finally, the survey summarized the open issues and future research directions for hardware design of CR-based IoT. Despite that the survey focused on the CR module and the possibility of employing it for adding cognitive capability to IoT devices; the survey did not cover how to share vacant spectrum bands and employed MAC protocol, how to select the appropriate SS approach and which class of SS (i.e., narrowband or wideband) fits for a specific IoT application.

TABLE 1. List of the acronyms and their definitions.

Acronym	Definition
3GPP	Third Generation Partnership Project
ADC	Analog to Digital Converter
AF	Amplify and Forward
AI	Artificial Intelligent
AWGN	Additive White Gaussian Noise
BPF	Band Pass Filter
BW	Bandwidth
CCC	Common Control Channel
CFD	Cyclostationary Feature Detector
CH	Channel Hopping
CNO	Central Network Operator
CR	Cognitive Radio
CRN	Cognitive Radio Network
CSMA	Carrier Sense Multiple Access
CSS	Cooperative Spectrum Sensing
CTC	Confirm To Cooperate
D2D	Device to Device
DF	Decode and Forward
DRL	Deep Reinforcement Learning
ED	Energy Detector
EMC	Electromagnetic Compliance
EMI	Electromagnetic Interference
ETTR	Expected Time to Rendezvous
FCC	Federal Communications Commission
FD	Full Duplex
FFT	Fast Fourier Transform
GMS	Global Mobile System
HD	Half Duplex
IoT	Internet of Things
ISM	Industrial Scientific Medical
KNN	K-Nearest Neighbor
LPWA	Low Power Wide Area
LR	Logistic Regression
LTE	Long term Evolution
MAC	Medium Access Control
MICS	Medical Implant Common Service
MF	Matched Filter
ML	Machine Learning
MTTR	Maximum Time to Rendezvous
NB	Naive Bayes
NB-IoT	Narrowband-Internet of Thing
NBSS	Narrowband Spectrum Sensing
NFC	Near Field Communication
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PSO	Particle Swarm Optimization
PU	Primary User
QoS	Quality of Service
RAW	Restricted Access Window
RD	Rendezvous Degree
REM	Radio Environmental Map
RF	Radio Frequency
RFID	Radio Frequency Identification
RI	Radar Imaging
RTC	Request TO Cooperate
S^2aaS	Spectrum Sensing as a Service
SDN	Software Defined Network
SNR	Signal to Noise Ratio
SS	Spectrum Sensing
SU	Secondary User
SVM	Support Vector Machine
TVWS	TV White Space
UHF	Ultra High Frequency
UWB	Ultra Wide Band
WBAN	Wireless Body Area Network
WBSS	Wideband Spectrum Sensing
WF	Water Filling
WLAN	Wireless Local Area Network
WMA	Wireless Medical Application
WMTS	Wireless Medical Telemetry Service
WSN	Wireless Sensor Network

On the other hand, the authors in [8] developed a comprehensive survey on the employed frameworks for spectrum sharing in CR-based IoT. The survey also reviewed the existing schemes of SS and spectrum sharing, the challenges and issues that might be encountered in the real world applications. In addition, the authors of the survey presented a general architecture with four layers for spectrum sharing process in CR-based IoT. The four layers are sensing, spectrum allocation, transmission power optimization, and security. However, the authors did not focus on the suitability of each SS approach for IoT applications and the selection of the proper MAC protocol.

Different architectures have been proposed to implement IoT systems. The survey in [9] discussed the structure of IoT element and provided a thorough analysis of the possible architectures of IoT. Moreover, the work in [10] focused on Service-Oriented Architecture (SOA) IoT which is composed of four layers, namely: applications, service, networking and sensing layers.

A recently published survey in [11] discussed SS approaches in CNRs and addresses the recent advances in this technology, its challenges and future research directions. The survey presented SS approaches as two main categories, wideband and narrowband. Moreover, it discussed many of the available techniques of each category providing comparisons in each category as well as applications. The survey was concluded by highlighting the open research challenge of tackling attacks targeting secure SS and sharing.

Nevertheless, all above-mentioned surveys paved the track for motivating more research works to tackle those points which were not covered. Table 2 summarizes the strong points of each survey paper along with some remarks on each.

III. DESIGN FACTORS OF CR-BASED IoT SYSTEMS

The main objective of using IoT systems is to connect numerous heterogeneous devices and systems together to provide some smart services with minimal device resource requirements, i.e., power, hardware complexity and cost, i.e., expenses. To achieve this objective, the connectivity between devices should always be maintained in all circumstances. This motivates us to focus on SS and spectrum sharing processes in CR-based IoT.

The designer should carefully select a proper SS approach for the CR-based IoT device. Moreover, the designer should determine the spectrum band allocation precisely to satisfy the PU protection constraints when exploiting the vacant spectrum band. To achieve those two goals, the following factors have to be considered:

- IoT applications.
- Enabling technology.
- Regulations.

Those design factors are used to determine the main characteristics of the CR-based IoT system, such as transmission range, transmission rate, Bandwidth (BW) occupancy,

TABLE 2. Remarks on the published survey papers on CR-based IoT.

No.	Survey	Positive Points	Remarks
1	**[5]**	• Described the principle of the emerging technologies such as IoT and CR and their applications. • Discussed the importance of adding cognitive capability to IoT devices (i.e., Geo-location database and embedding SS capability to the devices). • Presented challenges that might be faced cognitive radio such as security issues software radio issues, hardware constraints, WideBand Spectrum Sensing (WBSS) and sharing.	The work did not discuss: • how to add the cognitive capabilities to IoT devices. • the requirements, standards, practical issues of CR-based IoT.
2	**[6]**	• Classified IoT based on orientation and whether it is wired or wireless. • Discussed types of enabling technologies for IoT. • Described the spectrum sensing paradigms for CR-based IoT. • Discussed the challenges of adopting CR for IoT. • Classified the existing works up to its date according to their applications for CRN for IoT, features, CR uses and type of employed simulator.	The work did not discuss: • the applicable SS approaches for different IoT applications. • how to incorporate CR and IoT device. • the requirements, standards, practical issues of CR-based IoT.
3	**[7]**	• Introduced the demand of adopting CR for IoT application. • Discussed the standardization efforts in CRN-based IoT. • Thoroughly described architectures and frameworks of CR-based IoT. • Focused on CR modules and discusses their functions. • Discussed types of spectrum related functionalities in CR-based IoT. • Presented issues, challenges and future research directions of hardware design for CR-based IoT, semantic analysis, spectrum related functions, standardization activities, and networking addresses, as well as security and privacy.	The work did not discuss: • the applicable SS approaches for different IoT applications and challenges that might face. • the applicable spectrum sharing approaches for IoT applications and how to improve the spectrum efficiency. • the selection of MAC protocols for CR-based IoT system. Moreover, spectrum allocation and how to improve the energy efficiency of CR-based IoT system were only briefly discussed.
4	**[8]**	• Reviewed the principle of SS and spectrum sharing approaches and configurations. Moreover, discusses the • Focused on the applicable spectrum sharing approaches for CR-based IoT systems. • Developed in details a general four layers architecture for different applicable spectrum sharing approaches employed by CR-based IoT system. • Analyzed security threats and attacks scenarios that might occur during spectrum sharing process and proposes a solution for those attacks.	The work did not discuss: • how to select the proper SS approach for a specific IoT application. • the selection of MAC protocols for CR-based IoT system.

transmitted signal type, i.e., analog or digital, transmission nature, i.e., continuous or intermittent. Based on those characteristics, a designer can select the proper SS approach and MAC protocol as discussed in Section IV. For example, to design CR-based IoT enabling Narrowband-IoT (NB-IoT) technology, a designer should select one of the Narrowband Spectrum Sensing (NBSS) approaches, such as Energy Detector (ED), Cyclostationary Feature Detector (CFD), or Matched Filter (MF). Section IV-A provides more details about selecting the proper SS approach. From MAC protocol perspective, standard random MAC protocols, such as slotted ALOHA and Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA) can be employed in such case [12], [13].

Figure 1 demonstrates the factors to be considered for designing a CR-based IoT system. Moreover, the figure shows the relationship between the design factors.

A. IoT APPLICATIONS

IoT has enormous applications. The applications are selected based on the type of the service to be provided. For instance, if IoT devices are used for medical purposes; the Wireless Medical Applications (WMA) are classified as Medical Implant Communications Services (MICS), Wireless Medical Telemetry Service (WMTS), Wireless Body Area Networks (WBANs), Ultra Wideband (UWB), Radar Imaging (RI), and Telehealth [14]. The type of the application determines the nature of the signal to be transmitted (i.e., analog

TABLE 3. Transmission parameters and applicable SS class for some medical applications.

No.	Application	Transmission Parameters	Category	References
1	MICS	• Frequency Range: 401-406 MHz. • Transmission Type: narrowband transmission (e.g., Frequency Shift Keying (FSK)). • Bandwidth: 3 MHz • Data rate: 16 kbps • Range $\leq$ 10 m.	Narrowband	[15]–[17].
2	WMTS	• Frequency Range: 608-614 MHz, 1395-1400 MHz, 1429-1432 MHz. • Transmission Type: narrowband and spread spectrum (e.g., Frequency Hopping (FH)). • Bandwidth: 6 MHz • Data rate: 76 kbps • Range $\leq$ 100 m.	Narrowband	[16], [18], [19].
3	WBAN-UWB	• Frequency range: 3-10 GHz. • Transmission Type: Code Division Multiple Access (CDMA), MultiBand Orthogonal Frequency-Division Multiplexing (MB-OFDM). • Bandwidth: $\geq$ 500 MHz • Data rate: 850 kbps • Range $\leq$ 2 m.	Wideband	[19]–[21].

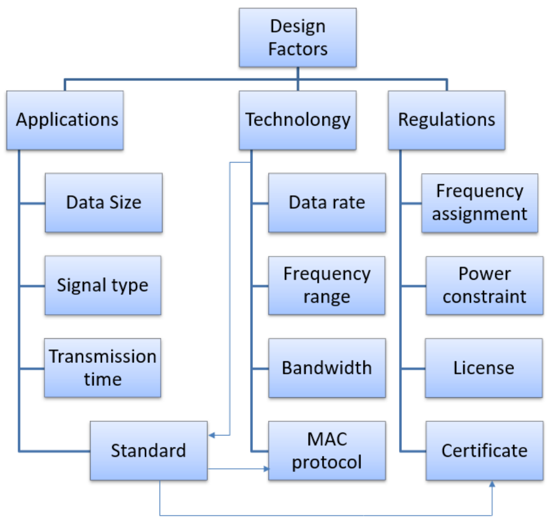


FIGURE 1. Design factors of CR-based IoT system.

or digital), data size, time transmission, type of transmission (i.e., intermittent or continuous), frequency range and the standards to be employed. As an illustrative example, Table 3 displays the transmission requirements of some medical applications.

All above-mentioned medical applications must employ low power device with transmission power constraint of $\leq$ 0.75 mW; so that they do not pose any harm to a human body; moreover, the applications are allowed to use some portions of Industrial Scientific Medical (ISM) bands [14].

B. ENABLING TECHNOLOGY

IoT networks employ many different enabling technologies for establishing the communication between the devices in the network. Radio frequency IDentification (RFID), Wireless Sensor Networks (WSN), Bluetooth, WiFi, and Near Field Communication (NFC) are some of enabling technologies that IoT might use for communication. The enabling technologies can be classified as short range coverage technologies and long range coverage technologies. For instance, Bluetooth, RFID and NFC are classified as short range coverage technologies, while WSN, and Long Term Evolution (LTE) fall in the class of long range coverage technology. Figure 2 shows an illustrative example of IoT network connecting different technologies and standards.

The enabling technology specifically determines the data rate of the shared information, its bandwidth, transmission range, and operating frequency. Moreover, the standard and the MAC protocol must be selected to fit the application and the enabling technology.

C. REGULATIONS

Every country has regulatory bodies and working groups which are responsible for imposing the regulations of frequency usage such as licences, allowable interference, and certificates [22]. Moreover, those bodies and groups determine the frequency assignment for licensed and unlicensed services and users. As an example, a CR system for e-health applications are allowed to operate on either unlicensed or licensed bands. Table 4 provides different regulations and applications for IoT adopting RFID technology in different countries. However, for some countries, it is important to satisfy an ElectroMagnetic Compliance (EMC) requirement. Therefore, certification of adopted wireless IoT device is necessary to meet their emission and susceptibility of ElectroMagnetic Interference (EMI). Moreover, the adopted

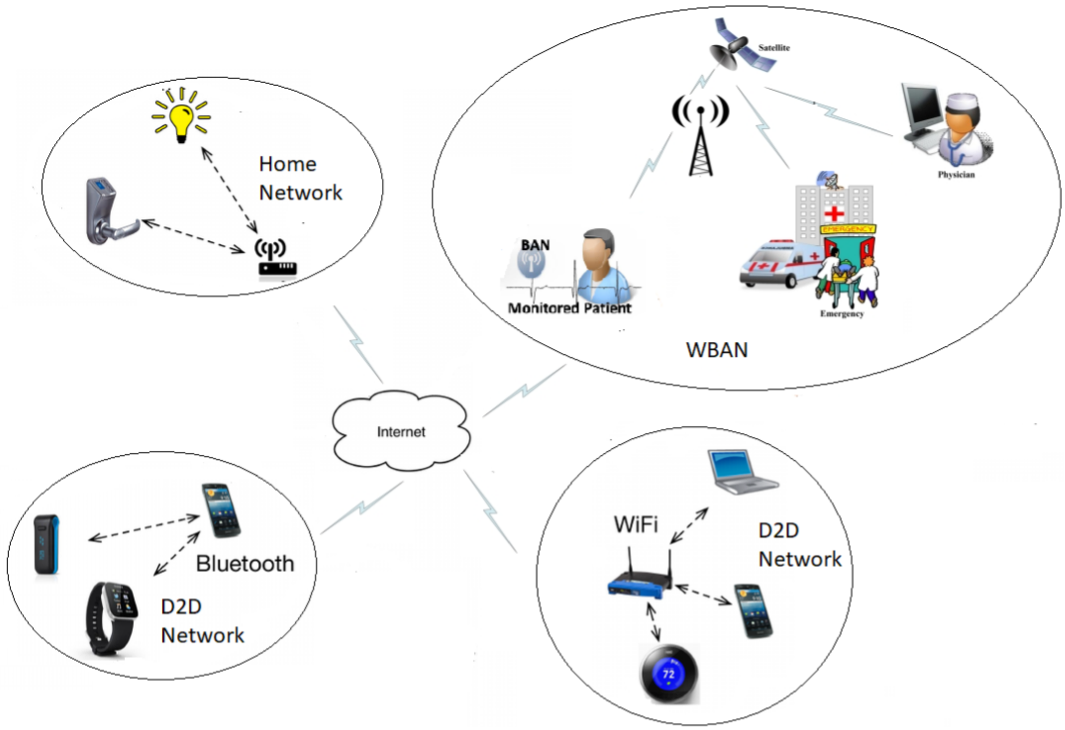


FIGURE 2. IoT Network with different technologies and standards.

standard determines whether the device needs certification or not. For instance, wireless medical device in Canada, under Radio Standard Specifications RSS-243 requires certification, while RSS 310 exempts those devices from certification.

From standard perspective, IoT use different standards such as ZigBee, Bluetooth, Wi-Fi, etc. Each standard is suitable for some applications. The suitability depends on the application's parameters such as data rate, transmission range and whether the transmission is continuous or intermittent. Here are some examples:

- Bluetooth and ZigBee are suitable for low data rate applications that need long battery life and secured networking. More specifically, ZigBee is suited for intermittent transmission with data rate of 250 kbps, and its range reaches 20 m.
- Wi-Fi is suitable for applications with high date rate over Wireless Local Area Network (WLAN) platform, and its range reaches 35 to 40 m for indoor and outdoor, respectively.

Furthermore, it is noticeable nowadays that most of IoT applications uses ISM band at 2.4 GHz, where various standards can be facilitated. However, there are some wireless IoT applications which employ 5 GHz WiFi and high-band cellular, while the low-power-long-range wireless IoT applications can employ TV White Space (TVWS), i.e., IEEE 802.22, in the band of 400 MHz to 700 MHz as in the United States [25].

In addition to the aforementioned factors; physical specifications such as weight, size, and power should also be taken into consideration when designing CR-based IoT devices, since the ultimate goal is to design low power constrained light weight CR-based IoT device with a compact size. Improving the energy efficiency of the devices is a vital research direction in this area, since most of IoT devices are battery power terminal with limited lifetime. Charging or replacing batteries is not a feasible issue, this fact necessitates determining other alternatives to prolong the battery's lifetime. Energy harvesting techniques are among the best alternatives, and many research works have been done in this area [26]–[29].

IV. CR-BASED IOT SYSTEM DESIGN FLOW

Adding cognitive capability to IoT device means incorporating CR technology with IoT device, which can be realized through designing three consecutive functional phases as illustrated in Fig. 3. The functional phases are, namely, SS, spectrum sharing, and spectrum management. Details in each functional phase are provided below.

A. SPECTRUM SENSING PHASE

In SS component, a designer of CR-based IoT system must carefully select the adopted SS approach and the sensing decision making technique. This section highlights the selection criteria of SS approach and decision techniques.

1) SS APPROACH SELECTION

The SS process can be performed either on narrowband or wideband levels. NBSS implies that the BW is lower than the coherence bandwidth. NBSS is performed when

TABLE 4. IoT-RFID parameters for different regulations.

No.	Frequency Range	Data Rate	Transmission Range	Countries	Remarks
1	125-134 kHz, Low Frequency	$\leq$ 1 kbps	0.5 m	USA, Canada, Japan, Europe	• License free [22]. • Applications: object identification such as animals and vehicles [23].
2	13.56 MHz High Frequency	$\approx$ 25 kbps	1.5 m	USA, Canada, Japan, Europe	• License free [22]. • Applications: contact-less payment, electronic ticketing, access control, garment tracking, and other security purposes [24].
3	433-435 MHz and 858-930 MHz Ultra High Frequency (UHF)	100 kbps	100 m	USA, Europe, Japan, South Korea, Australia, and New Zealand.	• Transmission power is constrained in USA, Australia and New Zealand [24]. • Checking the vacancy of the band before accessing it, is required in Europe. • France assigned 858-930 MHz for military uses, therefore, RFID is not allowed to this band [24]. • Applications: asset management, logistics purposes, and tracking purposes [23].
4	2.4-5.9 GHz Microwave range	$\geq$ 250 kbps	100 m	USA, Canada, Europe, and Japan.	• License free [22]. • Most of the IoT applications uses 2.5 GHz is in ISM band and can facilitate various standards such as ZigBee, Bluetooth and others [24]. • Applications: long range tracking, automatic vehicle identification [24].

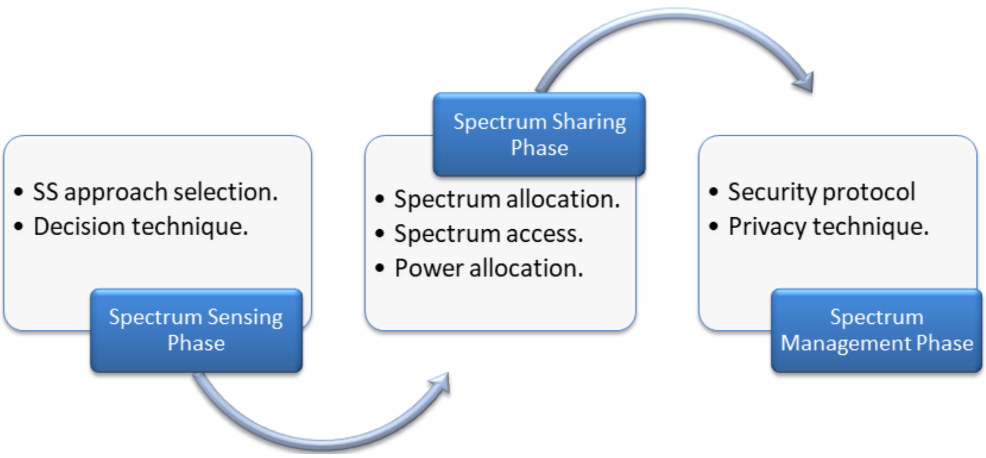


FIGURE 3. CR-based IoT system design flow.

there is enough information about the PUs' signal and BW. Many NBSS approaches have been developed in literature, including ED [30], [32]–[35], MF detection [31], [35]–[38], eigenvalue-based detection [35], [45]–[48], and CFD [35], [39]–[44], etc. Table 5 provides a general comparison between the different NBSS approaches.

In contrast, when the occupancy details of the PUs are unknown to the CR, WBSS provides better utilization of the frequency spectrum. However, the design and implementation of WBSS approaches are usually complex and consume more energy from high-rate Analog to Digital Converters (ADCs). Many WBSS approaches have been developed in literature, including Fast Fourier Transform (FFT)-based detectors [49]–[51], filter-based detectors [52]–[54], wavelet detection [55], sequential scanning [56], compressive sensing [57]–[63] and multi-coset sensing [64]–[67]. Table 6 provides a comparison between the different WBSS approaches.

TABLE 5. General remarks on NBSS approaches.

No.	Technique	Advantages	Remarks	Relevant References
1	**Energy detector (ED)**	• No prior knowledge required on received signal. • Low complexity. • Low operating cost. • Easy to implement.	• It can not differentiate between interference from SUs and PUs. • Its performance significantly degrades with noise uncertainty and under low Signal to Noise Ratio (SNR) scenarios. • Not suitable for spread spectrum techniques such as frequency hopping and direct sequencing.	[30]–[35].
2	**Matched filter detection (MF)**	• Shorter sensing time. • Performs well in stationary Gaussian noise. • Robust against interference.	• Requires exact synchronization and full prior knowledge of PU signal. • High complexity. • High power consumption.	[31], [35]–[38].
3	**Cyclostationary feature detection (CFD)**	• Detects low SNR signals. • Distinguishes between noise energy from received signal energy. • Can be used as automatic modulation control to determine the modulation scheme of the PU signal.	• Requires high cost and complexity. • Requires more signal detection time. • The detection performance degrades due to the poor estimate of cyclic spectral density.	[35], [39]–[44].
4	**eigenvalue-based detection**	• Detects low SNR signals. • Robust against noise uncertainty.	• High computational complexity. • Requires long sensing time.	[35], [45]–[48].

NBSS approaches concentrate on exploiting the spectral opportunities over narrow frequency range; however, due to the large number of IoT devices connected to the Internet, CR in IoT will involve the exploitation of spectrum opportunities over a wide frequency range in order to achieve higher opportunistic throughput [50]. For example, to exploit spectrum opportunities in TV bands, WBSS approaches should be implemented. These intend to sense frequency bandwidth with higher coherence since NBSS approaches cannot be utilized for WBSS as these approaches make a single binary decision and cannot identify single channel occupancy state that lie within a wideband spectrum.

In the same context, SS approaches can also be categorized as blind and knowledge aided based on the required knowledge for each approach. For instance, energy-based detection and eigenvalue-based detection approaches are categorized as blind spectrum sensing approaches as they need no prior knowledge about PU's signal characteristics while matched filter and cyclostationary feature detector are among knowledge aided approaches since they require a full or partial prior knowledge about the PU's signal [35].

Based on the above discussion, a CR-based IoT system detects the existence of the PU over a spectrum band of interest by adopting a SS approach. The designer can select a proper SS approach based on the design factors mentioned in Section III and the available awareness of the PU's information such as BW occupancy and signal characteristics. The selected SS approach should satisfies the following selection criteria:

- it should able to detect the PU over the target BW, i.e., spectrum band,
- it should consume low power, i.e., energy efficient, and
- it should incur minimum computational complexity, if possible,

As an example, for a SU that employs NB-IoT technology, an NBSS approach is selected. Then, based on prior knowledge about PU signal features, a designer can determine the most appropriate NBSS approach. Therefore, if the designer has no prior knowledge about the PU's signal features, the ED is the best candidate for its simple implementation and low complexity requirement. However, if the designer is expecting that the system will experience a noisy radio environment, one of the eigenvalue-based detection approaches can be selected. Similarly, if the designer has some prior knowledge of the PU signal features, such as cyclic prefix or cyclic spectral correlation function; then a CFD is the optimal selection for this case, due to its noise and interference immunity.

On the other hand, in case of WBAN enabling UWB technology, a multi-coset sensing approach is selected over the other WBSS approaches, such as wavelet detection or compressive sensing approaches, as no prior knowledge about the number of PUs, and sparsity assumption are required. In conclusion, the adopted SS approach is selected based on

TABLE 6. General remarks on WBSS approaches.

No.	Category	Advantages	Remarks	Relevant References
1	**FFT-Based detector**	• Improves acquisition performance compared with the conventional acquisition methods, since it increases the overall gain. • Cancels the effect of the phase rotation due to the carrier frequency offset.	• Requires high sampling rate. • Sequential scanning could be a solution to relax the high sampling rate.	[49]–[51].
2	**Filter Bank detector**	• High performance • Can capture the dynamic nature of wideband spectrum by using low sampling rates. • Can sense the PUs over multiple frequency bands jointly.	• Nyquist wideband. • High complexity requires a great number of RF front-end components, whose range of and amount are always pre-set. • Not practical in the cognitive radio networks.	[52]–[54].
3	**Wavelet detection**	• Formulates the wideband sensing as a spectral edge detection problem and uses wavelet transform to identify all piece-wise smooth sub bands.	• Nyquist wideband. • High complexity.	[55]
4	**Sequential scanning**	• Sub-Nyquist sampling. • Implemented using tunable narrow-band Band Pass Filters (BPF) with preselected tuning range. • Used to relax the high sampling rate requirement in the wideband spectrum.	• The sequential nature is slow and inflexible. • Could cause interference to existing users and result in missed opportunities.	[56]
5	**Compressive sensing**	• Low power. • Provides fast and accurate spectrum detection with sub-Nyquist sampling. • Low sampling rate.	• Very sensitive to signal noise. • Sparsity assumption. • Can attain a large dynamic range.	[57]–[63].
6	**Multi-coset sensing**	• Sub-Nyquist sampling. • Non-uniform sampler • Can reconstruct the spectrum • Blind joint sub-Nyquist scheme do not require prior knowledge of the number of occupied channels and SNR.	• Requires synchronization circuits.	[64]–[67].

available knowledge about the BW occupancy and PU signal features.

2) DECISION MAKING TECHNIQUES

According to the SS observations, the decision is made to declare the presence or the absence of the PU over the band of interest. In other words, a single CR can make itself sensing decision, i.e., local observation. However, channel impairments, such as multi-path fading, shadowing and noise power variation, adversely impact the detection making of the CR, especially when using NBSS approaches [68]. Therefore, another decision making technique should be employed to improve the local observation. A collaboration between CRs by sharing their SS observations can effectively alleviate the impact of those impairments. The collaboration process is called Cooperative Spectrum Sensing (CSS) and can be implemented using three main techniques, they are centralized, non-centralized and relay-assisted. Discussing the CSS techniques is beyond the scope of this survey, however, a brief description of each technique is provided below.

First, in the centralized CSS technique, all participant CRs detect PU over the designated spectrum band, then forwards their local observations to a central entity to determine the final decision about PU existence, next forwards back to all participants [69]–[71]. Second, in the non-centralized CSS technique, the participants share their local observations between each other and then the decision is made by reaching a consensus between the participants [72], [73]. Finally, relay-assisted technique can be realized by two strategies either Amplify and Forward (AF), or Decode and Forward (DF). In AF strategy, once a participant CR receives a decision from another CR, it amplifies it and then forwards it to another CR, while in DF strategy, a CR decodes the received decision, remodulates it and forwards it to another CR [74], [75]. Excessive research works and surveys have focused on CSS techniques, methodologies and challenges [56], [76], [77]. However, this survey paper mainly focuses on the recent works pertain to CR-based IoT systems.

B. SPECTRUM SHARING PHASE

The objective of this functional phase is to allocate the vacant band and then utilize it effectively. In other words, an energy efficient scheme that avoids collision between SUs and PUs or SUs themselves is mandatory. Generally, spectrum sharing can be implemented through network selection, spectrum allocation, MAC protocol, power allocation, and spectrum routing and mobility.

Once sensing decision is made over the designated bands, the SU should allocate the band to be used, this can be performed by selecting the suitable vacant PU band to be exploited and the way to access that band taking into consideration the channel constraints, such as maximum power and BW. For more understanding, spectrum sharing rules and models must be discussed before describing the selection of a suitable spectrum sharing approach.

1) SPECTRUM SHARING RULES

for efficient spectrum sharing process, some rules should be taken into consideration which are:

- at any given instant, each SU can only use one allocated channel over all available channels,
- total interference caused by all SUs over the allocated channel must not exceed a maximum allowable limit of interference, and
- the allocated channel should match the SU's requirements of BW and power.

In other words, spectrum sharing process is a three step process; they are spectrum allocation, spectrum access, and power allocation. Briefly, spectrum allocation is to select the PU and the spectrum band among the vacant spectrum bands. Spectrum access is to select the MAC, routing, and mobility protocols. Finally, power allocation is to avoid or minimize the interference of SUs to the PUs.

2) SPECTRUM SHARING MODELS

the spectrum sharing models can be classified into open sharing and managed sharing as shown in Fig. 4. In open access scheme, no central unit controls the access to the band to be used by the SUs. Thus, it is a unauthorized access model where a SU or a group of SUs can transmit data any time over some designated bands for short distance considering a power limited imposed by the regulatory body. For instance, Federal Communications Commission (FCC) allows ISM (2.4 GHz) for open access, but mandates that users should never exceed the imposed peak transmission power [78]. Note that, in this scheme the collision between SUs cannot be avoided, especially in areas crowded by IoT devices. Hence, IoT devices employ ZiGbee and WiFi standards, when no cognition capability is adopted [79].

On the other hand, to avoid the collision between SUs themselves and between them and PUs, a managed access is employed, where a central entity or a policy is required to control and manage SUs' access to a vacant band. The managed sharing techniques can be classified into three main classes, centralized, distributed and cooperation between PUs and SUs.

First, in a centralized class a SU can attain an exclusive use to exploit a designated spectrum band through a legitimate spectrum management process such as TVWS Geolocation database and spectrum market. Therefore, a regularity body or a PU allows a specific SU to use that spectrum band for a certain time over a certain geographical area; as a result, no competition between SUs occur to use that spectrum band. For instance, if a SU employs geolocation capabilities, e.g., White Space DataBase (WSDB) governed by FCC in the US, provides the SU with a list of available spectrum bands and maximum allowable transmission power over those bands. The SU, i.e., White Space Devices (WSD), should never go over the imposed power limit [80].

Spectrum marketing between PUs and SUs is an emerging trend for sharing spectrum bands by either trading or leasing spectrum bands [81]. The goal beyond spectrum marketing is to maximize the spectrum efficiency by increasing the capacity of networks include PUs and SUs. In spectrum trading, negotiations between PUs and SUs might take place to exchange benefits, such that PUs might provide SUs an exclusive use for their spectrum band for a certain time over a specific geographical location for either forwarding PUs' data to some area beyond their transmission range i.e., coverage area, or some fees. Different game models, auction mechanisms might be adopted to implement the contract model-based spectrum trading [82], [83]. In spectrum leasing, SUs might lease a specific spectrum band for a specific time interval to transmit their data over that spectrum band for a certain amount of money [81]. All those trades and leases should follow the regulations of government agencies in which spectrum marketing takes place [80], [81].

Second, distributed spectrum sharing models also can be categorized as either opportunistic, i.e., interweave or coexisting models. In interweave model, a SU can exploit the vacant band when PU is idle in one of these dimension time, frequency or geographical location. However, PU protection from the SU interference is a must; therefore, the SU should always detect the existence of the PU over the band during its transmission by adopting either Full Duplex (FD) by which a SU can sense and transmit simultaneously [84], or spectrum monitoring techniques for this purpose [85]. On the other hand, coexisting models are overlay, underlay or hybrid. In all these sharing models, a SU must be aware of PU's signal characteristics so that the SU can simultaneously coexist with

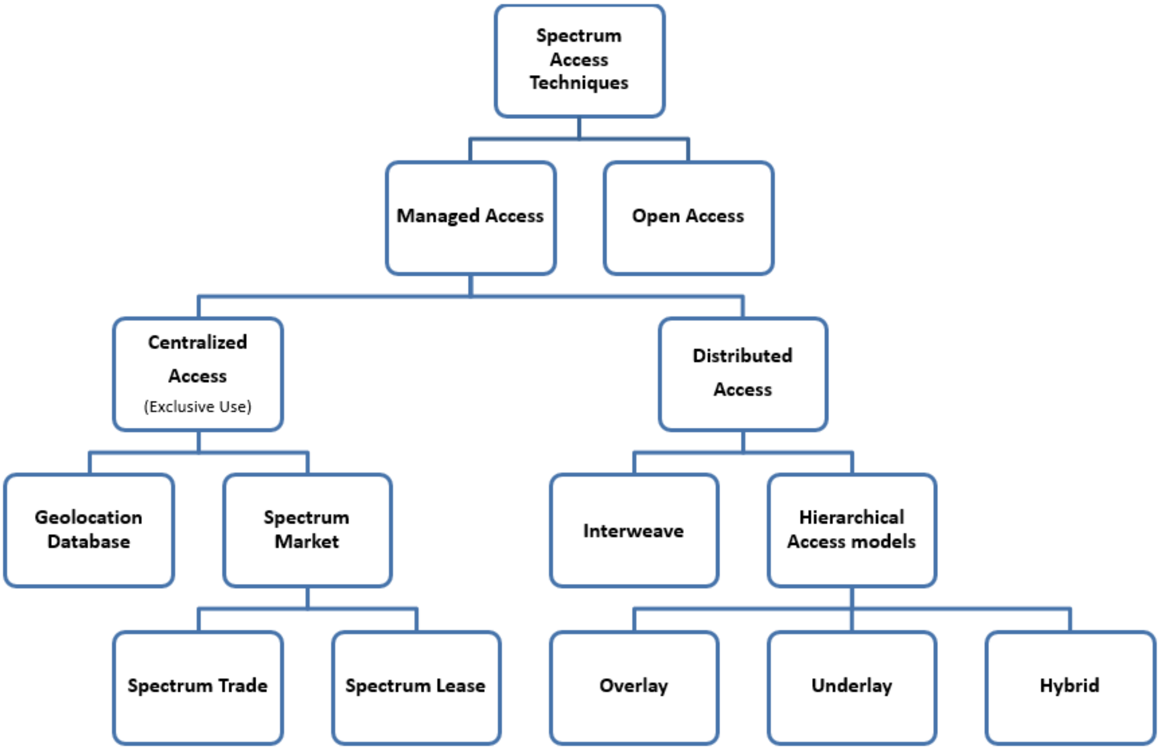


FIGURE 4. Spectrum sharing models.

the PU over its spectrum band. More specifically, in overlay model, the awareness of PU's signal, i.e., code, angle or polarization, enables the SU to transmit data without interfering PUs by changing code, angle of transmission or beamforming [56]. In underlay model, the SUs can coexist with PUs in their spectrum bands. If SUs know the PU's transmission power level, therefore, SUs can transmit data for a short range and never exceed a certain transmit power limit, while hybrid model is a combination of overlay and underlay model [8], [9].

Third, the cooperation between PUs and SUs can be implemented by either network coordination or spectrum relaying. In network coordination scheme it is assumed that there is a Central Network Operator (CNO) to coordinate and manage the spectrum sharing between SUs and PUs by minimizing the interference and optimizing the sharing time and power resources so that QoS of the SUs can be improved. The CNO selects the PU and SUs to be cooperated using Particle Swarm Optimization (PSO) or genetic algorithm [8].

In spectrum relaying, if a PU could not reach its throughput target, it asks SUs to cooperate by sending a Request To Cooperate (RTC) to the SUs. A SU with an interest to cooperate, replies by a confirmation message as Confirm To Cooperate (CTC). As an example, spectrum relaying based OFDM, SUs assist the PU using some of its sub-carriers to forward PU's signal, such a scheme is called spectrum relaying. Channel power allocation technique, such as Water Filling (WF) algorithms [86], [87], is required to satisfy PU's throughput target. Alternatively, various protocols have been devised to perform spectrum sharing based OFDM, where SUs assist the PU using some of its sub-carriers to forward PU's signal, such a scheme is called spectrum relaying. Channel power allocation technique, i.e., resource optimization technique, such as WF algorithms [86], [87] and interior point method [88], are required to satisfy PU's throughput target. Conventionally most of the SUs adopt Half Duplex (HD) relay, in other words, sensing and data transmission cannot be performed simultaneously; if the SU senses, no transmission occurs and vice versa. Such kind of system adversely impacts the spectrum efficiency. However, the spectrum efficiency of a SU can be significantly increased if a SU adopts a FD system [89]. However, this improvement comes at the expense of extra hardware complexity (e.g., extra antennas and electronics) and computational requirements.

The selection of a proper spectrum sharing approach has to consider the following three phases which are:

3) SPECTRUM ALLOCATION

The spectrum allocation starts with network selection, i.e., PU selection, is an important step towards allocating spectrum bands. For SUs use NBSS approaches, the SU determines the PU channel before starting detection. However, in case of employing WBSS approaches, there always are more than one deployed PU network, i.e., PU transmitters and

PU receivers. Many approaches can be employed to select the optimal PU network. PSO, genetic optimization and game theory are among the best approaches to be used for this purpose [8], [90].

Channel allocation is the second step of this functional phase, especially when there are multiple PUs and multiple SUs; by which each SU will select a designated spectrum band, i.e., channel, to exploit or to jointly share. The allocated spectrum band should fit the BW and QoS requirements fo the SU. Moreover, before transmitting data, SUs must be aware of the presence of other SUs intend to use that allocated channel, i.e., spectrum band, since SUs might use different spectrum bands but oblivious of each other. Learning about the existence of those intended SUs is known as channel rendezvous [91] and it is an important step to communication links between SUs,i.e., CRN configuration.

The conventional rendezvous algorithms assume to use a Common Control Channel (CCC) to establish links between SUs and configure a CRN. However, a CCC is always influenced by the dynamic behavior of the PUs over the allocated spectrum band and is vulnerable to security threats, therefore, a channel rendezvous might fail [92].

For an efficient channel allocation using rendezvous algorithms, a Channel Hopping (CH) is adopted to enable SUs to reach a channel consensus within a finite number of hops. The most important performance metrics are Maximum Time To Rendezvous (MTTR), Expected Time To Rendezvous (ETTR) and Rendezvous Degree (RD). The MTTR is defined as the rendezvous latency in the worst case. The ETTR is defined as the average rendezvous latency before successfully rendezvous on at least one channel, while the RD is defined as the minimum percentage of distinct rendezvous channels to the number of common available channels between any pair of SUs. It is hoped that the rendezvous can spread out evenly over all common channels in order to overcome the vulnerability of one single rendezvous channel and provide more rendezvous opportunities [91]–[93].

The work in [79] employed the Round Ribbon Tournament to devise a novel asymmetric asynchronous channel hopping algorithm for IoT-based CRNs. The devised algorithm achieves guaranteed rendezvous within a predefined time. Moreover, the algorithm outperforms the works in [91], [93] in the degree of rendezvous.

4) SPECTRUM ACCESS

This phase employs MAC, routing and mobility protocols. After allocating the channels, accessing those channels can be performed by adopting an appropriate efficient MAC protocol. The designer should select a MAC protocol of CR based IoT based on two main criteria.

- First criterion is related to IoT system characteristics, such as data size, transmission rate, transmission range, power consumption, latency, employed communication technology, and heterogeneity of the systems, i.e., deployment of the system whether it is individual or back-haul connection.
- Second criterion is related to the detected spectrum band such as its availability and BW.

More specifically, there are three factors that play an important role in selecting an energy efficient MAC protocol for IoT system. The factors are transmission probability, latency and power consumption. Hence, an efficient MAC protocol should incur low cost, low complexity and low energy consumption. Moreover, should have ability of channel switching while maintaining PU protection, low channel access delay, no collision between SUs when accessing the channel, and trades off between duty cycle and control overhead and balances between spectrum efficiency and energy efficiency. Finally, a MAC protocol must be able to correct errors, i.e., error correction.

As an example, the work in [94] provides a comprehensive comparison between MAC approaches of two well-known standards, namely, IEEE 802.11ah and IEEE 802.15.4. The standards are adopted for IoT systems. The comparison shows that IEEE 802.11ah outperforms IEEE 802.15.4 in data rate, data size, latency, and transmission range. Despite IEEE 802.14.5 operates with less data rate and over a shorter range than IEEE 802.11ah, it outperforms IEEE 802.11ah in power consumption and network capacity since it can accommodate more IoT devices than IEEE 802.11ah.

Different standard random access MAC protocols, such as slotted ALOHA and conventional CSMA/CA, CSMA/CA polling, Orthogonal Frequency Division Multiple Access (OFDMA), and Frequency Hopping Spread Spectrum (FHSS) have been employed by IoT systems to access the spectrum hole [80]. For instance, a CSMA/CA MAC protocol has been adopted in [13], while in [12] slotted ALOHA was adopted.

The authors in [12] employed an ED as a sensing approach and slotted ALOHA protocol as a random access channel for its popularity in Global Mobile System (GMS) and LTE. Moreover, the authors derived a closed expression for the optimal throughput of narrow band CR-based IoT device with slotted ALOHA for local and CSS mechanism. The optimization problem was proposed to maximize the throughput of CR-based IoT under constraint of PU protection. However, the work considered the channel with only Additive White Gaussian Noise (AWGN) and did not consider the impact of channel impairments on the performance of the ED, since ED is susceptible to dynamic environmental conditions and its performance significantly deteriorates under other channel impairments, such as multi-path fading, shadowing and noise uncertainty [35]. Moreover, the power consumption was not considered as well.

On the other hand, some recent works employed non-standard random access MAC protocols. For instance, the work in [95] employed conditional interference distribution to propose a new cognitive random access mechanism with adaptive transmission probability. The transmission probability varies according to the measured interference by the IoT device. The proposed mechanism allows the IoT device to share the spectrum band used by the PU in non-interfering basis. Moreover, the proposed mechanism improves the area spectral efficiency and outperforms the convention ALOHA mechanism.

Moreover, an energy efficient MAC protocol with a novel channel selection criterion was devised in [96]. The protocol significantly reduces the handshakes over control and data channels; therefore, improves the energy efficiency by increasing the throughput and minimizing the consumed energy. Moreover, the protocol was investigated by applying different PU activity models over the channel.

Furthermore, the work in [97] modified the MAC protocol of IEEE802.11 in order to enable the protocol of opportunistically select the channel by adding channel selection algorithm. The modified IEEE802.11 outperforms the standard IEEE802.11 with sequential selection (i.e., Round Robin) and random channel (i.e., CSMA/CA) selection algorithms in both throughput and energy consumption.

In addition, Restricted Access Window (RAW) is a promising MAC protocol which is adopted for low power IoT network for large number of devices with low collision probability. The RAW employs multiple equal time slot and allows a limited number of IoT devices to access a specific spectrum band at each time slot and spreads devices' attempts over a long period of time to enable an efficient communication for a large number of devices. The devices operate in active mode only if their slot turns; otherwise, they operate in sleep mode to save power [94].

Besides MAC protocols, spectrum routing and mobility protocols are needed to firmly guarantee a PU protection, especially, if a PU suddenly resumes its transmission over the licensed spectrum band which is opportunistically exploited by a SU. In this case, the SU must leave the spectrum band without causing an interference to the PU by switching to another vacant spectrum band or immediately cease transmission until that spectrum band becomes idle. The band switching process is called spectrum mobility. To perform this process efficiently, the SU should be aware of PU activity pattern, in order to predict the PU's behavior, therefore, it can alleviate a collision with the PU. Many approaches have been devised to perform an efficient spectrum mobility in CRNs. The works in [98], [99] thoroughly explained the principle, mechanism and merits of each spectrum mobility approach.

The way of when and how a SU switches from spectrum band to another band is performed by spectrum routing protocols. Those protocols play an important role to significantly improve the spectrum efficiency by exploiting the PU's time varying availability over its spectrum band [8]. A survey paper in [100] discussed the joint channel selection and routing from the perspective of CRNs. The work provided a comprehensive survey on routing and channel selection in CRNs. More specifically, the importance of joint channel selection and routing for CRNs. Moreover, the survey highlighted the classification and challenges of channel selection and routing strategies. Using the PU behavior models, performance metrics and routing metrics, the survey showed how to develop an efficient routing protocol.

5) POWER ALLOCATION

The key aspect of spectrum sharing is to optimize the power and energy consumption in order to increase the overall spectrum and energy efficiencies of the CR-based IoT. Therefore, power allocation approaches have to be employed to realize this objective. Among those approaches, point interior approach [88], WF algorithm [86], [101], and game theory [90]. The point interior method is generally employed for linear and non-linear convex optimization problems. The method mainly approaches the optimal solution from the strict interior of the feasible region. On the other hand, the WF algorithms are used for radio resource allocation problem for a system with multi channels or carriers, where it aims to maximize the sum of data rates or the capacity of all channels in the system by optimizing the power distribution of the transmitted signals. For CRN, the WF algorithms are used to maximize the sum of throughput of all participant CR in the CRN considering their individual peak power constraint to guarantee the QoS of the PUs.

On the other hand, in case of non-cooperative, i.e., a system with selfish CR, game theory is an appropriate tool to model those behaviors, since game theory provides the mathematical tools to study the complex interactions among interdependent rational players, i.e., selfish CRs, and to predict their possible strategies. Different non cooperative game models can be employed such as asymmetric Nash bargaining solution-based relay power allocation scheme which is used to achieve a balance between global network performance and user fairness. Stackelberg game is adopted to model the interaction between the relays and the users to find the optimal power allocation, and auction-based power allocation algorithms can be used for resource allocation among Device to Device (D2D) links reusing the same cellular channels subject to optimizing the system capacity [102], [103].

C. SPECTRUM MANAGEMENT PHASE

The popularity of IoT system encourages IoT users to exchange huge amount of data with their interested parties over public and untrusted networks. However, the data should not be exposed to every user since those data might be secure, safety critical, or contain private and sensitive information. Therefore, it is necessary to enforce security and privacy policies, i.e., protocols, to protect the data from any fraudulent acts or security threats. The complexity of selected protocol depends on the device specifications, networking, and applications [104]. For instance, most of the IoT devices are low energy, lightweight devices and use their energy mainly to execute their core function applications. This made traditional security algorithms not suitable for IoT since they consume much energy and incur high processing overhead. Hence, it is necessary to use lightweight energy efficient security protocols [105]. Many recent survey works [105]–[108] comprehended this area and discussed thoroughly the requirements, architectures, classifications and challenging issues for security and privacy protocols for various IoT systems and applications. However, in this work, a brief discussion on security and privacy is provided below. The discussion covers the important requirements and concepts in this field.

1) SECURITY

To establish a secure IoT system with a large number of IoT devices, services and users, three important measures are required. Those measures are confidentiality, data integrity, and authentication. First, confidentiality guarantees the availability of the data for only the authorized users throughout the data exchange process. Data encryption is adopted to avoid the interference and eavesdropping of unauthorized users; in other words, strictly limiting the data accessibility and disclosure to the authorized users [106]. Second, data integrity is providing accurate data to the authorized users during data delivery over the network by filtering false data, i.e., tampered and forged data, caused by intended or unintended interference. Third, authentication is delivering the data to the legitimate object, i.e., a user, a device or an application, which requests a specific data over the network.

Moreover, availability is an important feature in IoT system, which refers to persistent IoT connectivity by making data and devices always available when requested by the authorized users and avoid denial of service attack. Note that confidentiality, integrity and authentication are information security requirements while availability is a functional security requirement that also means continuing service provisioning during disruption conditions, i.e., the ability to provide a minimum level of service if a failure or power loss occurs [109].

2) PRIVACY

To prevent an adversary, i.e., undesired party, from discovering, eavesdropping or/and monitoring private information of other users and to ensure that data can be accessed and processed by only the pertinent user. Moreover, privacy allows the user to perform specific controls based on a specific portion of the received data while prevents it from reaching the rest of that data [110].

Privacy preservation mechanisms should be enforced during data collection, aggregation and mining phases to block data leakage to the public. Traditional encryption and key management mechanisms can be used as privacy mechanisms over data collection and mining phases, however, it is not the case for data aggregation phase, since data is aggregated and processed in various locations [111]. Despite that there are various attempts to tackle an efficient privacy mechanism for data aggregation such as perturbation-based privacy mechanisms and anonymity-based privacy mechanisms, this issue is still challenging and considered as an open research direction.

In summary, for an efficient CR-based IoT system, it is recommended to employ lightweight security protocols and privacy mechanisms which need minimum communication and processing resources, and incur low computational overhead to support the resource constrained IoT devices.

V. INTEGRATION OF EMERGING TECHNOLOGIES WITH CR-BASED IoT SYSTEMS

Integrating emerging technologies, such as blockchain and Artificial Intelligence (AI) techniques, i.e., Machine Learning (ML) approaches, with wireless systems is a new step towards creating next-generation wireless communication systems with additional capabilities such as robust security, autonomy, flexibility, and intelligent architecture. This section discusses the impact of adding blockchain and machine learning approaches to CR-based IoT systems.

A. BLOCKCHAIN-ENABLED CR-BASED IoT SYSTEM

The blockchain is defined as a tremendous, public, secure and decentralized datastore of ordered events, called blocks. Each block contains a timestamp and is linked to a previous block. The events can be updated by "only a majority of users" [112]. Erasing information is not allowed. The datastore is owned by no one, controlled by users and not ruled by any trusted third party or central regulatory instance. In fact, trust is encoded in the protocol and maintained by the community of users. The work in [113] presented a comprehensive survey on blockchain, its types, features, structures, protocols, and the integration of blockchain and IoT systems. On the other hand, the survey in [114] focused on blockchain applications and challenges for real world applications.

Adopting blockchain technology is a promising solution to improve system immunity against hacking activities. The blockchain prevents central point system failure and cyber attack which results in improving the security in IoT and CRNs. The blockchain protocols employ a two-key encryption system, i.e., public and private keys; therefore, robustness is added to the security of CRNs [115], [116].

However, the use of blockchain in IoT security is limited and focused on the following areas: asymmetric and symmetric key management [117], [118], trading of collected data [119], [120], incontrovertible log of events, and management of access control to data [121]. The security issues related to IoT include authentication and authorization, ownership and identity relationships, governance of data and privacy [122]. Blockchain-based research has been used to tackle some of these issues. The work by Pureswaran and Brody investigated how blockchain contracts support the autonomous workflow and sharing of services among IoT devices [123]. IoT devices can benefit from blockchain networks in areas related to billing, shipping, e-trading, supply chain management, and energy trading [123]. In another work, Bahga and Madisetti proposed a blockchain-based framework for industrial IoT [124]. The work by Saghiri et. al proposed a framework for IoT based on cognitive systems and blockchain [125]. Such work is still in its infancy and worth investigating since introducing blockchain in IoT and CR systems shows a promising future in supporting secure data sharing and protecting privacy.

On the other perspective, employing blockchain protocols in spectrum auction offers a decentralized validation which increases the accessibility of the CRNs and reduces the implementation complexity, since no central entity is required. In addition, blockchain-enabled spectrum access in CRN is a secure spectrum sharing approach where it provides an optimal collision-free method to access the spectrum opportunities. The work in [115] showed that blockchain-enabled spectrum access in CRN improves the security of the CRN and outperforms the conventional random MAC protocol in medium and severe radio conditions. The authors in [116] showed that adopting blockchain enhances security and performance of CRNs with moving CRs.

As a novel step towards next-generation wireless networks to enable flexible and secure spectrum sharing, the authors in [126] proposed a secure and intelligent architecture with three planes, namely., user plane, edge plane and cloud plane, to empower 5G technology by integrating blockchain and AI techniques, i.e., Deep Reinforcement Learning (DRL). The blockchain is utilized to enable secure and flexible spectrum access and enhance privacy protection of the SUs; however, DRL is utilized to provide an intelligent resource management since AI techniques can tackle issues such as uncertainty, time variant, and complex features.

B. MACHINE LEARNING-ENABLED CR-BASED IoT SYSTEM

ML approaches are AI applications that establish mathematical models based on observations, i.e., training data, to predict or make decisions. ML approaches enable systems to automatically learn and improve from experience without being explicitly programmed. In other words, ML approaches enable computers or processors to automatically learn without human intervention and to select actions accordingly. ML approaches have a potential ability to analyze and classify massive amounts of data which makes ML approaches as efficient and powerful tools for performing other processing tasks, such as data analysis, classification [127], feature detection, feature extraction [128] and identification [129]. Also, ML approaches improve the security and the data privacy for big data systems [130].

In addition to the aforementioned advantages, ML approaches can apply complex techniques in a simple way, and provide accurate results of identifying the targets. Therefore, integrating ML approaches with cognitive capabilities can improve the effectiveness of processing large volumes of information from various distinctive resources. ML approaches have tremendous applications which cannot be covered in this section; however, some related applications of ML approaches to IoT and CR are addressed below:

1) IoT HEALTH APPLICATIONS

The survey in [127] made an assessment for various ML approaches, such as Support Vector Machine (SVM), K-Nearest Neighbor (KNN), Naive Bayes (NB), Logistic Regression (LR), etc. In addition, the survey determined the criteria of selecting the most appropriate ML approach for IoT application. Moreover, the survey considered the application of ML approaches for developing IoT smart applications in a smart city as an illustrative example to discuss and address the challenges of adopting ML approaches in IoT data analytics of smart data traffic. Moreover, the work in [128] proposed a scalable IoT health monitoring framework which integrates IoT architecture with LR approach. The proposed framework employs 5G mobile networks for the transfer of clinical data into the clinical database to enable the necessary action for emergency situations. This framework is mainly used for early detection of heart diseases. In [131], the authors proposed a monitoring health framework that alarms when acute heart stress occurs. The proposed framework employed KNN and LR approaches to predict and detect heart stress and uses IoT devices to measure patient's stress level.

2) CRN APPLICATIONS

The work in [132] provided a comprehensive review of various ML approaches applied to CRNs. The work categorized ML approaches into decision-making and feature classification. Decision-making is employed to determine policies and decision rules for CRs while feature classification is used to identify and classify different observation models. This work also addressed several challenging learning issues that arise in CRNs, in particular in non-Markovian environments and decentralized networks, and provided possible solutions. Furthermore, the work identified the conditions under which each ML approach can be used. On the other hand, the authors in [133] devised CSS algorithms for CRNs based on ML approaches. The SVM and KNN approaches were used as classifiers. The energy level estimated at each CR was used to establish the feature vector which is categorized using the classifier into two classes, idle channel, "no PU activity", and busy channel, "at least one PU is active". In this work, the proposed algorithms outperformed the traditional CSS techniques, i.e., hard and soft fusion techniques, for two reasons. First, ML approaches have a capability of implicitly learning the surrounding environment, i.e., topology of the PU and CRNs and the channel fading. Second, ML approaches optimize the decision region based on feature space which is better than the optimization used by the traditional CSS techniques.

Moreover, ML approaches play an important role in constructing Radio Environment Map (REM) for their accurate prediction, classification and learning. The REM is an integrated database consisting of multi-domain information, i.e., temporal, spatial, spectrum sensing, etc., to supply CRs with a comprehensive radio environment information in their geographical locations [134]. In other words, REM is a global situation awareness system that helps CRs to make adaptations beyond their individual capabilities. Hence, using REM results in a improving detection performance of PUs and SUs, mitigating hidden terminal problem, and reducing CRN adaptation time. REMs utilize ML approaches to build a spatio-temporal model to predict spectrum usage, i.e., PUs' activities, [135], to learn radio environment parameters [136], and to establish a feature-based detection system. The latter is used as an automatic modulation classifier for PU signals and to estimate model parameters of the REM [137].

VI. CHALLENGES, OPEN ISSUES, AND FUTURE RESEARCH DIRECTIONS

A. IoT WITH 5G TECHNOLOGY (5G-IoT)

Each new generation of wireless technology has brought faster, more reliable cellular and Internet connects, starting with the first generation of wireless technology providing cellular communication, then 2G providing secure communication i.e., voice and text, next 3G introduced the smart phone era and 4G/LTE offered high-speed Internet allowing for streaming videos. Currently, the future era of wireless technology is moving to 5G, a generation promising life changing innovation with higher bandwidths, faster speeds, lower latency and increased capacity allowing more people and devices to communicate with each other at the same time, i.e., IoT. 5G requires frequencies reaching 300 GHz, compared to LTE which operates at bands below 6 GHz, hence allowing for higher capacity and speeds. Despite 5G offering a significant increase in speed and bandwidth, its more limited range will require further infrastructure. The initial cost to build 5G networks is very expensive since it is a new technology and cannot be built on top of an existing network. Therefore, the concept behind IoT is predicated on a fast network that can link devices and services together. This will allow devices to connect in new ways such as vehicles, city infrastructures, appliances, telehealth, etc. In addition, the need for compatible mobile devices is a challenge that manufacturers must combat to allow for a global spread of this technology.

In the last few decades, with each generation challenges have emerged and were tackled allowing each generation to move to the next and 5G is no exception. Therefore, the main challenges facing 5G-IoT include technical challenges, security assurance and privacy concerns, and standardization challenges [138], [139].

1) TECHNICAL CHALLENGES

Though many research efforts have been made on 5G-IoT, there are still many technical challenges that needs to be tackled:

- 5G-IoT architecture is the main challenge which needs to be addressed since architecture design still impose many challenges, including, scalability and network management, interoperability and heterogeneity, security assurance and privacy concerns [140]–[142].
- Wireless Software Defined Network (SDN) is a challenge for network scalability.
- Deployment of IoT applications is challenging due to its large scale, resource limited devices and heterogeneous environment; therefore, a multilevel and multidimensional service provision platform could be a solution to tackle these challenges an attempt is presented in [143].
- D2D communication are expected to provide high throughput for 5G-IoT. In D2D, the energy and spectral efficiencies are the two challenges.
- Several other technical challenges include dense heterogeneous networks deployment in IoT, multiple access techniques for 5G, full-duplex transmission at the same time, etc.

2) SECURITY ASSURANCE AND PRIVACY CONCERNS

With faster data speeds and higher capacity, security and privacy is a challenge that needs to be tackled to secure user's data. Therefore, new security capabilities at device and network levels need to address security and privacy in complex applications including smart city, smart networks, telehealth, etc. Moreover, the security and privacy factors that need to be considered in designing G5-IoT systems include intrusion software, security assurance, backward compatibility, authentication, key management, etc [139], [142].

3) STANDARDIZATION ISSUES

5G-IoT is a very complex system, its purpose is to connect humans to their surrounding environment, hence due to the diversity nature of networks and devices in 5G-IoT, there is a lack of consistency and standardization for both IoT systems and applications. Therefore, the main standards which are of concern in 5G enabled IoT are: technology and regulatory standards. Technology standards include wireless communication, network protocols, data aggregation standards; and regulatory standards, include security and privacy of data, security solutions, cryptographic primitives. Finally, investigating IoT as a service could be the solution for future standardization [139], [144], [145].

B. BIG DATA MANAGEMENT

The collected IoT data are streams of huge data volumes from various resources with different formats and patterns. IoT data analysis and management are important data processing steps towards converting the collected data to a useful knowledge that enables an IoT device to make decisions automatically. In other words, IoT devices can automatically extract hidden information from the collected IoT data and take the most appropriate action through data analysis and management. Data classification, clustering, patterning and feature extraction are the key functional components of data analysis and management. Data mining is the promising technology to perform data analysis and management, since data mining technology can extract knowledge from a large scale of data, i.e., big data, [146]. The discussion of data mining algorithms and architectures is beyond the scope of this survey; however, the surveys in [146]–[148] provided thorough overviews on the data mining algorithms, architectures and their challenges for IoT.

Data management challenges for IoT has seen to be emerging rapidly and no doubt with the use of IoT in CRN more and more data is being created. The data does not only include traditional data, but also streaming data generated from digital sensors from many devices connected to the Internet. The data is usually generated in both structured, which is organized and easy to analyze, and unstructured, i.e., images and video data, which needs advanced tools to analyze. Therefore, advanced data mining techniques are needed to mine streaming data from sensor networks. The challenge lies in the shortage of skilled data analysts and the need for more research to develop and implement advanced mining tools to mine streaming data from CRN and sensor networks [149].

The IoT e-Health envisions a seamless connectivity that spans over physical locations; therefore, several research challenges related to data management must be overcome in order to achieve this. The main challenge is the continuous change of state of data collected from the attached sensors on human bodies, i.e., data continuously transmitted and collected via the Fog computing nodes [150], hence the IoT e-Health systems has to handle the complexity of the data in terms of their variety, volume and velocity. Since, the data produced in different formats is application dependent and is a challenge that manufacturers or health organizations must tackle by setting standards. In addition, Fog admins are needed to monitor the capabilities of Fog node hardware and mange the data communication between different medical devices. In [150], [151], the challenge of receiving knowledge from big data analysis to acquire a valuable decision and big data security issues in healthcare is discussed and a proposed solution in [151], [152] is to implement an IoT Fog computing architecture which will process, and store data acquired from sensors. The architecture consists of two parts: Meta Fog-Redirection and Grouping and Choosing architecture.

The deployment of large-scale wireless sensors and IoT, can result in extremely huge data and hence optimized data processing and hierarchical communication solutions are needed to manage such deployments and data processing networks. More research work is needed for big data spatial processing specifically for wireless networking applications, as more scalable algorithms are required for performing different tasks, such as system identification, anomaly detection, and similar problems [153].

Moreover, from CR perspective, establishing a comprehensive spectrum modeling, accurate spectrum prediction, and flexible spectrum management necessitates the employment of big spectrum data techniques. Big spectrum data provides a comprehensive knowledge about the existing PUs over a designated geographical location, such as PU presence status, received signal strength, signal features, etc [154]. Geolocation database, REM and Spectrum Sensing as a Service (S^2aaS) are spectrum aware systems where a big data architecture takes place in CRNs. A SU can obtain accurate spatio-temporal spectrum availability and spectrum prediction from those systems [154]–[156]. On the other hand, development of an energy efficient and cost-effective big data architecture is still facing many challenges. Some of those challenges are:

- determining the volume of required spectrum data for a specific scale, since the volume of spectrum data increases by increasing the time duration, frequency band, spatial scale of interest, and resolution. Therefore, extra computational power is required which results in extra computational burden and latency. As a solution, the use of parallel and distributed computing can help alleviating such a problem; however, the configuration and maintenance of the parallel and distributed computing are still challenging and requires more investigation.
- alleviating the deterioration of the quality of collected spectrum data caused by ambient radio conditions can be solved by adopting an appropriate radio propagation model. This challenge is more complicated in scenarios that include moving spectrum data collectors.
- increasing the processing and networking capabilities of the adopted big data architecture with low overhead can efficiently increase the number of the data users, i.e., SUs.

C. IoT MOBILITY

The application of IoT in vehicular environments or moving wireless communication system is a new research area, since mobility is a prominent characteristic pertinent to the vehicular environment. Numerous problems and challenges still require further investigations and need robust solutions. Despite that mobility of a CR improves the sensing performance of the moving CR [157]–[159], the handoff process of a moving IoT device from one network to another incurs extra computational burden to the network coordinator units.

On the other hand, the mobility of IoT devices adversely impacts the security and privacy of the network, where mobility creates uncontrolled environment by merging and leaving of an unexpected IoT device to/from IoT networks. This seriously affects the scalability of the networks and their connectivity. Consequently, the privacy and resilience are significantly impacted because those measures mainly connected to the scalability of the networks [107], [111], [160].

In addition, mobility impacts the security, identity management, privacy, trust and resilience of IoT networks. The challenge becomes more complicated as heterogeneity of IoT devices increases; therefore, developing resilient security approaches becomes a demand [107], [110]. Moreover, developing an automatic trust computing platform, i.e., automatic trust management, to investigate the trustworthiness of emerging IoT device to the IoT networks is another challenge and future research direction.

D. GLOBAL STANDARDS

Standardization bodies exert tremendous efforts to develop standards for IoT and CRN independently. The work in [7] summarizes the standardization efforts for both IoT systems and CRN individually. However, the need to bring CR-based IoT into the reality becomes imperative. Therefore, some working groups and standardization bodies have developed some standardization efforts for CR-based IoT system, for instance, Third Generation Partnership Project (3GPP) has completed a standard for NarrowBand IoT (NB-IoT) using short range wireless technologies, such as RFID and NFC. Moreover, the work is still going on in developing a standard for IoT using 5G technology and Low Power Wide Area (LPWA) network connections [161].

The huge growth of IoT devices and applications, besides the upgrading the communication protocols, made the need to globalize standards a necessary issue. Hence, there exists no global standard for all different IoT devices, since different IoT devices adopt different wireless networks and standards. Moreover, data sharing between various IoT devices might lead to decrease the required level of security and privacy of communications. Furthermore, quality, reliability and transmission rate for remote IoT applications, such as telehealth over rural regions, are adversely impacted [14], [162].

Globalizing the standards is still a challenging task for the following factors

- various regulations that impose their own constraints, regularity assignments and recommendations on the standardization, as described in Section III-C,
- diversity of employed IoT devices, communication technologies, and protocols, which leads to difficulties in comprising and tackling all different requirements, especially with the rapid development in communication technologies and protocols and
- deployment scales, since the congestion and interference requirements for data transfer over large scale networks do not match those requirements for small scale networks. Besides, data privacy and security measures differ according to the deployment scale.

Finally, developing a global standard that comprises all aforementioned factors opens the door for a new future research direction in CR-based IoT evolution.

VII. CONCLUSIONS

The demand for smart and CRN enabled IoT systems is ever increasing to perceive the ambient radio conditions, analyze RF spectrum and make decisions how, when and where to transmit. This demand led to extensive research on designing CR-based IoT systems as typical paradigm for smart IoT systems by incorporating the cognition capabilities of CR. This survey has provided the existing frameworks of CR-based IoT systems, explored the recent SS and spectrum sharing approaches and highlighted the advantages and disadvantages of each approach.

Moreover, the survey has identified the essential requirements of constructing CR-based IoT systems and highlighted the design factors. Furthermore, the elements of cognition cycle of CR-based IoT systems has been presented and discussed. In addition, the main focus of this survey has been on SS and spectrum sharing, since it has developed the criteria of selecting a suitable SS approach and MAC protocol for a proper CR-based IoT application. Also, this survey has explored and showed the benefits of integrating some emerging technologies, such as blockchain and ML approaches, with the CR-based IoT systems. Finally, this survey has addressed and highlighted some challenges, future research directions and open issues in designing CR-based IoT systems.

REFERENCES

[1] Intel. (2019). *A Guide to the Internet of Things-How Billions of Online Objects are Marking the Web Wiser*. [Online]. Available: https://www.intel.com/content/dam/www/public/us/en/images/iot/guide-to-iot-infographic.png

[2] B. I. J. Greenough. (2015). *The Connected Car Report: Forecasts, Competing Technologies, and Leading Manufacturers*. [Online]. Available: https://www.businessinsider.com/connected-carstatistics-manufacturers-2015-2

[3] W. V. Beal. (2019). *Cognitive Radio (CR)*. [Online]. Available: https://www.webopedia.com/TERM/C/cognitive radio.html

[4] P. Joshi and A. Bagwari, "An overview of cognitive radio networks: A future wireless technology," in *Proc. Sens. Techn. Next Gener. Cogn. Radio Netw.*, 2019, pp. 1–26.

[5] M. A. Shah, S. Zhang, and C. Maple, "Cognitive radio networks for Internet of Things: Applications, challenges and future," in *Proc. 19th Int. Conf. Autom. Comput.*, Sep. 2013, pp. 1–6.

[6] A. A. Khan, M. H. Rehmani, and A. Rachedi, "When cognitive radio meets the Internet of Things?" in *Proc. Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Sep. 2016, pp. 469–474.

[7] 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 Commun.*, vol. 24, no. 3, pp. 17–25, Jun. 2017.

[8] H. Kour, R. K. Jha, and S. Jain, "A comprehensive survey on spectrum sharing: Architecture, energy efficiency and security issues," *J. Netw. Comput. Appl.*, vol. 103, pp. 29–57, Feb. 2018.

[9] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of Things: A survey on enabling technologies, protocols, and applications," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2347–2376, 4th Quart., 2015.

[10] R. Porkodi and V. Bhuvaneswari, "The Internet of Things (IoT) applications and communication enabling technology standards: An overview," in *Proc. Int. Conf. Intell. Comput. Appl.*, Mar. 2014, pp. 324–329.

[11] Y. Arjoune and N. Kaabouch, "A comprehensive survey on spectrum sensing in cognitive radio networks: Recent advances, new challenges, and future research directions," *Sensors*, vol. 19, no. 1, p. 126, Jan. 2019.

[12] T. Li, J. Yuan, and M. Torlak, "Network throughput optimization for random access narrowband cognitive radio Internet of Things (NB-CR-IoT)," *IEEE Internet Things J.*, vol. 5, no. 3, pp. 1436–1448, Jun. 2018.

[13] C. Tang, L. Song, J. Balasubramani, S. Wu, S. Biaz, Q. Yang, and H. Wang, "Comparative investigation on CSMA/CA-based opportunistic random access for Internet of Things," *IEEE Internet Things J.*, vol. 1, no. 2, pp. 171–179, Apr. 2014.

[14] S. A. Hanna, "Regulations and standards for wireless medical applications," in *Proc. 3rd Int. Symp. Med. Inf. Commun. Technol.*, 2009, pp. 23–26.

[15] M. N. Islam and M. R. Yuce, "Review of medical implant communication system (MICS) band and network," *ICT Express*, vol. 2, no. 4, pp. 188–194, Dec. 2016.

[16] L. Wang, P. Wang, C. Yi, and Y. Li, "Energy consumption optimization based on transmission distance for wireless on-body communication," in *Proc. Int. Conf. Wireless Commun. Signal Process.*, Oct. 2013, pp. 1–6.

[17] P. Phunchongharn, E. Hossain, D. Niyato, and S. Camorlinga, "A cognitive radio system for e-health applications in a hospital environment," *IEEE Wireless Commun.*, vol. 17, no. 1, pp. 20–28, Feb. 2010.

[18] P. Nagaraju, M. Ramasamy, and S. Noushad, "Implementation of CPLD based receiver of telemetry device for maternal-fetal monitoring," *Int. J. Current Eng. Technol.*, vol. 4, no. 3, pp. 1–6, 2014.

[19] M. R. Yuce and C. K. Ho, "Implementation of body area networks based on MICS/WMTS medical bands for healthcare systems," in *Proc. 30th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (IEEE EMBC)*, Aug. 2008, pp. 3417–3421.

[20] M. Hamalainen, A. Taparugssanagorn, R. Tesi, and J. Iinatti, "Wireless medical communications using UWB," in *Proc. IEEE Int. Conf. Ultra-Wideband*, Sep. 2009, pp. 485–489.

[21] R. Chavez-Santiago, K. E. Nolan, O. Holland, L. De Nardis, J. M. Ferro, N. Barroca, L. M. Borges, F. J. Velez, V. Goncalves, and I. Balasingham, "Cognitive radio for medical body area networks using ultra wideband," *IEEE Wireless Commun.*, vol. 19, no. 4, pp. 74–81, Aug. 2012.

[22] K. Domdouzis, B. Kumar, and C. Anumba, "Radio-frequency identification (RFID) applications: A brief introduction," *Adv. Eng. Inform.*, vol. 21, no. 4, pp. 350–355, 2007.

[23] RFID Working Group, "Radio frequency identification: Opportunities and challenges in implementation," Dept. Defence, Washington, DC, USA, Tech. Rep., 2005.
[24] *RFID Frequency Bands and Spectrum*, Electronics Notes, 2019. [Online]. Available: https://www.electronics-notes.com/articles/connectivity/rfid-radio-frequency-identification/frequency-bands-spectrum.php
[25] P. McNeil, "IoT wireless standards in a nutshell," Pasternack Blog, 2019.
[26] P. Kamalinejad, C. Mahapatra, Z. Sheng, S. Mirabbasi, V. C. M. Leung, and Y. L. Guan, "Wireless energy harvesting for the Internet of Things," *IEEE Commun. Mag.*, vol. 53, no. 6, pp. 102–108, Jun. 2015.
[27] S. Carreon-Bautista, L. Huang, and E. Sánchez-Sinencio, "An autonomous energy harvesting power management unit with digital regulation for IoT applications," *IEEE J. Solid-State Circuits*, vol. 51, no. 6, pp. 1457–1474, Jun. 2016.
[28] H. Kawabata, K. Ishibashi, S. Vuppala, and G. T. F. de Abreu, "Robust relay selection for large-scale energy-harvesting IoT networks," *IEEE Internet Things J.*, vol. 4, no. 2, pp. 384–392, Apr. 2017.
[29] Z. Yang, W. Xu, Y. Pan, C. Pan, and M. Chen, "Energy efficient resource allocation in machine-to-machine communications with multiple access and energy harvesting for IoT," *IEEE Internet Things J.*, vol. 5, no. 1, pp. 229–245, Feb. 2018.
[30] R. Umar, A. U. H Sheikh, and M. Deriche, "Unveiling the hidden assumptions of energy detector based spectrum sensing for cognitive radios," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 2, pp. 713–728, 2nd Quart. 2014.
[31] A. F. Eduardo and R. G. G. Caballero, "Experimental evaluation of performance for spectrum sensing: Matched filter vs energy detector," in *Proc. IEEE Colombian Conf. Commun. Comput. (IEEE COLCOM)*, May 2015, pp. 1–6.
[32] S. Dikmese, P. C. Sofotasios, M. Renfors, and M. Valkama, "Subband energy based reduced complexity spectrum sensing under noise uncertainty and frequency-selective spectral characteristics," *IEEE Trans. Signal Process.*, vol. 64, no. 1, pp. 131–145, Jan. 2016.
[33] Y. Alghorani, G. Kaddoum, S. Muhaidat, and S. Pierre, "On the approximate analysis of energy detection over n^* Rayleigh fading channels through cooperative spectrum sensing," *IEEE Wireless Commun. Lett.*, vol. 4, no. 4, pp. 413–416, Aug. 2015.
[34] E. Chatziantoniou, B. Allen, and V. Velisavljevic, "Threshold optimization for energy detection-based spectrum sensing over hyper-Rayleigh fading channels," *IEEE Commun. Lett.*, vol. 19, no. 6, pp. 1077–1080, Jun. 2015.
[35] F. Awin, E. Abdel-Raheem, and K. Tepe, "Blind spectrum sensing approaches for interweaved cognitive radio system: A tutorial and short course," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 1, pp. 238–259, 1st Quart., 2019.
[36] F. Salahdine, H. El Ghazi, N. Kaabouch, and W. F. Fihri, "Matched filter detection with dynamic threshold for cognitive radio networks," in *Proc. Int. Conf. Wireless Netw. Mobile Commun. (WINCOM)*, Oct. 2015, pp. 1–6.
[37] X. Zhang, R. Chai, and F. Gao, "Matched filter based spectrum sensing and power level detection for cognitive radio network," in *Proc. IEEE Global Conf. Signal Inf. Process. (GlobalSIP)*, Dec. 2014, pp. 1267–1270.
[38] Q. Lv and F. Gao, "Matched filter based spectrum sensing and power level recognition with multiple antennas," in *Proc. IEEE China Summit Int. Conf. Signal Inf. Process. (ChinaSIP)*, Jul. 2015, pp. 305–309.
[39] D. Cohen and Y. C. Eldar, "Compressed cyclostationary detection for cognitive radio," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process. (ICASSP)*, Mar. 2017, pp. 3509–3513.
[40] S. Atapattu, C. Tellambura, and H. Jiang, "Energy detection based cooperative spectrum sensing in cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 4, pp. 1232–1241, Apr. 2011.
[41] S. K. Sharma, T. E. Bógale, S. Chatzinotas, L. B. Le, X. Wang, and B. Ottersten, "Improving robustness of cyclostationary detectors to cyclic frequency mismatch using slepian basis," in *Proc. IEEE 26th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Aug./Sep. 2015, pp. 456–460.
[42] P. S. Yawada and J. W. An, "Cyclostationary detection based on non-cooperative spectrum sensing in cognitive radio network," in *Proc. IEEE Int. Conf. Cyber Technol. Automat., Control, Intell. Syst. (CYBER)*, Jun. 2016, pp. 184–187.
[43] I. Ilyas, S. Paul, A. Rahman, and R. K. Kundu, "Comparative evaluation of cyclostationary detection based cognitive spectrum sensing," in *Proc. IEEE 7th Annu. Ubiquitous Comput., Electron. Mobile Commun. Conf. (UEMCON)*, Oct. 2016, pp. 1–7.
[44] M. Yang, Y. Li, X. Liu, and W. Tang, "Cyclostationary feature detection based spectrum sensing algorithm under complicated electromagnetic environment in cognitive radio networks," *China Commun.*, vol. 12, no. 9, pp. 35–44, 2015.
[45] S. K. Sharma, S. Chatzinotas, and B. Ottersten, "Eigenvalue-based sensing and SNR estimation for cognitive radio in presence of noise correlation," *IEEE Trans. Veh. Technol.*, vol. 62, no. 8, pp. 3671–3684, Oct. 2013.
[46] Y. Zeng and Y.-C. Liang, "Eigenvalue-based spectrum sensing algorithms for cognitive radio," *IEEE Trans. Commun.*, vol. 57, no. 6, pp. 1784–1793, Jun. 2009.
[47] A. Kortun, T. Ratnarajah, M. Sellathurai, Y.-C. Liang, and Y. Zeng, "On the eigenvalue-based spectrum sensing and secondary user throughput," *IEEE Trans. Veh. Technol.*, vol. 63, no. 3, pp. 1480–1486, Mar. 2014.
[48] Y. Zeng and Y.-C. Liang, "Maximum-minimum eigenvalue detection for cognitive radio," in *Proc. IEEE 18th Int. Symp. Pers., Indoor Mobile Radio Commun.*, Sep. 2007, pp. 1–5.
[49] S. M. Spangenberg, I. Scott, S. McLaughlin, G. J. R. Povey, D. G. M. Cruickshank, and P. M. Grant, "An FFT-based approach for fast acquisition in spread spectrum communication systems," *Wireless Pers. Commun.*, vol. 13, no. 1, pp. 27–55, 2000.
[50] Z. Quan, S. Cui, A. H. Sayed, and H. V. Poor, "Optimal multiband joint detection for spectrum sensing in cognitive radio networks," *IEEE Trans. Signal Process.*, vol. 57, no. 3, pp. 1128–1140, Mar. 2009.
[51] Z. Quan, S. Cui, A. H. Sayed, and H. V. Poor, "Wideband spectrum sensing in cognitive radio networks," in *Proc. IEEE Int. Conf. Commun.*, May 2008, pp. 901–906.
[52] B. Farhang-Boroujeny, "Filter bank spectrum sensing for cognitive radios," *IEEE Trans. Signal Process.*, vol. 56, no. 5, pp. 1801–1811, May 2008.
[53] M. Kim and J. Takada, "Efficient multi-channel wideband spectrum sensing technique using filter bank," in *Proc. IEEE 20th Int. Symp. Pers., Indoor Mobile Radio Commun.*, Sep. 2009, pp. 1014–1018.
[54] M. Lin, A. P. Vinod, and C.-M. Samson, "Progressive decimation filter banks for variable resolution spectrum sensing in cognitive radios," in *Proc. 17th Int. Conf. Telecommun.*, Apr. 2010, pp. 857–863.
[55] Z. Tian and G. B. Giannakis, "A wavelet approach to wideband spectrum sensing for cognitive radios," in *Proc. Int. Conf. Cogn. Radio Oriented Wireless Netw. Commun.*, Jun. 2006, pp. 1–5.
[56] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *IEEE Commun. Surveys Tuts.*, vol. 11, no. 1, pp. 116–130, 1st Quart., 2009.
[57] X. Zhang, Y. Ma, Y. Gao, and W. Zhang, "Autonomous compressive-sensing-augmented spectrum sensing," *IEEE Trans. Veh. Technol.*, vol. 67, no. 8, pp. 6970–6980, Aug. 2018.
[58] X. Zhang, "Compressive spectrum sensing in cognitive IoT," Ph.D. dissertation, School Electron. Eng. Comput. Sci., Queen Mary Univ. London, London, U.K., 2018.
[59] Z. Tian and G. B. Giannakis, "Compressed sensing for wideband cognitive radios," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process. (ICASSP)*, vol. 4, Apr. 2007, pp. IV-1357–IV-1360.
[60] Z. Qin, Y. Gao, M. D. Plumbley, and C. G. Parini, "Wideband spectrum sensing on real-time signals at sub-Nyquist sampling rates in single and cooperative multiple nodes," *IEEE Trans. Signal Process.*, vol. 64, no. 12, pp. 3106–3117, Jun. 2016.
[61] W. Dai and O. Milenkovic, "Subspace pursuit for compressive sensing signal reconstruction," *IEEE Trans. Inf. Theory*, vol. 55, no. 5, pp. 2230–2249, May 2009.
[62] J. A. Tropp, J. N. Laska, M. F. Duarte, J. K. Romberg, and R. G. Baraniuk, "Beyond Nyquist: Efficient sampling of sparse bandlimited signals," *IEEE Trans. Inf. Theory*, vol. 56, no. 1, pp. 520–544, Jan. 2010.
[63] M. A. Davenport, J. N. Laska, J. R. Treichler, and R. G. Baraniuk, "The pros and cons of compressive sensing for wideband signal acquisition: Noise folding versus dynamic range," *IEEE Trans. Signal Process.*, vol. 60, no. 9, pp. 4628–4642, Sep. 2012.
[64] X. Zhang, Y. Ma, H. Qi, Y. Gao, Z. Xie, Z. Xie, M. Zhang, X. Wang, G. Wei, and Z. Li, "Distributed compressive sensing augmented wideband spectrum sharing for cognitive IoT," *IEEE Internet Things J.*, vol. 5, no. 4, pp. 3234–3245, Aug. 2018.
[65] Y. Ma, Y. Gao, Y.-C. Liang, and S. Cui, "Reliable and efficient sub-Nyquist wideband spectrum sensing in cooperative cognitive radio networks," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 10, pp. 2750–2762, Oct. 2016.

[66] D. D. Ariananda, G. Leus, and Z. Tian, "Multi-coset sampling for power spectrum blind sensing," in *Proc. 17th Int. Conf. Digit. Signal Process. (DSP)*, Jul. 2011, pp. 1–8.
[67] P. Feng and Y. Bresler, "Spectrum-blind minimum-rate sampling and reconstruction of multiband signals," in *Proc. IEEE Int. Conf. Acoust., Speech, Signal Process. Conf.*, vol. 3, May 1996, pp. 1688–1691.
[68] N. Al Hussien, "Narrowband and wideband spectrum sensing for cognitive radio networks in a log-normal shadowing environment," Ph.D. dissertation, Dept. Elect. Eng., United Arab Emirates Univ., Al Ain, United Arab Emirates, 2014.
[69] F. A. Awin, E. Abdel-Raheem, and M. Ahmadi, "Designing an optimal energy efficient cluster-based spectrum sensing for cognitive radio networks," *IEEE Commun. Lett.*, vol. 20, no. 9, pp. 1884–1887, Sep. 2016.
[70] F. A. Awin, E. Abdel-Raheem, and M. Ahmadi, "Optimization of multi-level hierarchical cluster-based spectrum sensing structure in cognitive radio networks," *Digit. Signal Process.*, vol. 36, pp. 15–25, Jan. 2015.
[71] F. A. Awin, E. Abdel-Raheem, and M. Ahmadi, "Novel energy efficient strategies for cooperative spectrum sensing in cognitive radio networks," in *Proc. IEEE Int. Symp. Signal Process. Inf. Technol. (ISSPIT)*, Dec. 2015, pp. 186–191.
[72] W. Zhang, Y. Guo, H. Liu, Y. Chen, Z. Wang, and J. Mitola, "Distributed consensus-based weight design for cooperative spectrum sensing," *IEEE Trans. Parallel Distrib. Syst.*, vol. 26, no. 1, pp. 54–64, Jan. 2015.
[73] A. Vosoughi, J. R. Cavallaro, and A. Marshall, "Trust-aware consensus-inspired distributed cooperative spectrum sensing for cognitive radio ad hoc networks," *IEEE Trans. Cogn. Commun. Netw.*, vol. 2, no. 1, pp. 24–37, Mar. 2016.
[74] S. P. Maity, S. Chatterjee, and T. Acharya, "On optimal fuzzy C-means clustering for energy efficient cooperative spectrum sensing in cognitive radio networks," *Digit. Signal Process.*, vol. 49, pp. 104–115, Feb. 2016.
[75] Y. Han, A. Pandharipande, and S. H. Ting, "Cooperative decode-and-forward relaying for secondary spectrum access," *IEEE Trans. Wireless Commun.*, vol. 8, no. 10, pp. 4945–4950, Oct. 2009.
[76] S. Althunibat, M. Di Renzo, and F. Granelli, "Towards energy-efficient cooperative spectrum sensing for cognitive radio networks: An overview," *Telecommun. Syst.*, vol. 59, no. 1, pp. 77–91, 2015.
[77] I. F. Akyildiz, B. F. Lo, and R. Balakrishnan, "Cooperative spectrum sensing in cognitive radio networks: A survey," *Phys. Commun.*, vol. 4, no. 1, pp. 40–62, Mar. 2011.
[78] A. Garhwal and P. P. Bhattacharya, "A survey on dynamic spectrum access techniques for cognitive radio," *Int. J. Next-Gener. Netw.*, vol. 3, no. 4, pp. 15–32, Dec. 2011.
[79] S. Mohapatra, P. K. Sahoo, and J.-P. Sheu, "Spectrum allocation with guaranteed rendezvous in asynchronous cognitive radio networks for Internet of Things," *IEEE Internet Things J.*, to be published.
[80] O. A. Mohammed, K. El-Khatib, and M. V. Martin, "A survey of cognitive radio management functions," in *Proc. 4th Int. Conf. COCORA*, 2014, pp. 6–13.
[81] M. Rahman, S. H. Ahmed, and M. Yuksel, "Proof of sharing in inter-operator spectrum sharing markets," in *Proc. IEEE Int. Symp. Dyn. Spectr. Access Netw. (DySPAN)*, Oct. 2018, pp. 1–5.
[82] Y. Zhang, L. Song, M. Pan, Z. Dawy, and Z. Han, "Non-cash auction for spectrum trading in cognitive radio networks: Contract theoretical model with joint adverse selection and moral hazard," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 3, pp. 643–653, Mar. 2017.
[83] A. V. Kordali and P. G. Cottis, "A contract-based spectrum trading scheme for cognitive radio networks enabling hybrid access," *IEEE Access*, vol. 3, pp. 1531–1540, 2015.
[84] M. Amjad, F. Akhtar, M. H. Rehmani, M. Reisslein, and T. Umer, "Full-duplex communication in cognitive radio networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 4, pp. 2158–2191, 4th Quart., 2017.
[85] A. Ali and W. Hamouda, "Advances on spectrum sensing for cognitive radio networks: Theory and applications," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 2, pp. 1277–1304, 2nd Quart., 2016.
[86] P. He, M. Li, L. Zhao, B. Venkatesh, and H. Li, "Water-filling exact solutions for load balancing of smart power grid systems," *IEEE Trans. Smart Grid*, vol. 9, no. 2, pp. 1397–1407, Mar. 2018.
[87] S. Arumugam and D. Perumal, "Power control through water filling game theory in adaptive modulation based MCCDMA-MIMO system," in *Proc. Int. Conf. Commun. Signal Process. (ICCSP)*, Apr. 2016, pp. 1415–1419.
[88] C. Guo, B. Liao, L. Huang, X. Lin, and J. Zhang, "On convexity of fairness-aware energy-efficient power allocation in spectrum-sharing networks," *IEEE Commun. Lett.*, vol. 20, no. 3, pp. 534–537, Mar. 2016.
[89] Y. Liao, L. Song, Z. Han, and Y. Li, "Full duplex cognitive radio: A new design paradigm for enhancing spectrum usage," *IEEE Commun. Mag.*, vol. 53, no. 5, pp. 138–145, May 2015.
[90] F. Wang, J. Wang, and W. W. Li, "Game-theoretic analysis of opportunistic spectrum sharing with imperfect sensing," *EURASIP J. Wireless Commun. Netw.*, vol. 2016, no. 1, pp. 141–152, Dec. 2016.
[91] J. Li, H. Zhao, J. Wei, D. Ma, and L. Zhou, "Sender-jump receiver-wait: A simple blind rendezvous algorithm for distributed cognitive radio networks," *IEEE Trans. Mobile Comput.*, vol. 17, no. 1, pp. 183–196, Jan. 2018.
[92] B. Yang, M. Zheng, and W. Liang, "A time-efficient rendezvous algorithm with a full rendezvous degree for heterogeneous cognitive radio networks," in *Proc. 35th Annu. IEEE Int. Conf. Comput. Commun. (INFOCOM)*, Apr. 2016, pp. 1–9.
[93] X. Liu and J. L. Xie, "Priority-based spectrum access in cognitive D2D networks for IoT," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2017, pp. 1–6.
[94] N. Ahmed, H. Rahman, and M. I. Hussain, "A comparison of 802.11ah and 802.15.4 for IoT," *ICT Express*, vol. 2, no. 3, pp. 100–102, 2016.
[95] H. Kim, S.-W. Ko, and S.-L. Kim, "Cognitive random access for Internet-of-Things networks," in *Proc. IEEE 85th Veh. Technol. Conf. (VTC Spring)*, Jun. 2017, pp. 1–5.
[96] F. F. Qureshi, R. Iqbal, and M. N. Asghar, "Energy efficient wireless communication technique based on cognitive radio for Internet of Things," *J. Netw. Comput. Appl.*, vol. 89, pp. 14–25, Jul. 2017.
[97] Y. B. Zikria, F. Ishmanov, M. K. Afzal, S. W. Kim, S. Y. Nam, and H. Yu, "Opportunistic channel selection MAC protocol for cognitive radio ad hoc sensor networks in the Internet of Things," *Sustain. Comput., Inform. Syst.*, vol. 18, pp. 112–120, Jun. 2018.
[98] I. Christian, S. Moh, I. Chung, and J. Lee, "Spectrum mobility in cognitive radio networks," *IEEE Commun. Mag.*, vol. 50, no. 6, pp. 114–121, Jun. 2012.
[99] P. Thakur, A. Kumar, S. Pandit, G. Singh, and S. N. Satashia, "Spectrum mobility in cognitive radio network using spectrum prediction and monitoring techniques," *Phys. Commun.*, vol. 24, pp. 1–8, Sep. 2017.
[100] Y. Saleem, F. Salim, and M. H. Rehmani, "Routing and channel selection from cognitive radio network's perspective: A survey," *Comput. Elect. Eng.*, vol. 42, pp. 117–134, Feb. 2015.
[101] P. He, L. Zhao, S. Zhou, and Z. Niu, "Water-filling: A geometric approach and its application to solve generalized radio resource allocation problems," *IEEE Trans. Wireless Commun.*, vol. 12, no. 7, pp. 3637–3647, Jul. 2013.
[102] L. Song, D. Niyato, Z. Han, and E. Hossain, "Game-theoretic resource allocation methods for device-to-device communication," *IEEE Wireless Commun.*, vol. 21, no. 3, pp. 136–144, Jun. 2014.
[103] J. Huang, R. A. Berry, and M. L. Honig, "Auction-based spectrum sharing," *Mobile Netw. Appl.*, vol. 11, no. 3, pp. 405–418, Jun. 2006.
[104] M. M. Hossain, M. Fotouhi, and R. Hasan, "Towards an analysis of security issues, challenges, and open problems in the Internet of Things," in *Proc. IEEE World Congr. Services*, Jun./Jul. 2015, pp. 21–28.
[105] A.-R. Sadeghi, C. Wachsmann, and M. Waidner, "Security and privacy challenges in industrial Internet of Things," in *Proc. 52nd ACM/EDAC/IEEE Design Autom. Conf. (DAC)*, Jun. 2015, pp. 1–6.
[106] J. Lin, W. Yu, N. Zhang, X. Yang, H. Zhang, and W. Zhao, "A survey on Internet of Things: Architecture, enabling technologies, security and privacy, and applications," *IEEE Internet Things J.*, vol. 4, no. 5, pp. 1125–1142, Oct. 2017.
[107] E. Vasilomanolakis, J. Daubert, M. Luthra, V. Gazis, A. Wiesmaier, and P. Kikiras, "On the security and privacy of Internet of Things architectures and systems," in *Proc. Int. Workshop Secure Internet Things (SIoT)*, Sep. 2015, pp. 49–57.
[108] A. R. Sfar, E. Natalizio, Y. Challal, and Z. Chtourou, "A roadmap for security challenges in the Internet of Things," *Digit. Commun. Netw.*, vol. 4, no. 2, pp. 118–137, 2018.
[109] Z.-K. Zhang, M. C. Y. Cho, C.-W. Wang, C.-W. Hsu, C.-K. Chen, and S. Shieh, "IoT security: Ongoing challenges and research opportunities," in *Proc. IEEE 7th Int. Conf. Service-Oriented Comput. Appl.*, Nov. 2014, pp. 230–234.
[110] M. Abomhara and G. M. Køien, "Security and privacy in the Internet of Things: Current status and open issues," in *Proc. Int. Conf. Privacy Secur. Mobile Syst. (PRISMS)*, May 2014, pp. 1–8.

[111] Z. B. Celik, E. Fernandes, E. Pauley, G. Tan, and P. McDaniel, "Program analysis of commodity IoT applications for security and privacy: Challenges and opportunities," 2018, *arXiv:1809.06962*. [Online]. Available: https://arxiv.org/abs/1809.06962

[112] M. Benchoufi and P. Ravaud, "Blockchain technology for improving clinical research quality," *Trials*, vol. 18, no. 1, p. 335, 2017.

[113] M. S. Ali, M. Vecchio, M. Pincheira, K. Dolui, F. Antonelli, and M. H. Rehmani, "Applications of blockchains in the Internet of Things: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 2, pp. 1676–1717, 2nd Quart., 2019.

[114] Z. Zheng, S. Xie, H.-N. Dai, X. Chen, and H. Wang, "Blockchain challenges and opportunities: A survey," *Int. J. Web Grid Services*, vol. 14, no. 4, pp. 352–375, 2016.

[115] K. Kotobi and S. G. Bilén, "Blockchain-enabled spectrum access in cognitive radio networks," in *Proc. Wireless Telecommun. Symp. (WTS)*, Apr. 2017, pp. 1–6.

[116] K. Kotobi and S. G. Bilen, "Secure blockchains for dynamic spectrum access: A decentralized database in moving cognitive radio networks enhances security and user access," *IEEE Veh. Technol. Mag.*, vol. 13, no. 1, pp. 32–39, Mar. 2018.

[117] L. Axon, "Privacy-awareness in blockchain-based PKI," Tech. Rep., 2015.

[118] C. Fromknecht, D. Velicanu, and S. Yakoubov, "Certcoin: A namecoin based decentralized authentication system 6.857 class project," Class Project, [Online]. Available: https://pdfs.semanticscholar.org/7288/9440eaeb7a1a17a8be830feff236b5a62b67.pdf

[119] Y. Zhang and J. Wen, "An IoT electric business model based on the protocol of bitcoin," in *Proc. 18th Int. Conf. Intell. Next Gener. Netw.*, Feb. 2015, pp. 184–191.

[120] D. Wörner and T. von Bomhard, "When your sensor earns money: Exchanging data for cash with Bitcoin," in *Proc. ACM Int. Joint Conf. Pervasive Ubiquitous Comput., Adjunct Publication*, 2014, pp. 295–298.

[121] G. Zyskind, O. Nathan, and A. Pentland, "Enigma: Decentralized computation platform with guaranteed privacy," 2015, *arXiv:1506.03471*. [Online]. Available: https://arxiv.org/abs/1506.03471

[122] M. A. Khan and K. Salah, "IoT security: Review, blockchain solutions, and open challenges," *Future Gener. Comput. Syst.*, vol. 82, pp. 395–411, May 2018.

[123] P. Brody and V. Pureswaran, "Device democracy: Saving the future of the Internet of Things," IBM, New York, NY, USA, Executive Rep., pp. 1–25. [Online]. Available: https://www.ibm.com/downloads/cas/Y5ONA8EV?mhsrc=ibmsearch_a&mhq=Device%20Democracy%3A%20 Saving%20the%20Future%20of%20the%20Internet%20of%20Things

[124] A. Bahga and V. K. Madisetti, "Blockchain platform for industrial Internet of Things," *J. Softw. Eng. Appl.*, vol. 9, no. 10, p. 533, 2016.

[125] A. M. Saghiri, M. Vahdati, K. Gholizadeh, M. R. Meybodi, M. Dehghan, and H. Rashidi, "A framework for cognitive Internet of Things based on blockchain," in *Proc. 4th Int. Conf. Web Res. (ICWR)*, Apr. 2018, pp. 138–143.

[126] Y. Dai, D. Xu, S. Maharjan, Z. Chen, Q. He, and Y. Zhang, "Blockchain and deep reinforcement learning empowered intelligent 5G beyond," *IEEE Netw.*, vol. 33, no. 3, pp. 10–17, May/Jun. 2019.

[127] M. S. Mahdavinejad, M. Rezvan, M. Barekatain, P. Adibi, P. Barnaghi, and A. P. Sheth, "Machine learning for Internet of Things data analysis: A survey," *Digit. Commun. Netw.*, vol. 4, no. 3, pp. 161–175, 2018.

[128] P. M. Kumar and U. D. Gandhi, "A novel three-tier Internet of Things architecture with machine learning algorithm for early detection of heart diseases," *Comput. Elect. Eng.*, vol. 65, pp. 222–235, Jan. 2018.

[129] Y. Meidan, M. Bohadana, A. Shabtai, J. D. Guarnizo, M. Ochoa, N. O. Tippenhauer, and Y. Elovici, "Profiliot: A machine learning approach for IoT device identification based on network traffic analysis," in *Proc. Symp. Appl. Comput.*, 2017, pp. 506–509.

[130] J. Cañedo and A. Skjellum, "Using machine learning to secure IoT systems," in *Proc. 14th Annu. Conf. Privacy, Secur. Trust (PST)*, Dec. 2016, pp. 219–222.

[131] P. S. Pandey, "Machine learning and IoT for prediction and detection of stress," in *Proc. 17th Int. Conf. Comput. Sci. Appl. (ICCSA)*, Jul. 2017, pp. 1–5.

[132] M. Bkassiny, Y. Li, and S. K. Jayaweera, "A survey on machine-learning techniques in cognitive radios," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 3, pp. 1136–1159, 3rd Quart., 2013.

[133] K. Thilina, K. W. Choi, N. Saquib, and E. Hossain, "Machine learning techniques for cooperative spectrum sensing in cognitive radio networks," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 11, pp. 2209–2221, Nov. 2013.

[134] H. B. Yilmaz, T. Tugcu, F. Alagöz, and S. Bayhan, "Radio environment map as enabler for practical cognitive radio networks," *IEEE Commun. Mag.*, vol. 51, no. 12, pp. 162–169, Dec. 2013.

[135] Y. Zhao, J. Gaeddert, K. K. Bae, and J. H. Reed, "Radio environment map enabled situation-aware cognitive radio learning algorithms," in *Proc. Softw. Defined Radio Forum Tech. Conf. (SDRF)*, 2006, pp. 1–6.

[136] C. Jiang, H. Zhang, Y. Ren, Z. Han, K.-C. Chen, and L. Hanzo, "Machine learning paradigms for next-generation wireless networks," *IEEE Wireless Commun.*, vol. 24, no. 2, pp. 98–105, Apr. 2017.

[137] H. Wang, D. N. Nguyen, D. T. Hoang, E. Dutkiewicz, and Q. Cheng, "Real-time crowdsourcing incentive for radio environment maps: A dynamic pricing approach," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2018, pp. 1–6.

[138] T. Kritsonis. (2019). *Five of the Biggest Challenges Facing 5G*. [Online]. Available: https://www.futurithmic.com/2019/02/26/five-biggest-challenges-facing-5g/

[139] S. Li, L. Da Xu, and S. Zhao, "5G Internet of Things: A survey," *J. Ind. Inf. Integr.*, vol. 10, pp. 1–9, Jun. 2018.

[140] M. Ndiaye, G. P. Hancke, and A. M. Abu-Mahfouz, "Software defined networking for improved wireless sensor network management: A survey," *Sensors*, vol. 17, no. 5, p. 1031, 2017.

[141] K. M. Modieginyane, B. B. Letswamotse, R. Malekian, and A. M. Abu-Mahfouz, "Software defined wireless sensor networks application opportunities for efficient network management: A survey," *Comput. Elect. Eng.*, vol. 66, pp. 274–287, Feb. 2018.

[142] M. Elkhodr, S. Shahrestani, and H. Cheung, "The Internet of Things: New interoperability, management and security challenges," 2016, *arXiv:1604.04824*. [Online]. Available: https://arxiv.org/abs/1604.04824

[143] S. Zhao, L. Yu, and B. Cheng, "An event-driven service provisioning mechanism for IoT (Internet of Things) system interaction," *IEEE Access*, vol. 4, pp. 5038–5051, 2016.

[144] A. Banafa. (2016). *IoT Standardization and Implementation Challenges*. [Online]. Available: https://iot.ieee.org/newsletter/july-2016/iot-standardization-and-implementation-challenges.html

[145] I. Ishaq, D. Carels, G. K. Teklemariam, J. Hoebeke, F. Van den Abeele, E. De Poorter, I. Moerman, and P. Demeester, "IETF standardization in the field of the Internet of Things (IoT): A survey," *J. Sensor Actuator Netw.*, vol. 2, no. 2, pp. 235–287, Apr. 2013.

[146] F. Chen, P. Deng, J. Wan, D. Zhang, A. V. Vasilakos, and X. Rong, "Data mining for the Internet of Things: Literature review and challenges," *Int. J. Distrib. Sensor Netw.*, vol. 11, no. 8, 2015, Art. no. 431047.

[147] C.-W. Tsai, C.-F. Lai, M.-C. Chiang, and L. T. Yang, "Data mining for Internet of Things: A survey," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 1, pp. 77–97, 1st Quart., 2014.

[148] M. Marjani, F. Nasaruddin, A. Gani, A. Karim, I. A. T. Hashem, A. Siddiqa, and I. Yaqoob, "Big IoT Data analytics: Architecture, opportunities, and open research challenges," *IEEE Access*, vol. 5, pp. 5247–5261, 2017.

[149] I. Lee and K. Lee, "The Internet of Things (IoT): Applications, investments, and challenges for enterprises," *Bus. Horizons*, vol. 58, no. 4, pp. 431–440, 2015.

[150] B. Farahani, F. Firouzi, V. Chang, M. Badaroglu, N. Constant, and K. Mankodiya, "Towards fog-driven IoT eHealth: Promises and challenges of IoT in medicine and healthcare," *Future Generat. Comput. Syst.*, vol. 78, pp. 659–676, Jan. 2018.

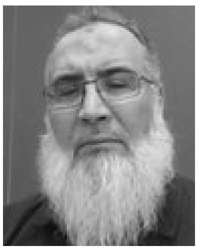
[151] G. Manogaran, R. Varatharajan, D. Lopez, P. M. Kumar, R. Sundarasekar, and C. Thota, "A new architecture of Internet of Things and big data ecosystem for secured smart healthcare monitoring and alerting system," *Future Gener. Comput. Syst.*, vol. 82, pp. 375–387, May 2018.

[152] A. A. Mutlag, M. K. A. Ghani, N. Arunkumar, M. A. Mohammed, and O. Mohd, "Enabling technologies for fog computing in healthcare IoT systems," *Future Gener. Comput. Syst.*, vol. 90, pp. 62–78, Jan. 2019.

[153] C. Jardak, P. Mähönen, and J. Riihijärvi, "Spatial big data and wireless networks: Experiences, applications, and research challenges," *IEEE Netw.*, vol. 28, no. 4, pp. 26–31, Jul./Aug. 2014.

[154] G. Ding, Q. Wu, J. Wang, and Y.-D. Yao, "Big spectrum data: The new resource for cognitive wireless networking," 2014, *arXiv:1404.6508*. [Online]. Available: https://arxiv.org/abs/1404.6508

[155] M. S. Hadi, A. Q. Lawey, T. E. H. El-Gorashi, and J. M. H. Elmirghani, "Big data analytics for wireless and wired network design: A survey," *Comput. Netw.*, vol. 132, pp. 180–199, Feb. 2018.
[156] G. Baruffa, M. Femminella, M. Pergolesi, and G. Reali, "A big data architecture for spectrum monitoring in cognitive radio applications," *Ann. Telecommun.*, vol. 73, nos. 7–8, pp. 451–461, 2018.
[157] A. W. Min and K. G. Shin, "Impact of mobility on spectrum sensing in cognitive radio networks," in *Proc. ACM Workshop Cogn. Radio Netw.*, 2009, pp. 13–18.
[158] F. A. Awin, E. Abdel-Raheem, and M. Ahmadi, "On the impact of acceleration on the performance of mobile cognitive radios," in *Proc. IEEE 56th Int. Midwest Symp. Circuits Syst. (MWSCAS)*, Aug. 2013, pp. 1330–1333.
[159] R. C. Abeywardana, K. W. Sowerby, and S. M. Berber, "Spectrum sensing in cognitive radio enabled vehicular ad hoc networks: A review," in *Proc. 7th Int. Conf. Inf. Automat. Sustainability*, Dec. 2014, pp. 1–6.
[160] S. Jana, K. Zeng, W. Cheng, and P. Mohapatra, "Trusted collaborative spectrum sensing for mobile cognitive radio networks," *IEEE Trans. Inf. Forensics Security*, vol. 8, no. 9, pp. 1497–1507, Sep. 2013.
[161] 3GPP. (2016). *Standardization of NB-IoT Completed*. [Online]. Available: https://www.3gpp.org/news-events/1785-nb-iot-complete
[162] A. R. Sfar, E. Natalizio, Y. Challal, and Z. Chtourou, "A roadmap for security challenges in the Internet of Things," *Digit. Commun. Netw.*, vol. 4, no. 2, pp. 118–137, 2018.



FAROQ A. AWIN (M'08) received the B.Sc. degree in electrical and electronic engineering from the University of Tripoli, Libya, in 1996, the M.Sc. degree in precision instruments and Machinery from Beihang University, Beijing, China, in 2004, and the Ph.D. degree from the University of Windsor, Canada, in 2016. He was a Researcher with the Electronic Research Center, Tripoli, Libya, from 1997 to 2008. From 2008 to 2010, he was a Lecturer with the Electrical and Electrical Engineering Department, University of Tripoli, where he is currently an Adjunct Professor. From 2011 to 2016, he was a Research Assistant with the University of Windsor, where he is also a Postdoctoral Fellow with the Wireless Communication and Information Processing Laboratory. He has published several articles in well-known journals and international conferences. His research interests include cognitive radio networks, spectrum sensing, signal processing in communication systems, wireless communications, the Internet of Things (IoT), and wireless sensor networks. He has been serving as a Peer Reviewer for several of refereed international journal and conferences.

YASSER M. ALGINAHI (M'02–SM'10) received the M.Sc. degree in electrical engineering from Wright State University, Dayton, OH, USA, and the Ph.D. degree in electrical engineering from the University of Windsor, Windsor, ON, Canada. He was an Associate Professor with the Department of Computer Science, College of Computer Science and Engineering, Taibah University. He is currently a Visiting Professor with the Department of Electrical and Computer Engineering, University of Windsor. He was a Principle Investigator and a Co-Principle Investigator of many funded research projects by the Deanship of Scientific Research, Taibah University, and other organizations, such as the King Abdulaziz City for Science and Technology. He has authored a book titled *Document Image Analysis* and over 80 journal and conference papers. He has authored or coauthored about 80 articles in refereed journal and conference publications. His most recent publication, as an editor, for a book titled *Authentication Technologies for Cloud Computing, IoT and Big Data* (IET, U.K.). His current research interests include cognitive radio networks, machine learning, information security, document image analysis, pattern recognition, and numerical computations. He is also a member of Professional Engineers Ontario. He has been a Senior Member of IACSIT, since 2010. He is on the editorial board of several international journals. He is a licensed Professional Engineer in Ontario, Canada.

ESAM ABDEL-RAHEEM (M'97–SM'00) received the B.Sc. and M.Sc. degrees from Ain Shams University, Cairo, Egypt, in 1984 and 1989, respectively, and the Ph.D. degree from the University of Victoria, Canada, in 1995, all in electrical engineering. In 1997, he joined Ain Shams University as an Assistant Professor. From 1999 to 2001, he was a Senior Design Engineer with AMD, Sunnyvale, CA, USA. He was an Adjunct Associate Professor with the University of Victoria, BC, Canada, from 2003 to 2009. Since 2003, he has been with the ECE Department, University of Windsor, Ontario, Canada, where he has been a Full Professor, since 2014. He has authored or coauthored about 100 articles in refereed journal and conference publications, including one published U.S./EU/world patent. His research interests include digital signal/image/video processing, signal processing for communications, VLSI signal processing systems, and spectrum sensing for cognitive radio networks. He was an Editorial Broad Member of *IET signal Processing*, from 2006 to 2018. He is also a member of the Association of Professional Engineers Ontario. He has served as the Technical Program Co-Chair for IEEE ISSPIT 2004 and 2005 and EIT 2009. He was the General Co-Chair for IEEE ISSPIT 2007, IEEE CCECE'2017, and IEEE ISSPIT 2018. He served as an Associate Editor for the *Canadian Journal of Electrical and Computer Engineering*, from 2006 to 2010, and *Circuits, Systems and Signal Processing*, from 2007 to 2015.

KEMAL TEPE received the B.Sc. degree from Hacettepe University, Ankara, Turkey, in 1992, and the M.A.Sc. and Ph.D. degrees from the Rensselaer Polytechnic Institute, Troy, NY, USA, in 1996 and 2001, all in electrical engineering. He was a Research Scientist with Telcordia Technologies, Red Bank, NJ, USA, and a Postdoctoral Researcher with Rutgers University, from 2001 to 2002. In 2002, he joined the University of Windsor and founded the Wireless Communication and Information Processing Research Laboratory (WiCIP). His research interests include wireless communication systems, vehicle-to-vehicle (V2V) communications, wireless sensor networking, and network protocols. He is particularly interested in real-time wireless communication protocols in sensor networks, applications of sensor networking in smart grid applications, vehicular networks, vehicular networks for safety/emergency messaging, vehicular Internet access protocols, the Internet of Things (IoT), and machine-to-machine (M2M) communications.