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A review of industrial wireless communications, challenges, and solutions: A cognitive radio approach

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Abstract

Integral and crucial to performance of wireless sensor networks (WSNs), and specifically industrial wireless sensor network (IWSN) is stable, robust, reliable, and ubiquitous communications system. Though, wired communications system is suitable for industrial communications and is resilient to shadowing and multipath fading effects of industrial-WSN environments, yet its wireless counterpart is a much preferred industrial communications technology due to reduced cost and high flexibility which it offers in comparison to wired communications. However, overcrowding of the industrial, scientific, and medical band, where IWSN is deployed together with other heterogeneous technologies, as well as resultant scarcity of usable frequency spectrum has restrained exclusive application of wireless technology for industrial communications. Nonetheless, cognitive radio (CR) has ability to increase spectrum utilization efficiency and channel capacity for industrial wireless communications (IWC) through opportunistic/dynamic spectrum access (DSA) technique. In this review article, we examine how DSA can benefit IWC through exploitation of new perspectives of white space definitions in the licensed bands as well as unlicensed bands. While discussing the potential of DSA for IWC, we have considered the unique characteristics of IWC as well as technical challenges and issues imposed by industrial-WSN. Accordingly, we have suggested and proffered appropriate CR-based solutions in mitigating some of the challenges where necessary.

1 | INTRODUCTION

Industrial wireless communication (IWC) is the communication system (hardware and software) of wireless communication networks. These systems are typically deployed in specific application areas that include industrial and process automation, avionics, and automotive, as well as control applications.[1] In addition, IWC has unique characteristics with specific challenges. For instance, the IWC has the ability to wirelessly connect several hundred sensors and devices. Undoubtedly, this ability imposes an inimitable requirement of delivering massive network throughput at guaranteed high level of quality of services (QoS).[2] For this reason, a major concern among industrial communication stakeholders has been whether wireless technology can be the exclusive tools for industrial communication revolution. Or, if it will only complement its wired counterpart in the advancements of IWC. Nonetheless, wireless technology has driven the telecommunication and information market in the last few years as a major competitor.[1] Still, from an industrial perspective, despite the huge benefits of wireless technology, it has not yet achieved the estimated wide deployment.

As an example, wireless technology offers benefits such as increased flexibility and reduced cost when compared with wired communications. Though, wired communications have been outstanding in defying the harsh conditions affecting wireless links in industrial environments. For instance, wired communications have defied harsh conditions such as shadowing, electromagnetic (EM) interference, as well as nonline-of-sight connectivity with occlusion.[3,4] Nonetheless, the existing partial deployment of wireless technology for industrial communications is partly due to challenges including communication reliability and guaranteed delay support which remain open issues in wireless technology. Even so, the real limiting factor for the complete deployment of wireless technology in industrial communication is scarcity of frequency spectrum. Moreover, frequency spectrum remains a shared resource whether allocated on an exclusive or nonexclusive basis.[1,5] For example, dedicated bands like the unlicensed national information infrastructure, and industrial, scientific, and medical (ISM) are perfect example of spectrum which are allocated to unlicensed users on nonexclusive basis. Indeed, this open approach leads to an all-comers layout as well as an intense competition for frequency spectrum on these dedicated and unlicensed bands.[6] Conversely, on the exclusive basis, only a licensed user is allocated to a licensed band with the exclusive right to utilize the licensed band of the radio spectrum. Yet, regardless of the scheme by which frequency spectrum is allocated the frequency spectrum remains a scarce resource for real-time IWC. Certainly, this is due to the competition for available frequency spectrum on unlicensed spectrum band. Or, the static spectrum access technique adopted on the licensed spectrum space. However, cognitive radio (CR), though a wireless technology, has the capacity to provide additional spectral-space for wireless communications. Unlike conventional wireless technology, CR exploits multidimensional EM spectral opportunities. Of course, this phenomenon creates extra spectrum prospect through opportunistic utilization of the multidimensional EM space. Moreover, the multidimensional spectrum opportunities are defined in terms of frequency, time, space, code, power, and angle of arrivals, as well as polarization of wireless signals. Besides, the main concept of CR is that unlicensed users also known as CR user in CR terminology can sense, detect, access, and use vacant spectrum or leftovers when the licensed users or the primary users (PUs) are not present.[7,8] As a result, this approach is envisaged as a novel ideal that will improve the utilization of scarce spectrum resource. For this reason, recent research efforts have shifted to CR as a candidate for the realization of broadband for IWC. In distinct contrast to cited articles, our main contributions in this article are summarized as follows:

- We present an objective analysis of spectrum scarcity with graphical illustrations and identify that spectrum scarcity is not physical scarcity of usable spectrum, but artificial scarcity of spectrum due to static spectrum management policies.
- A comparative review of different spectrum sensing techniques was presented, and we identify specific reasons why cooperative or collaborative cyclostationary feature detection is candidate spectrum sensing technique in multipath fading and shadowed environments
- We discussed different modes of CR transmission with respect to IWC, and specify how spectral opportunity depends largely on explicit dimensions used for white space exploitation, then, we showed that current definition of white space does not fully harness the potential of CR communication for full benefits of IWC.

The rest of the article is organized as follows. In Section 2, we discussed related works, afterward, Section 3 presents an overview of IWC. Thereafter, an overview of CR was presented in Section 4. In addition, dynamic spectrum access (DSA) was introduced as a requirement for realization of IWC in Section 5. After that, cognitive transmission in CRN was investigated in Section 6. Subsequently, in Section 7, we examined other applications of CR technology. Then, we identified some research challenges and future research directions in Section 8. Finally, Section 9 concludes the review.

2 | RELATED WORKS

Due to the potentials of CR in overcoming frequency scarcity shortcomings, the prospect of applying CR technology for solving each spectrum scarcity problem in various wireless networks is very tempting. For this reason, CR has now become one of the most researched topics in the last decades for solving frequency scarcity challenges. Similarly, lots of research works have been conducted in industrial wireless sensor network (IWSN) in literature. However, only a few studies have considered the application of CR technology for solving technical challenges in industrial wireless technology. Still, most works applying the CR concept to IWC do so without considering the unique QoS requirements of IWC aggravated by harsh IWSN environments.[9] For example, existing research works in CR have focused more on reviewing basics of CR paradigm than attempting to integrate CR technology into other applications. As a result, spectrum sensing which is considered a key function of CR network (CRN) and believed to enable other CR functionalities has been well researched. Thus, considerable research outcomes have been reported on spectrum sensing in literature. In Reference 10, a survey of spectrum sensing methodologies in CRN was presented. Authors observed that efficient spectrum sensing techniques needed to be developed for CRN to perform effectively. Therefore, an overview of CR architecture, spectrum sensing techniques, and challenges were discussed. A classification and explanation of cooperative spectrum sensing (CSS) concepts, including IEEE standards in spectrum sensing were also presented. In a similar survey[11] different techniques and types of CSS were presented. In addition, the different types of cooperation models including comparison of the characteristics of CSS were discussed. Furthermore, authors observed that using an efficient CSS technique can minimize the impacts of receiver uncertainty, multipath fading, and shadowing. In Reference 12, a survey of state-of-the-art schemes and optimization methods for CSS and information synthesis in CRNs was presented. However, the performance of these schemes with respect to specific challenges and characteristics of the IWSNs was not discussed. Another fundamental of the CR paradigm which is well researched is resource allocation. Accordingly, efficient resource allocation and sharing techniques have been identified as crucial for the optimum performance and guaranteed QoS of CRNs. This is because CRN is typically deployed next to other heterogeneous networks that compete for scarce spectrum resources. A survey article was presented in Reference 13, in which advances in radio resource allocation in CR sensor networks were discussed. In addition, the authors presented a classification on basis of performance optimization criteria. Similarly, in Reference 14 a survey carried out focused on resource allocation in underlay CRNs. Then, state-of-the-art resource allocation schemes were reviewed. Similarly, some research efforts have focused solely on IWSNs without explicitly incorporating CR technology. In Reference 15, different cooperative communication schemes with objectives of conserving energy, boosting network throughput, and improving network coverage were investigated. Accordingly, they showed that by deploying cooperative communication scheme instead of using a simple clustering and data aggregation technique the efficient use of energy in a network can be improved. They identified cognitive MIMO as an example of a cooperative communication scheme. Conversely, the following works have incorporated the CR technology for effective communications. In Reference 16, a survey of CR for aeronautical communication was presented. Similar to our work, this survey proposed CR solutions for solving spectrum scarcity crisis. However, unlike our work, where we integrate CR solutions into industrial challenges, in this work, they proposed solutions are for aeronautical communication systems. Similarly, in Reference 17, the survey focused on standardization and security in smart grid (SG) communications using CR technologies. Also in Reference 18, a survey article on communication in SG network using CR was presented. A detailed comparison of wired and wireless communication technologies including new technologies like CR which are intended for SGs was presented. In addition, a detailed survey on communication requirements including architecture of smart grid communication network (SGCN) was discussed. Then, appropriate CR-based network architecture and relevant features for SGCN were proposed. Similarly, in Reference 19, a comprehensive survey on SG network, discussing its architecture, applications, and communication technologies from a CR perspective were presented. The work in Reference 20 reports on full-duplex (FD) communications in CRNs, a comprehensive survey of FD-CRN communications covering enabling network architecture and diverse transceiver antenna designs were presented. In all of the CR surveys cited so far, CR has been proposed to drive the next generation of wireless networks due to CR ability to provide efficient spectral utilization. Similarly, in References 21,22, a resilient, stable, and ubiquitous communications system is identified as a requirement for optimal performance of IWSNs. For example, Reference 21 presents an efficient pseudonym-based communication scheme with privacy protection and network access security for industrial sensor nodes. On the other hand,[22] present a state-of-the-art literature survey on developments in wireless hardware design, modeling, and analysis for industrial applications. In Reference 23, a survey outlining design requirements of IWSN was presented. Then, wireless protocol standards and existing off-the-shelf wireless sensor platforms developed by the researchers were listed and compared. Unfortunately, survey articles combining both CR and IWSNs are few in literature. The work in Reference 5 is one of such few scholarly articles. The survey is a comprehensive study on the application of DSA techniques especially spectrum handoffs for the optimum performance of IWSNs. Similarly, in Reference 24, several CR and non-CR solutions for IWSN were considered. A complete assessment of both solutions for mission-critical and time-critical data transmission overseveral fading and interference channels was conducted. Furthermore, the study observed that CR-based solutions sustained the performance of networks in harsh channels and under interference than non-CR solutions. From foregoing discussion, it is obvious that existing related surveys have mainly focused on CR and IWSNs as independent topics. Conversely, only a few surveys/works have combined both CR and IWSNs. Or, considered the incorporation of CR for solving spectrum scarcity challenges, for example, in SGs networks, aeronautical communications, and IWSNs. Still, only a fraction has integrated the potentials of CR for the full benefits of IWC. Specifically, by harnessing new perspective of spectral opportunities in unlicensed bands for full benefit of IWC. Therefore, this survey article compliments and extends previous surveys that have integrated CR technologies for IWSNs challenges, for example, CR for IWC.

3 | IWC: AN OVERVIEW

Current advancements in electronics technology have facilitated the deployment of wireless technology in virtually every application. Particularly, in sensor network applications.[25,26] Figure 1 shows a diagram of different types of sensor networks and technologies that have been aided by wireless technology. However, advancements in wireless technology have generated a new challenge. Clearly, every new wireless technology and device developed has to compete for the available frequency spectrum. Technically, the spectrum-space shrinks progressively every time a new wireless communication device is built and deployed in the wireless environment.[27,28] In industrial radio environments, for example, this shrinkage in spectrum space is more pervasive. Specifically, because industrial wireless technologies share the 2.4 GHz-ISM band with other incompatible heterogeneous wireless communication technologies. For instance, industrial wireless technologies, for example, wide-band high-rate IEEE 802.11 b/b/n, ISA 100.11a, narrow-band low-rate IEEE 802.15.4-based WirelessHART, IEEE 802.15.1-related PNO WSAN-FA, and Bluetooth share the 2.4 GHz-ISM band with wireless technologies such as IEEE 802.11 WLAN/Wi-Fi, cordless phones, and microwaves technologies.[29] As expected, the resulting competition for available frequency spectrum leads to heterogeneous technologies coexisting on the same spectrum. To complicate matters, the different technologies have to share the available frequency leading to overcrowding and scarcity of frequency spectrum. To illustrate this, in Figure 2A the spectroscopy of the ISM band occupancy is compared with the spectroscopy of the TV band in Figure 2B taken in the same location and time. Obviously, the spectrum occupancy map of the ISM band in Figure 2A is more congested than the TV band map in Figure 2B. However, according to FCC and shared spectrum company, up to 85% of allocated frequency spectrum remains unoccupied/unused most of the time, in space, and location. This is because licensed users are not always permanently available on the licensed frequency spectrum. As a result, there is high percentage of underutilized spectrum on the licensed frequency spectrum. Therefore, underutilized spectrum, which is identified as spectrum opportunities are now known as spectrum holes or white spaces.[5] Moreover, spectrum holes are chunks of fractured frequency spectrum leftovers which can be opportunistically utilized by CR users. Similarly, due to recent migration of analog TV to digital broadcast, many spectrum leftovers known as TV whitespaces (TVWS) have been realized. According to recent researches, TVWS be utilized for wireless/CR communication. Consequently, suffice that spectrum scarcity is not a physical scarcity of usable radio spectrum, but of inadequate spectrum management policies stimulating spectrum scarcity. Nonetheless, in IWC inadequate

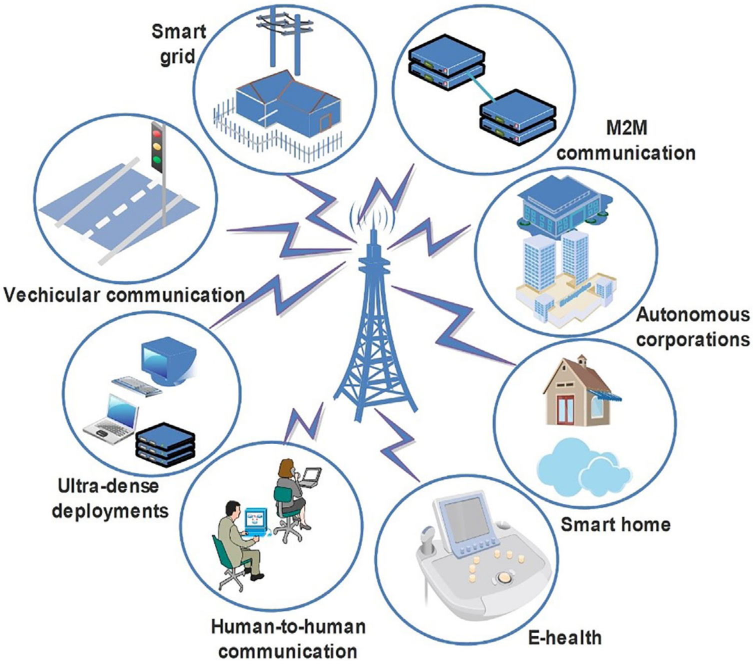
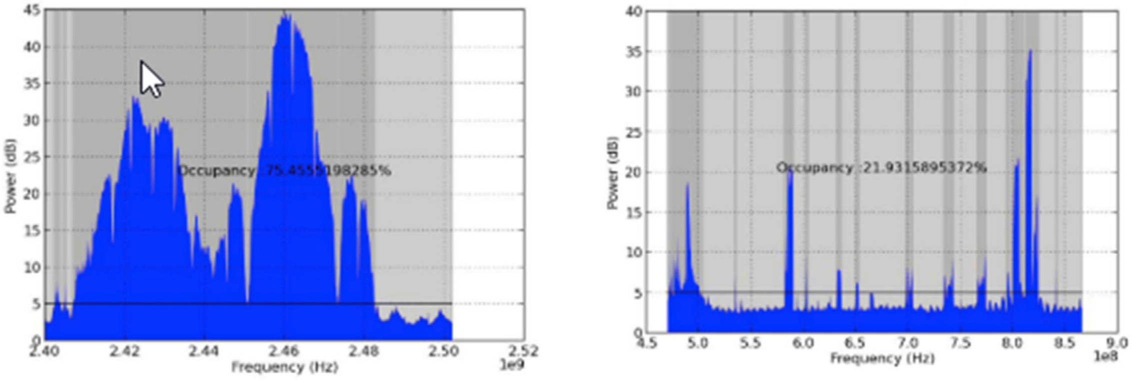


FIGURE 1 Illustration of different wireless sensor networks assisted by wireless technology[25]



(A) (B)

FIGURE 2 Frequency occupancy in A, the ISM band and B, TV band.[30] ISM, industrial, scientific, and medical

broad-spectrum band has been the underlying limiting factor for the complete utilization of wireless technology. In addition, the IWSN is distinctly different from CRN. Moreover, IWC is enabled by the IEEE 802.15.4 protocols, for example, ZigBee, ISA 100a, as well as wireless HART and operates in the unlicensed ISM band.[31] Furthermore, these technologies, for example, ZigBee support free short-range communication with limited numbers of simultaneous connections whereas IWC specifies high resource requirements. However, CR is the leading technology in resolving radio resource constraints. Therefore, innovative CR-IWSN solutions should be developed to exploit frequency spectrum leftovers such as TVWS. For instance, centralized CR schemes that opportunistically selects and utilizes available spectrum holes should be developed for IWSNs. Nonetheless, to apply CR technology for IWC, some specific requirements of IWC should be identified. For example, the IWC differs from other wireless communication paradigm because it focuses more on reliability and low latency. Furthermore, IWC differs from other communication paradigm because of its ability to connect several hundred devices having entirely dissimilar functionalities. For instance, devices, for example, sensors and actuators are connected with entities having entirely different capabilities, for example, units for monitoring, control, and data logging components.[1,32] Similarly, IWC is applied for highly application-oriented IWSN applications with diverse characteristics, for example, delay tolerance, packet size, mobility, and connection frequency.[25] At present, technologies, for example, ZigBee that enables IWC do not support massive number of users, simultaneous connections, and pervasive connectivity. Therefore, the CR technology should be incorporated in IWSN to meet IWC requirements. Accordingly, future CR-IWSN should have built-in support for IWC and its related technologies. Similarly, IWC suffers from mobility support challenges due to the dynamic and mobile nature of some industrial wireless applications. For example, WirelessHART and ISA100a do not support dynamic and mobile large-scale network due to a centralized network management schemes which limits flexibility. As result, CR-IWC solutions that can provide reliable and real-time connectivity with dynamic self-healing and self-configuring mechanisms for mobile industrial wireless networks should be designed. Similarly, extended spectrum band operations and consideration of operation in new spectrum regimes should be considered for IWC solutions. For instance, the potential of IEEE 802.15.4 in the 868 MHz frequency band can be investigated as solution for networking large-scale industrial applications with softer latency constraints. Furthermore, the IWC imposes new challenges on existing conventional wireless communication technology. Take, for example, IWC high requirements in terms of latency (low latency), synchronization, and reliability (ultrareliability).[33] Moreover, these challenges are aggravated by interference, high impulsive noise, overcrowding in the ISM band, and channel fading due to intense multipath effects of industrial environments.[34,35] Similarly, shadowing caused by huge amount of massive metallic obstacles in the propagation channel within the industrial environments aggravates the problems.[36] Still, existing protocols such as WirelessHART, WIA-PA, ISA100a, WSAN-FA, and WISA lack the communication robustness required for tight real-time IWC. For example, these protocols lack the communication robustness required in factory automation. However, CR offers promising solution regarding spectrum occupancy issues, spectrum scarcity, timeliness, and robustness required for IWC. This is because of the significant benefits CR offers in managing available frequency spectrum bands. In addition, due to the robustness of the modulation scheme adopted by CR to multipath effects, that is, orthogonal frequency division multiplexing (OFDM). It is for this same reasons that CR has been identified as the appropriate scheme for mitigating industrial channel multipath challenges in IWC.[33,37,38] However, DSA has to be integrated with IWC in order to apply CR as solution for current IWC spectrum inefficiency problems.[5,39-41] Correspondingly, Figure 3 explains what the DSA concept is in CR technology. In addition, to implement DSA as a CR capability CR user should be able to sense and detect unused frequency spectrum,

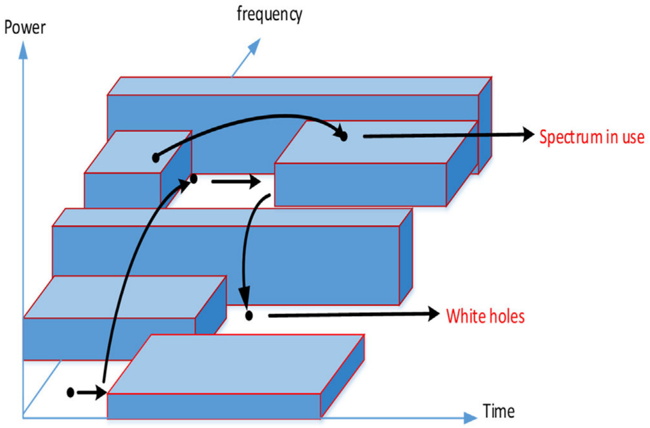


FIGURE 3 An illustration of DSA.[5] DSA, dynamic spectrum access

that is, *spectrum sensing*. In addition, CR users should be able to maintain seamless communication during transition to better frequency spectrum, that is, *spectrum mobility*.[42]

4 | CR: AN OVERVIEW

The CR paradigm has been identified as candidate for the next generation of wireless communication systems.[43] For this reason, new paradigms such as CR-wireless sensor network (CR-WSN), and CR-Internet of things/machine-to-machine (CR-IoTs/CR-M2M) have become the focus of recent research efforts. For example, in Reference 44 a comprehensive survey on CR for M2M and IoTs is presented. Furthermore, CR has been defined differently by different authors in literature. However, in all definitions; two main characteristics of CR are recurrent, that is, *(1) Cognitive capability and (2) Reconfigurability*. For example, in Reference 42 authors define CR as a radio that can modify its transmitter parameters according to its communication with the environment in which it operates. However, we will give further explanation to the two main recurring characteristics of CR identified in literature in details. First, *cognitive capability* is defined as ability of CR user to sense temporal and spatial variations in its radio environments. In addition, to identify unused portion of the spectrum and to select the best spectrum as well as select appropriate operating parameters. On the hand, *reconfigurability* is ability of CR user to transmit and receive on different frequency bands and to use diverse access technologies supported by its hardware design.[42,45,46] In addition, radio parameters such as (1) operating frequency, (2) modulation, (3) transmission power, and (4) communication technology can be reconfigured by a CR user for efficient bandwidth utilization.[25] However, for CR to effectively manage available frequency spectrum, it has to be able to make an opportunistic decision about it radio environments from previous experiences.[47] Primarily, a CRN or CR related/enabled/assisted network usually comprise of smart devices that are capable of dynamically modifying system parameters for efficient bandwidth utilization.[25] Moreover, these devices are intelligent enough to make opportunistic decision by detecting users' communication needs. As well as providing radio resources and wireless services for those needs.[48] Typically, a cognitive-based network can be classified into different groups based on the position of the decision-making entity in the network as (1) centralized CRN, (2) distributed CRN, or (3) cluster-based CRN. This categorization is shown in Figure 4. In addition, a brief explanation of the different categories is given in the following subsections.

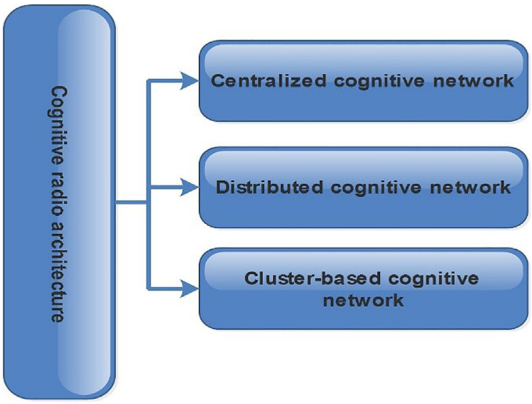


FIGURE 4 Cognitive radio network architecture based on position of decision-making entity[5]

4.1 | Centralized CRN

In a centralized CRN, a centrally connected node makes cognitive decisions for all network entities.[25] Moreover, when this concept is applied in an industrial perspective, some advantages of this model includes, optimized CR decision, and efficient resource utilization. However, this model is vulnerable in terms of security, specifically when the central entity is compromised,[49] in addition, it suffers high control overhead when the single central entity fails. Similarly, this architecture restricts exchange of information between nodes in the network.[50] The IEEE 802.22 wireless regional area network (WRAN) is an example of CR-based network where a central authority monitors the administration of the infrastructure. Similarly, another example is an access point linked with a set of unlicensed CR enabled nodes.[44]

4.2 | Distributed CRN

This model allows each entity in the CRN to perform decentralized CR operations such as spectrum sensing and adapting network to spectrum dynamics. Similarly, it allows establishing channel rendezvous for distributed coordination and performing network-centric DSA, as well as crosslayer optimization.[51-53] Therefore, a fully implemented distributed CR-IWSN will allow CR nodes to perform asynchronous distributed negotiation and coordination of channels, as well as adapting to network dynamics by discovering local neighbors. In addition, it will allow CR-IWSN nodes to update channel and queuing information, this is particularly beneficial in mitigating funnel effects in multihop IWC.[54] Similarly, this architecture helps to enhance efficient aggregation and utilization of fractured frequency spectrum for real-time IWC. In addition, it reduces delay in packet transmission of individual nodes in the crowded ISM bands.[55] However, some drawbacks of this model include the fact that each node in the network must implement and operate an identical protocol stack. Similarly, the setting encourages CR nodes to be selfish. Therefore, CR nodes are at liberty to withhold information which may be inimical to information flow. Similarly, information updates and distributed coordinated functions are affected adversely.

TABLE 1 Summary of attributes, advantages, disadvantages of CR network categories[50-52,56,57,59]

CR network	Strategy	Strength	Weakness	Suitable for industrial-WSNs
Centralized CR network[50,61]	Central entity makes CR decision	• Optimized CR decision • Efficient resource utilization • Optimized spectrum sharing • Processing and energy efficiency • Centralized architecture.	• High control overhead • Single node failure	x
Distributed CR network[51,52]	Individual entities perform CR decisions	• Asynchronous distributed negotiation and coordination of channels • Adapting to network dynamics • Enhance efficient aggregation and utilization of fractured frequency spectrum • Ad hoc and flexible, minimal control overhead, and autonomous architecture.	• Nodes must implement and operate identical protocol stack • Selfish decision making • Unnecessary handoffs • Nodes become selfish and withhold information.	✓
Cluster-based CR network[56,57,59]	Individual entity collects information for CR-CH to make CR decisions	• Organized and autonomous architecture • Efficient in processing and energy management • Integrated and flexible. • Optimized frequency spectrum allocation.	• Single node failure • High control overhead	✓

Abbreviations: CR, cognitive radio; WSNs, wireless sensor networks.

4.3 | Cluster-based CRN

In this architecture, a centralized entity usually known as cognitive-enabled cluster-head (CR-CH) executes CR decisions for a small set of CR nodes called clusters. Moreover, cluster-based CRNs usually consist of several clusters of CR sensor nodes with each cluster having its own CR-CH.[56] Similarly, the CR sensor nodes in a cluster, sense, collect and send data to the CR-CH through the ISM band. Whereas, the CR-CH transmits the sensed data, real-time over a licensed channel opportunistically to a sink node.[57,58] By combining approaches of the two previously mentioned categories, cluster-based CRNs harness the advantages of the two categories.[59] However, to achieve an enhanced and efficient cluster-based operation, reliable sensing, and data processing schemes with distributed medium access control and coordination should be developed for cluster-based CRNs. Moreover, candidate protocols should be energy-aware and application-aware to reduce packet collision and decrease response time.[60] However, similar to centralized CRN, cluster-based CRN suffers single node failure and increased control overhead. For easy understanding, we have presented the advantages and disadvantages as well as the suitability of previously mentioned CRN categories for IWSNs in Table 1.

5 | DSA TECHNIQUE AS A REQUIREMENT FOR REALIZATION OF IWC

For IWSNs nodes to enjoy the benefits of CR technology as anticipated, DSA capabilities developed for CR nodes have to be integrated into IWSN nodes functionalities. Moreover, DSA provides individual sensor nodes in IWSN with CR ability. As a result, the nodes are able to detect unused frequency spectrum in congested ISM band as well as to opportunistically utilize the channel for their communications. However, the realization of DSA capabilities for IWSN nodes involves executing spectrum sensing and spectrum mobility requirements which are two important CR functionalities. We illustrate the two-level implementation in Figure 5.

5.1 | Spectrum sensing

Spectrum sensing is an important functionality of CR technology that is fundamental in providing information on the availability of usable frequency spectrum leftovers,[10,62] Moreover, CR node requirements of being aware of, and being sensitive to changes in its environments specifically make spectrum sensing an essential prerequisite for the realization of CRNs.[42,56] Furthermore, spectrum sensing is very important in executing two tasks in IWC. These include (a) for discovering accessible spectrum holes over a wide frequency range for CR nodes transmission and (b) for monitoring the spectrum band during CR nodes transmission to detect the presence of PU in order to avoid harmful interference.[42] Nevertheless, understanding the appropriate spectrum sensing techniques that is most fitting for specific industrial scenarios and applications is not a trivial task. This task remains an open problem in many cognitive-related networks.[63,64] For instance, in Reference 42 authors observed that the most proficient method of detecting spectrum holes is by sensing PUs transmitter/receiver that is transmitting in the proximity of CR nodes. However, they observed that in reality it is difficult for CR nodes to have direct access to measure and obtain information from channels between a PU transmitter and receiver. For

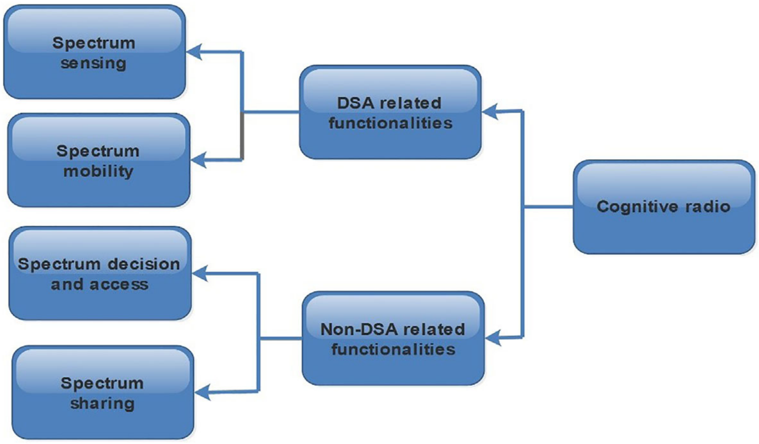
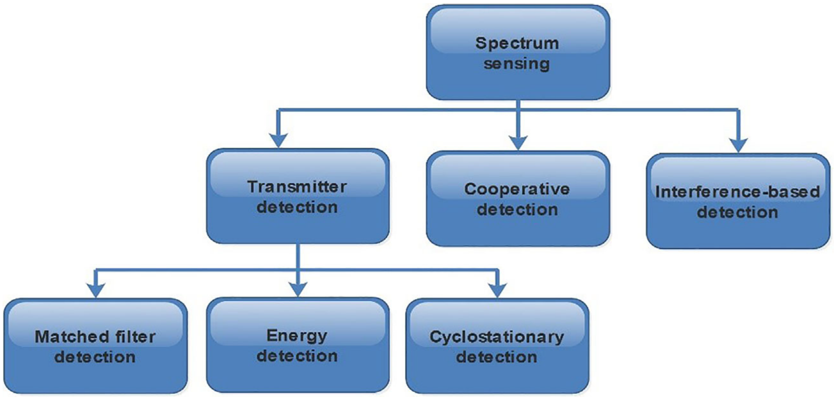


FIGURE 5 Illustration of DSA and cognitive radio functionalities.[5] DSA, dynamic spectrum access

FIGURE 6 Diagram of classification of different spectrum sensing techniques[42]



this reason, different spectrum sensing techniques have been studied in literature. Nonetheless, recent research efforts have focused on PU transmitter/receiver detection based on CR users' local sensing.[10,12,62] In subsequent sections, we briefly discuss the different spectrum sensing techniques and we suggest the most appropriate for IWC. Furthermore, In Figure 6, an illustration of different spectrum sensing techniques reviewed in literature is presented.

5.1.1 | Transmitter detection

In this method, CR users exploit weak signals emitted from PU transmitter/receiver to make CR decisions by observing its immediate local surroundings.[65] In addition, by observing the local radio frequency (RF) signals, CR nodes make CR decisions based on a hypothesis model.[66] By sensing weak signals leakages from local oscillator (LO) leakage power radiated by RF front-end of a PU receiver in its proximity a CR user is able to distinguish between used and unused frequency spectrum.[42,67] The PU transmitter/receiver detection is by far the most effective method of sensing available spectrum hole. Currently, it is restricted to detection of only TV receiver because of existing technical drawbacks in its design.[68] Another approach deploy in PU detection is interference temperature management technique. In this technique, an aggregate interference level called *interference temperature limit* is estimated through cumulative RF energy from multiple transmissions.[69] This value is then used as a threshold level that the PU receiver should tolerate. Furthermore, as long as CR users do not exceed this limit by their transmissions, they are permitted to use the spectrum band for their transmission with other PUs without harmful interference.[70] Nonetheless, the drawback of interference management temperature approach is that CR users usually miss-detect noise/interference signals as the actual PU signals. As a result, wrong measurements which makes it difficult to implement interference temperature limits have been used. Correspondingly, this makes interferences from CR users' transmissions to exceed the set limit of interference temperature leading to harmful interference.[71] Therefore, an effective and efficient spectrum sensing technique should be developed for CR user. This is to enable CR user to distinguish between their own signals and PU transmitter as well as noise/interference signals.[67] Based on the hypothesis model three schemes can be used in sensing and detecting PU transmitter/receiver. These include *(1) matched filter detection, (2) energy detection, and (3) cyclostationary feature* detection techniques.

5.1.2 | Matched filter detection

This method is the optimal detector in stationary Gaussian noise. It maximizes signal to noise ratio (SNR) in the presence of additive stochastic noise by correlating known information of actual PU signal with extracted information of a received signal.[72] By comparing both signals, a spectrum band is acknowledged to be occupied by a PU transmission if the sampled output of the matched filter at a synchronized time is greater than a threshold.[73] In addition to realization of a fast spectrum sensing time, this method achieves a high target detection probability with minimal samplings. In addition, it has a high processing gain with less time. However, this method requires knowledge of the characteristics of the PU signal well in advance.[74] In addition, aside priori knowledge of modulation type and order, packet format, and pulse shape, it also requires synchronization between PU transmitter and CR users.[75] As a result, the matched filter performs poorly once this information is incorrect. Moreover, matched filter detection requires dissimilar multiple matched filters to be assigned to each type of PU signals. Thus, increasing design complexity as well as implementation cost. However, it is the most used detection technique in WSNs since most wireless network systems have pilot, spread codes, and preambles. Similarly, since most WSNs transmitters normally send pilot signals with data the CR users have perfect knowledge of the signals.

5.1.3 | Energy detection

In this approach, CR user leverages on the energy of the received signals. However, energy detection does not require priori knowledge of the received signal as long as that the noise power is known.[76] As a result, once the noise power is known CR proceed to measure the energy of the received signal over an observed interval. Then, the measured energy is compared with a predefined threshold to decide if a PU signal is present or not.[44] Consistently, energy detector is the optimal detector when only the power of the random Gaussian noise is known to the CR receiver.[77] Although it is easy to implement it has many shortcomings. For instance, energy detection suffers from low detection probability when detecting weak PU signals. Take detecting a PU signals between −10 and −40 dB, for example, energy detection will take longer time to detect the signal compared with matched filter detection.[67] However, because it is easy to implement recent research works on detecting PU signals have implemented energy detection overmatched filter detection.[78] Still, because energy detection relies only on noise power for PU signal detection its performance is seriously affected by uncertainty in noise power.[79] To counter this challenge, a fixed threshold value called *SNR wall* is normally used to indicate an uncertainty level. Thus, below the *SNR wall* the energy detector cannot detect the PU signal reliably again. Similarly, another approach is to use a pilot tone from PU transmitter to improve energy detection accuracy of CR user.[78,80]

5.1.4 | Cyclostationary feature detection

In this method, similar to energy detection technique, a CR user analyzes the spectral correlation function of the received signal. Accordingly, a CR user takes the average of correlation function of a received signal over a time interval then compares the average value with a test statistical value.[81] On the basis of this comparison, a CR user is able to detect whether a PU signal is present or not.[82] Moreover, feature detection decides if PU signal is present on a spectrum band by detecting a built-in periodicity in a modulated signal introduced by certain features.[83] These features include pilot signals, symbol rate, prefixes, spreading codes, and modulation type from local observations.[67] However, unlike energy detection and matched filter detection techniques feature detection is robust to uncertainty of noise power. In addition, it allows CR user to perform spectrum sensing independently without synchronization with its neighbors.[78,84] However, by addressing the weaknesses of both energy detection and matched filter detection techniques feature detection becomes computationally complex and requires comparatively longer sensing time.

5.1.5 | Suitability of different PU signal detection techniques for spectrum sensing requirement in IWC

In this section, we summarize the different PU signal detection techniques discussed so far in Table 2. We highlight the advantages and disadvantages as well as their suitability of the techniques for spectrum sensing in IWC. In addition, we identify the CR architecture well matched for each of the techniques. In summary, although energy detection is easy to implement and has marginal requirements for signal processing it is seldom used for spectrum sensing in industrial communications. This is because its sensing accuracy depends on well-defined noise power. In addition, it has high probability of false detection and longer sensing duration. Therefore, it is unsuitable for spectrum sensing in heavily shadowed and fast fading environment. Some drawbacks of energy detection are addressed by the matched filter detection method, for example, long spectrum sensing period and high power consumption. Nonetheless, the matched filter method still requires CR user to be synchronized with the PU. Similarly, the matched filter method does not meet spectrum sensing requirements in IWC. Conversely, feature detection method has been outstanding in defying noise variation and has high probability of detecting PU signal. These attributes make feature detection method robust in fast fading and shadowing environment. As a result, it is able to meet the requirements for spectrum sensing in IWC.

TABLE 2 Summary of the different PU signal detection techniques[67,72-74,77,78,81,83,84]

PU signal detection technique	Advantages	Disadvantages	Affected by fast fading and shadowing	Suitable for spectrum sensing in IWC	Compatible with
Energy detection[67,77,78]	• Low signal processing requirements • Easy to implement	• Longer sensing periods • High power consumption • Accuracy depends on noise power • High false detection probability.	✓	x	Centralized cognitive network/distributed cognitive network/cluster-based network[50,51,59]
Matched filter detection[72-74]	• Less power consumption • Less sensing period.	• Requires synchronization with PU • High complexity • High implementation cost.	✓	x	Centralized cognitive network[85]
Feature detection[81,83,84]	• Robust against noise variations • High detection probability.	• Requires high computational capability of nodes.	x	✓	Centralized cognitive network/distributed cognitive network/cluster-based network[54,57,85]

Abbreviation: IWC, industrial wireless communications.

5.1.6 | Cooperative detection

By design, a CR user' transmission range stretches further than its detection range. For this reason, a CR user can only sense and utilize vacant frequency spectrum within its detection range. Therefore, its transmission can still cause harmful interference to PU signals within its transmission range.[86] Consequently, a CR user must depend on neighboring CR users to prevent interference to PU activity outside of their detection range. So, a CR user must inform other CR users promptly when it detects PU activity in a spectrum previously occupied by a neighboring CR user. So that they can evacuate the busy spectrum immediately. However, these chain of spectrum sensing and management functions require cooperation among the CR users. Accordingly, cooperative detection denotes any spectrum sensing technique(s) in which clusters of information from several cooperative CR users based on local observations are combined to make a global decision. For example, to detect PU signals/activities, as well as, to detect spectral opportunities for opportunistic-utilization of CR users' transmission.[42,87] Hence, *centralized-CSS* is when diverse sensing information from multiple cooperative CR users are combined to detect an unused frequency spectrum by a central entity or a fusion center, for example, a base station (BS) or AP.[88] Otherwise, it is called *distributed-CSS* when it involves decentralized exchanges of sensing information between different cooperative CR users to detect a spectrum hole.[89] Yet, in a multihop CSS scenario where spectrum sensing information pass through several hops of noncooperative nodes which only act as relays to reach the destination CR users it is referred to as *relay-assisted CSS*.[88] The main advantage of cooperative detection is that it improves spectrum sensing accuracy. This is achieved by minimizing uncertainty in a single CR user detection through cooperation.[90,91] Generally, there is a trade-off between sensing time (when wideband spectrum sensing is deployed) and sensing accuracy (when narrowband spectrum sensing is used). However, CSS reduces spectrum sensing time and improves spectrum sensing accuracy. By contrast, non-CSS is susceptible to multipath fading and shadowing effects. In addition, CSS has been exceptional in defying multipath fading and shadowing affecting severely shadowed environments including IWSNs.[5,42,92] Nonetheless, shortcoming of CSS is inadequate information exchanges between cooperating CR users. As well as, additional communication and processing overheads. Similarly, due to primary receiver uncertainty problems knowledge about primary receiver location remains an open issue in CSS.[93,94] Some of these challenges are resolved by interference-based detection technique, which we discussed in the following subsection.

5.1.7 | Interference-based detection

This is a new approach introduced by FCC as a different solution to replace previous techniques of mitigating interference at the transmitter. According to recent trends, previous techniques for mitigating interference at the transmitter are deemed inappropriate. This is because recent research has shown contrary to prevailing assumption that interference actually occurs at the receivers not at the transmitters.[42] As a result, a new model of sensing spectrum which focuses on measuring interference at the receiver was introduced by FCC in 2003.[65,88,95,96] Therefore, interference-based detection techniques are different from the transmitter-centric approaches, but similar to ultrawideband (UWB) technology which mitigates interference at the receiver of the PU.[97,98] This is achieved by setting an upper limit of interference to prevent harmful interference to the PU signal. In addition, it is a new DSA concept. This method also known as interference temperature limit represents the amount of new interference that the PU receiver can tolerate. Thus, to detect the presence of PU receiver a CR user identifies the LO leakage power emitted by a PU receiver that is communicating with a PU transmitter.[99] Similarly, a CR user can get this information from a local sensor installed close to the PU receiver by using relay-assisted cooperative sensing. Then, the LO leakage power information received from the sensors is then analyzed by CR users through a global decision to decide on the status of the spectrum.

5.1.8 | Spectrum sensing in IWC systems for real-time IWC

IWSN environments are heavily shadowed due to massive numbers of moving objects, for example, moving machines, mobile radio devices, and moving robots. Obviously, shadowing induce time-variance into the industrial radio environment. In addition, IWSN environment is susceptible to multipath fading effects due to smart repulsive objects, for example, metallic machines and thick concrete walls. Typically, shadowing effects is when the power of a received signal is reduced by objects obstructing the propagation path between a transmitter and a receiver.[100] Similarly, multipath fading implies that different versions of a signal are transmitted through different paths due to interference and noise as a result arrive at a receiver at different time leading to reduction in the energy and phase shift of the received signal.[101] Generally, these phenomena affect the efficiency of the different spectrum sensing techniques in IWSNs environments and IWC. For instance, while energy detection technique has high accuracy in sensing spectrum and is easy to implement its performance is affected by noise power and interference. Therefore, is not the appropriate detection technique for spectrum sensing in IWSN radio environments. Similarly, because of different types of signal in IWSN and the high probability of false detection in energy detection technique it cannot be deployed for spectrum sensing in heterogeneous network such as IWSN. Moreover, this drawback is further aggravated by colocation and transmission of dissimilar signals from heterogeneous networks and technologies that coexist in IWSNs. Likewise, though matched filter detection technique performs well in the presence of additive stochastic noise it requires a priori knowledge of transmitted signal which is not feasible in IWSNs. Therefore, it is not likely a candidate technique in sensing spectrum for utilization in IWC. Conversely, recent research efforts have claimed with results that signal with strong cyclostationary properties can be detected at low SNRs. Similarly, that detection techniques which use inherent properties of a digital modulated signal, for example, pilot signals, symbol rate, spreading codes, and modulation type can be used to solve multipath fading and shadowing effects.[102] Therefore, these research outcomes make cyclostationary feature detection technique the candidate for spectrum sensing in IWSNs and IWC. For example, in Reference 102 authors showed that multicycle (MC) detection has inherent properties to distinguish between PU signal and CR users signal. In addition, they demonstrated that MC detection can differentiate interference signals provided that the signals have dissimilar cyclic features. Therefore, they proposed an improved MC detector. In addition, by simplifying test statistic of conventional MC detector they reduce computational complexity usually caused by computing test statistic. Then, they derive the closed-form expression of detection and false alarm probabilities, respectively, and introduce square-law combining (SLC) to improve the detection capability. They analyze the performance of the improved MC detector by comparing the improved MC detector with SLC with a case without SLC. Finally, the performance of the SLC was investigated over Raleigh, Rican, and Nakagami fading channels. However, to overcome the high computational capability requirements of cyclostationary detection technique cooperative or collaborative spectrum sensing should be incorporated into cyclostationary feature detection in IWSN. Similarly, massive multiple antennas can be deployed in severe fading and shadowing environments to improve spectrum sensing performance. Moreover, the CR users must continuously scan the spectrum band for PU activity after sensing and occupying an unoccupied spectrum in order not to interfere with the primary network. Therefore, if specific portion of spectrum previously allocated by CR users is preferred by PU the CR user must immediately pause their communication. In addition, they must select another unoccupied portion of the spectrum to continue their communication. This event is called *spectrum mobility* and requires DSA-type of handoff known as *spectrum handoff*.

Unlike traditional vertical or horizontal handoff, spectrum mobility and spectrum handoff are new DSA functionalities in CRN.

5.2 | Spectrum mobility in IWSNs environments

Basically, there are three situations that can trigger a spectrum handoff in a CRN. First, a PU reappears on the spectrum previously occupied by a CR user. Therefore, the CR user needs to move to a new channel to continue its ongoing communication. Second, a CR node moves into another cell and its current operating frequency is not available in the new cell. Therefore, the CR user needs to find another channel to continue its communication. Finally, the conditions in current channel becomes degraded and does not meet the specific QoS requirements of CR user application. Hence, the CR user needs to move to another channel that meets its predefined QoS requirements.[5] Nonetheless, spectrum handoff should consider fast and smooth switching so that the delay associated with spectrum handoff does not affect the tolerable delay limits of industrial systems adversely. Take, for example, the delay tolerance of safety and monitoring systems in the industry is typically less than a hundred milliseconds (≤ 100 ms). Whereas, control systems specify a tighter delay limits of less than 25 milliseconds (≤ 25 ms),.[5] Furthermore, industrial systems define stricter and stringent QoS requirements, for example, reliability, availability, and timeliness. Specifically, it is difficult to meet these requirements in harsh industrial environment because of negative effects of noise and interference, for example, loss of synchronization, data loss, and transmission delay. Unfortunately, existing industrial standards such as WIA-PA, ISA 100a, ZigBee, and WirelessHART have not matched the industrial systems strict and stringent QoS requirements. For example, ZigBee and Bluetooth do not deliver guaranteed end-to-end wireless communication delay tolerance capacity.[103] Similarly, ZigBee usually fails in harsh industrial environments since it does not define a built-in channel hopping technique. While, ISA100a does not support acknowledged transactions. Nonetheless, IWC can benefit from the flexibilities that spectrum handoff offers. For instance, in real-time surveillance systems minimum communication delay can be guaranteed through opportunistic spectrum utilization with minimal switching delay, efficient target channel recovery techniques, and effective link recovery maintenance. Similarly, increased bandwidth, smooth and reliable, as well as interference-free communications can be provided from the flexibilities that spectrum handoff offers. However, the approach used in designing a spectrum handoff technique partly determines how effective the handoff process will perform in specific scenarios/applications. Since, for instance, each module involved in spectrum handoff design is subject to limitations based on unique requirements of different applications/scenarios. On the other hand, the performance of a spectrum handoff process depends on the time it is implemented. Clearly, a spectrum handoff can be performed prior to occurrence of an event that triggers it. Otherwise, it can be performed after the event has occurred. In the following subsections, the different strategies in spectrum handoff techniques are briefly discussed. These include *(1) nonhandoff strategy, (2) pure reactive spectrum handoff, and (3) pure proactive spectrum handoff*.

5.2.1 | Nonhandoff spectrum strategy

When a situation that triggers a spectrum handoff occurs this method requires a CR user to remain in the original channel until the channel becomes free again. Therefore, a CR user must pause its communication and remain idle in original channel until the PU vacates the busy channel. Then, the CR user can reselect the current channel as a new target channel to continue its transmission.[5,104,105] This approach can be very useful in a scenario where the channel conditions in current channel becomes degraded. In this case, a CR user cannot continuously attempt to move to a new channel. This is because establishing communication in a new target channel is not a trivial task. Similarly, it is subject to specific factor like availability of channel during the period of spectrum handoff, availability of common control channel, channel capacity, and the probability of availability of channels in the future. In addition, it is not feasible to always have idle channels in IWSNs environments due to spectrum resource constraints, mobility of nodes, and traffic fluctuations.[5] Certainly, poor target channel selection will lead to unnecessary spectrum handoffs and longer communication latency leading to poor network performance. As an alternative, a CR user can leverage on its potential of frequency adaption to adjust to variations in channel parameters. Similarly, by optimizing diverse transmission parameters a CR user can still transmit on a degraded channel until channel conditions improves. For example, transmission parameters such as modulation, coding schemes, and transmission power can be adapted based on specific measured environmental parameters such as estimated channel bit error rate, channel data estimation, and network QoS requirements.[106] Similarly, to prevent frequent unnecessary spectrum handoffs reinforcement learning can be deployed to adapt to channel conditions to improve CR user transmission until channel conditions in the current channel improves.[107] This will prevent switching to a new target channel each time channel condition is impaired.[106] Nonetheless, the major drawback of this method is a high waiting latency since waiting time of the CR user is equivalent to length of time the PU is active on the channel. Therefore, this approach will fail in delay-sensitive IWSN applications, for example, air traffic control system, as well as system and process control systems.[104]

5.2.2 | Pure reactive spectrum handoff strategy

Under this approach, a CR user deploys reactive spectrum sensing and reactive spectrum handoff.[104] As a result, a CR user only selects target channel from instantaneous outcomes of wideband spectrum sensing at the instant PU appears. In addition, the CR user implements reconfiguration of its RF front-end and spectrum switching when a PU appears on the channel previously occupied by CR user.[5] In other words, pure reactive spectrum strategy is an event-triggered approach where both target channel selection and spectrum handoff actions are implemented only in response to a triggering event. Similar to nonhandoff strategy, there is high latency in pure reactive spectrum handoff. However, unlike nonhandoff strategy, here, the high latency is due to spectrum sensing and reconfiguration delays, and not due to waiting delay/latency.[108,109] To address this, crosslayer optimization frameworks and optimal probabilistic channel selections should be considered to mitigate spectrum mobility delays in reactive spectrum handoff protocols.[110] Similarly, CR user should be able to sense weak PU signals in real-time sensing in wideband spectrum range to mitigate delays usually incurred from on-demand spectrum sensing.[5] Likewise, the use of optimal channel sensing sequence to minimize spectrum sensing overhead can be investigated. In addition, virtual reservation channels can be implemented to maximize network spectrum allocation. So that when CR users are switching reactively, the virtual channels are continuously available to enhance process of spectrum handoff.[106] Nonetheless, this approach has high accuracy in target channel selection, due to the fact that spectrum sensing is implemented in wide spectrum range albeit with increased sensing time.

5.2.3 | Pure proactive spectrum handoff strategy

In pure proactive spectrum handoff technique, a CR user implements proactive spectrum sensing as well as executes proactive spectrum handoff schemes. Based on a PU traffic model prediction a CR user is able to select a target channel for spectrum handoff before it commences spectrum mobility by correctly predicting when a PU will be available on or vacate a channel.[111] As a result, a CR user can reconfiguration its RF front-end and execute spectrum switching before a PU appears on the channel.[112] The major disadvantage is that the performance of this technique depends on accurate prediction of PU traffic model. Take real IWSNs environment, for example, a CR user may not always be privy to information about PU traffic model due to certain policies which a CR user must respect. For instance, a CR user' access to the information between a PU transmitter and receiver is regulated. Consequently, the CR users are not able to predict the PU traffic accurately.[113] Furthermore, the performance of this technique depends on periodic and continuous observations and updating of the information about PU transmission channels. So, there is a high probability that the prepared backup channels would have been occupied at the time of spectrum handoff by other users. Therefore, poor prediction due to inaccurate PU traffic model information may negatively affect the overall performance of spectrum mobility in this technique.[5]

5.2.4 | Comparison of different spectrum handoff strategies

In Table 3, we summarize attributes of different spectrum handoff strategies discussed so far. Moreover, existing research efforts have primarily studied each spectrum handoff strategy as a separate technique. Similarly, each spectrum handoff strategy requires a different PU network. However, adaptive spectrum handoff algorithm which combines multiple spectrum strategies should be developed with spectrum leaving factors incorporated into the process design. For example, the advantages of two or more spectrum handoff strategies can be integrated to create a hybrid technique with superior attributes than constituent spectrum handoff strategy.

TABLE 3 Summary of different spectrum handoff strategies[85,105,107-109,111-114]

Approach	Strategy	Strength	Weaknesses	Latency	Recommended scenario
Proactive spectrum handoff[111-113]	Sensing and switching done before PU appears	Target channel selection availability, and fast switching response time	Needs accurate PU traffic model, continuous observation and update of channels and target channel becomes outdated	Very low latency when well-planned and designed	Well-modeled cognitive radio network
Reactive spectrum handoff[108-110]	Sensing and switching are done after PU appears	Accurate target selection	High sensing and reconfiguration delay resulting in slow response	Very high latency	General cognitive radio networks
Hybrid spectrum handoff[85,114]	Sensing done before PU appears and switching done after PU appears	Smart target channel selection and fast switching response time	Target channel selection may become outdated	Medium latency	Well-modeled cognitive radio networks
Nonhandoff[105,107,109]	Handoff is not performed	Smooth commu;nication	Complex computation, botched/disrupted communication, may cause interference to license user	Low to high latency	Well-modeled cognitive radio networks

6 | CR TRANSMISSION IN CRNS

Another approach employed by the CR users in CRN to improve spectrum utilization efficiency is by dynamic spectrum allocation and sharing. However, the amount of spectral opportunities available to a CR user is subject to the mode of transmission adopted by the CR user. Moreover, some spectrum challenges can be solved by the mode of transmission adopted by a CR user. For example, challenges like when and how to allocate the spectrum band. Furthermore, issues like how to coexist with PUs and other CR users. Finally, challenges like which spectral opportunity can be accessed if current channel becomes busy. To this end, a CR transmission based on the mode adopted by CR user is categories into *(1) underlay, (2) overlay, and (3) interweaved*. We examine the different transmission mode and highlight the application and benefits of the modes in IWSN and IWC.

6.1 | Underlay transmission in industrial-WSNs

In underlay transmission, the CR users are permitted to transmit on a licensed band at the same time the PUs are transmitting. However, this is allowed provided that interference generated by CR user transmitter is within PU receiver interference temperature limits and PU QoS constraints.[5,88,115,116] To fully utilize a wide range of spectrum when this mode of transmission is employed a CR user essentially implements spread spectrum technique. As a result, the CR user transmission is regarded as noise by PUs. However, the transmit power cannot be increased to obtain higher SNR for enhanced data rate and throughput like in other wireless communications.[5] In underlay transmission, there is a constraint on the transmit power of CR user. Therefore, a CR user can only achieve short-range communication when implementing underlay transmission.[115] Although, higher bandwidth is achievable albeit with slight increase in complexity. For example, in industrial perspective, a CR user can transmit with PU in licensed band using the *underlay* mode without performing spectrum sensing to find available spectrum band. Specifically, if the PU activity can be modeled by a historical spectrum statistics of the PU. In addition, if the PU transmission is always in a continuous mode. For example, if the PU activity is based on human activity and is statistically conclusive. For this reason, underlay transmission is ideal for a real-time, short-range, high data rate IWC.[117] For instance, in process control systems, since time is saved by eliminating spectrum sensing time. However, in the IWSN domain it is difficult for a CR user to estimate interference temperature limits of the PU receiver due to noise and interference. As a result, a CR user transmission might constitute harmful interference to the PU transmission. Therefore, industrial-WLAN an enhancement over IEEE802.11-based consumer Wi-Fi that is a deterministic solution with improved roaming and reliable longer communication ranges should be investigated. Similarly, power control algorithms, for example, that allows a CR user transmission to be considered as noise by a PU signal should be developed. For example, algorithms that use OFDM and UWB techniques which allows a CR user to spread its transmission overlarge band of spectrum. Similarly, modified version of ZigBee, Bluetooth, and WirelessHART should be developed for opportunistic IWC in real and time critical IWSNs. For instance, new version of these protocols that use lower transmission power for underlay transmission.[117]

6.2 | Overlay transmission in industrial-WSNs

The overlay transmission only permits a CR user to transmit on specific portion of spectrum if the PUs are not transmitting. Intrinsically, there is no constraints imposed on a CR user' transmit power. However, a CR user must continuously sense and detect spectrum white space for available spectrum in order to avoid harmful interference to PU activity.[118] Therefore, a wide range of spectrum is not always available for a CR user transmission overextended time. As a result, overlay transmission is not the ideal mode for time and mission critical IWC.[119] However, techniques, for example, dynamic frequency selection (DRS) should be investigated to create more spectral opportunities overextend wideband spectrum range. For instance, DRS allows a CR user to take advantage of knowledge, for example, of code, polarization angle, and beamforming to cause minimal interference to PU. Another weakness of overlay form IWC perspective is that a CR user must maintain constant awareness of PU activity patterns to avoid harmful interference to PU. In addition, constant awareness is maintained to continually identify potential spectrum opportunities for exploitation.[117] As a result, there is a high communication delay in overlay transmission due to high spectrum sensing latency contrary to low latency requirement of IWC. Therefore, standardization efforts in CR, for example, IEEE 802.15 WPAN, IEEE 802.11WLAN, and IEEE802.22 WRAN that are capable of exploiting TVWSs for CR-IWC communication should be investigated. For example, study should be conducted on how to extend these standards for IWC to provide additional extended spectral opportunities. Specifically, study can be conducted on how to extend the IEEE802.15.4 m to IEEE802.15.4 industrial-based protocol, for example, WirelessHART, ISA100a, WIA-PA, and ZigBee to exploit TVWSs for IWC.

6.3 | Interweaved transmission in IWSNs

Several hundreds of sensors are required to be connected together in IWSNs via IWC. This imposes strict challenges to deliver high level of guaranteed QoS as well as fixed, stable, and reliable links. Similarly, the ever-increasing demands for radio spectrum for high-speed internet and multimedia services aggravated by the fixed spectrum allocation policy leads to a huge competition for available spectrum.[120] Moreover, the competition for available spectrum is more pervasive in the industrial environment. This is as a result of noise and interference effects which leads to data loss, false alarm and commands, transmission delay, jitters, and loss of synchronization. Ultimately, resulting into botched communications/internetworking.[5] One way of solving this challenges is by increasing spectrum usage efficiency through spectrum sharing process.[121] Take *underweave*, for example, which is another approach of spectrum utilization with the potential of mitigating spectrum shortage.[118,122,123] Recently, it was observed that the current white spaces definition has seriously undermined the potential of CR technology.[117,124] Specifically, it showed that existing studies have only focused on detecting white spaces in idle licensed spectrum band with limited signal space dimension of time, frequency, and space. However, according to recent definitions, white space is not limited to these signal space dimensions. For example, CEPT report 24, states that white space does not only exist in idle band and is not limited to specific dimension of signal space. In addition, that white space is not necessarily restricted to licensed spectrum band. It considers, for instance, how a CR user behaves in the unlicensed ISM band if the three conventional dimensions of white space are occupied in the licensed band[117] Therefore, improvements that incorporate this new perspective with the conventional CR communication model should be investigated. For example, enhanced interweave transmission incorporating new white space perspective can be extended for dynamic usage in IWC. Nonetheless, the original concept of interweave is that a CR user can exploit vacant white space in time, frequency, or space as long as it does not interfere with the activity of the PUs.[118,122] Though, this conventional concept of time and frequency dimensions of spectrum hole is simplistic it does affect the utilization of spectrum. Particularly, if the scope is not well delineated for *interweave* transmission in IWSNs. Take “idle bands” in the current definition of white space, for example. This terminology does not give a clear time duration of how long a channel needs to be vacant to be regarded as “idle”.[117,125] As a result, specific part of frequency spectrum which is “idle” during a PU communication has not been fully harnessed for a CR user opportunistic usage. Similarly, allocating spectral resources in accordance with a PU/CR user behavior or context may reduce spectrum usage efficiency. Therefore,

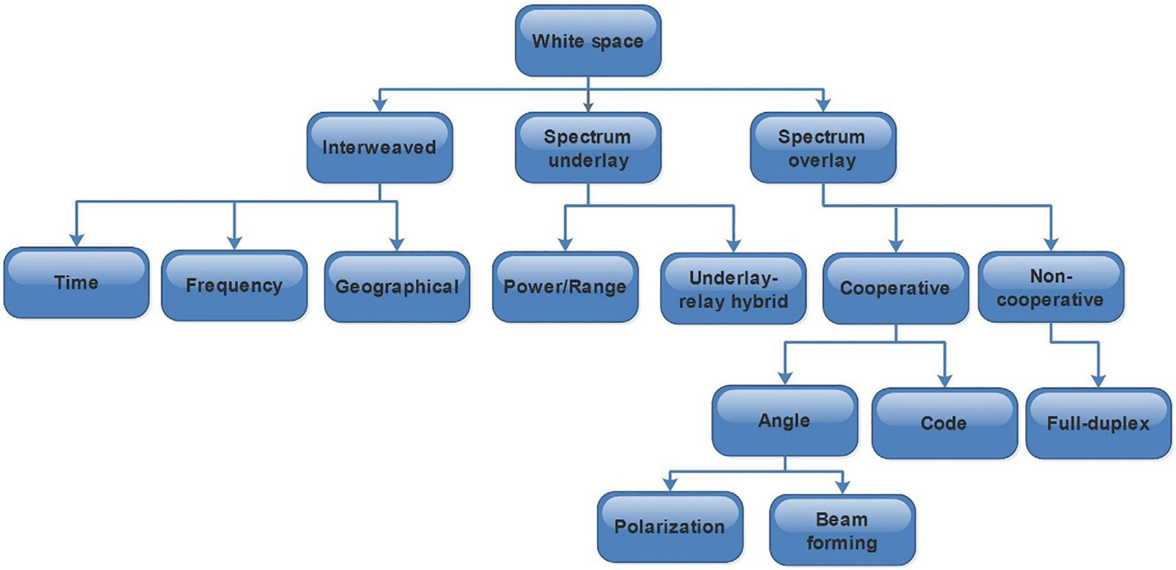


FIGURE 7 Diagram of relationship between CR user transmissions and current white space dimensions.[117] CR, cognitive radio

integration of time-frequency resource conversion with IWC should be investigated to manage resource allocation. This will guarantee that spectrum access for application(s) not currently in use by the PU/CR users are not reserved. Figure 7 shows the different modes of CR user transmission discussed to this point in relation to current definition of white space.

7 | OTHER APPLICATIONS AREAS OF CR TECHNOLOGY

CR has been recognized as a candidate for next-generation wireless networks. Accordingly, in the last few years, CR has become one of the most talked about topics in future next-generation networks workshops and researches. In this section, we have identified and discussed a few topics that are considering CR technology as a future enabling technology.

7.1 | CR smart grid

Traditional grid only transmits or distributes electric power without any form of automation.[18,19] However, a SG optimizes energy efficiency by integrating actions of suppliers and consumers in real-time by incorporating information technology into existing power grid.[126] The two-way exchange of electricity information and control capacities in SG has brought about new functionalities (with enabling technologies), solutions, and challenges.[19] Some solutions proposed by SG networks,[127] include (1) reliable, secured, and efficient electric grid, (2) deployment and fusion of distributed resources and generation, (3) installation of smart metering and distribution automation, (4) installation of smart appliances and consumer devices, (5) advanced electricity storage and plug-in hybrid electric vehicles, (6) thermal-storage air conditioning, and (7) real-time information and control options. Some new functionalities of SG are, (1*) control*, for example, advanced fault management control methods and the virtual power plant control technology and *communication*, for example, new multipath routing algorithms, smart metering, blind processing framework, and related communication technologies, (2) *sensing*, for example, synchrophasors or phasors measurement units and *measurement*, for example, digital smart meters, (3) *security*, for example, location-based security, integrated systems security,[49] and Ortho code privacy mechanism, and (4) micro *grids*, *pilots, and projects*, for example, in Australia, Canada, Great Britain, USA, South Korea, Ireland, and Japan. Nonetheless, a SGCN is a very crucial component in the realization of SG. The SGCN is intended as a low-cost, reliable, and secure communication infrastructure that meets the QoS requirements of SG. However, the design and implementation of SGCN are very intimidating challenges.[18] This is because SGCN is required to integrate different segments of a communications network with huge number of heterogeneous elements distributed overlarge distances with dissimilar QoS requirements. From competing technologies point of view, apart from traditional power line communications other key wired technologies competing for realization of SGCN are optical communication and digital subscriber line. However, wireless technologies have had advantage overwired technologies due to low cost of installation, higher flexibility, and increased scalability. Therefore, wireless technology is now preferred to wired technologies in SGCN. Here are some examples of wireless technologies that have been proposed for takeoff of SG- ZigBee, IEEE 802.11ah (low Wi-Fi), IEEE802.11af (super Wi-Fi, or White-Fi), IEEE 802.22WRAN, IEEE 802.16-based network (WiMAX), cellular and satellite communications. Nonetheless, CR has been the preferred technology for SG environments. This is because of the enormous potential of improving spectral efficiency and transmission capacity through opportunistic spectrum utilization.[18] The major benefits of CR technology for SG is transmission of data over SG communication links with less communication latency and solving spectrum scarcity shortcomings in SG.

7.2 | Cognitive-unmanned aerial vehicles

Another important area with growing CR interest is unmanned aerial vehicle (UAVs) otherwise known as drones. Basically, UAVs are aircrafts operated without human pilots. UAVs are usually deployed in areas that are potentially too dangerous, highly risky, very expensive, or difficult for human activities. For example, earthquake prone regions, war zones, fire control, including tracking, and surveillance applications. Fundamentally, UAVs are built for surveillance and reconnaissance mission. As a result, they are usually equipped with sensors, cameras as well as communication equipment. However, deployment of UAVs in the ISM band implies that UAVs have to compete with other technologies, for example, Wi-Fi, Bluetooth, and IEEE 82.15.4-based technology for available spectrum band. This leads to scarcity of usable spectrum for the deployment of UAVs.[128] However, CR can mitigate the problem of spectrum scarcity through DSA techniques. As well as, improve channel capacity by opportunistic spectrum utilization for UAVs. Other benefit of applying CR for UAVs include (1) reduced energy consumption and delay, and (2) overlaid deployment. Similarly, potential application areas of CR-UAVs (CR-UAVs) includes, (1) commercial drones, (2) traffic surveillance, (3) crop monitoring, (4) disaster management, (5) border patrolling, and (6) wildfire monitoring. For a detailed survey on issues, opportunities, and future research challenges on integration of CR technology with UAVs see Reference 128.

7.3 | Cognitive-IoTs

IoT is a new paradigm introduced in the late 1990s. The IoT objective is to connect sets of anyone, anything, any service, and any network anytime.[5] The huge research interest generated by IoT in recent years is due to the values it promises to create.[129] The IoT vision aptly summarizes as; IoT promises to connect people and things anytime at anyplace with anything and anyone. If possible, using any route or network and any platform to build a better world for human beings. A world where things around us have the capabilities to distinguish between our likes, our wants, and our needs. Accordingly, act without explicitly being trained. When IoT is fully implemented, it has the capacity to provide solutions for a wide range of applications. For example, References 130,131; smart and connected cities, for example, mobile crowd sensing and cyber-physical sensing. Health care including; health services, for example, internet of m-health and wearable access, health applications including single condition like glucose level sensing and clustered-condition such as medical management. Traffic congestion, security, emergency services, logistics, and industrial control. However, some challenges of IoT that should be of interest to future research includes[5,132]; challenges associated with resource limitations and energy management. In addition, cyber-security and privacy, as well as security requirements (eg, confidentiality, integrity, authentication, authorization, and fault tolerance). In addition, security challenges (eg, computational, energy, and memory limitations, with scalability), as well as interoperability issues and legacy devices. However, the CR technology can solve the challenges of resource limitation for IoT applications by providing access to more bandwidth, for example, through enhanced spectrum sensing techniques.[133-135]

7.4 | Cognitive-M2M

M2M communication is a new communication paradigm similar to IoT. However, unlike IoT, which main distinguishing feature is information, for example, the "connected things" interconnections with each other and with humans.[5,136] In M2M communication, the differentiating characteristic from other communication paradigms is its capability to completely eliminate human activities in the communication cycle. In addition, the main focus in M2M communications is connectivity.[5] M2M interconnects intelligent machines in a digital network using diverse communication technologies to autonomously monitor and control machines without any human intervention. However, the full self-governing automation in M2M has given rise to several heterogeneous applications having entirely dissimilar capabilities and functionalities to leverage on advantages of M2M. Consequently, the number of devices taking part in M2M is massive. According to a report by Ericsson, this number will rise to 50 billion devices by 2020. This geometric explosion necessitates huge improvement on existing access technique to maintain QoS requirements of different applications running on millions of machines. Some challenges created by M2M technology include congestion and overload in network, energy efficiency, heterogeneity, reliability, QoS, and ultrascalable connectivity. To cater for millions of machines in M2M and to overcome challenges imposed by M2M there is a need for more spectrum.[137,138] Accordingly, authors in Reference 139 suggest the incorporation of CR technology in M2M. They argue that to prevent M2M devices from consuming more energy and degrading network performance and efficiency due to limited licensed spectrum a secondary spectrum is needed. However, developing techniques that would allow M2M to access and utilize primary spectrum as well as to opportunistically use the secondary spectrum remain an open issue in M2M. Nonetheless, when this is fully realized, M2M would find application in areas such as; smart metering, traffic monitoring, eHealth care, and SG. As well as cyber-physical production systems and industrial internet of things, as well as transportation.[139,140]

7.5 | Cognitive-5G networks

To fully realize the vision of 5G wireless network as intended the present wireless-based networks would have to improve several capacities.[141] Much of these new advancements should involve different ways of accessing the spectrum. To a large extent, it should involve techniques of accessing higher frequency ranges using DSA technique developed for CR technology. In addition, other part of proposed improvements should include deployment of massive antenna configurations. Similarly, direct device-to-device communications, as well as ultradense deployments should be incorporated into proposed advancements.[5,142,143] Notwithstanding, the innovations in mobile wireless communication has evolved from analog voice calls to the present high-quality mobile broadband services with end-user data rates of several hundreds of megabits per second.[144] However, the envisioned future of mobile technology is a networked society with boundless and limitless data rates. A network with access to infinite information and data sharing which is everywhere, every time for everyone and everything. Therefore, the vision of 5G technology is to provide a network that supports, for example, 1000 times increased data volume per area, and 10 times increased numbers of connected devices. In addition, 10 to 100 times increased typical user data rates, 10 times extended battery life for low power massive machine communication devices and five times reduced end-to end latency. To achieve this goals, new technology components would have to be developed for the evolution of existing wireless-based technologies into the intended future 5G network.[5] Accordingly, future advancements and solutions to achieve the vision 5G network should include[145,146] incorporation of CR technology for 5G network. This also includes extended spectrum band operations as well as consideration of operation in new spectrum regimes to address issues and challenges such as heterogeneous network and coexistence as well as colocation of devices. Other needed improvements include the following—high-speed packets access, long time evolution, orthogonal frequency division multiple access, and scheduling.[147] As well as indoor/outdoor communications technologies, for example, millimeter wave and visible light communication utilizing high frequencies/large antenna arrays, mobile and static small cells.[148] In addition, Wi-Fi overlay/offloads, massive MIMO (multiusers),[149,150] and multihop/meshed networks.[5]

8 | RESEARCH CHALLENGES AND FUTURE RESEARCH DIRECTIONS

In this section, we present research challenges with respect to IWC. Furthermore, we identify current open issues that will define the future research efforts in this area.

8.1 | Effects of white space exploitation for IWC from existing licensing perspective

Under the current licensing rules types of licenses are not explicitly stated. For instance, it states clearly that the CR users should not interfere with the PUs activity on the licensed band. However, no restrictions were imposed expressly on the PUs or other CR users regarding the activity of a CR user in the unlicensed bands.[151] Therefore, it is assumed, albeit without stating it, that currently white spaces only exist in the licensed bands and that unlicensed bands are freely available without restrictions. These assumptions have dire consequences from a technical perspective, since it means, for example, that among the CR users in the unlicensed bands, some CR users cannot be given higher priority. Nevertheless, in specific scenarios, priorities which imposed challenges on the usage of unlicensed bands are defined among CR users.[117] Take, for instance, control and monitoring systems in a manufacturing plant sensor network, which utilizes the unlicensed band, and requires uninterrupted connection with predefined delay tolerance and error margin. Certainly, the operation of this system does not require interference and should definitely be given highest priority. However, if a CR user enters the network without respecting the priority it will cause harmful interference to activity of the manufacturing plant. Therefore, it is vital to mark out the roles and duties of each CR users in the unlicensed bands. In addition, it is important to emphasize the existence of white spaces in the unlicensed bands. Similarly, certain CR applications, for example, time and mission critical applications like control process should be given higher priority in IWSNs.

8.2 | Exploiting additional and extended perspective of white space for deployment in IWC

Current CR users can only exploit white spaces based on the existing constrained dimensions of white space definition.[124] However, new perspectives that consider wider definitions of white space, for example, time granularity of white space, and three regions of white space (ie, gray, black, and white regions) should be focus of future research efforts. The present definition of white space only considers three dimensions of spectrum space, namely, time, frequency, and geographical location. Apart from inherent ability to expand the potential and overall capacity of CR this new perspective can bring about development of new communication applications and new spectrum sharing techniques. In addition, similar to how guard bands were effectively exploited in broadcasting environments for short-range communications by noninterfering symbiotic white space devices. The potential deployment of guard bands and full-duplex by CR user in IWSNs for IWC should be investigated,.[152] To facilitate this research, the use of multiple antennas for full-duplex IWC where CR users can transmit data and sense the spectrum simultaneously should be the takeoff point for future research. Other challenges that might arise from this development, specifically in IWSNs and regarding IWC, includes increased cost, and self-interference between different antennas. In addition, increased energy consumption which is contrary to low energy requirement of industrial systems should be jointly considered.

8.3 | Fusion of cognitive-femtocells for short-range IWC with overlay/underlay/interweave hybrid in industrial-WSNs

An emerging trend in literature for reducing interference in CRN is cognitive femtocells.[153,154] Basically, femtocells are low-power, low-cost, compact BSs deployed to boost cellular capacity and coverage inside small offices and enterprise network.[117] Femtocells with cognitive capabilities have been found to enhance opportunistic spectrum utilization with minimal transmit power as well as interference to incumbent PUs. Similarly, small cell networks approach with cognitive femtocells can be deployed in IWSNs to reduce interference, additionally reliable and stable communication links with significant increase in capacity can be guaranteed through this approach.[155] Similarly, the integration of the three communication paradigms (underlay, overlay, and interweave) with cognitive femtocells for implementation of IWC should be investigated.[156] The fusion should be built in a way that combines advantages of one/two/more of the paradigms whereas mitigating their weaknesses. Some combination has already been considered for exploiting channel capacity and improving spectrum usage efficiency to some extent in literature. For instance, interweave and underlay as well as underlay and overlay combinations.[117] Others novel combination adopted for white space exploitation includes an underlay-relay hybrid. However, potential combination of the three perspectives remain an open issue. Therefore, future research work can consider investigating these open issues to exploit low power/range transmission in both licensed and unlicensed bands.

9 | CONCLUSION

In this review article, we have examined unique QoS requirements, as well as typical technical challenges of IWC in achieving reliable wireless connectivity in heavily shadowed, and multipath fading industrial-WSNs environments. We discussed how difficult it is to achieve reliable, and stable wireless connectivity with significant channel capacity due to overcrowding of ISM band which results to scarcity of spectrum band, and stiff competition for available frequency spectrum. Similarly, we isolated and discussed negative effects of noise and interference in detecting usable frequency spectrum through different spectrum sensing techniques in industrial-WSNs. In our attempt to proffer solutions, we introduced DSA, which is a new CR paradigm, and we identify DSA and CR as potential candidates for enabling full implementation of wireless technology in IWC for industrial systems and applications, and for solving spectrum scarcity shortcomings. We have also discussed various research issues, and challenges regarding IWC and CR, and we presented as well as suggested solutions where possible, and then finally, we identified open issues for future research works.

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