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INVESTIGATION ON COGNITIVE RADIO NETWORKS: INTRODUCTION, SPECTRUM SENSING, IEEE STANDARDS, CHALLENGES, APPLICATIONS

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Abstract -
During the last decade, Cognitive Radio (CR) has become a popular research topic. The availability of radio spectrum is in shortage, and CR technology can solve the problem by enabling dynamic spectrum access. This innovative technology has been used to manage the radio spectrum since it was introduced. These developments have led to rapid advances in this research field. A review of recent advances in Spectrum Sensing (SS) is presented in this paper, from its origins to its present state. A CR network has been found to be a highly effective and intelligent technology. Frequency spectrum is a bounded natural resource and an essential component of wireless communication networks. We explored CR in this paper and its various phases. Different definitions of CR are then presented from various institutions. Many different types of communications systems use CR techniques. It is anticipated that they will improve commercial and military data services, as well as increase the use of underutilized radio frequencies. In this paper, CR standards have been discussed, as well as its applications in various areas.

Keywords **- Cognitive Radio(CR); Communication; 5G; 6G; Spectrum Sensing (SS); IEEE; Standards; Narrowband Sensing; Duplex, Wideband Sensing; Compressive Sensing; Channel Sensing; Interference Sensing.**

I. INTRODUCTION

There is a shortage of radio spectrum due to the dramatic growth of Static radio spectrum management and wireless devices [1]. It is estimated that by 2025, there will be over 50 billion wireless devices, all of which will require access to the Internet [2]. Access to all these devices cannot be granted through the Static radio spectrum management. The radio spectrum is allocated so that some portions are heavily utilized while others are not or rarely used. It is possible that denial of service events may arise as a result of users not sharing the radio spectrum. Radio spectrum scarcity is therefore a leading concern for network research in the future, that has yet to be addressed. Research has been conducted on CR technology for almost two decades [3], and it has been found to be useful in solving these problems and many others. CRs sense electromagnetic fields through wireless devices, make decisions about the frequency channels, and dynamically adjust their communication parameters to balance energy consumption and quality-of-service requirements [4]. As long as their Primary Users (PU) are not active, these devices can work on both unlicensed and licensed bands together, preventing adverse interference. Greater band width leads to greater speed, so greater band width is in high demand. In contrast, crescent width bands can interfere with other frequencies. This is illustrated below. The use of CR can improve the efficiency of a wireless system by using already used frequencies without causing interference. Additionally, cognitive radios are able to locate open channels in radio spectrum. Using a CR, more users can be telecommunicated without needing more infrastructure.
Currently, wireless communication demands a high rate of speed and throughput [5]. Wireless communication has become increasingly popular since high-speed wired communication became common decades ago [5]. Most wireless networks use OFDM for their downlink [5]. They can be used with difficult channels thanks to their adaptable characteristics [5]. This technology is a wonderful choice for 4G communications. Its main disadvantage is its PAPR [5].

With wireless 6G networks, we expect to see more integrated radio services, compared to massive MIMO, Wireless communication and heterogeneous devices are made possible by larger surfaces, as opposed to 5G [6]. Artificial intelligence will support automated 6G [6]. In addition to enabling the transition from cognitive to intelligent radio, 6G will exploit the full potential of radio signals. [6]. Mobile communications technology and wireless technology are rapidly improving every day [7]. In wireless communication, signals are sent and received without the use of wires or other enhanced conductors [7]. It is possible to connect wirelessly through mobile phones, two-way radios, handheld audio players, and personal digital assistants [7].

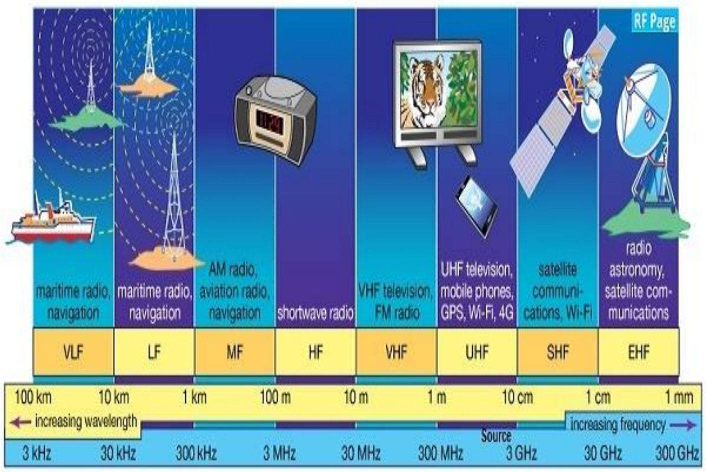

Figure 1. Frequency applications

Radio spectrum is becoming increasingly scarce due to the ever-increasing usage. According to an analysis, the inefficiency of fixed spectrum allocation is responsible for this scarcity. In spite of the ease of implementing these techniques, they result in a great deal of variation in their utilization of space on different frequency bands. By distributing users differently in different bands, the spectrum seems like a finite resource which will soon become overwhelmingly congested with potential users. Some of the most effective remedial measures have been suggested as dynamic spectrum access (DSA) or Future Generation (xG) Networks. The DSA recommends that users in the more congested bands choose less congested spectrum bands. Over the past decade, the IEEE 802.22 standard has evolved from a definition to a proposed IEEE standard. It is a popular research area to examine the Digital Television (DTV) band for the purposes of DSA by the Federal Communications Commission (FCC).

II. COGNITIVE RADIO (CR)

The proper use of radio frequency spectrum is of prime importance for wireless communication networks. A non-flexible license allocation prevents efficient use of the frequency spectrum. Service providers are assigned these licenses by government agencies for a long period of time and a large area of geography. It is possible to improve spectrum utilization by adopting a dynamic access policy. In addition to mobile telephony, digital video broadcasting (DVB), wireless local area networks (WiFi), and wireless sensors networks (ZigBee), the radio spectrum used by Internet of things (IoT) applications is enormous and continuing to grow. We can expect this growth to continue for a long time to come.

In low-bandwidth areas, CR can dynamically allot spectrum to each device, maximizing their capabilities. Software-defined radios, accessible through a program, allow them to change their frequency as they need. In a research paper published at the University of Stockholm, Dr. Joe Mitola introduced cognitive radio. To communicate differently based on their environment, handsets, mobile phones, and cell networks were designed [59]. As described in the official definition, Radio Knowledge Representation Language is a standard language that may be used to dynamically define unanticipated data exchanges [8]. CRs can take advantage of this to increase battery life and improve performance. Furthermore, the system is also capable of choosing the most appropriate network to serve the user's service requests [9]. In recent years, mobile phones have incorporated this component via Wi-Fi calling.

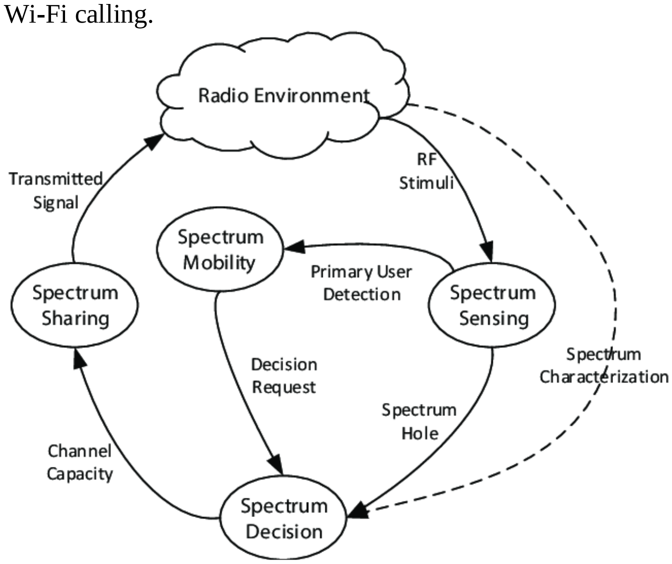

Figure 2. CRNs illustrate the cognitive cycle.

Using Wi-Fi, or the phone's mobile connection if Wi-Fi isn't available, WiFi calling uses the connected Wi-Fi network.

Additionally, it is capable of switching between these two networks during a call, according to the strength of the signal [10]. As an example of how cognitive radios can improve communications in the future, this is one example. It is possible to use Li-Fi as well, transmitting information with visible light from the web to a device. When Li-Fi is used, devices have high bandwidth and a connection that is heavily reliant on visibility from point-to-point. Those devices supporting this technology must maintain an active connection even if they switch to another radio [11]. Two types of users are present in a cognitive radio. The Primary Users (PU) of the available spectrum are those devices that have a higher priority. Those with a lower priority can take advantage of underutilized spectrum used by SUs.

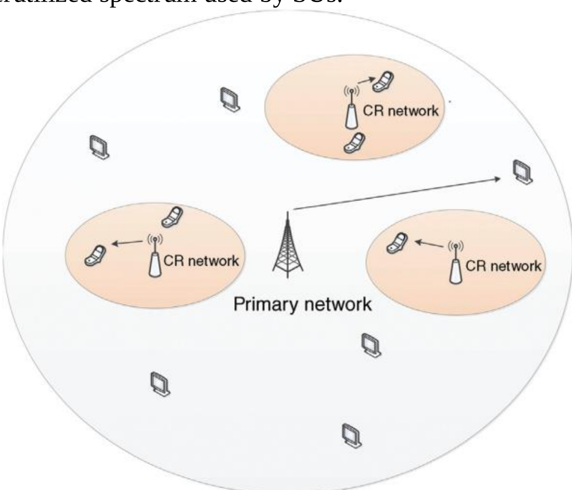

Figure 3. A primary network containing CR networks.

CR provides very reliable radio communications while ensuring that spectrum is utilized efficiently [57]. In cognitive radio, there are several major issues to consider, including intelligence, awareness, learning, reliability, adaptivity, and efficiency. Time, frequency, and energy should be efficiently utilized by this technology. By designing an antenna appropriately, it can resonate on multiple frequencies [12]. Spectrum efficiency will play an increasing role on future wireless communication systems as users increase at a rapid rate [13].

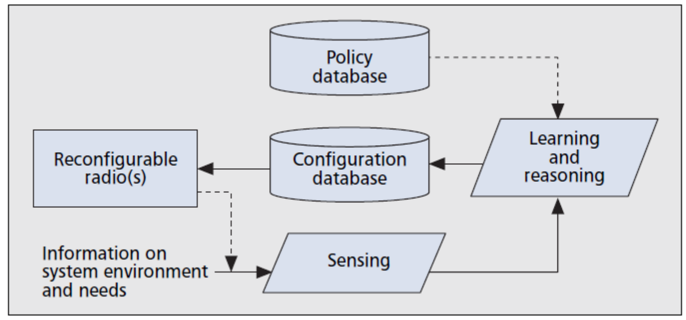

Figure 4. Components in a CR system

III. SPECTRUM SENSING TECHNIQUES

According to Figure 5, below, there are two categories of sensing techniques: narrowband and wideband.

3.1 Narrowband Spectrum Sensing

The SU can detect the presence of the PU at a certain frequency channel utilizing narrowband SS techniques. If X_1 doesn't exist, then we assume that there is a PU signal, and if X_2 is not present we assume that there is no primary signal from the user. The received signal can be expressed in terms of these two assumptions, X_1 and X_2 .

$X1 : R(n) = G(n)$

$X2 : R(n) = T(n) + G(n)$

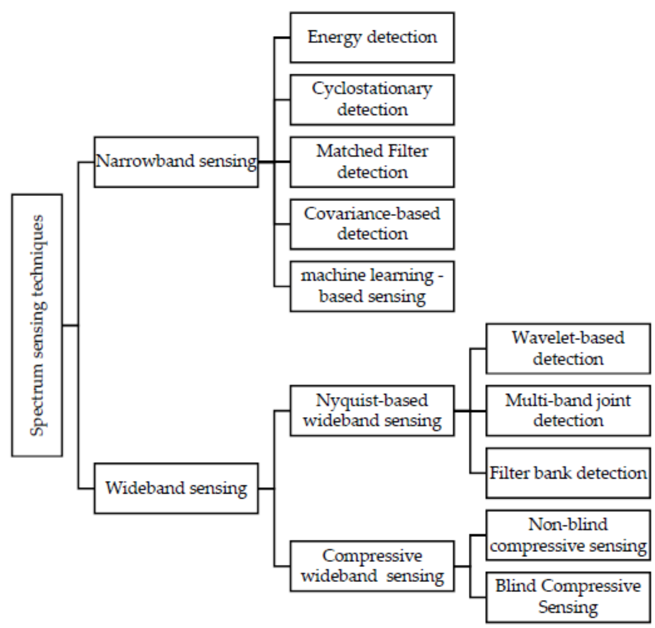

Figure 5. Spectrum Sensing Techniques

PUs are absent in state X1, while PUs are present in state X2. The receiving signal is represented by R(n), Gaussian white

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noise is represented by G(n) with a mean of '0' and variance 'σ^2'the transmitted signal is represented by T(n). n is the sensing time.
The probability of false alarm is $p_f = p(X_1 \mid X_2)$
The probability of detection is $p_d = p(X_1 \mid X_1)$

3.1.1. Energy Detection

By calculating the energy of the sample and comparing it with a threshold, energy detection can be performed [56]. If the energy is greater than this threshold, the PU signal will be present; otherwise, the PU is absent. Figure 6 illustrates how the energy of the samples can be calculated as the squared magnitude of the FFT accumulated over N samples. It is given by

$$T_{ED} = \frac{1}{N}\sum_{n=1}^{N}\left[R(n)\right]^2$$

R[n] represents the nth sample received, and N represents the total number of samples received.

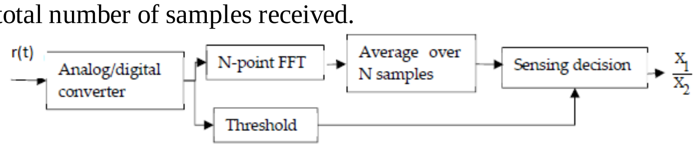

Figure 6. Energy Detection

3.1.2. Cyclostationary Feature Detection

Signal characteristics that are received during cyclostationary feature detection are important. There are certain statistics in the transmitted signal, such as modulation rate and carrier frequency, that are cyclostationary and observed as such. Using cyclostationary feature detection techniques, it is possible to distinguish between signal and noise based on a spectral correlation function of the signal's amplitude, which is stationary but has no correlation with the signal [1]. If the mean and autocorrelation of the received signal r(t) are periodic, then the signal is said to be cyclostationary. It can be expressed mathematically as follows:

$$m_r(t) = E\left[r(t)\right] = m_r(t+t_0)$$

$$R_r(t,\tau) = R_r(t+t_0,\tau)$$

Let, the period of the signal r(t) is t_0; expectation operator is E; autocorrelation function of r(t) is R_r and τ denotes the time offset. The autocorrelation of the received signal is given by:

$$R_r(\tau) = E\left[r(t+\tau).r^*(t-\tau)e^{j2\Pi\alpha t}\right]$$

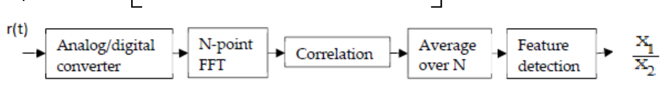

Figure 7. Cyclostationary features based techniques

Energy detection techniques are inferior to cyclostationary techniques in terms of detection performance. Moreover, these techniques have a lower false alarm probability since they are able to distinguish between signals and noise, making them less susceptible to noise uncertainty. Increasing the number of samples can further improve the performance of cyclostationary energy detection. With an increasing signal length, this can result in an increase in the sensing time and complexity. To reduce this complexity and achieve a satisfactory detection performance, a balance needs to be struck between sensing time and performance detection.

3.1.3. Matched Filter Detection

In order to compare the received signal to predetermined and pilot samples from the same transmitter, matched filter sensing can be performed. Test statistics are computed using these pilot samples and compared to a threshold. The signal is considered to exist if higher than the threshold. Figure 8 depicts this process.

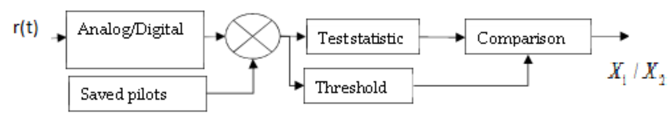

Figure 8. Matched filter based SS

According to the matched filter technique, the test statistic is as follows:

$$T_{MFD} = \frac{1}{N}\sum_{n=1}^{N} r(n)x_p^*(n)$$

Here, N represents the number of samples, y represents the numbers of Vector samples, and x_p represents the number of pilot samples.

3.1.4. Covariance-Based Detection

Singular Value Decomposition (SVD) is used in covariance-based detection to determine whether there is a PU signal in a signal. A covariance matrix of the received signals is evaluated to determine this. A PU's signal can be separated from other signals like noise when they are correlated. By decomposing this matrix by singular values, eigenvalues can be determined. A threshold is used to decide between X_1 and X_2 based on the ratio of the maximum eigenvalue to the minimum eigenvalue.

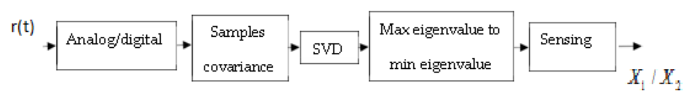

Figure 9. Covariance-based based techniques

3.2 Wideband Spectrum Sensing

Communication systems of the future will need high data rates and high bandwidth. As a result, SUs need to be able to sense the spectrum over a wide frequency range to determine the best channels. To deal with the wideband SS problem, several different types of solutions have been proposed [14]. In most cases, the wideband spectrum is divided into narrow bands, with sensing taking place in sequential order. This process increases sensitivity times as each band is scanned individually. Using multiple sensors and performing joint detection is another solution for sensing narrow bands in parallel. Due to the high hardware costs and the requirement for sensor synchronization, this approach is also impractical. Compressive sensing techniques have been studied as an alternative, reducing the number of samples and sensing delays.

3.2.1 Nyquist Wideband Spectrum Sensing

To sample the wideband signal by conventional wideband SS technologies, Nyquist rate ADC converters are used. There are many types of wavelet type coding, such as wavelet, multiband joint detection, and filter bank sensing. A discussion of these techniques is provided in the following sections, along with a description of their strengths and weaknesses.

3.2.1.1 Wavelet Detection

Consider a situation in which the received signal occupies M bands with unknown frequency locations and power spectral density, which should be detected. Wavelet transforms are used to characterize the edges of an occupied band in a wavelet approach for SS. In Figure 10, we see how wideband signals are decomposed into elementary subbands, each characterised by local irregularities in the frequency domain. We then apply a wavelet transform to detect local spectral irregularities that contain important information about the frequency locations and the power spectral density of each subband [15-20]. It introduces significant latency to divide a band into many channels and then sense each channel sequentially. An RF front end with a bank of narrow band pass filters may be used to jointly sense multiple bands in order to reduce latency.

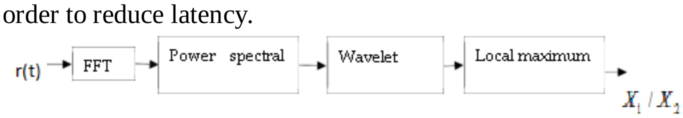

Figure 10. Wavelet based SS

3.2.1.2 Multi Band Joint Detection

The Multi band joint detection technique in Figure 11 detects the presence or absence of the PU simultaneously over more than one frequency band [21-22]. The energy of the received signal over N samples is calculated using a CR device sensing K narrow bands, and the energy is compared to a threshold to determine whether the band is occupied. As a function of the threshold, the probability of false alarms and detections for each band changes. Through solving an optimization problem, multi-band joint detection is about finding an optimal threshold vector for all the bands that will increase the detection probability and decrease the false alarm probability for all.

3.2.1.3 Filter Bank-Based Sensing

Power spectral density (PSD) is usually estimated with wideband SS. Using a poly-phase decomposition of the prototype filter [23] can be an effective means of estimating this function using the filter bank approach [23-26]. An array of band-pass filters forms the basis of filter bank analysis, as shown in figure 12. Normally, a low-pass filter is shifted into frequency by a frequency-shifting algorithm. Each filter bank has an energy detector installed after its output. It measures whether the PU is active or not.

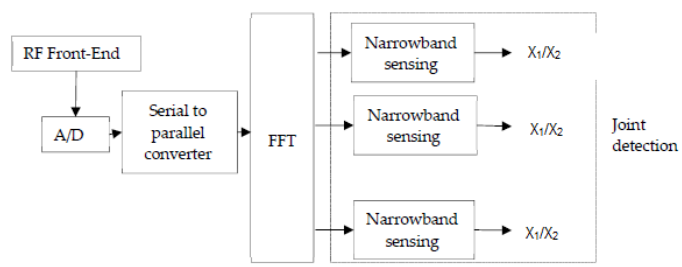

Figure 11. Multiband Joint Detection

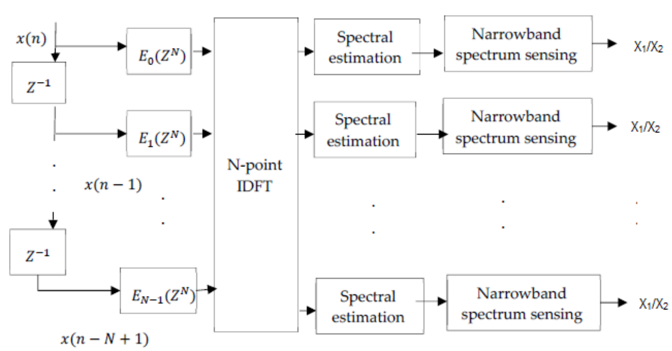

Figure 12. Filter bank based Spectrum Sensing

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3.2.2 Sub-Nyquist Wideband Sensing

Considering the limitations such as sampling rates and power consumption, Nyquist-based sensing is a promising candidate for next-generation communication systems. Many compression-based methods have been proposed to reduce sampling rate issues. These methods have been applied to wideband SS in the context of the scarcity of spectrum and the sparsity of wideband signals in the frequency domain.

3.2.2.1 Compressive Sensing-based Wideband SS

Multi-Bit Compressive Sensing Mathematical Model- Recent research studies have focused on compressing wideband SS [27,28,30]. A wideband signal becomes sparse in the frequency domain when compressed sensing is used in this context because most frequency channels are free. A compressive approach consists of a few measurements to recover the sparse signal [31]. As a paradigm, sparsity and incoherence underlie its foundation. Figure 13 illustrates the three main steps of compressive sensing. The compressive sensing method is only applicable to sparse signals, a sparse representation projects the signal onto a suitable basis to make it sparse. The techniques of sparse representation include FFT, DFT, and DCT. In measuring sparse signals, signals are multiplied by measurement matrices in a few measurements, which retrieves the original sparse signal.

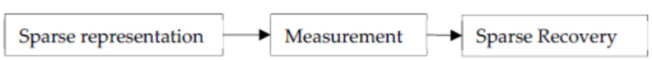

Figure 13. Compressive sensing

1-Bit Compressive Sensing - Prior to the signal processing step, most communication systems require a quantization step, resulting in multi-level quantization errors. In most cases, quantization has been modeled as noise with limited energy [32]. Recent research has proposed 1-bit compressive sensing as a promising solution to minimize multi-level quantization errors [33]. Typically, this technique uses a comparator implementation to perform 1-bit quantization.

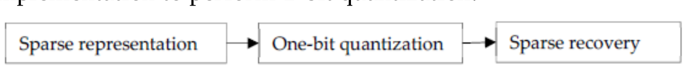

Figure 14. One-bit compressive sensing

IV. CR STANDARDS

4.1 IEEE 802.22 (Wireless Regional Area Network)

Some of the terrestrial TV channels are reserved for usage only in certain locations or geographical areas. The switch from analogue to digital creates significant vacancies within both UHF and VHF spectrums [34]. IEEE 802.22 WRAN [35], which focuses on wireless broadband access for rural areas, aims to provide unlicensed use of television frequency bands (54-862MHz) on a non-interfering basis with PUs. As a result of this standard, the maximum range is 100 km [37], and the standard adopts cellular architecture and cell radius is typically 17-30 km. Standardizing the physical and MAC layers of CR-enabled interfaces is a first [34]. Spectrum availability is required to be communicated to the SUs at a given instance because this standard requires it. Geolocation databases and SS are two methods used to achieve spectrum awareness [36-37]. A GPS-enabled device is required for the geolocation process to function accurately. In addition to analog and digital television bands, low-powered auxiliary devices [37] are also spectroscopically characterized. Furthermore, all 802.22 devices must be able to detect beacons broadcast by devices equipped with a UHF power output of 250 mW and VHF power output of 50 mW with a bandwidth of 77 kHz on the TV band. In addition, the devices required to comply with the standard must change channels dynamically if the current channel becomes crowded. There is a point to multi point network topology where base stations can serve up to 255 clients at a minimum peak downlink data rate of 1.5 Mbps, and a maximum uplink data rate of 384 kbps for cell edges. In the physical layer, 2048 carriers are used for orthogonal frequency division multiple access. Because paired television channels are not readily available, uplinks and downlinks are time division duplexed.

4.2 IEEE DySPAN (Dynamic Spectrum Access Networks) Standards

New technologies and techniques are supported in this set of standards for advanced spectrum management and DSA, which include new operational and coordination techniques for wireless networks, including sensors, network management, and coordination of wireless networks. Formerly known as the IEEE P1900 Standards Committee and Standards Coordinating Committee 41 (SCC41), the IEEE DySPAN Standards Committee is operated by IEEE. Different groups are currently developing seven different standards; IEEE 1900.1 to IEEE 1900.7.

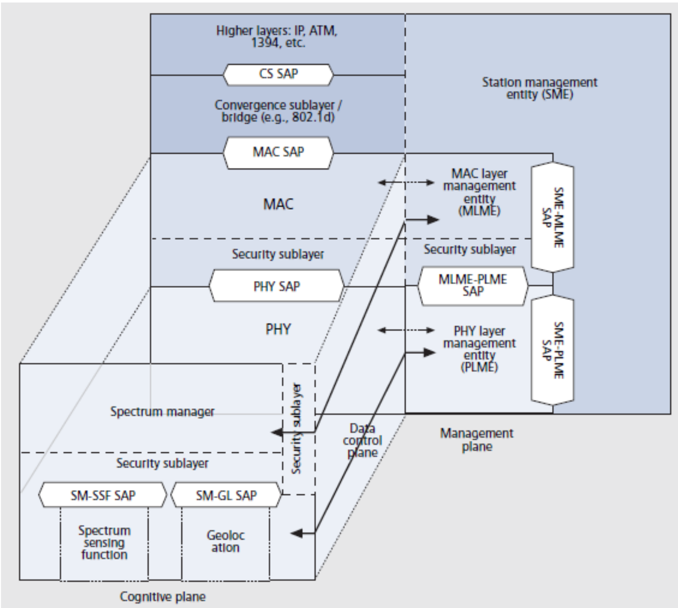

Figure 15. CR interface : IEEE 802.22

4.3 IEEE 802.19.1

TV spectrum holes can be exploited by devices to ensure coexistence, this standard has been developed. A coexistence system refers to the self-existence of CR devices that use a system using the same CR standard coexists with another system using a different CR standard. It is the ability to coexist between devices that use different standards that is more challenging, rather than self-coexistence, which is almost always included in the CR standard. Three main tasks are addressed by this standard: (1) Identifying the different CR systems that need to coexist, (2) adjusting operating parameters so that performance is improved for the different CR systems, and (3) providing a unified interface between CR devices using different technologies.

4.4 IEEE 802.15.4m (Zigbee)

Wireless Zigbee devices, also called transceivers, transmit and receive data [38]. Zigbee is based on IEEE802.15.4. Approximately 100 meters can be covered by Zigbee. This device has a ten-fold greater range than Bluetooth devices [38]. Low-power, low-cost, and easy to install, ZIGBee-based wireless control networks provide flexible deployment options that provide low-power, low-cost wireless networks [38]. The IEEE 802.15.4 standard uses the TV spectrum holes to reband frequencies used by conventional IEEE 802.15.4 devices. With the increasing popularity of wireless sensor networks, active radio frequency identification, body area networking and smart utility networks, IEEE 802.15.4 has become a popular standard. While the current spectrum is limited, it is vital to look into additional spectrum opportunities as more applications emerge. This is accomplished by the IEEE 802.15.4m, which incorporates peer-to-peer connectivity as well as device-to-device connectivity to maintain its relevance to its intended sensor network applications.

4.5 IEEE 802.11af (WiFi)

In IEEE 802.11af, the physical layer and the MAC layer will be modified by TV spectrum holes to allow LANs to access them. Geolocation databases, registered users, secure servers, and geolocation database-dependent entities (GDD) such as GDD enabling and dependent stations are the main elements. In RLQP, the dependent station provides information such as power, bandwidth, and spectral band parameters that are sent to GDD enabling stations.

V. FUTURE CHALLENGES

CR is based on the principle of dynamic spectrum sharing among wireless technologies. As a result, advancements and the growth of these technologies have a major impact on SS for CR. In addition to new concepts, new technologies, and a number of other techniques, wireless communication is undeniably evolving from many perspectives including infrastructure deployment, systems operation, and management. Thus, SS should maintain a pace with the evolving technological environment. Several challenges are discussed below.

Channel Coding for Interference Sensing:

TR mode of the FDCR is where most IS applications are applied. The TR mode allows two SUs to communicate bidirectionally using only one available channel, in comparison with TS mode or HDCR, it has a higher frequency efficiency [39-40]. To determine whether a PU is in operation, TR decodes signals based on the chosen channel coding algorithm. When the weak technique is used, the secondary network may lose performance, but when the strong technique is used, the SU can decode the signal even when PU is active. A challenge emerges here in finding the optimal channel coding technique that matches the quality of service of SUs while enabling SUs to detect PUs at the same time.

Switching protocols between CR functioning modes:

Currently, only PU statistics are taken into account in techniques for switching between CR modes [41-42]. As each mode has different requirements, it is important to also consider other parameters, like energy and frequency resources. As a consequence, TS and TR, which are based on SIC, require more hardware and energy resources. Some battery-powered devices, such as LPWAN IoT devices, cannot be charged in this way, especially the ones planned to work for a long time. A mode's adoption is determined by the available bandwidth and the need to establish bidirectional communication between two peer SUs: TR could be a good choice given that only one channel is needed, but it suffers from poor sensing in low PU SNR regions [58]. The frequency as well as the energy efficiency should be considered for making the right choice as to which mode of transmission to use.

Access Strategy for IoT/WSN networks:

Due to the large number of sensors, there is a high level of contention between SUs in IoT applications. To manage the access of different types of sensors in such an application effectively, the spectrum sharing strategy is of utmost importance [43-45]. Depending on the sensor type, redundancy of data, and criticality of data, the strategy may vary. The sensors with the potential to transmit critical data, such as those that transmit data regarding natural disasters and e-health, could be prioritized over the other sensors. As a strategy to alleviate interference, a weighting strategy is often used in Wireless Sensor Networks (WSNs). It may be useful in CR-IoT applications to manage access to channels and maximize spectrum efficiency by enabling multiple nodes to access available channels simultaneously [46].

Exchange Protocol of SS data for IoT/WSN:

For CR-IoT systems to function properly, adequate protocols must be developed to manage the communication between nodes and the central entity [47-48]. Nodes are requested to sense a given channel and to provide channel availability updates to the concerned nodes. IoT nodes need energy to respond to sensing requests, especially when they are battery-powered. It should be determined by the central entity of the IoT/WSN network how the sensors will sense the channel, how many sensors will be used each day, and the maximum sensing time per sensor to ensure optimal resource utilization. The central entity should a priori inform the nodes of the channels that will be available for data transmission. A protocol should therefore ensure that the end-nodes and the central entity share time and frequency at all times.

Use of Intelligent Reflecting Surfaces:

Intelligent Reflecting Surfaces (IRS) might be useful for SS, which are expected to play a pivotal role in 5G and B5G technologies [49-50]. An Intelligent Reflecting Surface will passively reflect the radio signal to a target receiver. By reflecting the PU signal towards the SUs, which have low PU SNR, the IRS may be able to overcome the hidden PU problem. When IRS is used to assist SS, multiple challenges will be encountered, since PU and IRS, IRS and SU, and PU and SU all have different channels. Channel estimation becomes challenging when SU and PU do not cooperate. A good candidate to assist with the problem could be blind channel estimation and cascaded channel estimation [51].

Sensing the Spatial Dimension for CR :

The spatial availability of spectrum is provided by beam-based sensing for PUs, which makes SUs more and more dependent on PUs. It is still challenging for SU to estimate the PU's transmission beam, since PU does not cooperate with SU [52]. Even when the PU beam can be adjusted, the SU beam is also challenging because the SU transmitter is likely to interfere with the SU receiver. The number of transmit antennas, the beam direction, and the transmit power must therefore be adjusted carefully. Although beam-based CR for IoT/WSN devices is technically feasible, multiple antennas are required in order to adjust the SU beam.

VI. MODES OF COGNITIVE RADIO

CRs can reconfigure themselves according to their interactions with their radio environments in order to best suit them. CRs can exist in three different scenarios:

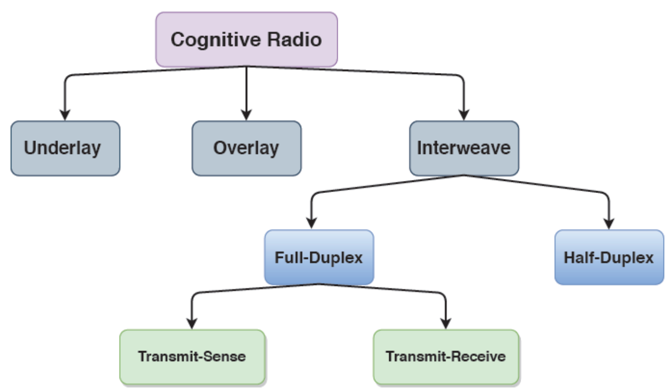

Figure 16. CR access paradigms

6.1 Overlay Cognitive Radio

A cognitive overlay radio identifies that white space in the radio spectrum that does not currently have a PU licensed to use it. In this white space, overlay cognitive radios are acting as unlicensed SUs. There is a considerable amount of research in the multi-layer protocols that define these interactions. Generally, overlay cognitive radios use SS techniques that focus on transmitter detection. SUs can transmit on the same channel simultaneously with PUs up to their maximum power, but at the cost of acting as relays between two or more PUs [54-55]. Here, the SU relays the PU's data and sends its own data. In order to achieve this type of access, PUs and SUs would need to work together at a high level, which might compromise the privacy of PUs.

6.2 Underlay Cognitive Radio

Coexisting in the same spectrum, the underlay cognitive radios use ultra wide band transmission. To ensure that interference temperature caps defined by regulatory agencies are not exceeded, SUs' transmission power is so adjusted. As a result, the PU disregards the transmissions of the SUs. There may be simultaneous transmissions by the SU and PU on the same channel. For the interference on the PU to remain below a tolerable level, the transmitted power should not exceed a certain threshold [53].

6.3 Interweave Access

The maximum power of SU can only be used when PU is absent. Considering its popularity, this paper focuses on the classical paradigm, also known as the CR.

6.4 Leased Networks

Licensed users are able to lease off a portion of their spectrum to SUs through leased networks. Specifics of the contracts dictate how such a relationship will be established. It may even be possible for licensed users to participate in the identification of spectrum holes.

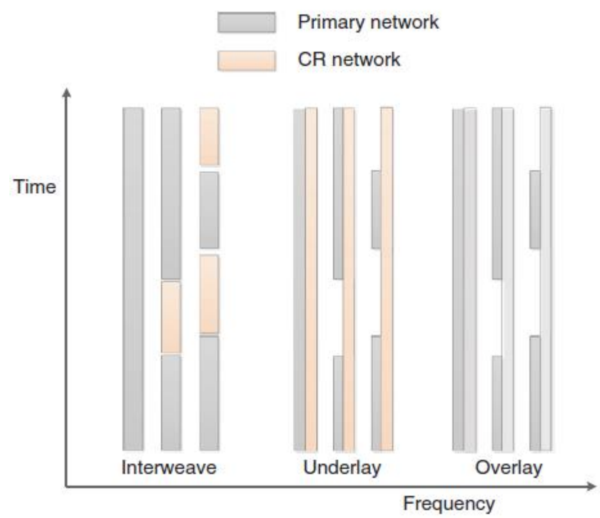

Figure 17. Cognitive radio: Interweave, Underlay, and Overlay

VII. APPLICATIONS

Market growth in CR can be attributed to technological advancements, better spectrum utilization, and 5G adoption. Communications world has been made popular by the capability of CR to adjust according to the surrounding. Military, public, government, commercial and safety are just some of the areas where CR has many benefits.

- CR networks are used to communicate in emergency and public safety situations through the use of white space.
- DSA on CR networks is a potential application of CR networks.
- An application of CR networks to military operations, including detection and investigation of chemicals, biologicals, radiologicals, and nuclear weapons attack, command control, assessment of battle damage, battlefield surveillance, and intelligence assistance.
- Wireless sensor networks can also benefit from cognitive radio, in which packet relaying can rely on primary and secondary queues to forward packets without delay and with minimal power consumption.

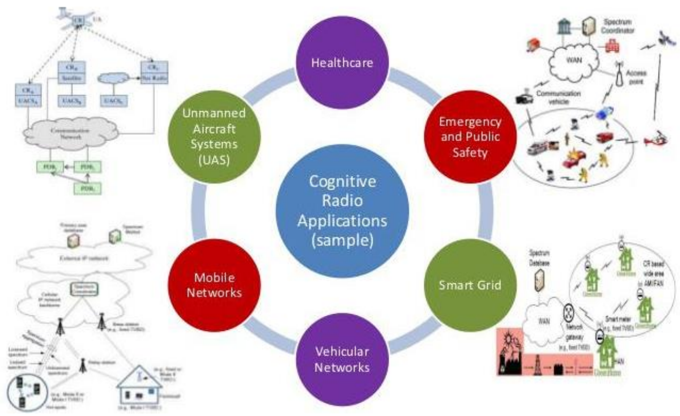

Figure 18. CR Applications

7.1 Efficient Spectrum Utilization:

CR can efficiently utilize spectrum, as shown in Figure 19. Effective spectrum utilization has led to improvements in various fields, as shown in the following.

Military :

CRs have become very useful and essential because of the flexibility and agility of their spectrum. Since it is capable of interoperating with a variety of different radio frequency standards, as well as sensing interference, its wide spread application has become apparent. The military has recognized this important technology's benefits and properties and has begun employing it. It is understandable that they are more concerned with secret and secure communications. CR has started being used extensively and has taken the lead in the communication equipment being used by the armed forces because of its ability to monitor its surroundings and identify any communication equipment belonging to the enemy. In military applications, these intelligent radios are widely used due to their ability to transmit data continuously, secure and secretly. CR technologies for intelligent communication have recently been a focal point of the Defense Department of the USA, and new initiatives have been developed.

Public Safety :

In terms of public safety and emergencies, CR plays an important role. In the event of an emergency, agencies that provide public safety need an additional spectrum. Spectrum from CR can relieve congestion during an emergency situation. Sharing of radio spectrum is basically what this concept is all about, as it determines the main concern of the call and the reaction time of the caller. In case of suspicion, jurisdictions can employ CR technology to operate the communications equipment of others and retrieve their information. If two stations are using different radio systems, a CR can provide a channel between them. In this way, secrecy can be protected. The Justice Department of the United States has taken note of CR technology due to its capabilities, and as a result they have instituted the NPSTC (National Public Safety Telecommunications Council) to focus on the field of CR technology.

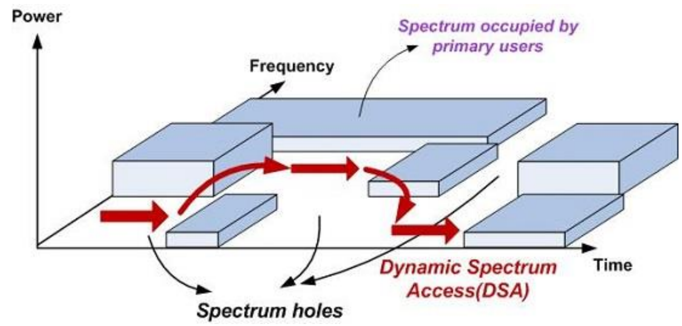

Figure 19. CR : Efficient utilization of spectrum

Broader Impacts and Commercial Use :

DSA involves the sharing of spectrum. We know that regulatory and policy authorities are the biggest obstacles to implementing a CR network. Also of concern is the potential availability of radio spectrum and the accuracy of prediction. By using CR technologies, the traditional method of assigning frequencies has been transformed into dynamic spectrum assignment. This demand is getting more and more difficult to meet with the growing demand for mobile devices and the increasing demand for spectrum. It is very important for the dynamic allocation of spectrum to know when there are any devices present as well as identify any interference caused by them. Devices given access to a wider spectrum become more problematic when given access to a wider spectrum. Interference in the ISM band has become more of a problem since wireless local area networks have been added to the band.

7.2 Increasing Link Reliability

The enhancement of link reliability is another very important application of this technology after improved and efficient radio spectrum utilization. With adaptive radios, transmission power, modulation, and error correction can all be dynamically tailored, enhancing link reliability [2-23]. CRs are capable of learning, remembering and adapting to their surroundings, so the situation can be improved greatly.

7.3 Less Expensive Radios

Any radio that has complex circuitry is extremely expensive, but by adding the cognitive principle, the cost can be reduced dramatically. Most of the features of CR can be implemented at a lower cost and with less complexity, therefore reducing cost. SDR, which is the foundation of CR implementation, also contributes to the reduction in costs. Comparing the CR to analog components, this allowed the CR to perform at a higher level with a lower cost. In contrast, adding 200 software cycles per second doesn't cost much, but improving a RF front end's performance by 3 dB is rather expensive. Taking advantage of opportunistic opportunities at the same time improves spectrum capacity, as we have seen previously. In addition to improving channel capacity, CR includes some components that allow signal components outside the limit of the channel to enter the system. This can be achieved using analog components in the CR.

VIII. CONCLUSIONS

CR is very popular in the world of communication due to its ability to adjust to the surroundings. This discovery will lead to more efficient use of spectrum. We can probably expect that accessing the radio spectrum by 2025 will be a big challenge, the Internet is expected to be accessed by billions of wireless devices in the near future. The problem that has not yet been addressed is one of the most urgent ones. A CR system may be able to aid in overcoming spectrum access challenges. Research on wideband SS is a recent frontier of CR technology, and this paper explores the latest advancements and challenges in this field. The CR technology has been developed according to many standards. In this study, CRs are described in detail and elaborately.

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