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Cognitive Radio Networks: a comprehensive study on scope and applications

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Abstract— The work aims to investigate into the modern concept of cognitive radio and details about its functioning. The ideas that led to its invention and the thoughts that led to this modern technology of using white spaces in the most efficient way. It aims to take a dig into the earlier radios namely the conventional radio and the software defined radio and later on modifications of those that ultimately led to cognitive radio. Not only that but it deals with every nuance between each of them. Various persons including the person who was the propagator of the concept of cognitive radio technology Dr. Joseph Mitola and various organizations have tried to define cognitive radio and the discussion considers all those definitions to let the reader get a clear picture regarding their understanding as far as defining cognitive radio is concerned. The requirements of cognitive radio in various fields and the future scope of the technology are profoundly dealt with. A network of cognitive radios known as cognitive radio network (CRN) is also the matter of discussion in the latter half of the work. Various components of the CRN and certain details regarding it are included with appropriate diagrams as per requirements

Keywords— Reconfigurable radio, Electromagnetic spread spectrum, Underlay Sharing, Overlay sharing, Generic hardware, Digital signal processor, Sensor, Actuator, ALOHA, Pulse train, Spread spectrum, Hopping sequence, Cyclic prefix.

I. INTRODUCTION

Before going into the concept of cognitive radio, it's essential to have the concept of two important terms **cognition** and **artificial intelligence**. According to the authors of **[1] cognition** may be thought of as the set of all mental abilities and processes related to knowledge, attention, memory and working memory, judgment and evaluation, reasoning and computation, problem solving and decision making, comprehension and production of language etc. According to the authors of **[2] artificial intelligence** can be described as the study of making computers and computer softwares do things that presently human beings do better. It's the study of making computers and computer softwares do things in an intelligent way much like the thought process of human beings. **Cognition** along with **artificial intelligence** are the main transformers of the present digital civilization and possesses enough potential to keep on doing so. Cognitive Radio can be described as a radio for wireless communications in which either a network or a wireless node can change its transmission or reception parameters automatically based on the interaction with the environment to communicate effectively without interfering with the licensed users, serving the secondary users in an intelligent way. Thus it will aim to utilize white spaces in the most efficient way possible, learning from its previous experiences of transmission. These techniques along with a software definition for **reconfigurable radios** will be the stepping stone for an early and successful evolvement of cognitive radio, which can affect much traditional business. The functionality of a cognitive radio can be summed up in two words**- IT ADAPTS [1]**. Elaborating it can be said that the radio must be smart, capable of learning services available in locally accessible wireless computer networks, and can interact with those networks in their preferred protocols, so there would be no confusion in finding the right wireless network for a particular work. It must also be capable of using the frequencies and choose waveforms that minimize and avoid interference with existing radio communication systems. This has to be the most important work of a cognitive radio, finding the unused spaces between the allocated spectrum bands, also known as **white spaces**. However it must abide by the regulations which control the range of spectrum allotted for each service. **[3]** The primary reason as to why there arose the need of such a radio like cognitive radio, that can use white spaces effectively as well as efficiently, was the severe dearth of spectrum for new applications and systems. The **electromagnetic radio spectrum** is a natural resource which is currently licensed by regulatory bodies for various applications like AM radio and broadcast VHF television. Studies have proved that at any time and place a very little of the **licensed spectrum** is actually utilized. The unutilized part of the spectrum results in **spectrum holes** or white spaces. As a result of this unutilization of spectrum, it was recently proposed to utilize the unused spectrum at a time to other users who doesn't hold the license. This will be possibly by cognitive radio technology being developed now. Cognitive radios utilize them and look after our needs in the most cooperative manner.
Taking an example of day to day life it can be described as a very faithful retainer that can assist everything that's important to our daily life, capable of taking note about our schedule, integrating our tasks without causing interference to our already allocated tasks, then synopsizing the reports into an integrated picture and finding ways to fit new plans into our schedule.

A cognitive radio can be thought of as this faithful retainer that can adapt to the current situation and find ways to utilize unused frequencies to aid the current service without causing interference. Cognitive radios will perform **Radio Environment Analysis** to identify the spectrum holes before operating on these holes. In cognitive radio terminology **primary user** refers to an user who is allocated the rights to use the spectrum. **Secondary user** refers to an user who try to use the frequency bands allocated to primary user when the primary user is not using it.

II. WHAT IS COGNITIVE RADIO

II.A Definition by Dr. Joseph Mitolla: Dr. Joe Mitola was the propagator of the concept of cognitive radio technology. Dr. Joe Mitola coined the term in the late 1990's and has since refined and distilled it most recently to the following, stating that a Cognitive Radio is—'A really smart radio that would be self-, RF- and user-aware, and that would include language technology and machine vision along with a lot of high-fidelity knowledge of the radio environment.'

II.B Definition by the Institute of Electrical & Electronic Engineers (IEEE): A cognitive radio is a radio frequency transmitter/receiver that is designed to intelligently detect whether a particular segment of the radio spectrum is currently in use, and to jump into (and out of, as necessary) the temporarily-unused spectrum very rapidly, without interfering with the transmissions of other authorized users.

III. C Definition by Intel Corporation*:* Radios that automatically find and access un-used (sic) spectrum across different networks (licensed and un-licensed including the features of **optimization** and **adaption**)
Optimization: Find the best link (in space, time) based on user requirements, e.g., cost per unit throughput, latency.
Continuously Adapt: Seamlessly roam across the networks always maintaining the "best link" possible.

III.D Definition by the Global Standards Collaboration (GSC)*:* A radio or system that senses and is aware of its operational environment and can be trained to dynamically and autonomously adjust its radio operating parameters accordingly.

III.E Definition by IEEE Intelligent Systems magazine: IEEE Intelligent Systems magazine states that "Cognitive radios are adaptive and extremely programmable, learning users' preferences and automatically adjusting to changes in the operating environment."

III.F: Definition by Dr. Simon Haykin: Dr. Simon Haykin is a pioneer in the field of cognitive radio technology and the present director of the cognitive systems laboratory in Canada defined cognitive radio as: An intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operation parameters (e.g., transmit-power, carrier-frequency, and modulation strategy) in real-time, with two primary objectives in mind:

HIGHLY RELIABLE COMMUNICATIONS WHENEVER AND WHEREVER NEEDED.
EFFICIENT UTILIZATION OF THE RADIO SPECTRUM.

Thus providing a very technical, AI-influenced, analytical definition of the cognitive radio technology.

III. COGNITIVE RADIO CYCLE

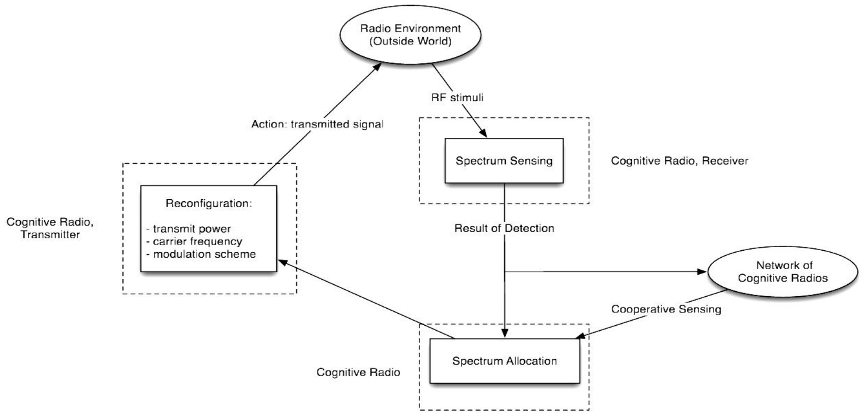

Fig 1: Cognitive radio cycle

The Cognitive radio cycle consists of **four main steps** as per the author of **[4]**

***Step 1: Spectrum sensing**:* During spectrum sensing the cognitive radio detects spectrum holes with the help of spectrum sensing techniques such as **transmitter/energy detection**, **matched filters** and **cooperative detection**, which are explained in details later. During spectrum sensing not only must the cognitive Radio detect the spectrum holes but it must also **continuous monitor** the spectrum. Time, accuracy and detection range are important considerations for sensing. Spectrum sensing has its own share of problems like:
False Alarm: Detection of primary user by the cognitive radio even if there is none present.
Missed Detection: Inobservance of the presence of primary user in the surroundings of cognitive radio in-spite of it being present there. After sensing the spectrum, the cognitive radio can share the result of its detection with other cognitive radios. This is known as cooperative sensing. Cooperative sensing can be centralized or decentralized.

Step 2: Spectrum allocation: After spectrum sensing comes the spectrum allocation phase where the best available spectrum band for user requirements is obtained through spectrum analysis. If multiple secondary users are present, they must share the available spectrum.

***Step 3: Reconfiguration**:* After the spectrum in which it will transmit is allocated the cognitive radio reconfigures itself to transmit in the open band, potentially changing its **carrier frequency**, **transmit power** and **modulation scheme** to better match the available band. Reconfiguration must occur quickly to ensure seamless communication during the transition from one band to another.

Step 4: Transmission.

IV. SOFTWARE DEFINED RADIO

Software Defined Radio or Software Radio or SDR can be described simple as a "**Radio in which some or all of the physical layer functions are software defined**".

As explained in **[5]** the SDR Forum, working in collaboration with the **Institute of Electrical and Electronic Engineers (IEEE) P1900.1 group has** defined the **two** main types of radio containing software in the following fashion:
***Software Controlled Radio*:** Radio in which some or all of the physical layer functions are Software Controlled. In other words this type of radio only uses software to provide control of the various functions that are fixed within the radio.
Software Defined Radio: Radio in which some or all of the physical layer functions are Software Defined. In other words, the software is used to determine the specification of the radio and what it does. If the software within the radio is changed, its performance and function may change.
The definition provides a consistency and clear overview of the technology and its associated benefits.

From another point of view SDR can be defined as, having a **generic hardware platform** on which software runs to provide functions including **modulation** and **demodulation**, filtering (including bandwidth changes), and other functions such as **frequency selection** and if required **frequency hopping**. By reconfiguring or changing the software, the performance of the radio is changed. However to achieve this type of SDR the software defined radio technology must use software modules that run on a generic hardware platform consisting of **digital signal processing** (DSP) **processors** as well as **general purpose processors** to implement the radio functions to transmit and receive signals. In an ideal situation the signal at the final frequency and at the correct level would emanate, and similarly for reception, the signal from the antenna would be directly converted to digits and all the processing be undertaken under software control. Thus there are no limitations introduced by the hardware. To achieve this, the Digital to Analogue conversion for transmission would need to have a relatively high power, dependent upon the application and it would also need to have very low noise for receive. As a result full software definition is not normally possible.

V. DRAWBACKS OF SDR

V.A The most common argument against SDR is cost. The argument is particularly important for high volume low margin consumer products.
V.B There are technology limits on achievable RF performances.
V.C SDR has the lowest level of reconfigurability:**-**
- **V.C.1** Radio not easily changed.
- **V.C.2** Preset signal bandwidth and center frequency
- **V.C.3** Few and preset modulation formats, protocols and user functions.

V.D The choice of architecture depends on the available technology e.g. ADC performance, semiconductor technology.
V.E Software reliability (or the lack thereof) may define overall radio reliability, rather than hardware limitations
V.F Even medium performance SDR tends to require more power for a given function than equipment designed specifically for purpose with optimum analogue/digital architectural partitioning.

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V.G Both **subscriber** and **base units** should be SDR for maximum benefit.
V.H SDR faces problems keeping up with higher data rates.

VI. A SIMPLE COMPARISON

In the early 1990s, Joseph Mitola introduced the idea of software defined radios (SDRs). These radios typically have a radio frequency (RF) front end with a software-controlled tuner. Baseband signals are passed into an analog-to-digital converter. The quantized baseband is then demodulated in a reconfigurable device such as a field-programmable gate array (FPGA), digital signal processor (DSP), or commodity personal computer (PC). The reconfigurability of the modulation scheme makes it a software-defined radio. In his 2000 dissertation, Mitola took the SDR concept one step further, coining the term cognitive radio (CR). CRs are essentially SDRs with artificial intelligence, capable of sensing and reacting to their environment. Pictorially it can be described as:

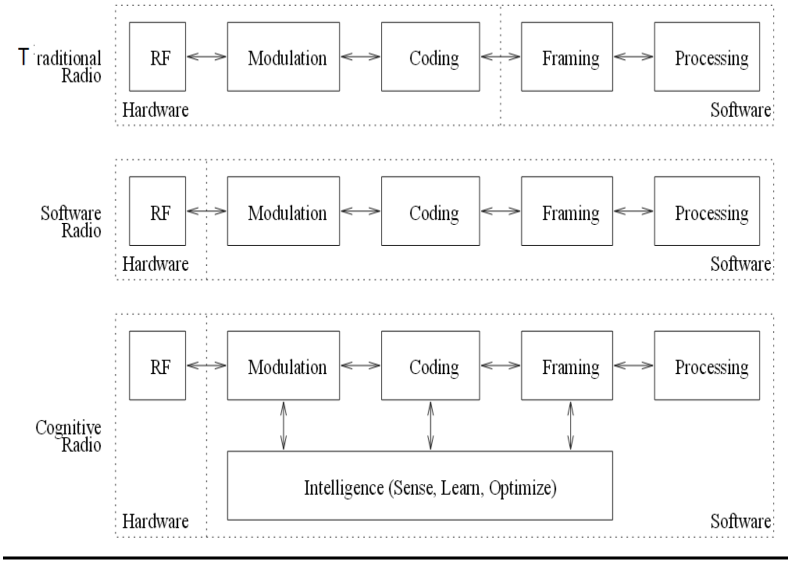

Fig 2: Logical diagram contrasting traditional radio, software radio, and cognitive radio

CONVENTIONAL RADIO	SOFTWARE RADIO	COGNITIVE RADIO
TRADITIONAL RF	CONVENTIONAL RADIO+	SDR+
TRADITIONAL BASEBAND DESIGN	SOFTWARE ARCHITECTURE	INTELLIGENCE
	RE CONFIGURABILITY	AWARENESS
	PROVISIONS FOR EASY UPGRADES	LEARNING
		OBSERVATION

Table I: Comparison of conventional radio, SDR and CR features

CONVENTIONAL RADIO	SOFTWARE RADIO	COGNITIVE RADIO
CANNOT BE MADE '**FUTURE PROOF**'	IDEALLY SOFTWARE RADIO COULD BE '**FUTURE PROOF**'	SDR UPGRADE MECHANISMS
TYPICALLY RADIOS ARE NOT UPGRADABLE	MANY EXTERNAL UPGRADE MECHANISMS. LIKE OVER-THE-AIR(OTA)	INTERNAL UPGRADES
		COLLABORATIVE UPGRADES

Table II: Comparison of conventional radio, SDR and CR based on possible upgradable features

VII. COGNITIVE RADIO AS AN EXTENSION OF MODERN SDR

If the modern **software defined radio** is the centre then the cognitive radio is the circle drawn around it. The applications executing on the radio distinguish a cognitive radio from a software-defined radio. Additional hardware in the form of **sensors** and **actuators** enables more cognitive radio applications. Various artificial intelligence approaches to machine learning and decision making may be applied to the cognitive radio systems **[3]**. A Cognitive Radio is an extension of modern Software Defined Radio. This extension creates new capabilities for users. An "**aware radio**" has sensors and is aware of the environment (or at least a subset of the environment). An "**adaptive radio**" is aware of its environment and is capable of changing its behaviour in response. The next level is CR, and the following characteristics are included
In the concept of a CR:

Sensors creating awareness in the environment. It must autonomously exploit unused spectrum to provide new paths to spectrum access.

Actuators enabling interaction with the environment.

Memory and a model of the environment. It can roam across borders and self-adjust to stay in compliance with local regulations.

Learns and models specific beneficial adaptations. That is they can negotiate with several service providers to connect a user at the lowest cost.

Have specific performance goals. Elaborating, it can be said that it adapts themselves and their emissions without user intervention and/or understands and follow the actions and choices taken by their users and over time learn to become more responsive and to anticipate the users' needs.

VIII. COGNITIVE RADIO NETWORKS

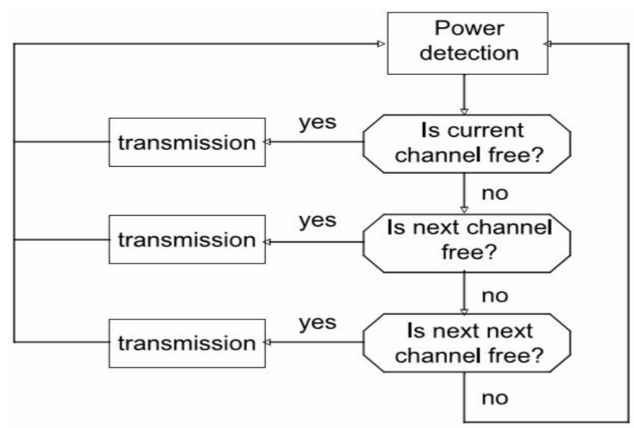

Fig 3: Flow- chart of Cognitive Transmitter

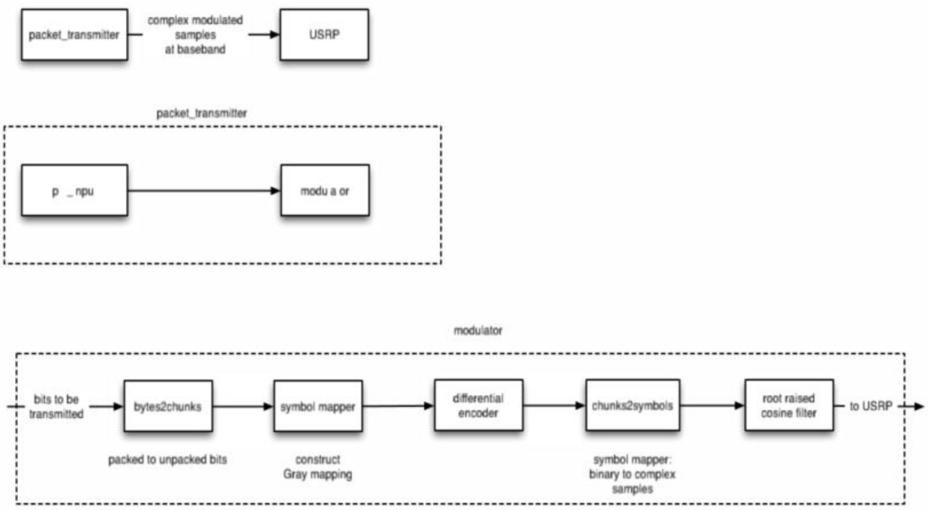

Fig 4: Flow Graph of the Transmitter Part of the Cognitive Transmitter

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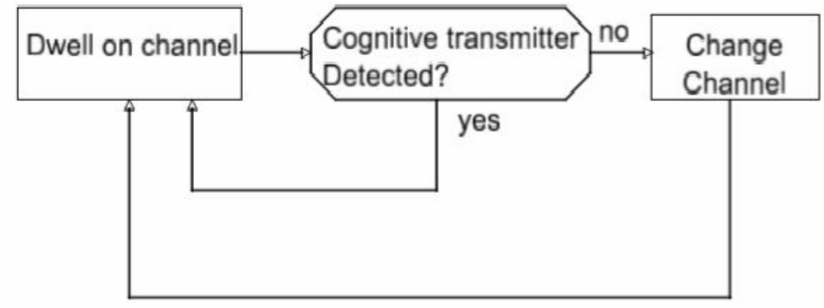

Fig 5: Flow- chart for the Cognitive Receiver

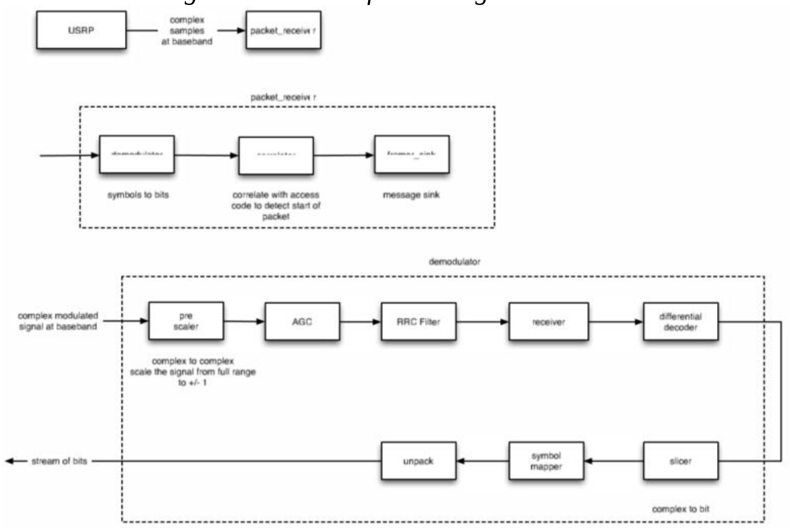

Fig 6: Flow Graph of the Cognitive Receiver

The above diagrams **[4]** show how a **cognitive radio receiver** and **cognitive radio transmitter** may look like.

Cognitive Radio Networks (CRNs) (a network of cognitive radios) are emerging as a solution to increase the spectrum utilization by using unused or less used spectrum in radio environments. The basic idea is to allow unlicensed users access to licensed spectrum, under the condition that the interference perceived by the licensed users is minimal. Technologies are developed, to allow the use of the spectrum in a more efficient way and to increase the spectrum utilization. This means that a number of technical challenges must be solved for this technique to get acceptance. The most important issues are regarding **Dynamic Spectrum Access (DSA)**, **architectural issues (with focus reconfigurability)**, **deployment of smaller cells** and **security**.

IX. COMPONENTS OF A COGNITIVE RADIO NETWORK ARCHITECTURE

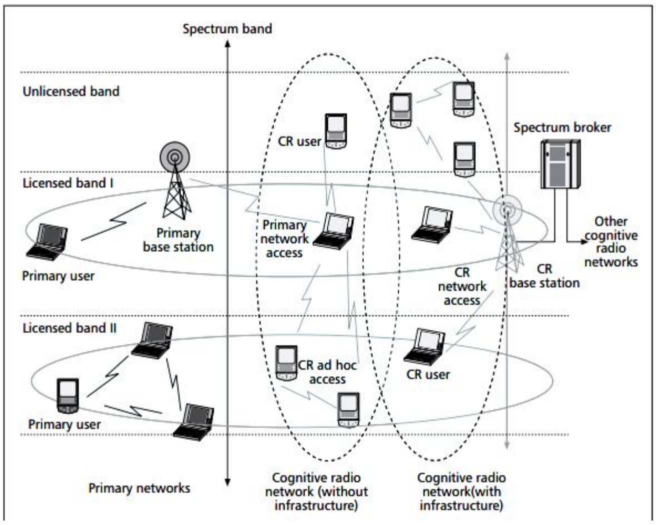

Fig 7: Cognitive Radio Network Architecture

IX.A Components of a CRN:

The components of the cognitive radio network architecture can be classified into **two groups**: the **Primary network** and the **Cognitive Radio network [11]**.

IX.A.1 Primary network: The primary network (or **licensed network**) is the existing network where the primary users enjoy a license to operate in certain spectrum bands. Provided primary networks have an infrastructure, primary user activities are controlled by virtue of **primary base stations**. As the primary users enjoy preference in spectrum access, the operations of primary users should not be harmed by unlicensed users.

IX.A.2 Cognitive Radio Network: The cognitive radio network (also called the **dynamic spectrum access network**, **secondary network**, or **unlicensed network**) users on the other hand do not enjoy a license to operate in a desired band. Cognitive radio users need additional functionality so that they can share the licensed spectrum band. Cognitive radio networks too can have **cognitive radio base stations** that provide **single-hop** connection to cognitive radio users. Cognitive radio networks may have **spectrum brokers** which play a significant role in distributing the spectrum resources among different cognitive radio networks.

Opportunity determines the ways of measuring and exploiting the spectrum space. The conventional definition of the **spectrum opportunity** is "**a band of frequencies that are not being used by the primary user of that band at a particular time in a particular geographic area**".

Conventional sensing methods usually relate to sensing the spectrum in the three dimensions namely **- frequency**, **time**, and **space**. New spectrum management functions are required for cognitive radio networks with the following critical design challenges:

Interference avoidance*:* Cognitive radio networks should avoid interference with primary networks.

Quality of Service (QoS) awareness: To decide on an appropriate spectrum band, cognitive radio networks should support QoS-aware communication keeping in consideration the dynamic and heterogeneous spectrum environment.

Seamless communication: Cognitive radio networks should provide seamless communication irrespective of the presence of primary users

To address these challenges a directory for different functionalities required for **spectrum management** in cognitive radio networks, is provided.

IX.B The spectrum management process

The spectrum management process consists of **four steps** according to the authors of **[11].**

IX.B.1 Spectrum sensing: A cognitive radio user can allocate only an unused portion of the spectrum. For that a cognitive radio should detect the radio environment continuously for available spectrum bands, capture their information, and then detect spectrum holes. The goal of the spectrum sensing mechanism is to determine the **status of the spectrum** by detecting the signature of a signal from a licensed user and to monitor the **activity of the licensed user** by periodically sensing the target frequency band. Spectrum sensing details are discussed later.

IX.D.2 Spectrum decision*:* Based on the spectrum availability as obtained during spectrum sensing, cognitive radio users can allocate a channel. This allocation not only depends on **spectrum availability**, but is also determined based on **internal** as well as **external policies**.

Two major components of spectrum management mechanisms are **spectrum analysis** and **spectrum access optimization**.

Spectrum analysis: Information from spectrum sensing is analysed to understand the surrounding RF environment (e.g., the behaviour of licensed users) and gain knowledge about the spectrum holes (e.g., interference estimation, duration of availability, and probability of collision with licensed user due to sensing error). A knowledge base of the spectrum access environment can be built and maintained on the basis of learning and knowledge extraction. Machine learning algorithms from the field of artificial intelligence can be applied for learning and knowledge extraction.

Spectrum access optimization: Spectrum access optimization involves **decision related to accessing the spectrum** like frequency of the spectrum, bandwidth, modulation mode, transmission power, location, and time duration for which the spectrum can be accessed given the desired objectives of maximizing throughput of the unlicensed user and constraints like maintain the interference caused to the licensed users below the target threshold.

IX.D.3 Spectrum sharing and access: As multiple cognitive radio users may be vying to access the spectrum, cognitive radio network access should be coordinated to prevent multiple users colliding in overlapping portions of the spectrum.

After the spectrum access decision is made the **spectrum holes** or **spectrum opportunities** are accessed by the unlicensed users. Spectrum access is performed on the basis of a **cognitive medium access control (MAC) protocol** that intends to avoid collision/harmful interference with/to licensed users and also with other unlicensed users. A cognitive radio transmitter performs **negotiation** with the cognitive radio receiver to synchronize the transmission so that the transmitted data can be received successfully.

A cognitive MAC protocol could be based on a **fixed-allocation MAC** (e.g., frequency-division multiple access, time-division multiple access, and code division multiple access **[CDMA]**) or a **random access MAC** (e.g., **ALOHA** and **CSMA** with collision avoidance).

In a cognitive radio network, the secondary users may use either an **interference control** (or **spectrum underlay**) approach or an **interference avoidance** (or **spectrum overlay**) approach for exploiting **spectrum opportunities**.

In the **spectrum underlay approach** the secondary users transmit over the same spectrum as the primary users as long as the interference caused to the primary users does not exceed a threshold level. Such an approach requires a sophisticated power control scheme for secondary transmitters.

In the **spectrum overlay approach** the secondary users need to have the knowledge about spectrum holes so the secondary users can exploit them, ensuring that no interference is caused to the primary users.

Thus the **spectrum overlay approach is more conservative than the spectrum underlay approach** with no strict power control requiring for this spectrum access paradigm.

IX.D.4 Spectrum mobility: Cognitive radio users are mere visitors to the spectrum. They can use a particular spectrum iff the specific portion of the spectrum is not required by a primary user. Communication must continue in another vacant portion of the spectrum if the earlier case occurs. Spectrum mobility is a function that relates to changing of the operating frequency band of cognitive radio users. **When a licensed user starts accessing a radio channel that is currently being used by an unlicensed user, the unlicensed user must switch to the idle spectrum band**. This change in operating frequency band is referred to as **spectrum hand-off**. During spectrum hand-off, the protocol parameters at the different layers in the protocol stacks have to be adjusted to match with the new operating frequency band. Spectrum hand-off must ensure that the data transmission by the unlicensed user can continue on the latest spectrum band.

X. SPECTRUM SENSING TECHNIQUES

Spectrum sensing techniques can be classified as:

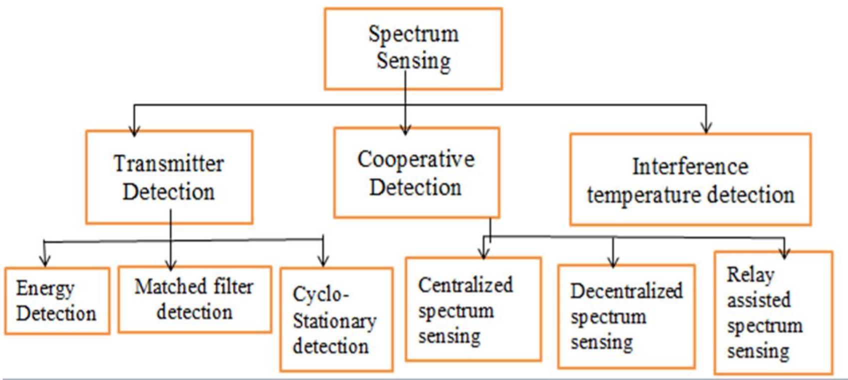

Fig 8: Hierarchical representation of spectrum sensing techniques

X.A Transmitter detection: In **transmitter detection**, the usage of the spectrum is determined by checking whether the signal from a primary transmitter is present in the spectrum.

According to the authors of **[7]** this can be done using **three techniques**:

X.A.1 Matched Filter detection: **Matched filter** is the optimal linear filter for maximizing the **signal to noise ratio (SNR)** in the presence of **additive stochastic noise.**

Matched filters are commonly used in radar, in which a known signal is sent out, and the reflected signal is tested for common elements of the out-going signal. In **matched filter detection technique** the user uses prior knowledge of the primary user's waveform to determine whether the spectrum is in use. When secondary user has a priori knowledge of primary user signal, matched filter detection is applied. Matched filter operation is equivalent to correlation in which the unknown signal is **convolved** with the filter whose impulse response is the mirror and time shifted version of a reference signal. The operation of matched filter detection is expressed as:

$$Y[n] = \sum_{K=-\infty}^{\infty} h[n-k]x[k]$$

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Where 'x' is the unknown signal (vector) and is convolved with the 'h', the impulse response of matched filter that is matched to the reference signal for maximizing the SNR. Detection by using matched filter is useful only in cases where the information from the primary users is known to the cognitive users.

Fig 9: Matched Filtering block diagram

***X.A.1.1 Advantages of matched filter detection**:* Matched filter detection needs less detection time because it requires only O (1/SNR) samples to meet a given probability of detection constraint. When the information of the primary user signal is known to the cognitive radio user, matched filter detection is optimal detection in stationary Gaussian noise.
***X.A.1.2 Disadvantages of matched filter detection**:* Matched filter detection requires a prior knowledge of every primary signal. If the information is not accurate, matched filter performs poorly. Also the most significant disadvantage of matched filter is that a cognitive radio would need a dedicated receiver for every type of primary user.

X.A.2 Energy Detection: Energy detection is a **non-coherent detection method** that detects the primary signal based on the sensed energy. Due to its simplicity and no requirement on a priori knowledge of primary user signal, energy detection) is the most popular sensing technique in cooperative sensing.

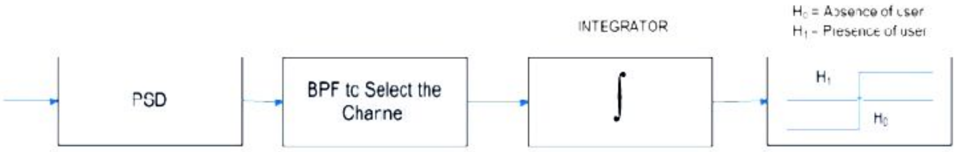

Fig 10: Energy Detector Block Diagram

In this method, signal is passed through **band pass filter** of the bandwidth W and is integrated over time interval. The output from the integrator block is then compared to a **predefined threshold**. This comparison is used to discover the existence or absence of the primary user. The threshold value can set to be fixed or variable based on the channel conditions. The energy detector is said to be the **Blind signal detector** because it ignores the structure of the signal. It estimates the presence of the signal by comparing the energy received with a known threshold ν derived from the statistics of the noise. Analytically, signal detection can be reduced to a simple identification problem, formalized as a hypothesis test,

$$y(k) = n(k)......................H_0$$
$$y(k) = h * s(k) + n(k)........H_1$$

Where y (k) is the sample to be analysed at each instant k and n (k) is the noise of variance σ^2. Let y (k) be a sequence of received samples k Є {1, 2….N} at the signal detector, then a decision rule can be stated as,

$$H_0....if \varepsilon < v$$
$$H_1....if \varepsilon > v$$

Where ε = E | (k) |^2 the estimated energy of the received signal and ν is chosen to be the noise variance σ^2.
X.A.2.1 Disadvantages of energy detection

- Sensing time taken to achieve a given probability of detection may be high.
- Detection performance is subject to the uncertainty of noise power.
- Energy detector cannot be used to distinguish primary signals from the CR user signals. As a result CR users need to be tightly synchronized and refrained from the transmissions during an interval called Quiet Period in cooperative sensing.
- ED cannot be used to detect spread spectrum signals.

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X.A.3 Cyclo-stationary Feature Detection:

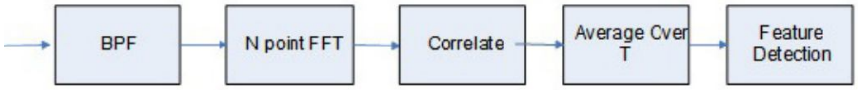

Fig 11: Cyclo-stationary Feature Detection

Cyclo stationary feature detection exploits periodicity in the received primary signal to identify the presence of primary users (PU). The periodicity is commonly embedded in **sinusoidal carriers**, **pulse trains**, **spreading code**, **hopping sequences** or **cyclic prefixes** of the primary signals. Due to the periodicity, these cyclo-stationary signals exhibit the features of periodic statistics and spectral correlation, which is not found in stationary noise and interference. Thus, cyclo-stationary feature detection is robust to noise uncertainties and performs better than energy detection in low SNR regions. Although it requires a priori knowledge of the signal characteristics, cyclo-stationary feature detection is capable of distinguishing the cognitive radio transmissions from various types of primary user signals. This eliminates the synchronization requirement of energy detection in cooperative sensing. Moreover, cognitive radio users may not be required to keep silent during cooperative sensing and thus improving the overall cognitive radio throughput.
Cyclo stationary feature detection has its fair share of disadvantages as well including its **high computational complexity** and **long sensing time**. Due to these issues, this detection method is less common than energy detection in cooperative sensing.

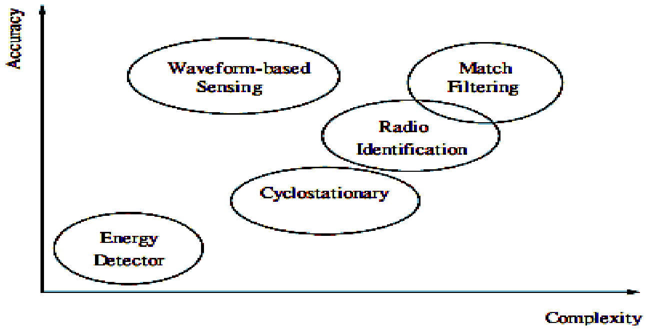

Fig 12: Sensing accuracy and complexity of various sensing methods

***X.B Cooperative detection*:** Cooperative detection is when systems of cognitive radio users who cooperate with each other try to detect licensed transmissions.

X.B.1 Centralized cooperative sensing: In **centralized cooperative sensing**, a central identity called **fusion centre** (FC) controls the **three-step process of cooperative sensing**.
Firstly: The FC selects a channel or a frequency band of interest for sensing and instructs all cooperating cognitive radio users to individually perform local sensing.
Secondly: All cooperating cognitive radio users report their sensing results via the control channel
Thirdly: The FC combines the received local sensing information, determines the presence of PUs, and diffuses the decision back to cooperating cognitive radio users.

The authors of **[8]** has explained centralized cooperative sensing very efficiently. Fig 13(a) gives a pictorial description of centralized cooperative sensing. CR0 is the FC and CR1–CR5 are cooperating CR users performing local sensing and reporting the results back to CR0. For local sensing, all CR users are tuned to the selected licensed channel or frequency band, where a physical point-to-point link between the PU transmitter and each cooperating CR user for observing the primary signal is called a **sensing channel**. For data reporting, all CR users are tuned to a control channel where a physical point-to-point link between each cooperating CR user and the FC for sending the sensing results is called a **reporting channel**. Centralized cooperative sensing can occur in either centralized or distributed CR networks. In **centralized CR networks**, a **CR base station** (BS) is naturally the FC. Alternatively, in **CR ad hoc networks** (CRAHNs) where a CR BS is not present; **any CR user can act as a FC** to coordinate cooperative sensing and combine the sensing information from the cooperating neighbors.

X.B.2 Distributed cooperative sensing: **Distributed cooperative sensing** does not rely on a FC for making the cooperative decision. Here cognitive radio users communicate among themselves and converge to a unified decision on the presence or absence of PUs by iterations.

Fig 13 (b) **[8]** gives a pictorial description of distributed cooperative sensing. After local sensing, CR1-CR5 share the local sensing results with other users within their transmission range. Based on a distributed algorithm, each CR user sends its own sensing data to other users, combines its data with the received sensing data and decides whether or not the PU is present by using a local criterion. If the criterion is not satisfied, CR users send their combined results to other users again and repeat this process until the algorithm is converged and a decision is reached. In this manner, this distributed scheme may take several iterations to reach the unanimous cooperative decision.

X.B.3: Relay-assisted cooperative sensing: R**elay-assisted cooperative sensing** is a sensing technique which is quite efficient in two scenarios where both sensing channel and report channel are imperfect.
Firstly: A cognitive radio user having a weak sensing channel and a strong report channel
Secondly: A cognitive radio user with a strong sensing channel and a weak report channel.
Now both of them can complement and cooperate with each other to improve the performance of cooperative sensing.

Fig 13 (b) **[8]** gives a pictorial description of relay assisted cooperative sensing. CR1, CR4, and CR5, who observe strong PU signals, may suffer from a weak report channel. CR2 and CR3, who have a strong report channel, can serve as relays to assist in forwarding the sensing results from CR1, CR4 and CR5 to the FC. In this case, the report channels from CR2 and CR3 to the FC can also be called relay channels. Although (c) shows a centralized structure, the relay-assisted cooperative sensing can exist in distributed scheme. In fact, when the sensing results need to be forwarded by multiple hops to reach the intended receive node, all the intermediate hops are relays. Thus, if both centralized and distributed structures are one-hop cooperative sensing, the relay-assisted structure can be considered as multi-hop cooperative sensing. In addition, the relay for cooperative sensing here serves a different purpose from the relays in cooperative communications, where the CR relays are used for forwarding the PU traffic.

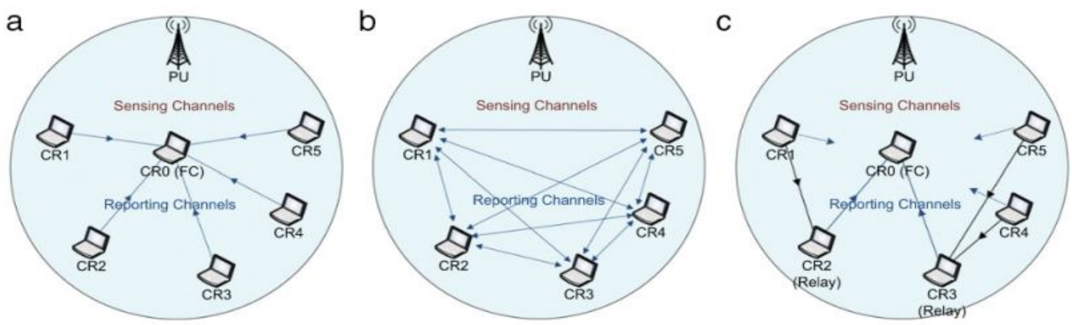

Fig 13: Classification of cooperative sensing (a) centralized, (b) distributed (c) relay-assisted

Cooperative sensing is advantageous as it is a solution to the **hidden node problem**. The hidden node problem occurs when a primary user is far away from the cognitive transmitter (it is not detected) but close to the receiver. The receiver will not receive the samples correctly because the cognitive transmitter and primary user transmit on the same band. With cooperative spectrum sensing, cognitive users closer to the licensed system will help the ones far away from it.

Cooperative sensing has disadvantages too which include Limited Bandwidth, Short Timescale and Scalability.

X.C Interference temperature detection: In interference temperature detection approach, cognitive radio system works as in the ultra-wide band (UWB) technology where the secondary users coexist with primary users and are allowed to transmit with low power and are restricted by the interference temperature level so as not to cause harmful interference to primary users.

XI. SPECTRUM SHARING

Cognitive radios share spectrum either with **unlicensed radio systems** or with **licensed radio systems** which are designed for exclusive use of otherwise unused spectrum. According to the authors of **[9]**
The sharing of licensed spectrum with primary radio systems is referred to as **vertical sharing**.
The sharing between radio systems with similar regulatory priority, in unlicensed band as the case may be is referred to as **horizontal sharing**.

Horizontal spectrum sharing can also be defined as the usage of the same spectrum by dissimilar cognitive radios operated by may be different or same cognitive network operators, which are not designed to communicate with each other. These dissimilar cognitive radio systems have the **same regulatory status** compared to coexisting devices operating in unlicensed spectrum.
In vertical spectrum sharing the licensed radio systems assist cognitive radios to identify spectrum opportunities. This support is termed as **operator assistance**
In horizontal spectrum sharing the cognitive radios autonomously identify opportunities and coordinate their usage with other cognitive radios usually in a distributed way.

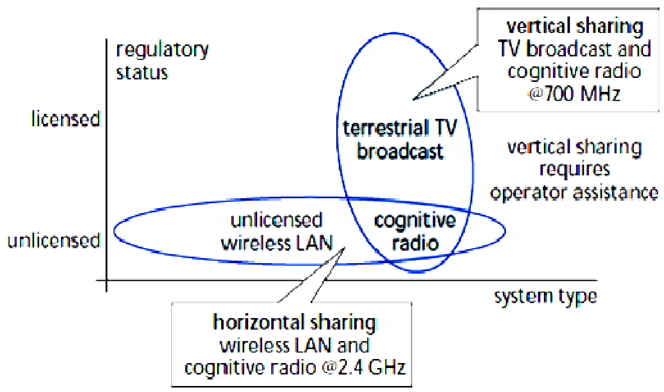

Fig 14: Horizontal and vertical spectrum sharing techniques

XII. FUTURE SCOPE

Cognitive radio provides a pioneered solution to the problem of spectrum crunch and represents a new paradigm for designing intelligent wireless networks to reduce the spectrum scarcity problem and provide significant gain in spectrum utilization efficiency. Thus in future CRs can be a help in the field of indoor sensing applications like telemedicine, home monitoring, emergency networks, factory automation etc. The main problem with indoor sensing applications is that the unlicensed bands, for indoor usage are often crowded. So, conventional radio networks may experience significant challenges in achieving reliable communication due to packet losses, collisions and contention delays, according to the authors of **[10]**.
On time delivery of multimedia elements like audio, still images, video can be aided by cognitive radio networks. Cognitive Radio networks provide the freedom of dynamically changing communication channels according to the environmental conditions and application-specific Quality-Of-Service (QoS) requirements in term of bandwidth, bit error rates, and access delay. Over traditional radio networks it is extremely challenging due to inherent high bandwidth demand of multimedia.
Cognitive radios can also be of great help in situations where information needs to be gathered from different networks and fused to provide a single decision like in case of weather conditions.

XIII. ABBREVIATIONS AND ACRONYMS

CR**: Cognitive Radio;** RF**: Radio Frequency;** FCC**: Federal Communication Commission;** MIMO**: Multiple Input Multiple Output;** DSP**: Digital Signal Processor;** MAC**: Medium Access Control;** CDMA**: Code Division Multiple Access;** CSMA/CD**: Carrier Sense Multiple Access/Collision Detection;** CSMA/CA**: Carrier Sense Multiple Access/Collision Avoidance;** SNR**: Signal to Noise Ratio.**

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