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# Spectrum Monitoring Techniques for Spectrum Mobility in Connected Environments: A Technical Review

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**ABSTRACT**

The internet of everything (IoEs) has become a well-known tool for transforming the concept of connected environments into reality in near future. The cognitive radio network is a potential candidate that addresses the issues of efficient spectrum utilization for next generation connected environments. Further, the spectrum mobility plays a significant role in cognitive connected environments during communication, for switching the channel on the appearance of primary user (PU) throughout the cognitive users' (CUs') data transmission. The performance of spectrum mobility relies on the ability of the system: 1) to detect the appearance of PU as soon as possible and 2) to stop the data transmission as-well-as switch to another channel. The potential approaches to detect the appearance of PU during CUs' data transmission are the "spectrum prediction (SP)" and "spectrum monitoring" (SM). The SP relies on the pre-available information about the channel and PUs' activities which is well explored technique, however, the SM is a real-time approach and is in its infancy. In this paper, several SM techniques with their effects on the spectrum mobility are illustrated. Moreover, the concept of imperfect SM is introduced and its effects on various performance metrics are investigated. Further, a potential approach of cooperative SM is proposed to diminish the effects of imperfections. In addition to this, the potential issues as well as research challenges regarding these techniques are presented.

## 1. INTRODUCTION

With the rapid and recent progresses in the field of technologies such as "Internet-of-Things (IoTs)" [1-8] "Machine-to-Machine communication (M2MC)" [9, 10], next generation (XenG) communication systems, the entire word becomes like a global village where everything (human, devices, machines etc.) is connected with each other and referred as connected environments which is contributing significantly in Industry 4.0 [9-18]. In the connected environments, always/ on demand connectivity is the prime desire which directly depends on the spectrum available however as per the various reports, Due to the fast growth of wirelessly connected gadgets, the spectrum will be scarce for new services in near future [5, 19]. But, according to the "Federal-Communication-Commission" (FCC) report [20], most of the spectrum bands that have been given out are underused at certain times and places. Therefore, the "Dynamic-Spectrum-Access" (DSA) has come out as the prospective contender in the wireless communication to deal with the problem of not having enough range which arises because of fixed spectrum allocation scheme [21-24]. The "cognitive radio (CR)" is a well-known framework to support the idea of DSA in which the "unlicensed/cognitive-user" (CU) is permitted to utilize the spectrum of the "licensed/primary-user" (PU) in such a way that the PU communication remains impermeable, and it uses the following features to do this.: 1) "spectrum sensing" [25-28], 2) "spectrum analysis and decision" [29-31], 3) "spectrum sharing/accessing" [32, 33] and 4) "spectrum mobility" [34-37] as depicted in the Figure 1. First, the CU does spectrum reading to find the channels that aren't being used. Then, after spectral analysis, it chooses the best channel. Also, the CU uses a selected channel for transmission and tells other users in the CRN about it so that they don't use the same channel. Also, the CU has to stop talking when the PU starts talking again on the same channel. If the CU wants to continue the conversation that was interrupted, it has to change the channel. Spectrum switching, hand-off, or mobility is the process of moving from one channel to another. Spectrum accessing methods like "interweave" [38-40], "underlay" [41-43], "overlay" [44, 45], and "hybrid spectrum access" [46-51] protect PU communication from interference caused by CU transmission. Interweave spectrum access is the most commonway to get to the spectrum. With this technique or approach, the CU uses the channels that aren't being used for communication. But in the base spectrum access, the CU uses the PUs' spectrum at the same time that the PUs is talking by putting limits on how much power can be sent. This is done to avoid interference at the PU. In the overlay spectrum accessing strategy, the CU and PU performs communication at same time with full-power however, for interference management, the advance encoding techniques such as “Gel’fand-Pinsker binning” [52] and “dirty paper coding” [53] are used. It is worth to mention that the prerequisite of interference management using advance encoding techniques increases the complexity of overlay spectrum accessing strategy consequently, less popular as compare to other strategies. Conversely, the interference management in underlay technique using power control require the channel state information (CSI) either perfectly or partially [54]. However, the formulation of perfect and partial CSI at the CU transmitter is a challenging task due to uncertainty of channel. So, it's clear that the interweave spectrum accessing strategy is a well-known and possible event that plays a big part in spectrum mobility. This is because the CU only uses the empty channels of the PU for communication, and when the PU shows up, the CU needs to switch the spectrum. In general, there are two ways to move the spectrum: 1) the reflexive, as shown in Figure 1, and 2) the proactive. In the first method, the CU changes its communication after the PU shows up. In the second method, the CU changes its communication before the PU shows up. The complete details about both the approaches are illustrated further below.

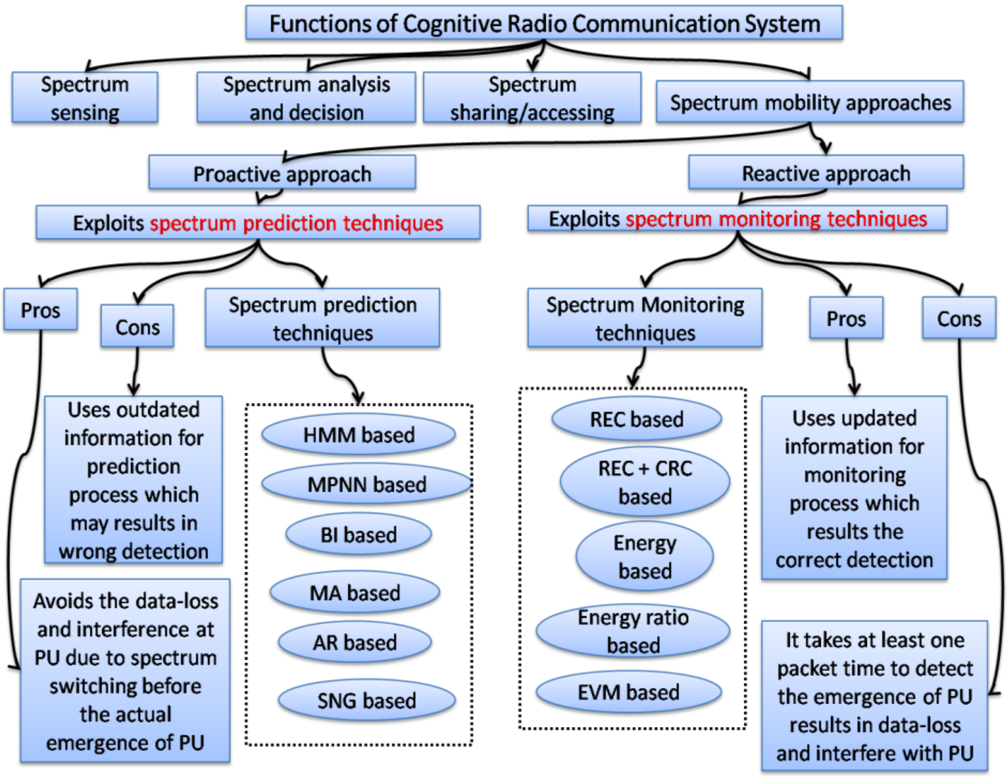


**Figure 1.** Classification of spectrum mobility approaches

### 1.1 Reactive spectrum mobility

In the traditional CRNs as stated by Kaushik et al. [55], the CU performs spectrum sensing on the channel for time ***s*** and transmits data during time (***T-τs***) when the channel is detected as idle/free or else performs spectrum sensing on another channels. Once the data transmission has started on the idle-sensed channel, the CU keeps checking the state of the channel. When the PU appears, the CU stops sending data and starts talking on another idle channel, as shown in Figure 2(a). Since data transfer stops during the spectrum sensing period, the throughput of CU goes down. However, the PUs can be found after a certain amount of time, which is called the detection delay. This causes "interference at PU" and "data loss of CU" [56]. So, experts have come up with an idea where the sensing and data transmission are done at the same time, as shown in Figure 2(b), so that the whole time period (T) can be used for data transmission and the emergence of PUs can be found during that time. The CU yields this function by exploiting two transceiver-units, where one unit is dedicated for spectrum sensing while the other unit is for the data transmission.

Spectrum monitoring (SM) is the term for this process of detecting the spectrum and sending data at the same time. In the SM, the PUs shows up after the detecting delay. To change the channel, you also need a set switching delay. Consequently, switching delay and detection delay are added to the total time that data loss and interference occur. The PUs is identified throughout this entire process after their true/actual appearance, which is followed by spectrum switching, for which the reactive technique is termed.

Further the major limitations of the reactive approach are as follows: after the PUs show up, the CU needs to change how they talk to each other. However, there is a time gap between the actual emergence of PU and its detection as shown in Figure 2(a). If we assume that the SM system is perfect and detection plus switching delay is less than the packet time even though the single packets’ data get lost. On the other hand, in the proactive approach, the CU can change how it communicates before the PU shows up.

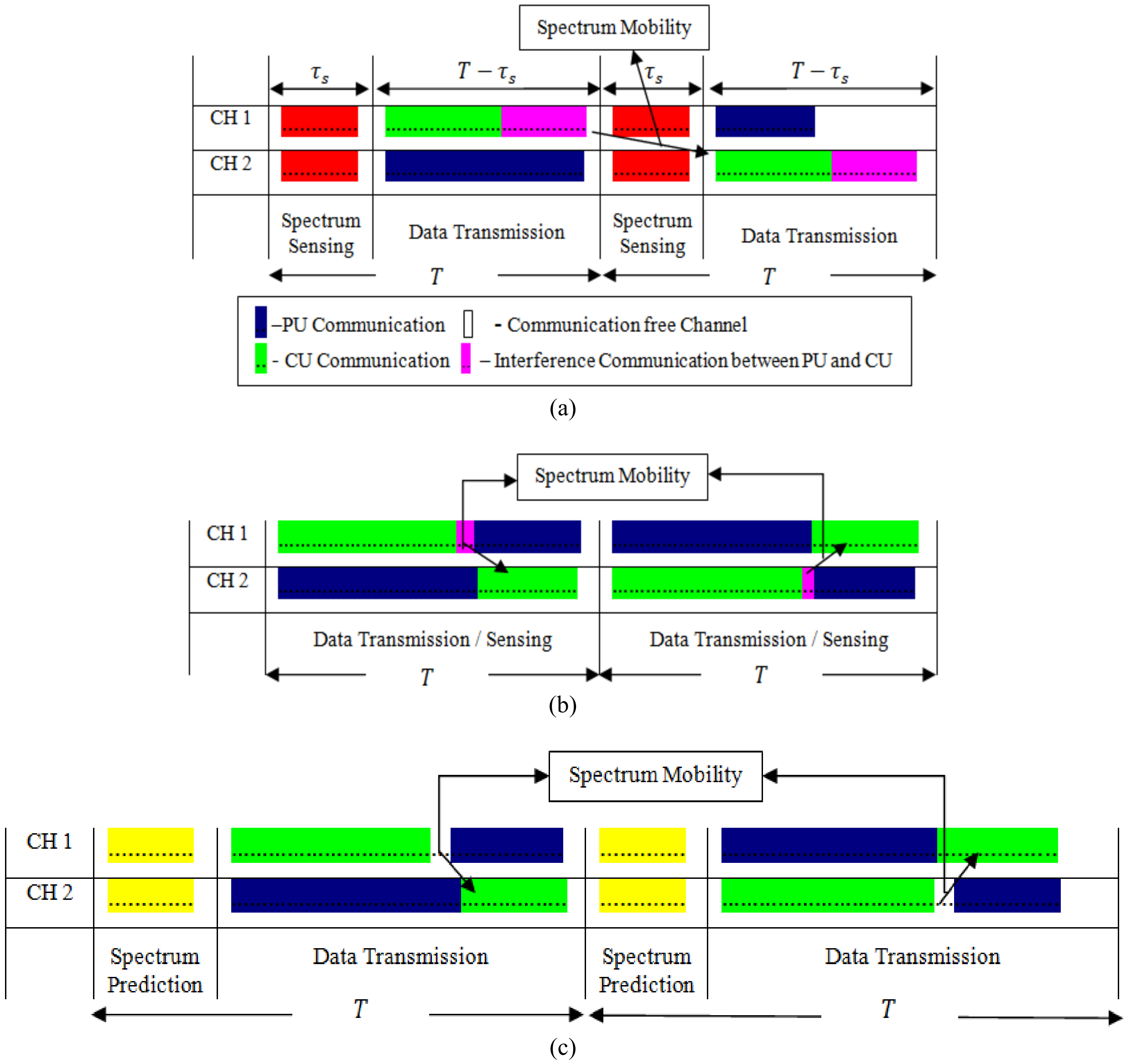


**Figure 2.** The spectrum mobility in cognitive radio networks using (a) periodic sensing (reactive approach), (b) spectrum monitoring with two transceivers at CU (reactive approach), and (c) spectrum prediction (proactive approach)

### 1.2 Proactive spectrum mobility

From the discussion above, it is clear that the detection and switching delays are inseparable. Yang and Zhao [56] have come up with a new method for "spectrum mobility" in which the "spectrum prediction" method is used to predict the channel states in the future. As seen in Figure 2(c), the CU uses the anticipated information to switch or shift its communication prior to the "true/actual emergence of PU." This method is referred to as a proactive strategy and it solves the "data-loss" and "interference-at-PU" receiver problems.

Each CU unit requires two transceivers under the traditional SM method, which increases both cost and power usage. A unique method for the SM has recently been developed, in which the development of the PUs is seen during the data transmission time using a single transceiver [57]. As shown in Figure 2 (b), this SM technique is therefore preferable than the previously stated monitoring technique (two transceivers), and the remainder of this paper's discussion is predicated on the same. However, the development of the PUs must be detected by a reliable mechanism for the process of effective spectrum mobility. "Spectrum monitoring" and "spectrum prediction" are the only ways to deal with this problem right now.

### 1.3 Bibliometric survey

We have performed a bibliometric survey on the Scopus data base by using the keywords “Cognitive Radio Network” and have collected the 2000 entries. Further, we have used the VOSVIEWER ToolBox for the Bibliometric run on the bases of co-occurrence of the keywords where we have picked the 60 keywords [58]. The connections of the keyword “Cognitive Radio Network” with other keywords are shown in the Figure 3. Some of the prime keywords or research fields related to the CRN are cognitive systems, Internet of Things, Intelligent systems, Sensors, Adhoc networks, energy efficiency, and fading scenario. From here, it is perceived that the cognitive radio is well explored technology for various key performance indicators (eg., quality of service (QoS), energy efficiency, interference efficiency etc.) and well-established mathematical techniques such as deep learning, game theory, reinforcement learning, Markov process etc. Cognitive Radio networks also explored with existing reputed technologies such as Adhoc networks, Internet of Things, 5G mobile. In the

Figure 4, we have used the data obtained after a Scopus run by using the keywords cognitive radio and spectrum monitoring. Further, we have used the VOSViewer for processing of this data and obtained this graph on the bases of co-occurrence of the keywords. The prime keywords we receive here are spectrum monitoring, spectrum sensing, closed form expression and throughput. So from the above discussion, it is perceived that the spectrum management and spectrum monitoring are the prominent parts of the cognitive radio communication systems.

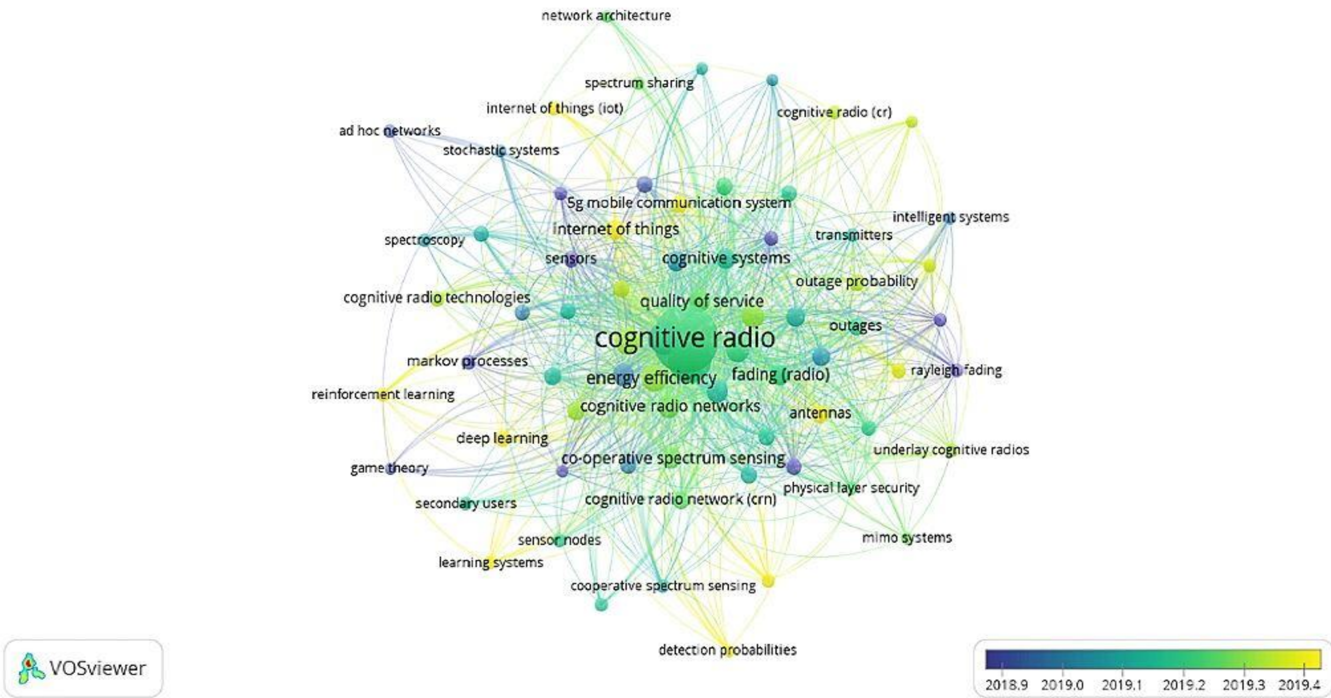


**Figure 3.** The relation of the keyword Cognitive Radio Network with other keywords

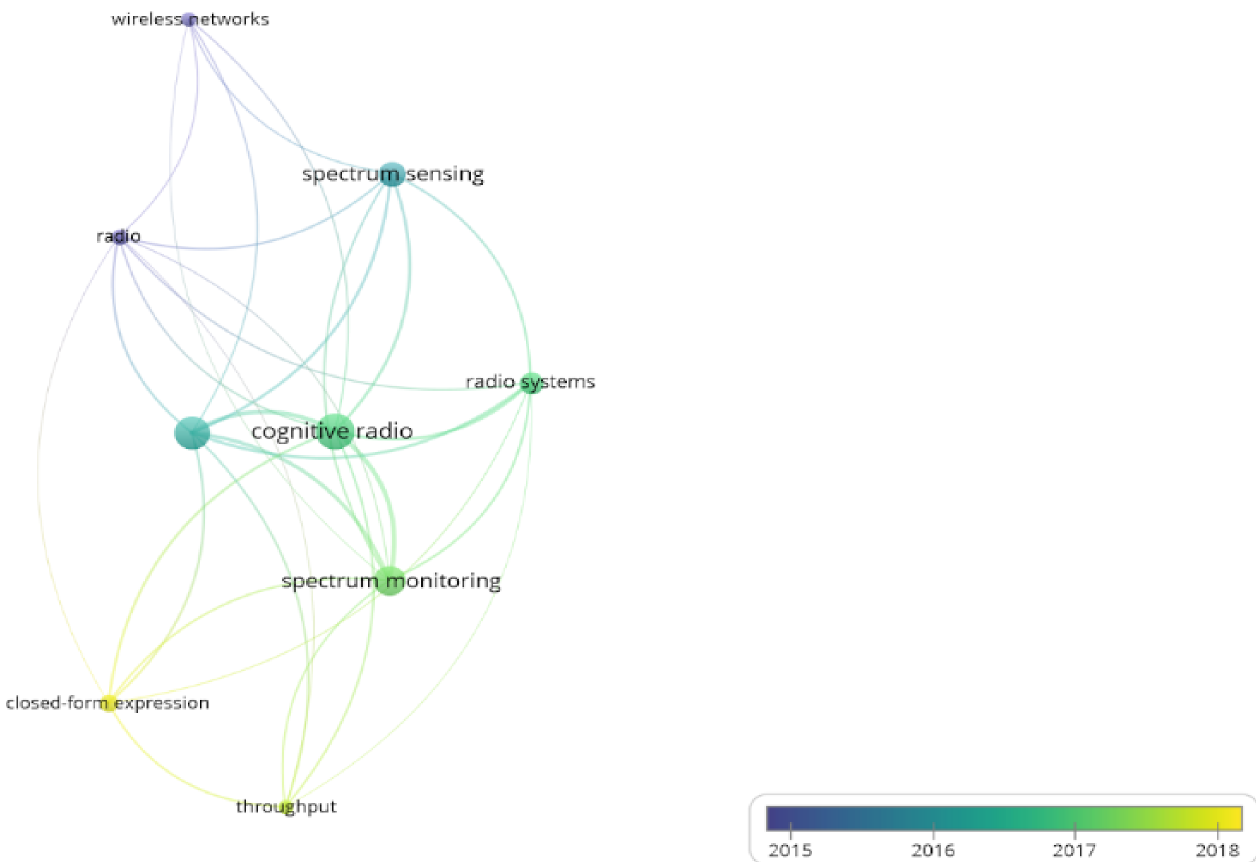


**Figure 4.** The relation of the keyword cognitive radio network with few prime keywords

### 1.4 Motivation

In the spectrum prediction process [59], the CU predicts when PUs will appear based on the information about the channel that is already known. However, the SM is a possible technique in which the CU finds PUs during data transmission by using the statistics of the received packets, such as the number of receiver errors (REC), the number of iterations (IC), etc. Spectrum prediction needs to know the state of the channel ahead of time. Spectrum monitoring, on the other hand, doesn't need to know anything ahead of time because the decision is made based on the statistics of the current packet. Researchers have looked at different ways to predict the spectrum in the study by Xing et al. [59]: 1) "Hidden Markov model" (HMM) based, 2) "Multilayer perceptron neural network" (MLNN) based, 3) "Bayesian interference" (BI) based, 4) "Moving averages" (MA), 5) "Auto-regressive", and 6) "Static neighbour graph" (SNG) based approaches. In addition, some recent spectrum prediction techniques are explored by researchers for high frequency communication [60, 61]. Moreover, the SM techniques emphasizing on REC and energy-ratio are discussed briefly in a survey presented to explore the advance spectrum sensing techniques [62]. But, as far as the authors know, research into SM techniques for spectrum mobility is still in its early stages. Because of this, we have reviewed the SM techniques to "detect the emergence of the PU during CU data transmission" in this work.

The prominent inputs of the authors to this paper are summed up as follows:

- Techniques for predicting and keeping an eye on the spectrum are used to show how spectrum movement works.
- The SM with suitable hypothesis and its potential techniques for appropriate application scenarios, is described in detail.
- A novel and generalized SM technique on the bases of energy fluctuation of the received signal is proposed.
- The impact of SM implementation on performance metrics like "data-loss", "power-wastage", "interference-efficiency", and "energy-efficiency" are studied.
- A potential solution to manage the effects of imperfect SM on the performance of CUs is proposed and investigated.
- The potential issue and future research challenges regarding different SM techniques are presented.

The remaining part of this paper is structured as follows. In section II, the SM process with various SM techniques is illustrated. The prospective architecture of the CRN for spectrum monitoring process is presented in section III. The effects of implementation of SM with perfect and imperfect nature are described in section IV. The section V comprises the potential issues and research challenges. Finally, section VI concludes the work presented in this paper.

## 2. FRAMEWORK OF SPECTRUM MONITORING TECHNIQUES

The SM is a possible method that lets the CU see the "emergence-of-PU simultaneously with the CU data transmission." This means that the CU has to "detect the presence of PU signals s(t) with the already existing CU signal *C(t)* and noise *n(t)."* So, the considered binary hypotheses for the received signal r(t) are $H_0$ and $H_1$, which prove, respectively, that PU is not present and is present.

$$r(t) = \begin{cases} h.s(t) + w(t) + C(t) & H_1, \\ w(t) + C(t) & H_0 \end{cases} \tag{1}$$

where, $h$ is the "channel-gain" and $w(t)$ designate the "additive white Gaussian noise" (AWGN). The complete process of spectrum mobility using SM is depicted in Figure 5 and illustrated as follows. At first, the CU feels the channel and starts sending data with SM on the idle/free channel it finds. If it doesn't find an idle/free channel, it switches the channel and does spectrum sensing again. In Figure 6, the SM is shown as a black box because there are different ways to show the SM. But at the black box's output, a condition check is done. If the "emergence-of-PU" is confirmed, the CU stops sending data, changes the channel, senses it, and so on. If it doesn't, the CU keeps sending data until the end of the time frame. Various SM techniques are as follows: A) Receiver error count (REC) based, B) REC plus cyclic redundancy check (CRC) based, C) Energy-based in OFDM, D) Energy-ratio-based in OFDM, E) Error vector magnitude (EVM) based, and F) Energy fluctuation based. These techniques are illustrated in detail as follows.

### 2.1 Receiver error count (REC based) spectrum monitoring

2.1.1 System model

The statistics for REC based spectrum monitoring are derived using almost same or with slight modified hardware and is simpler as compare to the channel measurements that are usually essential on adaptive modulation and coding (AMC) [62]. It is assumed that the CU establishes session-based communication where each session needs to deliver thousands of packets. The CU uses standard spectrum sensing to find an empty channel and start a session on it. However, this session will last until the SM finds the PU after it has appeared. Also, the CU again checks the channel, and if it seems to be free, it starts the session again. If not, it changes to another free channel, as shown in Figure 6, and so on. A "data sequence made up of binary symbols that is sent from the transmitter, goes through the communication channel, and is received by the CU receiver" is the definition of a "packet." The properties of the channel, such as multipath fading, shadowing, etc., affect the passing order that leads to the two hopeful cases: 1) "The packet is decoded successfully at the receiver, and the received sequence does not overlap with the sent data sequence in some places for the successfully decoded sequence." The error count (EC), also called the receivers' error count (REC), is the number of places where the data sequence that was sent does not match the data sequence that was received. 2) "The packet doesn't decode correctly, which means that the received data sequence isn't available. Because of this, the error count can't be set." Boyd et al. [57] explain the structure of both the transmitter and the receiver as a whole. Most of the time, it is thought that the CU decoder decodes the signal well and has a certain number of errors that depends on the channel conditions. Also, the randomness of the channel causes the value of REC to change. However, a maximum value of REC is set, which is called the error count cutoff, so that the packet can be decoded quickly. Also, the EC gets better if the PU talks to the PU while data is being sent, since the packet gets messed up when interference happens. So, the development of the PUs is confirmed if the number of errors goes up and goes over the threshold or if the packet is decoded properly.

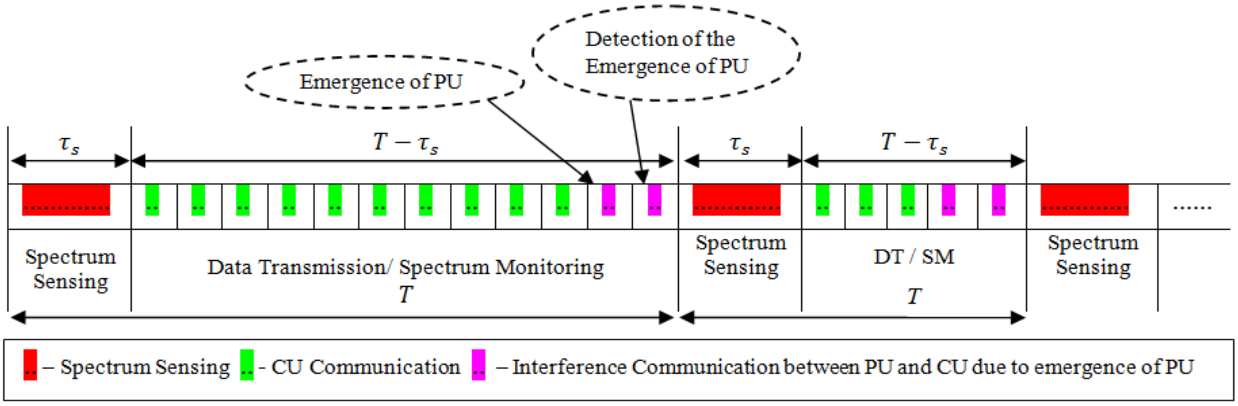


**Figure 5.** Illustration of system model for packet transmission using time frame

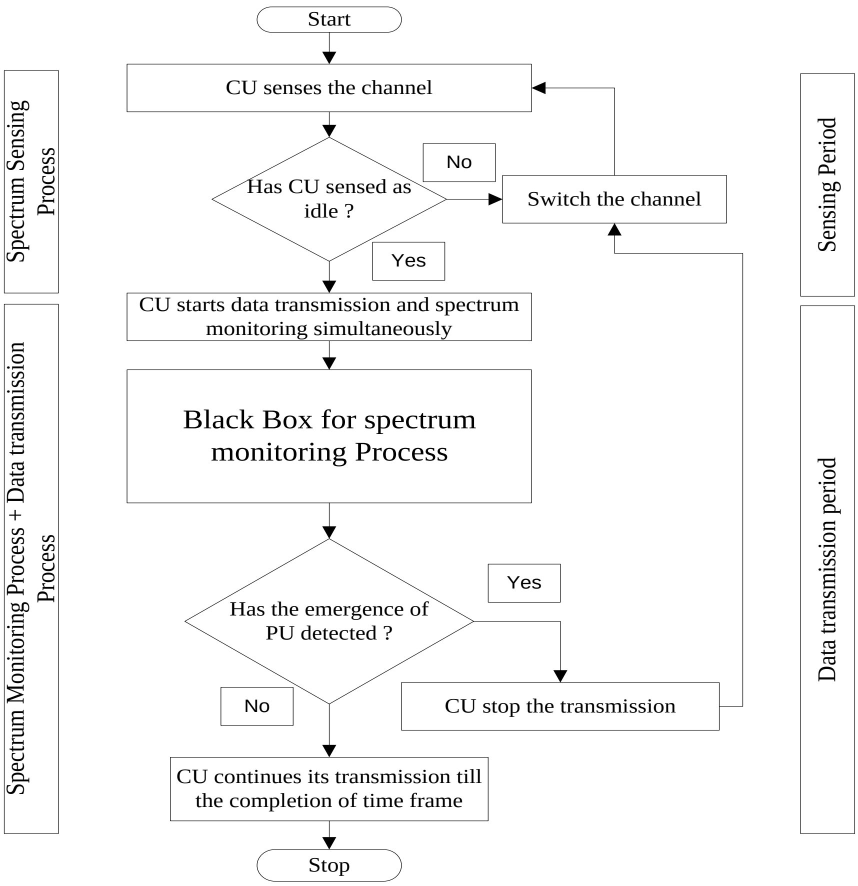


**Figure 6.** Flow diagram of spectrum mobility process using spectrum monitoring techniques

In addition to this, if CU receiver exploits the iterative decoding, a new receiver statistic is defined and known as iteration count (IC). The IC for a packet is the "ratio of the number of iterations needed to decode all the words and symbols in a packet to the total number of code words." If a packet has large value of IC, it signifies the corruption of received packet which may be due to the interference caused by PU transmission. Therefore, IC is also an important receiver statistic to detect the PUs' emergence. In the wireless communication, a popular decoder used for turbo codes has the maximum limit of 32 iterations, therefore the IC for the packet is bounded by 32 [57].

### 2.2 REC with CRC based spectrum monitoring technique

The REC based SM technique seems to be immature for the frequently varying and unknown channel conditions since the receiver error count is very sensitive to the channel and operative conditions. Therefore, one advance technique is proposed by Soltanmohammadi et al. [63] and Orooji et al. [64] that is known as REC with CRC based technique. In this technique cyclic redundancy check (CRC) is additionally exploited with REC to detect the emergence of PU and denoted as REC+CRC as depicted in Figure 7. The entire process is very similar to the previously presented REC based framework except the CRC block as shown in Figure 7. At the sending end, the CU encodes the chain of data by using the CRC code to figure out the error in detection. This is followed by "forward error correction" (FEC) to get the N-bit packet. At first, demodulation and decoding are done on the received packet at the receiver end. Also, the CRC block is added to the decoded packet, which is then encoded using a copy of the encoder on the sender. Also, the outputs of the decoder and demodulator are compared so that the error counts (EC) or REC can be estimated. It is a well-known fact that "emergence of PU during data transmission" causes interference at the CU receiver, which can cause the REC in the CU packets to go up, which causes the REC to go up.

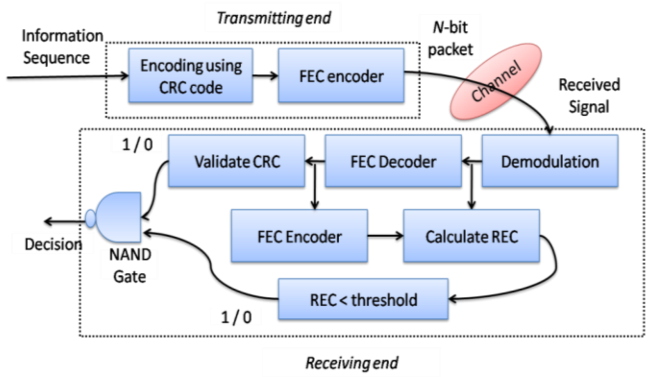


**Figure 7.** The framework of REC+CRC monitoring process at transmitting and receiving end

In addition to this, the CRC block is used to check the validity of CRC. The $C_v$ and $C_{nv}$ denotes the CRC is valid and invalid, respectively. In the proposed framework, initially, the CRC validation is checked. If CRC is valid, then the REC is compared with threshold ($\lambda_{RC}$) and greater the value of decision variable indicates the emergence of PU. On the other hand, the invalidation of CRC immediately indicates the emergence of PU. Thus, the proposed decision rule is presented mathematically as:

$$\begin{cases} \{(REC \geq \lambda_{RC}) \cap C_v\} \cup C_{nv}, & Decide \quad H_1 \\ else, & Decide \quad H_0 \end{cases} \tag{2}$$

The maximum number of errors in a packet that FEC technique can correct is denoted by $t_{FEC}$ and the threshold is selected in such a way that $t_{FEC}$ should be greater than or equal to threshold. The emergence of PU is confirmed if it decides $H_1$ otherwise absent as illustrated in Eq. (2).

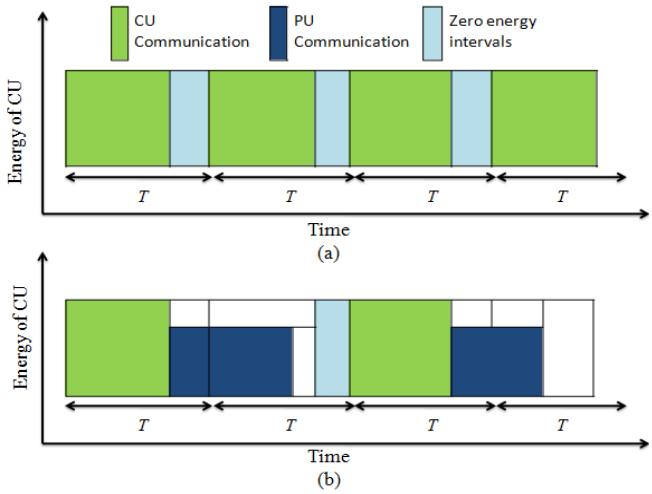


**Figure 8.** Energy-based spectrum monitoring technique

### 2.3 Energy-based spectrum monitoring technique

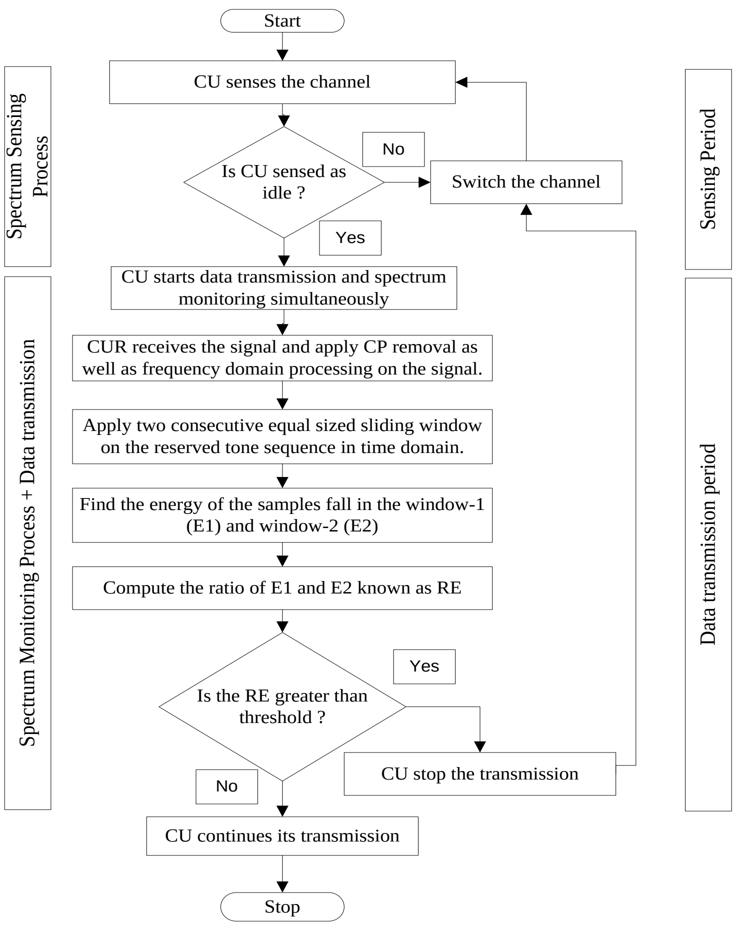


**Figure 9.** Flow-diagram of the spectrum mobility using energy-ratio algorithm

In the energy-based SM techniques presented in the study by Ko et al. [65], the CU communication uses OFDM and full-duplex mode [66-68]. But the signal sent by CU has periods of no energy in a certain subcarrier, which are used to find out if PU is present during that time. As shown in Figure 8, the CU plans its transmission with regular zero energy intervals and as shown in Figure 9, the energy of PU is detected and emergence of the PU is confirmed which continues till the completion of PU communication and CU discontinue its transmission. Moreover, the 2nd interval has zero energy which means the PU is absent, therefore the CU resume its communication. The major limitation of this technique is the resource wastage due to zero energy intervals. Therefore, in order to avoid these zero-energy intervals, a new energy-based detection algorithm has been proposed.

### 2.4 Energy-ratio-based spectrum monitoring technique

When the CU uses OFDM as the "physical layer transmission technique," a frequency-domain-based method called "energy ratio-based SM technique" [69] will work for SM by adding extra features to the normal OFDM signal. The main point of "energy-ratio-algorithm" is to look at how the energy of stored tones changes over time. The entire outline of the energy-ratio algorithm is illustrated in Figure 9. Firstly, the CU sensed its channel during sensing interval and performs data transmission if channel is free otherwise sense alternative channel. The CU employs energy-ratio (SM) algorithm parallel to the data transmission.

The CU emitter (CUT) sends out an OFDM signal, which is picked up by the CU receiver (CUR) and processed in the frequency domain. As part of the energy ratio method, the cyclic prefix (CP) is removed. Also, the reserved tones from the different OFDM symbols are put together to make the complex sample sequence, which is then moved through in the time domain by two moving windows of equal size. Also, the energies of samples that fall within a certain window are measured, and the ratio of the two energies is used as the "decision-making-variable" ($D_k$). In addition, the decision-making variable is compared to the set threshold ($\lambda_k$) to "detect the emergence of PU". To help mathematicians understand the idea, the decision-making variable is described as:

$$D_k = \frac{E_k}{F_k} = \frac{\sum_{i=N+k}^{2N+k-1} |Z_i|^2}{\sum_{i=k}^{N+k-1} |Z_i|^2} \quad (3)$$

where,

$Z_i$ - ith sample of the reserved tone sequence,

*N:* - number of samples in each window,

$E_k$ and $F_k$ energy in the 2nd and 1st window, respectively.

k - integer such that k= 1,2 ,3......

If $D_k > \lambda_k$, the emergence of PU is confirmed.

The mathematical representation is as:

$$\begin{cases} D_k \overset{H_1}{\underset{H_0}{\gtrless}} \lambda_k \end{cases} \qquad \begin{cases} Decide\ H_1 \\ Decide\ H_0 \end{cases} \quad (4)$$

### 2.5 Error vector Magnitude based spectrum monitoring technique

The receiver statistics are the function of channel and system operating conditions. In real-world situations, the receiver error is affected by things like "carrier-frequency-offset" (CFO), "phase noise," "nonlinear impairments," "carrier leakage," "sampling frequency offset" (SFO), and "IQ imbalance and clipping." The "error-vector-magnitude" (EVM) gives the most important information about these problems, so it's important to use EVM to describe receiver data [70, 71]. The EVM overcomes the limitation of prerequisites of both the REC and energy-based approaches i.e. this technique does not require the reserved subcarrier and zero interval during data sequence transmission. The block diagram of the EVM-SNR estimator is presented in Figure 10. The EVM is defined on the bases of measured pilots from received (Rx) signal when compared with transmitted (reference) pilot signals. The "result-in-error-vector" ($\vec{e}$) is the difference between the measured ($\vec{w}$) and reference symbol vector ($\vec{v}$) which means $\vec{e} = \vec{w} - \vec{v}$. Further, the EVM is defined as [70, 71].

$$EVM_{rms} = \sqrt{\frac{\frac{1}{N_i}\sum_{n=1}^{N_i} |S_r(n) - S_t(n)|^2}{P_0}} \quad (5)$$

where, $N_i$ – "number of pilot symbols over which the EVM is measured",

$S_r(n)$ – "normalized received nth pilot symbol corrupted by noise",

$S_t(n)$ – "transmitted value of the nth pilot symbol",

$P_0$ - "average power for the chosen modulation".

In addition to this, for large values of $N_i$, the EVM can be approximated as:

$$EVM_{rms} \approx \sqrt{\frac{N_0}{P_0}} = \sqrt{\frac{1}{SNR}} \quad (6)$$

where, SNR and $N_0$ represents the signal-to-noise ratio and noise power spectral density (PSD), respectively. Furthermore, the decision on the emergence of PU is yielded by comparing $EVM_{rms}$ with the threshold value of $EVM$ ($\lambda_{EVM}$). If the value is greater than $\lambda_{EVM}$, the emergence of PU confirmed otherwise PU is assumed to be absent.

Mathematical representation of the decision process is as follow:

$$\begin{cases} EVM_{rms} \overset{H_1}{\underset{H_0}{\gtrless}} \lambda_{EVM} \end{cases} \qquad \begin{cases} Decide\ H_1 \\ Decide\ H_0 \end{cases} \quad (7)$$

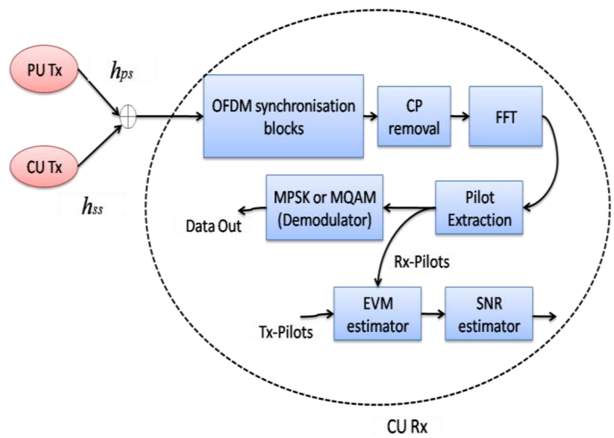


**Figure 10.** The process of spectrum monitoring technique using error vector magnitude (EVM)

### 2.6 Energy fluctuation based SM

The major limitations of the presented approaches (having good immunity level the channel variations) are the non-generalized nature i.e. only defined for OFDM signal however, the REC+CRC based technique has immunity to the environmental, channel or operating system variations. Thus, a technique with good immunity to environmental variations and of generalized nature is required. Therefore, we have proposed energy fluctuation-based SM technique. In this technique, the power of received signal $r(t)$ is measured continuously over certain time intervals immediately after the spectrum sensing interval. It is assumed that the PU emerges after certain time as the data transmission starts therefore, the entire frame time (T) is divided into number of intervals i.e. $t_1$ to $t_2$, $t_2$ to $t_3$, and so on. Initially, the energy of received signal is computed as follows. $E_{r1} = \int_{t_1}^{t_2} |r(t)|^2 = \int_{t_1}^{t_2} |w(t) + C(t)|^2\, dt$. Further, let us assume that the PU emerges and it interferes with the CU communication constructively or destructively. In case of constructive interference, the effective energy increases, however, destructive interference reduces the effective energy. Now, the energy of $r(t)$ in next interval is defined as $E_{r2} = \int_{t_2}^{t_3} |r(t)|^2 dt = \int_{t_2}^{t_3} |h.s(t) + w(t) + C(t)|^2\, dt$. If we exclude the effect of noise the hypothesis is formulated as follows:

$$E_{r2} = \begin{cases} \int_{t_1}^{t_2} |h.s(t)+w(t)+C(t)|^2 dt & \text{Contructive interfernce} \\ \int_{t_1}^{t_2} |w(t)|^2 dt & \text{Destructive interfernce} \end{cases} \quad (8)$$

Moreover, the destructive interference may provide zero energy if both the waveforms i.e. PU and CU are same. Therefore, the modulus of difference between energies (DE) $E_{r1}$ and $E_{r2}$ is the decision variable i.e. $DE = |E_{r1} - E_{r2}|$. If the DE is greater than predefined threshold value ($\lambda_P$), the emergence of PU is confirmed otherwise it is identified as absent. Mathematical representation of this is as follow:

$$\begin{cases} DE \underset{H_0}{\overset{H_1}{\gtrless}} \lambda_P \end{cases} \quad \begin{cases} Decide\ H_1 \\ Decide\ H_0 \end{cases} \quad (9)$$

In addition, to this it is possible that the channel condition may vary the energy level, however the energy levels after the constructive and destructive interference are extreme therefore, this approach is more suitable as compare to that of the energy ratio algorithm which is designed only for OFDM signal.

## 3. ARCHITECTURE BASED SPECTRUM MONITORING

On the bases of architecture, the spectrum monitoring techniques are divided into two parts namely centralized spectrum monitoring and distributed spectrum monitoring which are further explained as follows.

### 3.1 Centralized spectrum monitoring

The centralized architectures for CRN are the ones where the communication of all the nodes/CU is controlled and managed by a centralized entity called as centralized controlling unit (CCU). Here, every CU has to exchange the information with the CCU and final decision about any process such as spectrum sensing, channel allocation, accessing etc. is taken by the CCU. Similarly, for the centralized SM, the CUs need to be controlled by a CCU however, in the SM, the SM is performed during the data transmission on particular channel. Therefore, generally, it is not possible to perform centralized SM, therefore, we have presented a scenario where a wideband channel is divided into number of narrowband channels and the CUs are permitted to exploit these channels for communication. Here, all the CUs perform SM on different narrowband channels however, the PU status remains same for these all channels. Thus, the centralized architecture can be implemented for the spectrum monitoring process. The key challenge with the centralized spectrum monitoring is that huge information needs to be exchange with the CCU which increases the complexity of the system. Moreover, if CCU crashes, the whole CRN gets down which is unavoidable in the centralized architecture. The solution for this issue is provided by the distributed architecture.

### 3.2 Distributed spectrum monitoring

In a distributed design, each CU does all of SM's tasks on its own, and the CCU and CUs don't need to share information with each other. This takes some of the extra work off of the CUs. In addition to this, the distributed design solves the major problem of CRN crashing when CCU fails. But the distributed design can also be broken down into CRNs that work together and ones that don't. In the distributed cooperative SM, the CUs share information about the appearance of PUs with their neighbours. However, only the particular CU makes the final choice. In the non-cooperative SM, on the other hand, each CU can only find PUs by studying the information at its own CU. This means that CUs don't share information with each other.

## 4. EFFECT OF SPECTRUM MONITORING ON PERFORMANCE METRICS OF COGNITIVE RADIO NETWORKS

We have studied different SM techniques and concludes that it is very difficult to achieve perfect SM which means immediate detection of PU on its emergence since all the techniques has imperfect nature due to random channel, system errors etc. Because of this, it's important to look at the "effect of imperfections in the SM," and these mistakes are measured by the probability of SM error (*P_me*). The system model is set up so that *P_me* has a straight proportional relationship with the detection delay. This means that the larger the value of *P_me*, the longer it takes for PU to appear and be found. Also, the appearance of PU is a function of the traffic intensity of PU (), and a high value of means that PU will appear early in the time frame, while a low value means that it will appear later. In this part, we looked at how SM (perfect nature) affects data loss, power waste, and interference at PU compared to when SM is not present. Further, how the imperfections in the SM worsen the system performance is also studied.

### 4.1 Performance comparison of CRN systems with and without spectrum monitoring

In the system model [72] that was looked at, it was believed that the more traffic there was, the sooner PU would appear in the time frame shown in Figure 5.

In a CRN with SM (perfect nature), the appearance of a PU can be seen within a packet's time. When this happens, the CU stops communicating, which means that a single packet is lost and that the amount of power wasted is equal to the amount of power sent for one packet. The relation of data-loss and power wastage with traffic intensity with and without SM is described in Figure 11 (a) and Figure 11 (b), respectively. In addition to this, the detection delay is the time of interference to PU, therefore the SNR at PU remains at 10dB however increases after one packet time as shown in Figure 11 (c). On the other hand, in case of without SM system, the "entire data after the emergence of PU till the frame completion time" get lost since there is no detection mechanism which results more power wastage and interference.

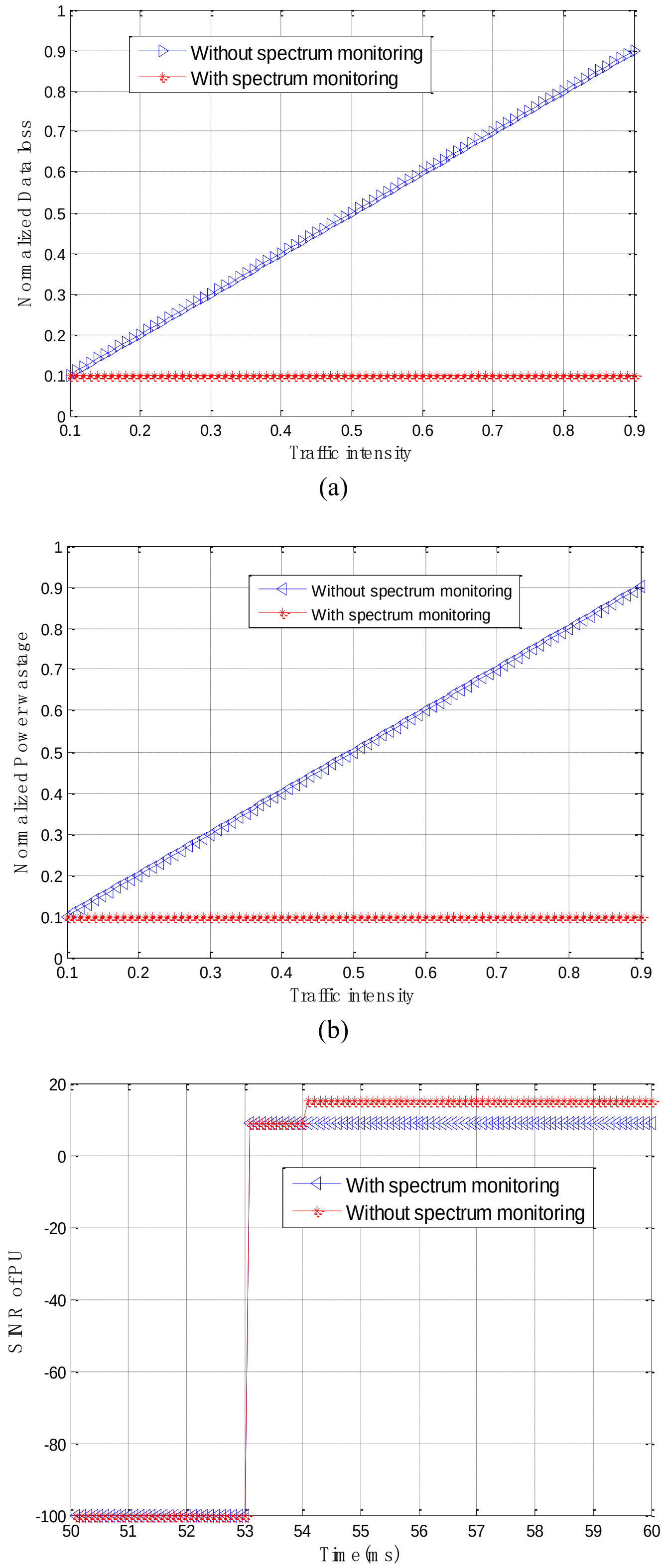


**Figure 11.** Effect of spectrum monitoring on the (a) normalized data-loss versus traffic intensity (b) variations of power-wastage with traffic intensity and (c) SNR at PU versus time ($P_{me} = 0.5$) [72]

### 4.2 Performance comparison of CRNS with perfect and imperfect spectrum monitoring system

The imperfect SM is a real and possible situation. Because of this, it is worth analyzing the cognitive radio network with an imperfect SM system, as described in CiteSeerX [71]. Figure 12 shows the "interference at PU in the form of SNR at PU" for different values of *P_me*. It seems that the time interval of low SNR (which means interference with PU) is directly related to *P_me*. The "interference-efficiency" is a very useful performance metric for studying the "effect of interference-at-PU," which is described as the amount of data sent per unit of interference power introduced at the PU receiver.

Figure 13 shows that the interference-efficiency is much higher for perfect SM, but it goes down as *P_me* goes up. For green communication and to stop people from wasting power, the most important thing is to make sure that conversation uses as little energy as possible. So, it's a good idea to compare the energy efficiency of a cognitive radio network with a perfect SM system to one with some flaws. The energy efficiency is the ratio of the data rate that CU can achieve to the total amount of power it uses [73]. As shown in Figure 14, the energy economy in CRN is more for perfect SM than for imperfect SM. Also, as the "probability-of-SM-error" goes up, the energy efficiency goes down. From what we've talked about so far, it's clear that imperfect SM hurts the performance of cognitive radios in terms of the studied factors, such as "interference-efficiency" and "energy efficiency." It would be better to use perfect SM, but that's not possible. So, it's hard and interesting to find another SM method that works or to improve the *P_me* of the ones that already do.

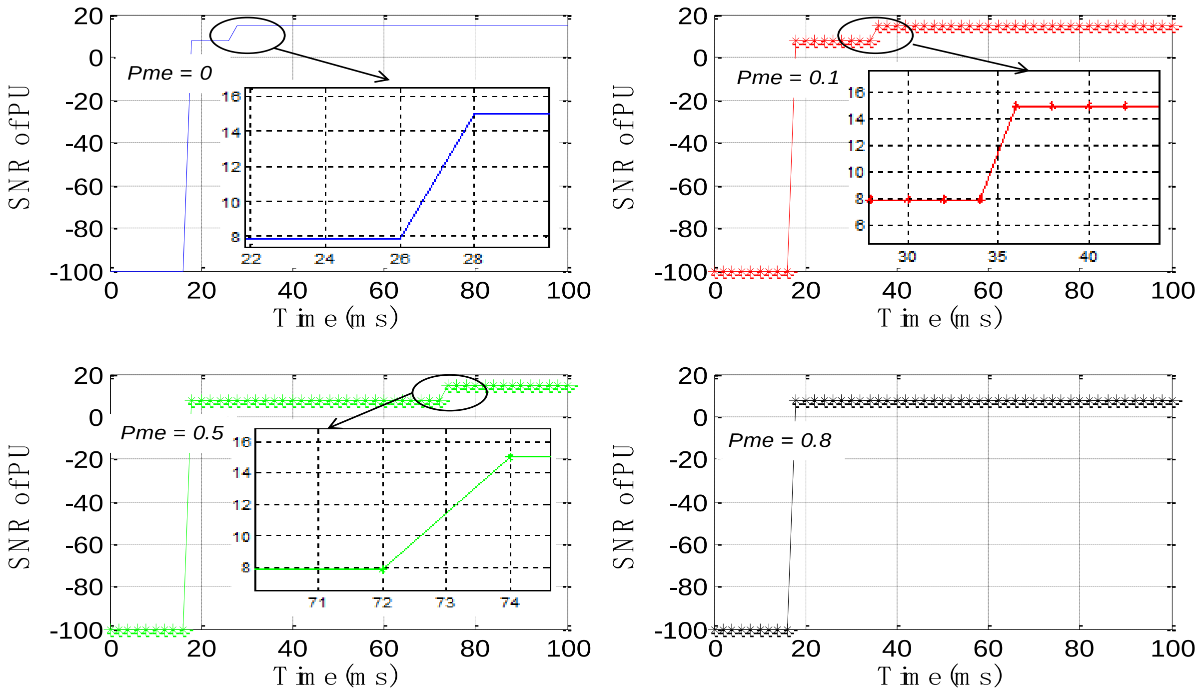


**Figure 12.** SNR of PU versus time for different values of $P_{me}$ [73]

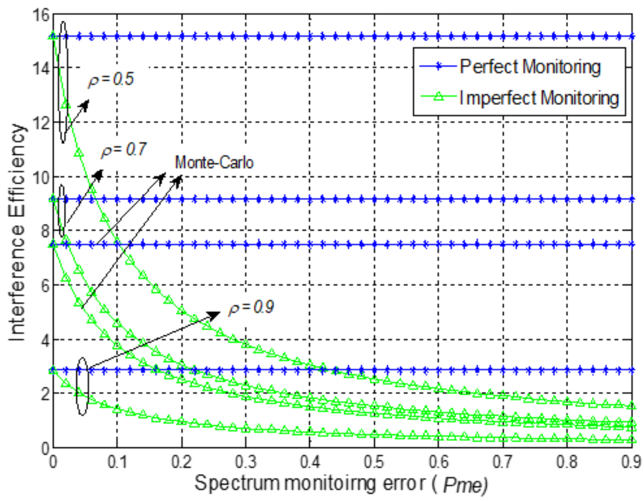


**Figure 13.** The interference efficiency versus spectrum monitoring error [73]

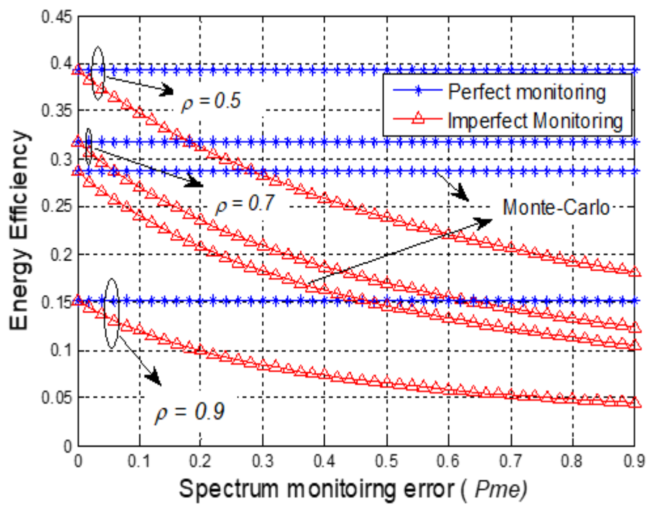


**Figure 14.** The variations of energy efficiency with spectrum monitoring error [73]

### 4.3 Combined effect over CRNS' performance of imperfect spectrum monitoring and spectrum prediction

In order to improve the performance of spectrum mobility which relies on the minimized detection delay, we have analyzed the combined effect of the spectrum prediction and monitoring techniques to detect the emergence of PU [36]. The AND and OR fusion rules are exploited to combine the effects of both and it is reported that AND rule outperforms regarding the resource wastage which results the improved achieved throughput. However, the OR rule outperforms in terms of data-loss and interference introduction at PU. Therefore, the selection of AND rule is preferred when the PU has high interference tolerable limit and deliberate introduction of "interference-at-PU" results the increase in the achieved throughput. On the other hand, when the PU protection is constrained by very low interference tolerable limit, the OR rule is better option.

### 4.4 Effect of cooperation among CUs over CRNs' performance

The cooperation among users always improves the performance of wireless systems by tolerating the randomness of the environment/channel. In the recently proposed technique to enhance the performance of CRN [74-76], we have exploited the cooperation among CUs where a suitable scenario for the cooperation among CU is proposed and further have investigated the effect of cooperation on the data-loss, achieved throughput, interference efficiency and energy efficiency. In the proposed system, a wideband PU channel with bandwidth B is assumed to be selected for the data transmission by the CUs after the spectrum sensing. The N number of CUs are allowed to access the bandwidth B on the frequency sharing bases which means every CU communicates using bandwidth B/N. When PU resumes its communication during the CUs communication, then all the CU detect the emergence of PU with certain probability of SM error ($P_{me}$). Further, every CU reports its results to the central unit where the data from all CUs fused by using hard combining technique (l out of N rule). Furthermore, if the combined decision confirms the emergence of PU, then the CUs switch their communication on another idle channel otherwise continue the same channel. Using cooperation, the emergence of PU is detected with a probability-of-cooperative-SM-error" ($Q_{me}$) which is computed as follow [77, 78].

$$Q_{me} = \sum_{j=l}^{N} (^{N}_{j}C)(P_{me})^{j}(1-P_{me})^{N-j} \qquad (10)$$

where, C denotes the mathematical combination and if l or more number of CUs confirms the emergence of PU, the final decision is that the PU has emerged. Here, the role of l is very prominent and significant approach to compute the optimal value of l is illustrated by Banavathu and Khan [77]. In this article, it is concluding that the cooperation among CUs reduces the value of "probability-of-SM-error" which results the early detection of the PU and lessens the detection delay. The variations of the various performance metrics with the "probability of spectrum monitoring error" is depicted in the Figure 15, Figure 16 and Figure 17.

The relationship between data loss (measured in packets) and *P_me* is seen in Figure 15, where data loss varies exponentially for cooperative SM but virtually linearly for non-cooperative SM. Additionally, the cooperative SM outperforms the non-cooperative SM in terms of performance. According to Figure 16, which shows the fluctuations in interference-efficiency with *P_me*, cooperative SM has a higher interference efficiency than non-cooperative SM. The Figure 17 is the witness of superior performance of the cooperative SM over the non-cooperative SM. Thus, from the afore-discussion, it is perceived that cooperative SM is a prominent solution to manage the effects of imperfections in SM process.

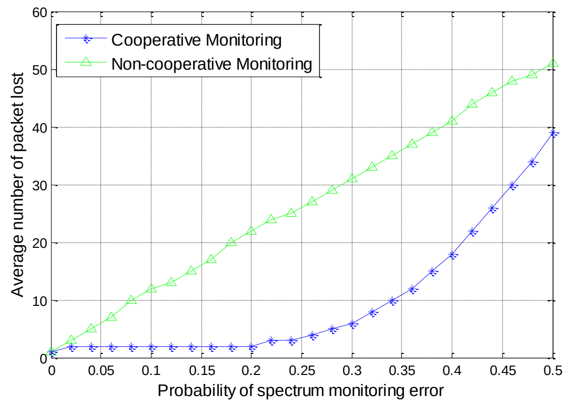


**Figure 15.** The variations of data-loss with probability of SM error [74]

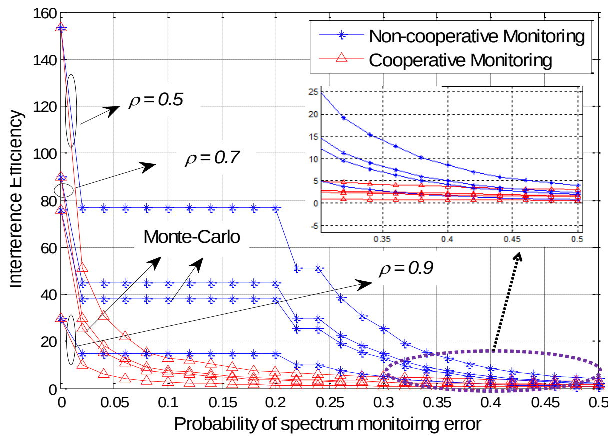


**Figure 16.** The relation between interference efficiency (bits/joule/Hz) and probability of SM error [74]

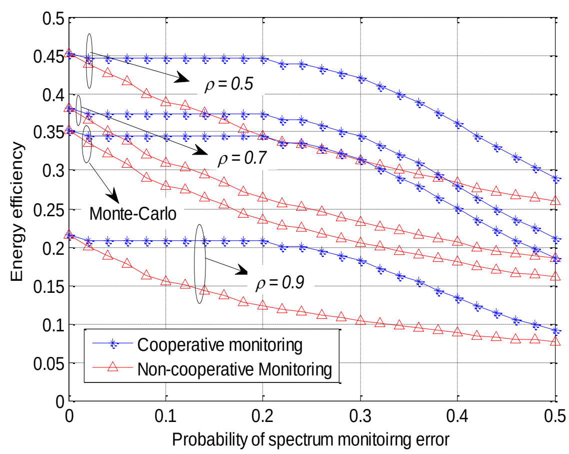


**Figure 17.** The relation between energy efficiency (bits/Joule/Hz) and probability of SM error [74]

## 5. POTENTIAL RESEARCH CHALLENGES WITH SPECTRUM MONITORING TECHNIQUES

In this section, the potential issues and research challenges of the SM techniques in common are of the different SM techniques such as REC and REC + CRC based, energy and energy-ratio-based, and EVM based are presented in Table 1.

### 5.1 REC+CRC based spectrum monitoring

5.1.1 Cooperative spectrum monitoring (CSM)

The REC is a metric which relies on various operating conditions such as the channel conditions, system error, hardware impairments etc. The REC is very sensitive to any of the condition e.g. the worsening of channel and system error may increase the REC which results false detection of the emergence of PU. The potential solution for this issue is cooperative SM (CSM) which is investigated in section 3 for an environment where number of CUs have exploited the channel of a wideband PU channel. The PU channel is equally divided into N number of sub-channels that are allocated to the CUs. In addition to this, the probability of SM error for every CU is assumed same i.e. $P_{me}$. Here, both the cases i.e. $P_{me}$ and bandwidth allocation for all the CUs is same, however the CRN where CUs with different $P_{me}$ and bandwidth, is much feasible scenario which is a challenging research issue.

5.1.2 Threshold selection (TS)

The REC computed at the CU receiver needs to compare with the threshold value to decide the emergence of PU. Significantly higher value of threshold misses the emergence of PU that results the rise in probability of miss-detection [79]. However, lower value of threshold causes the "false detection of emergence-of-PU" and leads to rise in probability of false-alarm [79]. The selection of threshold is very critical phenomenon and the efforts towards this are in infant stage which recommends it as an open research issue.

5.1.3 Security

The secure spectrum monitoring is very important however a challenging milestone to achieve in case of REC+CRC based SM, because if in a network, attackers can introduce number of malicious nodes, which can transmit on the same channel and increase the REC count that results in the false detection of the channel. The false detection of the channel always leads to resource wastage. Therefore, the exploring the secure detection mechanisms and protocols in the REC+CRC based SM is a potential research issue. The use of artificial intelligence based mechanisms are also appeared as a potential candidate for spectrum monitoring.

### 5.2 Energy and energy ratio spectrum monitoring

5.2.1 Complexity (Comp)

The complexity of the energy-ratio-based SM technique is twice as compared to that of the conventional energy detector. Therefore, the SM techniques with less complexity are desired which is an open research challenge.

**Table 1.** The performance comparison of various spectrum monitoring techniques

| Reference | Boyd et al. [57] | Soltanmohammadi et al. [63] | Ko et al. [65] | Ali and Hamouda [69] | Nepal et al. [70] | Proposed Technique |
|---|---|---|---|---|---|---|
| Technique NAME | REC based | REC+CRC based | Energy-based | Energy-ratio- based | EVM based | Energy fluctuation based |
| Generalized NATURE | Yes | Yes | No | No | No | Yes |
| Channel used | AWGN | Rayleigh fading | --------- | AWGN and frequency selective fading | Rayleigh fading | AWGN |
| Immunity to environmental effects | Very poor | Poor | Average | Good | Good | Good |
| Quite periods | No | No | Yes | No | No | No |
| Application scenarios | Suitable for slowly varying PU activities | Suitable for slowly varying PU activities | Suitable when CU uses OFDM scheme with zero energy intervals | Suitable when CU exploits OFDM without zero energy intervals | Suitable when CU requires high accuracy on the cost of high computation ability | If CU exploits signal rather than OFDM |
| Potential research challenges | CSM, TS, SMUMA, Security | CSM, TS, SMUMA, Security | NGN, COPCZEI, SMUMA, TS, Security | Comp, NGN, SMUMA, TS, Security | NGN, TS, Security | TS, Security |

5.2.2 Non-Generalized nature (NGN)

Both the energy and energy-ratio-based SM techniques (EBSMT) are defined when the CU transmits OFDM signals however, in general, the CU needs to support all other modulation techniques. Due to which the monitoring technique should be defined for all the frameworks used in communication which means the design of a generalized energy-based SM techniques is an open research issue.

5.2.3 Collision of PUs' and CUs' zero energy intervals (COPCZEI)

If the PU transmits OFDM signal it is possible that the zero energy intervals of signals transmitted by PU and CU coincide and the energy detection algorithm unable to detect the emergence of PU. Therefore, in order to avoid this issue, more research efforts are required. One potential solution is to exploits the pre-knowledge about the PUs' signal which means if PU uses OFDM signal then CU needs to avoid energy-based SM technique.

5.2.4 Spectrum monitoring using multiple antenna techniques (SMUMA)

The EBSMT is also explored for the multiple antenna systems such as "single-input multi-output" (SIMO) and "multi-input multi-output" (MIMO). However, the multiantenna system enhances the complexity of the EBSMT, therefore, the complexity management using multiple antenna systems for EBSMT is a challenging issue.

5.2.5 Threshold selection

The energy of the 1st and 2nd window may vary due to variation in the channel conditions which results the increase in energy ratio. Therefore, the selection of threshold value to take the decision is critical issue that need to be investigated. The dynamic threshold exploitation to decide the emergence of PU can be a suitable option as compare to the static threshold.

5.2.6 Security

Similar to the security section in 5.1, the malicious nodes in the network can transmit with high power on the same channel and results in the high energy level which leads to false detection the PU in energy-based SM. Moreover, the malicious nodes can vary its power level and may cause the energy difference at the CU receiver that leads to false-detection in case of energy-ratio-based SM. Therefore, secure detection mechanism in the energy and energy-ratio-based SM techniques need to explore.

### 5.3 EVM based spectrum monitoring

5.3.1 Non-Generalized nature (NGN)

The EVM technique is also defined for OFDM however due to same limitation mention in 5.2, it must be analyzed for all the modulation techniques.

5.3.2 Threshold selection (TS)

Due to the same reason as mentioned in section 5.1, the threshold selection is a challenging issue.

5.3.3 Security

Similar to the other SM techniques, malicious nodes and attackers alters the decision of SM phenomenon, therefore, sufficient security aspects need to be explored.

## 6. CONCLUSION

The spectrum monitoring is a prominent approach to detect the "emergence of PU during CUs' data transmission" and different techniques are available to perform this however every technique has certain advantages and disadvantages and the selection of the SM technique for particular scenario is a challenging issue. Therefore, in this paper, we have studied and investigated various SM techniques with their pros and cons as well as suggest the application scenario for those techniques. Further, it is palpable that the use of SM (with perfect nature) improves the performance of CRN however, the imperfections in SM techniques degrades this. Furthermore, the potential issues and research challenges regarding different SM techniques are presented. The presented work has good potential for the effective implementation of the dynamic spectrum access which is a potential candidate for Beyond 5G/6G.

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