Comprehensive Survey on Quality of Service Provisioning Approaches in Cognitive Radio Networks: Part One

Abstract Much interest in Cognitive Radio Networks (CRNs) has been raised recently by enabling unlicensed (secondary) users to utilize the unused portions of the licensed spectrum. CRN utilization of residual spectrum bands of Primary (licensed) Networks (PNs) must avoid harmful interference to the users of PNs and other overlapping CRNs. The coexisting of CRNs depends on four components: Spectrum Sensing, Spectrum Decision, Spectrum Sharing, and Spectrum Mobility. Various approaches have been proposed to improve Quality of Service (QoS) provisioning in CRNs within fluctuating spectrum availability. However, CRN implementation poses many technical challenges due to sporadic usage of licensed spectrum bands, which will be increased after deploying CRNs. Unlike traditional surveys of CRNs, this paper addresses QoS provisioning approaches of CRN components and provides an up-to-date comprehensive survey of recent improvement in these approaches. Major features of the open research challenges of each approach are investigated. Due to the extensive nature of the topic, this paper is the first part of the survey which investigates QoS approaches on spectrum sensing and decision components respectively. The remaining approaches of spectrum sharing and mobility components will be investigated in the next part.

Keywords CRNs; QoS Provisioning Approaches; QoS Objectives; Spectrum Sensing; Spectrum Decision; CRNs' open issues.

1 Introduction

The rapid proliferation of wireless technologies and services has led to a scarcity of available wireless resources [1]. According to the International Telecommunication Union- Radio communication sector (ITU-R) there will be a demand for 1280-1720 MHz of extra band in 2020 to fill up the current allocated radio spectrum in wireless networks [2]. Furthermore, inflexible static spectrum management policies followed by government agencies have led to a critical degree of spectrum underutilization. Recent spectrum occupancy measurement campaigns revealed that many allocated spectrum bands are used only in bounded geographical areas or over limited periods of time [3]. To improve spectrum utilization, Cognitive Radio (CR) technology has been proposed to sense the spectrum and permit unlicensed devices to use the free spectrum portions on a non-injurious to licensed users basis [4].

In the context of CR, unutilized portions of spectrum bands are referred to as “White Spaces” (WSs) or “Spectrum Holes”. Additionally, the opportunistic Dynamic Spectrum Access (DSA) of CR technology is referred to as Overlay or Interweaves [5, 6]. By periodically sensing its surrounding environment, a Secondary User (SU) adapts its transmission parameters (e.g. spectrum band, transmission power, and modulation and coding schemes) autonomously, using Software Defined Radio (SDR). The SU avoids harmful interference to Primary (licensed) Users (PUs) by evacuating the utilized channels once they return [7]. Moreover, when the CRs generate interference that is below the interference threshold of the PUs, they can coexist simultaneously with PUs in Underlay mode. By the "Underlay" paradigm, the CR uses knowledge of the PUs’ transmission power to choose a transmission scheme that may cause an acceptable amount of interference [8]. Accordingly, the main characteristics of CR are: Cognitive capabilities (provides spectrum awareness) and Reconfigurability (communicates on a variety of channels using different transmission access technologies) [9].

In the literature, CR Networks (CRNs) refer to adaptive and self-organization wireless networks capable of providing services to end users (i.e. SUs) within continuous environmental changes [10]. As CRNs are wireless in nature, they inherit all topologies present in traditional wireless networks, which are classified into: a) Centralized CRNs such as IEEE 802.22 Wireless Regional Area Network (WRAN), where a Base Station (BS) is deployed with several SUs associated with it [11]; and b) Distributed or CR Ad Hoc Networks (CRAHNs), where the SUs communicate directly with each other without any central node [9]. These networks are depicted in Fig. 1. Unlike in centralized CRN, route and spectrum selections are jointly considered in CRAHNs [1]. Furthermore, Hybrid transmission strategy has been proposed as a third spectrum access strategy (in addition to Overlay and Underlay strategies) in order to increase spectrum utilization [12]. To support intelligent and efficient utilization for the available spectrum, CRN functions are categorized in four main components. These functions are: Spectrum sensing (detecting the spectrum holes), Spectrum decision (identifying and selecting the best channels), Spectrum sharing (coordinating access to channels among the network users) and Spectrum mobility (switching to other candidate channels and maintaining seamless communication during the transition) [13].

Since first proposed by Dr. Joseph Mitola in 1999 [4], CR technology has drawn considerable attention in the research community as the key enabler for significant wireless systems. Most of the study of implementing CR includes: a) **Military applications** [14]; b) **CR based Smart Grids** [15]; c) **CR based Sensor Networks** [16]; d) **CR based Femtocells** [17]; e) **CR based M2M communications** [18]; f) **Vehicular Networks** [19]; g) **Green Energy Powered CRNs** [20]; h) **CR based Satellite Communications** [21]; i) **Aeronautical Communications** [22]; and j) **Disaster Response Networks** [23]. Furthermore, the success of CR can be seen in its being adopted as a key technology in fifth generation (5G) wireless communications systems. Moreover, a large number of studies has been for completing (or advancing in) networks standardization of IEEE 802.22b, 802.11af, 802.15.4, and 802.19.1 [24]. In addition, due to the highly demand for extra spectrum, the growth of CR applications is expected to continue to address other modern communications systems.

To implement all of the above-mentioned CR based applications, the network requires an end-to-end quality of Service (QoS) to keep its connectivity. Furthermore, providing a satisfactory QoS and user experience at the lowest price is key to the commercial success of CRNs [25]. However, guaranteeing QoS provision in CRNs is very challenging, due to the sporadic presence of PUs and SUs of other CRNs. More specifically, PUs are the owners of the band and have higher priority over SUs; therefore, SUs have to stop transmitting immediately once PU returns, and switch to another best available spectrum. Furthermore, with the anticipated growth in the number of CRNs, there is the possibility of a dramatic decrease in the available spectrum due to SUs' activities [26] with a resulting degradation in the services offered, which has dramatic implications for these promising networks.

A huge number of studies have proposed measures that effectively address the challenges in CRN components to maintain QoS objectives (or metrics [27]). These studies can be categorized within certain QoS provisioning approaches in CRNs. Therefore, this paper conducts a comprehensive survey of QoS approaches and extensively investigates the recent achievements. Due to the extent of improvements in these approaches; the article will be divided in two parts. In this part, we investigated the improvements of the approaches in spectrum sensing and spectrum decision components respectively, while the contributions in remaining approaches of spectrum sharing and mobility will be investigated in the second part of the survey.

Therefore, the main contributions of this work are listed as follows:

- Summarizing the QoS provisioning approaches.

- Classifying the improvements of these approaches into different categories and discussing the relevant recent important articles.
- Outlining several major open research challenges in spectrum sensing and selecting which hinder the capacity enhancement of CRNs from coexisting with PNs within a reliable DSA system.

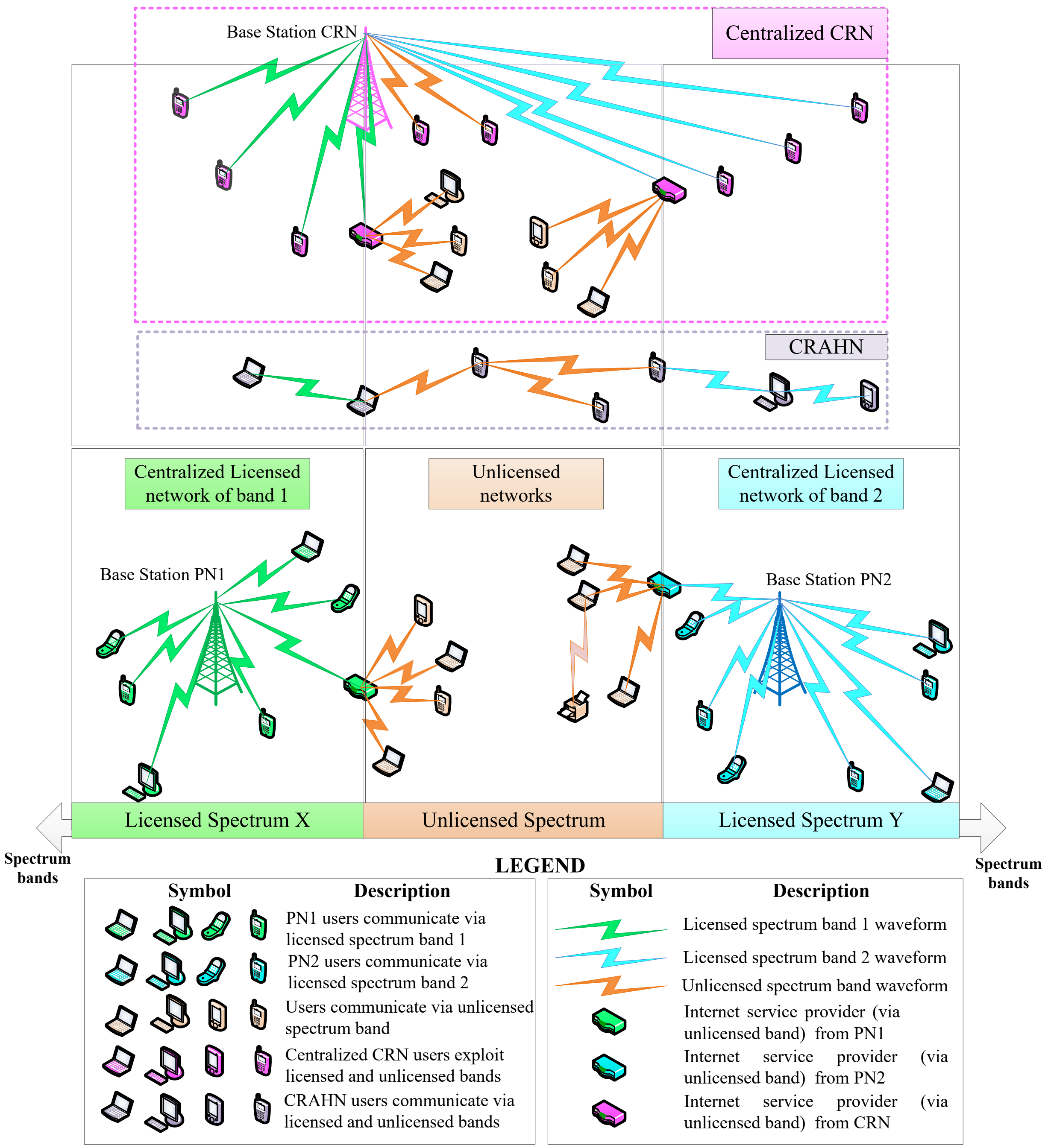

Fig. 1. The concept of communications in CRNs and PNs.

The remainder of this paper is organized as follows. Section 2 discusses related works (i.e. surveys on CRNs) and the motivation of this article survey. Section 3 describes and classifies QoS objectives and the approaches of QoS provisioning in CRN components. In Section 4 and Section 5, the QoS provisioning approaches of spectrum sensing and spectrum decision components and the corresponding recent contributions are explained thoroughly. Furthermore, we point out crucial open issues on both components. Finally, Section 6 concludes the paper.

2 Related work

Over the past ten years, we have witnessed a tremendous growth of the research by academia and industry on developing CRNs. Each CRN component has received close attention from researchers to address QoS requirements. To assimilate the rapid achievements, it is noticeable that every year several surveys are published on the state of the art, aiming to address particular points in the CRNs context. Indeed, the surveys published in the highest impact factor journals are organized with extensive description and discussion to cover the area that they prepared for. After an extensive search, we found that these surveys could be grouped into five main categories: (a) Concern on a certain QoS objective, such as [8, 14, 21]; (b) Describing the technical development in one CRNs component, as in [1, 28-32]; (c) Extensively explaining a function of a CRN component, as in [17, 33-43]; (d) Investigating various security challenges, as in [44-46]; and (e) Presenting the latest developments in a CR based application, as in [15, 18-20, 47].

All previous surveys highlighted the advantages and the disadvantages of the existing techniques, algorithms and schemes to improve QoS objectives. To the best of our knowledge, none have presented the approaches adopted to improve QoS objectives in CRNs components. There have been investigations into these approaches, such as [13, 34]; however, they have not provided a comprehensive summary of all proposed approaches in each component. Clearly, some of these approaches have been considered in CR technology's components and continued even after proposing CR as a network. In CR as a technology, the approaches of each component were limited to Physical layer (PHY) and Link Layer; however, in CRN the approaches have been extended to cover the remaining layers in the Open System Interconnection (OSI) model [13].

Therefore, this work conducts a comprehensive survey of the existing QoS provisioning approaches in CRNs components and extensively investigates the recent achievements in each approach.

3 QoS Objectives and Approaches in CRNs

Satisfying QoS in any mobile communication system means preserving all the requirements needed by the applications to guarantee a certain level of successful sessions [48]. Similar to any wireless communication network, administrators of CRNs should provide an optimum possible QoS to the end users. However, QoS provisioning is a more challenging factor in CRNs than in traditional wireless networks, since the spectrum bands are not dedicated. Specifically, QoS must be optimized at the CRN user terminal within intermittent PU and SU (in case of overlapping CRNs) activities without interfering with both PUs' and other SUs' applications. This section explains and introduces the reader to the QoS objectives and the proposed approaches in the CRN literature.

3.1 QoS Objectives

As CRNs are wireless in nature, the QoS objectives of CRNs are similar to traditional mobile networks; however, different techniques and schemes are used due to the nature of undedicated spectrum access. Thus, QoS objectives may be classified into five categories as follows [13]:

- *Throughput*: Defined as the amount of successfully delivered data, as in [49-63].
- *Spectrum efficiency*: Indicates the data rate per frequency band (bit/sec/Hz), such as [39, 64-73].
- *Delay*: Refers to the total time that the data (or packets) have taken from when the data is transmitted till it is successfully received, as in [62, 64, 74-82].
- *Power consumption*: Denotes the total power consumed by the SU terminal device for communications, such as [8,20, 54, 83-92].
- *Reliability*: Refers to the performance of the network in completing and starting sessions, as in [93-109].

Furthermore, some of the articles consider two objectives jointly, such as in [8, 110-113]. Moreover, a few papers consider three QoS objectives in the research methodology, such as [87, 114, 115]. However, all QoS objectives have not been considered in any research studies. Fig. 2

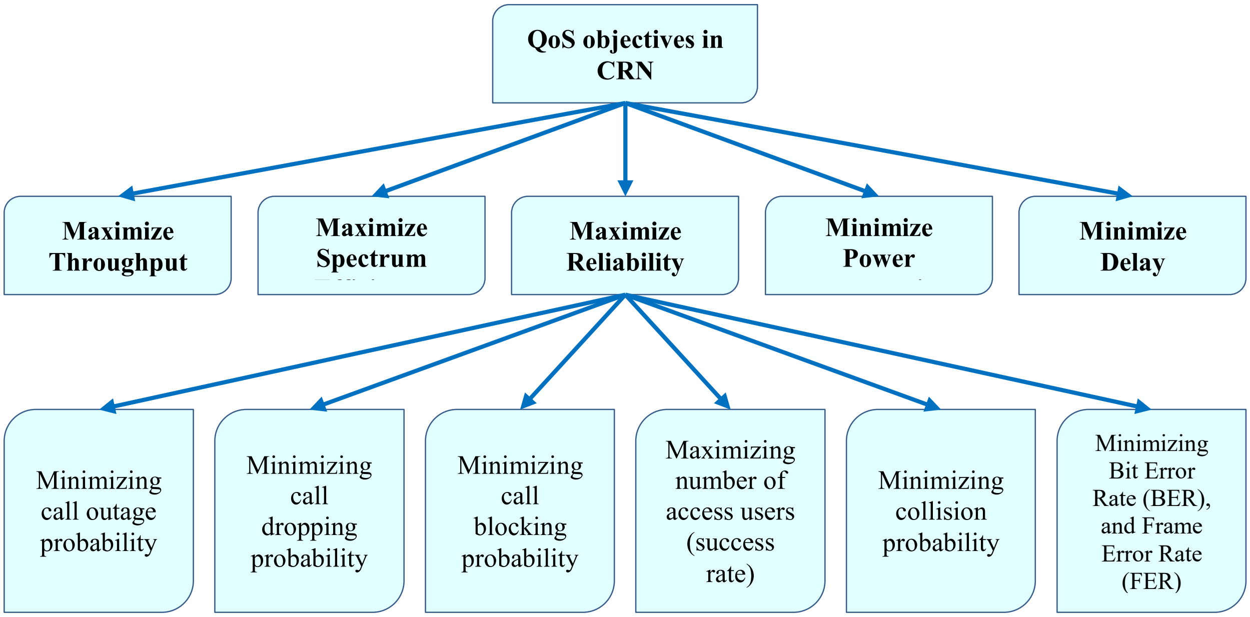

Fig. 2. QoS provisioning objectives in CRNs.

illustrates these objectives corresponding to their related sub-objectives. To date, several approaches to improving QoS objectives have been proposed. The next sub-section is dedicated to classifying them according to the network components.

3.2 QoS Provisioning Approaches

To describe QoS provisioning approaches in CRNs coexisting components for reliable spectrum sharing among themselves and with PNs, it is necessary here to clarify exactly what is meant by these components. As illustrated in Fig. 3 these components as well as their QoS approaches can be explained briefly as follows.

3.2.1 Spectrum Sensing

It refers to detecting the vacant channels to be utilized via Overlay or the bands that are able to be utilized by Underlay strategy [12]. Therefore, it has a crucial impact on CRN performance. According to the CRN literature, two main QoS provisioning approaches in spectrum sensing stage, which include: a) **Sensing Accuracy;** and b) **Sensing Efficiency**. Furthermore, these two main approaches include several approaches such as: (i) Optimizing threshold of detection, as in [97-99, 102, 116]; (ii) Cooperative sensing, as in [55, 74, 87, 95]; (iii) Multi-stage sensing [93, 100, 103, 104]; (iv) Wideband as in [86-90, 117-131]; (v) Adaptive sensing [49, 115]; and (vi) Obtaining sensing outcomes from external sources, as in [132-138]. It is worth mentioning that several studies have been published on achieving accuracy-efficiency tradeoff, such as [75, 76].

3.2.2 Spectrum Decision

It concerns on selecting the best detected channels according to certain constraints (e.g. channel holding time, channel capacity, and channel SU location) [41]. In this category, two QoS provisioning approaches were proposed in the literature: (a) **Optimizing Channel Selection**, as in [105, 106, 139-142]; and (b) **Minimizing Channel Selection Overheads**, such as [77, 91, 143-149]. Indeed the spectrum prediction based on spectrum modelling plays a crucial role in the selection, as in [107, 128, 150-152].

3.2.3 Spectrum Sharing

The approaches of this component are concerning accessing the selected bands and adapting transmission parameters accordingly [153]. Therefore, the findings of QoS approaches in this component concern proposing: (a) **Sharing Strategies and Techniques**, such as Hybrid transmission, as in [59,60], multi-zone access, as in [71], and Multiple Input Multiple Output (MIMO) technique [154-157]; (b) **Transport Protocols** such as in [35, 158, 159]; (c) **Resource Allocation Techniques with Different Admission Algorithms** (also called Intranetwork spectrum sharing), as in [109, 145, 160-163]; (c) **Routing and Queuing Algorithms** (especially in CRAHNs), as in [62, 79-82, 164]; (d) **Cooperative Sharing Methods**, such as in [29, 165-168]; (e) **Power Allocation Algorithms**, as in [63, 92, 113]; (f) **Minimizing the Security Threats and Vulnerabilities** that may degrade QoS provision of some or all networks, such as, PUEA, and Byzantine attack in [44, 168-172]; and (g) **Internetwork spectrum sharing frameworks** that manage spectrum bands sharing among overlapping CRNs. Based on the concept of spectrum pooling, the majority of the proposed frameworks consider cost-benefit trade-off (cost = payment to PN, and benefit = achieved spectrum band for CRN) as in [134-138], or by resource allocation for overlapped WRANs [173-177].

3.2.4 Spectrum Mobility

Spectrum mobility refers reconfiguring SUs by evacuating their utilized spectrum bands when PUs are detected and maintain seamless communications requirements during the transition to other available spectrum bands [37]. This component depends mainly, on CRNs' cognitive engine (in case proactive handing off) and how long delay that the running applications may permit [1]. In other words, spectrum decision and sharing strategies have the main influence to spectrum mobility. According to CRNs literature, QoS approaches in this component concern on (a) **Minimizing number of hand off event**, such as in [36], [132]; and (b) **Minimizing handoff overheads** as in [178].

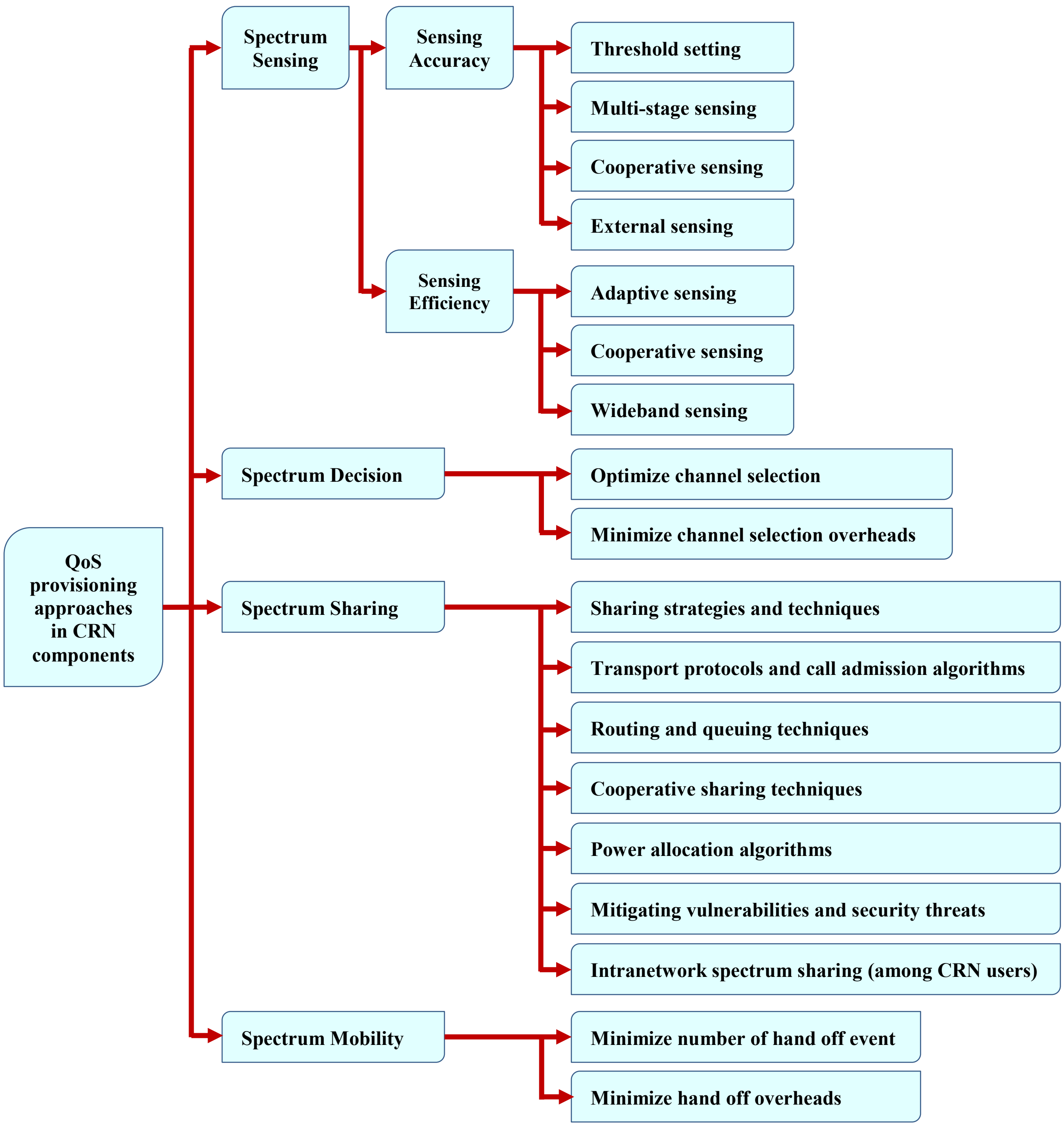

Fig. 3. QoS Provisioning approaches in CRN components.

Note that the QoS approaches of both spectrum sharing and mobility are presented in order to present all approaches in CRNs literature. Their characteristics with the recent improvements will be investigated the second part of this survey. The survey goes in the next section to describe the solutions and improvements in QoS approaches of spectrum sensing component.

4 QoS Provisioning Approaches in Spectrum Sensing Component

Spectrum sensing is an essential component of a CRN system aiming to obtain awareness of the spectrum occupancy and the activities in a specific region in order to achieve successful spectrum selection [179]. Additionally, periodic sensing of the selected bands is necessary to be aware of any sudden reappearance of the PUs, in order to evacuate them quickly [35]. In the CRN literature, the main QoS provisioning approaches are: a) **Spectrum sensing accuracy**; and b) **Spectrum sensing efficiency**. The section is dedicated to describing recent improvements in these two approaches and proceeds as follows: at the beginning, preliminaries of sensing strategies, elements and techniques will be explained briefly.

4.1 Introduction to Spectrum Sensing Features

There is a large volume of published studies describing spectrum sensing accuracy and sensing efficiency without clarifying the approaches used. For example surveys such as that conducted in [180] evaluate most sensing types including their capabilities and weaknesses, without highlighting on the QoS provisioning approaches. Spectrum sensing procedures can be described using a hypothesis testing problem that is given in Eq. 1 [93]:

$$y(n) = \begin{cases} w(n) & \mathcal{H}_0 \\ s(n)h(n) + w(n) & \mathcal{H}_1 \end{cases} \quad (1)$$

Where $y(n)$ is the received signal at SU, $s(n)$ is PU or other SUs (hence forward referred to as Incumbent User (IU)) transmitted signal with zero mean and variance σ_s^2 and $w(n)$ is a zero-mean Additive White Gaussian Noise (AWGN) with variance σ_w^2 . $h(n)$ denotes the fading channel gain of the sensing channel between SU and IU, and $\mathcal{H}_0$ represents the hypothesis that IUs are absent, while hypothesis $\mathcal{H}_1$ indicates that IUs are present. After that SU will compute the test statistics Γ of the received signal and compare it with a predetermined threshold (static threshold approach) (λ) for each band. Mathematically, the comparison is written as [117].

$$\widehat{\mathcal{H}}_0: \Gamma < \lambda$$
$$\widehat{\mathcal{H}}_1: \Gamma \geq \lambda \tag{2}$$

where $\widehat{\mathcal{H}}_0$ and $\widehat{\mathcal{H}}_1$ indicate the sensing decision that the IUs are inactive and active respectively. IU detection probability P_d should be high enough to avoid harmful interference to PU; however, two types of detection errors are highly possible measured in terms of (a) **False alarm probability** P_{fa}: which is defined as the detector indicating the IU is present while it is absent (i.e. $Pr\{\widehat{\mathcal{H}}_1|\mathcal{H}_0\}$); and (b) **Missed detection probability** P_{md}: which is defined as the detector deciding that the channel is vacant while it is not (i.e. $Pr\{\widehat{\mathcal{H}}_0|\mathcal{H}_1\}$). Accordingly, the probability of error detection P_E can be calculated by the following [94]:

$$P_E = P_{fa} * Pr(\mathcal{H}_0) + P_{md} * Pr(\mathcal{H}_1) \tag{3}$$

where $P_{fa} * Pr(\mathcal{H}_0)$ indicates that IU is absent while the detection device is reporting that IU to be present, whereas $P_{md} * Pr(\mathcal{H}_1)$ denotes that IU is present while the device reports it is not. As illustrated in Fig. 4, all spectrum sensing component that have been proposed in the literature are summarized briefly as follows:

- There are two kinds of spectrum sensing in CRN tasks: a) **In Band Sensing (IBS)**: Indicates sensing the current utilized channels; and b) **Out of Band Sensing (OBS)**: Refers to sensing unutilized channels to be used in case of handoffs [132].
- There are two different sensing dependency: a) **Internal sensing**: Defined as the CRN performs spectrum sensing task locally by its users; and b) **External sensing**: Indicates obtaining the channels' statues from either a Wireless Sensor Network (WSN) which may report the outcomes to CRNs for certain fees [3] or databases (spectrum pooling) which act as spectrum brokers between PNs and CRNs [134].
- There are two spectrum sensing frequency: a) **Proactive sensing**: Defined as periodic sensing of the spectrum; and b) **Reactive sensing**: Denotes on-demand sensing that depends on the modelling of the utilized spectrum [36].
- There are two procedures of spectrum sensing: a) **Cooperative sensing**: Refers to collaborating and sharing sensing outcomes by SUs to achieve detection; and b) **Non-cooperative sensing**: Indicates that each SU depends on its own sensor to obtain the status of the spectrum (in CRAHNs only) [95].

- There are three types of detection methods: a) **Transmitter based sensing**: Defined as the SU analyzing the state of the channel to identify its status; b) **Interference temperature based sensing**: Indicates interference strength brought by SU to IU, which can be measured by interference temperature [181]; and c) **Receiver based sensing**: Refers to the SU identifying channel status by exploiting the emitted leakage power from a local oscillator of IU RF frontend [37].
- There are two ways of spectrum bands sensing: a) **Narrow Band Sensing:** Refers to SUs performing sensing for a single utilized channel; and b) **Wideband Sensing**: Indicates sensing of SUs for multiple channels simultaneously [38].
- There are two design elements of spectrum sensing: a) **Test statistic**: Defined as formulating appropriate modelling of test statistics that may provide reliable information about a channel's occupancy; b) **Threshold setting**: Refers to assigning a certain threshold value used to differentiate between the hypotheses H_0 and H_1, which can be fixed [116] or adaptive [182].
- There are three types of spectrum sensing techniques: a) **Blind sensing technique**: Defined as a detector requiring no information about the received signal, such as *Energy Detector* (ED), *Eigen Value based Detector* (EVD), and *Covariance Absolute value Detector* (CAD); b) **Semi-blind sensing technique**: Indicates a detector that needs some prior information about the IU, for example noise power estimation, such as *Cyclostationary Detection* (CSD); and c) **Non-blind sensing techniques**: Refers to the detector needing an IU signature as well as noise power estimation, such as *Matched Filter* (MF), and *Coherent detector* [180].
- There are two main QoS provisioning approaches topics in spectrum sensing: a) **Spectrum sensing accuracy**: Defined as the total amount of reliability of detecting spectrum opportunities, where P_{md}, and P_{fa} are measurement metrics of the trustworthiness of sensing [83]; and b) **Spectrum sensing efficiency**: Defined as the total period (unit of time) that a CRN spends to determine the spectrum opportunities [13].

Finally, efficient detection techniques are pivotal to reducing data transmission interruptions, and to selecting the best channels with a seamless handoff from one band to another [117].

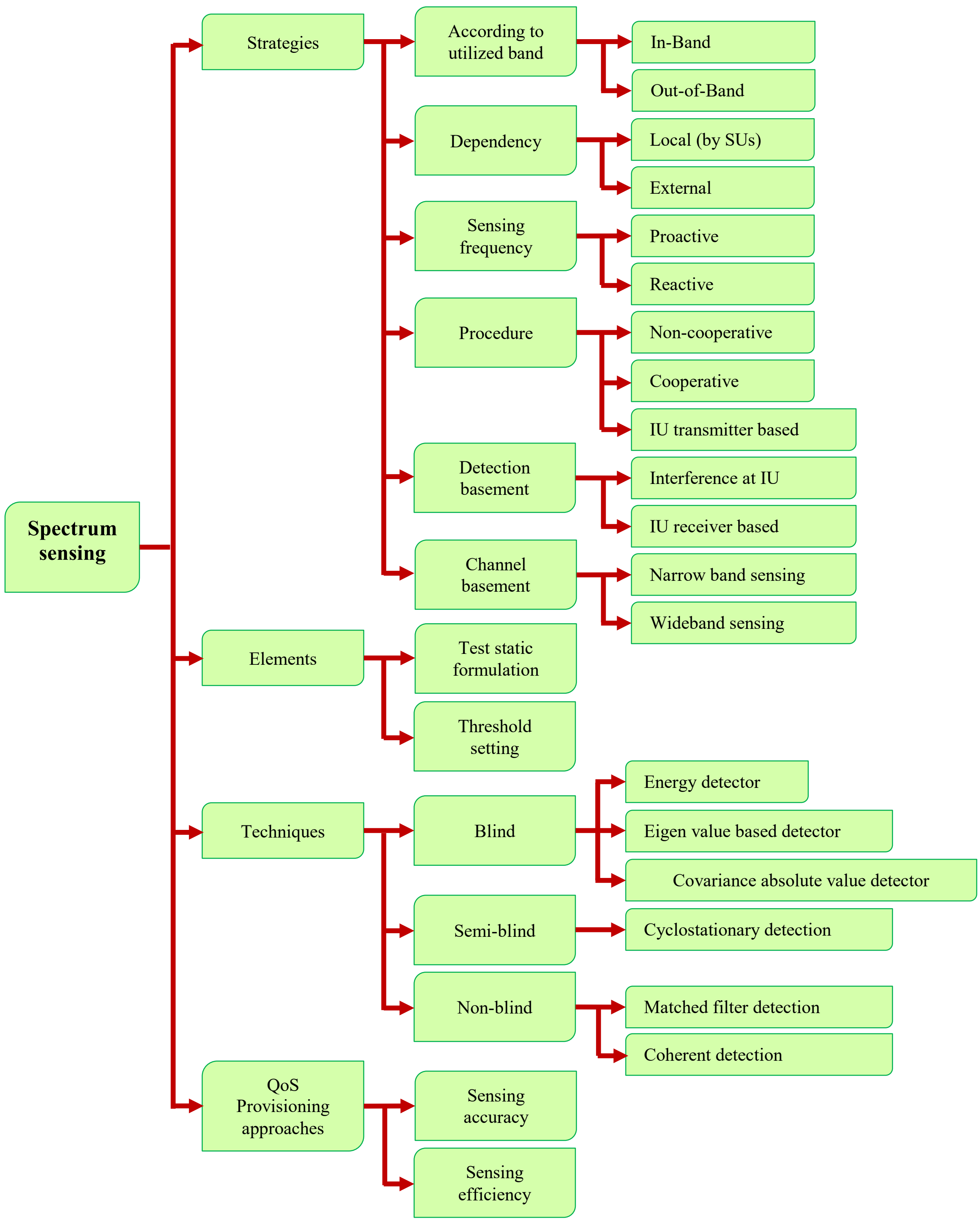

Fig. 4. Taxonomy of spectrum sensing components in CRN.

4.2 Spectrum Sensing Accuracy

The performance of spectrum sensing in CRN depends on received Signal to Interference and Noise Ratio (SINR). There are four causes of error detection related to SINR, which can be summarized as follows [28]:

- Static threshold setting.
- Low received (SINR), for example hidden terminal problem.
- SU is in a deep fade from shadowing and multipath.
- Sampling requirements.

The basis of error detection using the energy detection method is best explained in Fig. 5. Although the figure is not based on any empirical measurement, it enables the reader to understand the error detecting concept. More specifically, Fig. 5(a) presents utilization from PUs in a licensed channel, and Fig. 5(b) depicts perfect energy detection. However, because of the aforementioned four challenges, SU detection may deteriorate, and this starts with error sensing (i.e. false alarms and missed opportunities) as illustrated in Fig. 5(c). In recent years, much research has been conducted in order to solve and mitigate problems of error sensing. According to the literature, four techniques have been adopted by researchers to improve sensing accuracy. These techniques with their characteristics are as follows:

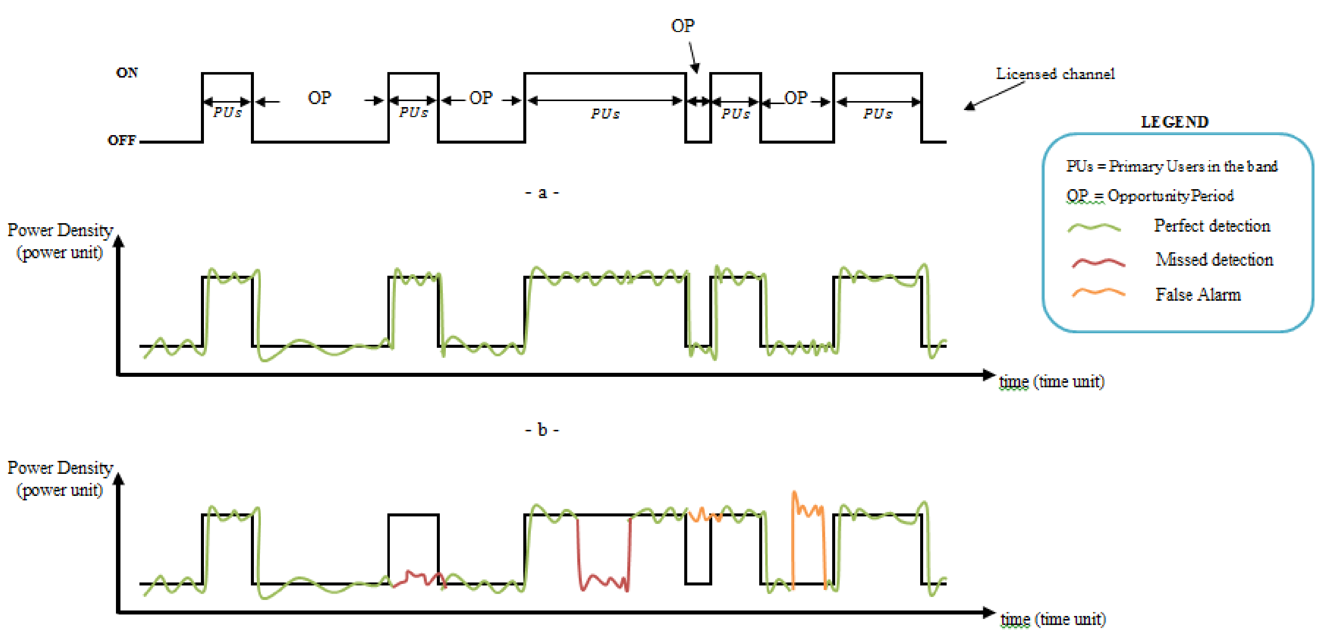

Fig. 5. Example of error detection probabilities.

4.2.1 Threshold Setting

Traditionally, SU exploits a spectrum sensor of energy or features of IU to determine whether the channels are occupied or not [96]. In ED, the decision threshold λ that distinguishes a channel's status is very important, and this parameter is configured by the system designer. In the literature, optimum λ has been chosen based on: a) *trade-off between P_d and P_{fa}* (as shown in Fig. 6) [183]; and b) *the knowledge of IU signal power as well as noise power* [97]. The IEEE 802.22 working group on WRANs recommended that the target false alarm probability $\overline{P_{fa}}$, and target detection probability $\overline{P_d}$ should be 0.1 and 0.9 respectively [184]. Therefore, the optimal threshold based on each target is calculated as follows [98]:

$$\lambda_{P_d} = \sigma_w^2 \left(\sqrt{\frac{2(2\gamma+1)}{M}} Q^{-1}(\overline{P_d}) + \gamma + 1 \right) \tag{4}$$

$$\lambda_{P_f} = \sigma_w^2 (\sqrt{\frac{2}{M}} Q^{-1}(\overline{P_f}) + 1) \tag{5}$$

where M is number of samples, γ is Signal to Noise Ratio (SNR) ($\frac{\sigma_s^2}{\sigma_w^2}$), and $Q^{-1}(\cdot)$ is the inverse of $Q(\cdot)$ which is a complementary Cumulative Distribution Function (CDF) of a standard Gaussian random variable (i.e. $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp\left(\frac{-t^2}{2}\right) dt$). As is clear in Eq. (4) & Eq. (5), an increase in observed samples increases P_d and noise uncertainty may decrease it [184]; this fact is illustrated

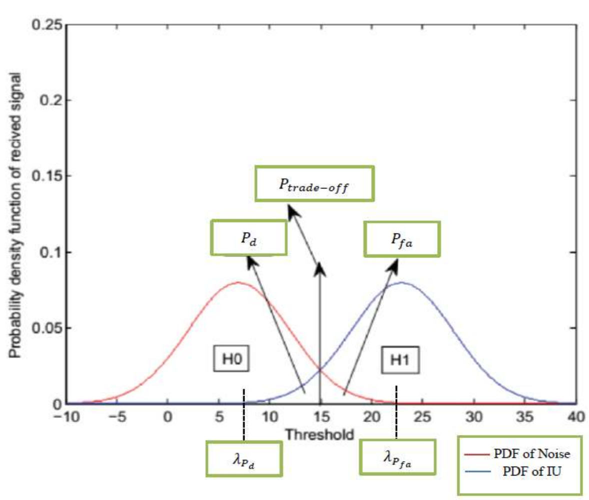

Fig. 6. Threshold setting (modified from [183]).

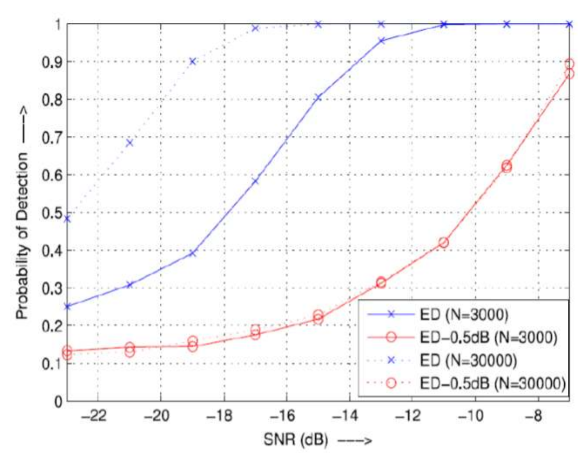

Fig. 7. Performance of P_d with and without Noise uncertainty [185].

in Fig. 7. Recently, the authors in [99] proposed a dynamic threshold detection algorithm, where the algorithm proposes two threshold levels for average received PUs energy during a specified observation period. However, the algorithm suffers from computational complexity. Finally, dozens of threshold optimizing ideas correspond with those proposed in the literature; however, this approach has been extensively studied, therefore, recently very few articles [183, 185, 186] have proposed to consider optimizing λ corresponding with optimizing a set of QoS objective targets.

4.2.2 Multi-Stage Spectrum Sensing

Each spectrum sensing technique has its own cons, for example ED performance degrades with noise uncertainty (as depicted in Fig. 7), and CFD consumes power, in addition to a priori information about IU being required. Additionally, the blind techniques suffer from complexity and power consumption. Consequently each spectrum sensing technique has its own merits and demerits, thus none of these techniques has an optimal performance in all scenarios [64]. Therefore, dual stage spectrum sensing was proposed in the literature to mitigate the drawback of single stage sensing.

The majority of recent research studies, such as [64, 65, 74, 84, 100-103] assume the first stage is ED, but few studies considered other techniques for example how the authors in [104] exploited entropy of power spectrum density in the first stage. In the second stage significant studies such as [84, 100, 102] considered CFD, whereas other studies such as [103] considered EVD as a second stage. More specifically, in the first stage the observed samples of received signal may be compared with the first threshold λ_A using eq. (2); in the case of $\mathcal{H}_0$, there is no need to operate the 2nd stage, otherwise the second threshold λ_B will be examined. The flowchart of multi-stage spectrum sensing is clarified in Fig. 8. The first stage is chosen for coarse sensing, while the second stage is considered in fine sensing.

The aforementioned researchers considered optimizing spectrum accuracy under constraints and/or QoS objectives. For example the authors in [64] proposed an optimizing scheme of sensing reliability with minimum delay, whereas the authors in [84] optimized spectrum reliability corresponding with minimum energy consumption. However, most articles have drawbacks from different perspectives, such as sensing overheads and complexity as documented in Table 1. In same way, a scheme of three parallel stages of detectors ED, CFD, and MF was proposed in [66] where each detector is used for a certain type of received signal. However, increasing stages may increase the complexity at SUs.

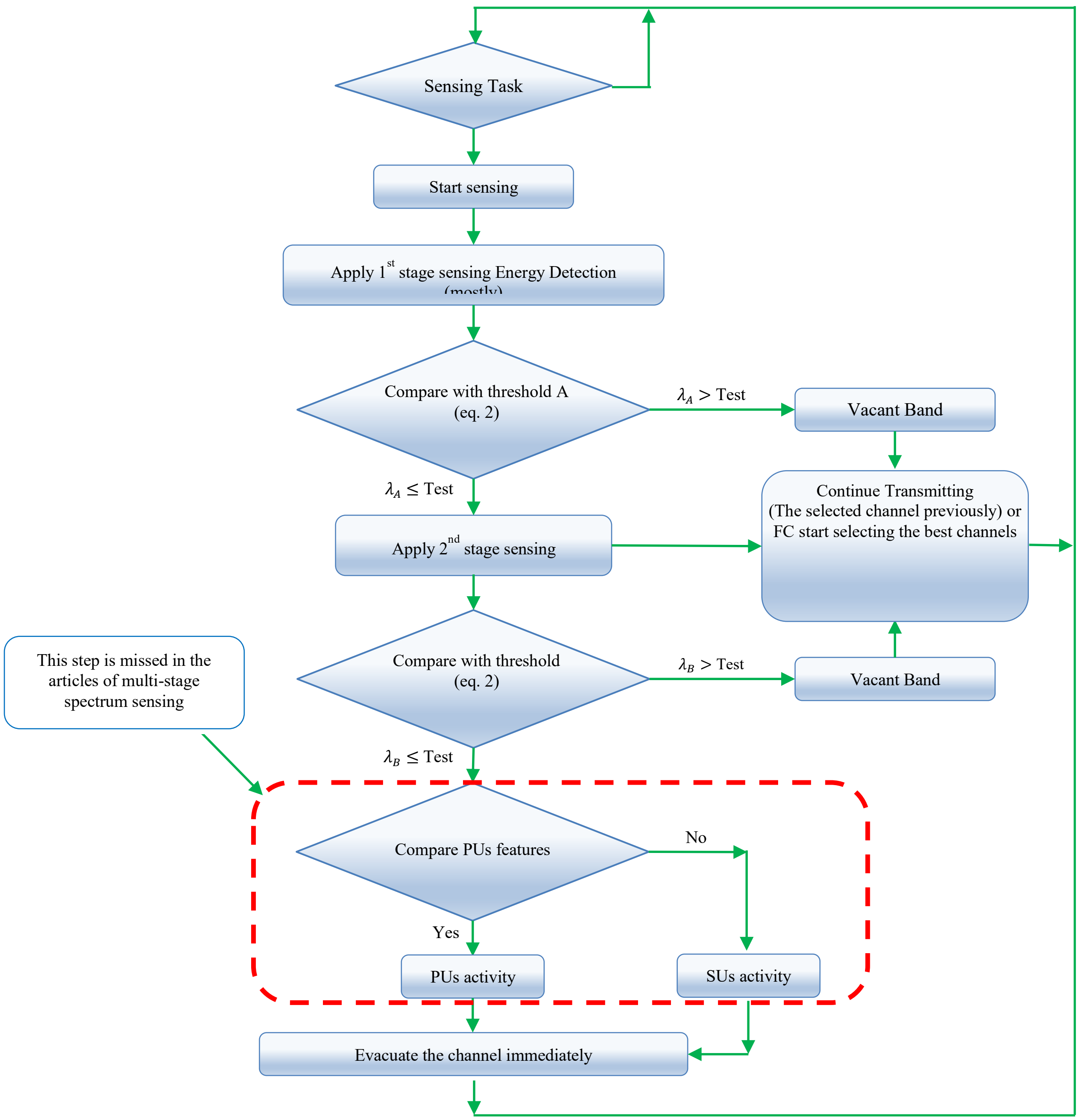

Fig. 8. The flow chart of multi-stage spectrum sensing.

Finally, we noticed that distinguishing step between PUs and existing SUs was missed in the aforementioned studies. It is believed that distinguishing PUs activity than SUs activity is very important for reliable spectrum modelling and this step belongs to spectrum sensing component responsibilities.

Table 1 Specifications of multi stage spectrum sensing schemes in sub-section (4.2.2).

Reference	Detection techniques						QoS objectives					Cons			
	Energy Detection	Cyclostationary	Maximum Eigenvalue detection	co-variance absolute value	Matched filter detection	Entropy of Power spectrum density	Throughput	Spectrum Efficiency	Delay	Power Consumption	Reliability	Sensing overhead	Required information about PUs	Power consuming	Complexity
[64]	√	-	-	√	-	-	-	√	√	-	√	-	-	-	√
[65]	√√	-	-	-	-	-	-	√	-	-	√	√	-	-	-
[66]	√	√	-	-	-	√	-	√	-	-	√	-	√	√	√
[74]	√√	-	-	-	-	-	-	-	-	-	√	√	-	-	-
[84]	√	√	-	-	-	-	-	-	-	√	√	-	√	-	-
[100]	√	√	-	-	-	-	-	-	-	-	√	-	√	-	-
[101]	√√	-	-	-	-	-	-	-	-	-	√	√	-	-	-
[102]	√	√	-	-	-	-	-	√	-	-	√	-	√	√	-
[103]	√	-	√	-	-	-	-	-	-	-	√	√	-	-	-
[104]	-	-	-	-	-	√√	-	-	-	-	√	√	-	-	√

4.2.3 Cooperative Spectrum Sensing for Sensing Accuracy

Cooperative Spectrum Sensing (CSS) has been proposed in the literature for gathering detection information from multiple SUs in order to solve the second and third challenges of improving detection accuracy (i.e. hidden terminal detection, and uncertainty due to the SU being in deep fade) [143]. CSS has been extensively studied in the literature, as shown in Fig. 9 the CSS concept concerns sharing sensing outcomes between SUs (in CRAHNs) or forwarding their local observations to a Fusion Center (FC) located at the central node or Base Station (BS) (in centralized CRN) which will make the global decision [29]. For brevity, CSS features can be summarized as follows:

- The proposed methods for CSS in the literature are classified into three categories: a) **All SUs simultaneously** [49]; b) **Certain selected SUs** [143]; and c) **Multi groups (cluster based)** [144]. IEEE recommended CSS to CRN standards IEEE 802.22 WRAN, and is still in process in IEEE 802.11ah White Fi [187]. It is worth mentioning that the majority of CSS researchers assumed that the reported channels (i.e. Common Control Channels (CCCs)) are exclusively dedicated among SUs.
- There are two reporting schemes in CSS as follows: a) **Hard CSS**: SUs may report their local decision to the FC [50]; and b) **Soft CSS**: SUs transmit their detection samples (i.e. measurements) to the FC [105]. Clearly, Soft CSS may increase the reliability of decisions; however, it may increase the overheads of transmitting signals samples instead of transmitting one bit decisions.
- There are four decision rules that can be applied at FC which are as follows: a) **AND**: means that all the participated SUs must report the channel as busy (low protection to IUs). b) **OR**: means only one of the SUs reports an occupied channel (high restricted). c) **Majority**: indicates that most participating users consider the channel is occupied. d) **K of N**: means a certain amount (K) of participating SUs (N) report the scanned channel as not vacant (more reliable than the Majority method) [29].

It is worth mentioning that another method of CSS was proposed in the literature, called collaborative CRNs, where several CRNs share their spectrum sensing outcomes to improve their sensing reliability [29]. Additionally, the K of N rule is similar to the OR rule, except that K users from total N users (i.e. SUs) will participate to calculate in decision making. Thus, total P_d^T and P_{fa}^T in the FC rules will be as follows [67], [106]:

- AND

$$P_y^T = \prod_{i=0}^{N} P_{y,i} \tag{6}$$

- OR

$$P_y^T = 1 - \prod_{i=0}^{N} (1 - P_{y,i}) \tag{7}$$

- Majority

$$P_y^T = \sum_{x=\left\lfloor \frac{N-M}{2} \right\rfloor}^{N-M} \binom{N-M}{x} P_{y,i}^x (1-P_{y,i})^{N-M-x} \tag{8}$$

A large number of articles have proposed to improve CSS elements such as maximizing energy efficiency in [110], and reliability of CSS as in [188]. The main challenge of CSS is reporting false detections from SUs; this issue is called Spectrum Sensing Data Falsification (SSDF) or Byzantine attack [44]. This problem and other problems will be discussed in the next part of this research on spectrum sharing challenges. Finally, the merits and demerits of cooperative sensing and sharing elements have also been well researched and documented in a recent survey [29], and summarized in Fig. 10.

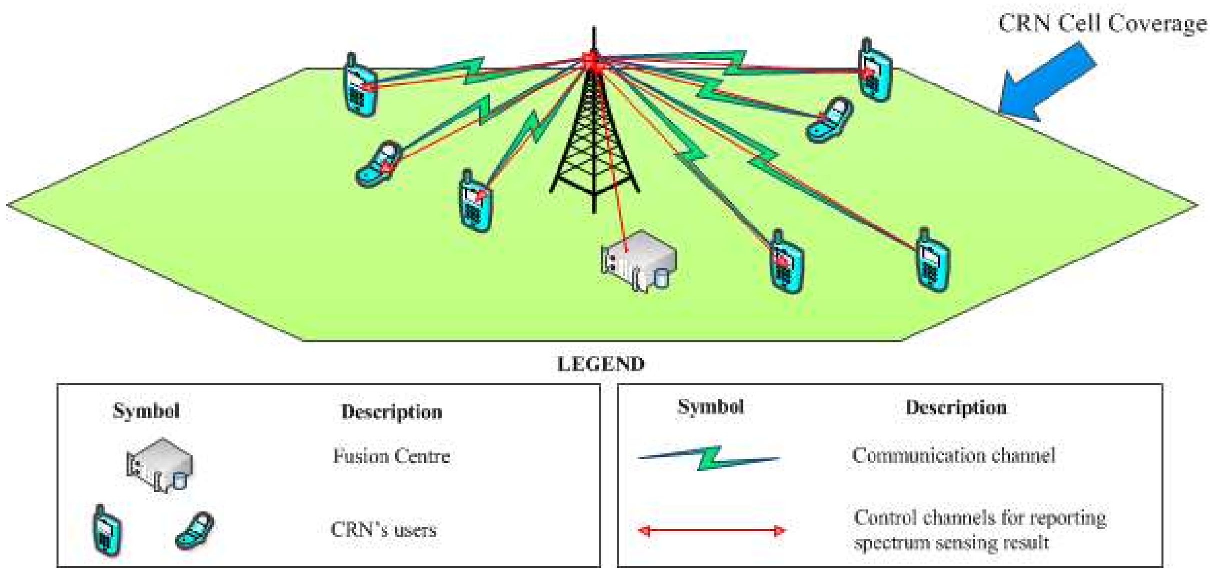

Fig. 9. Cooperative spectrum sensing.

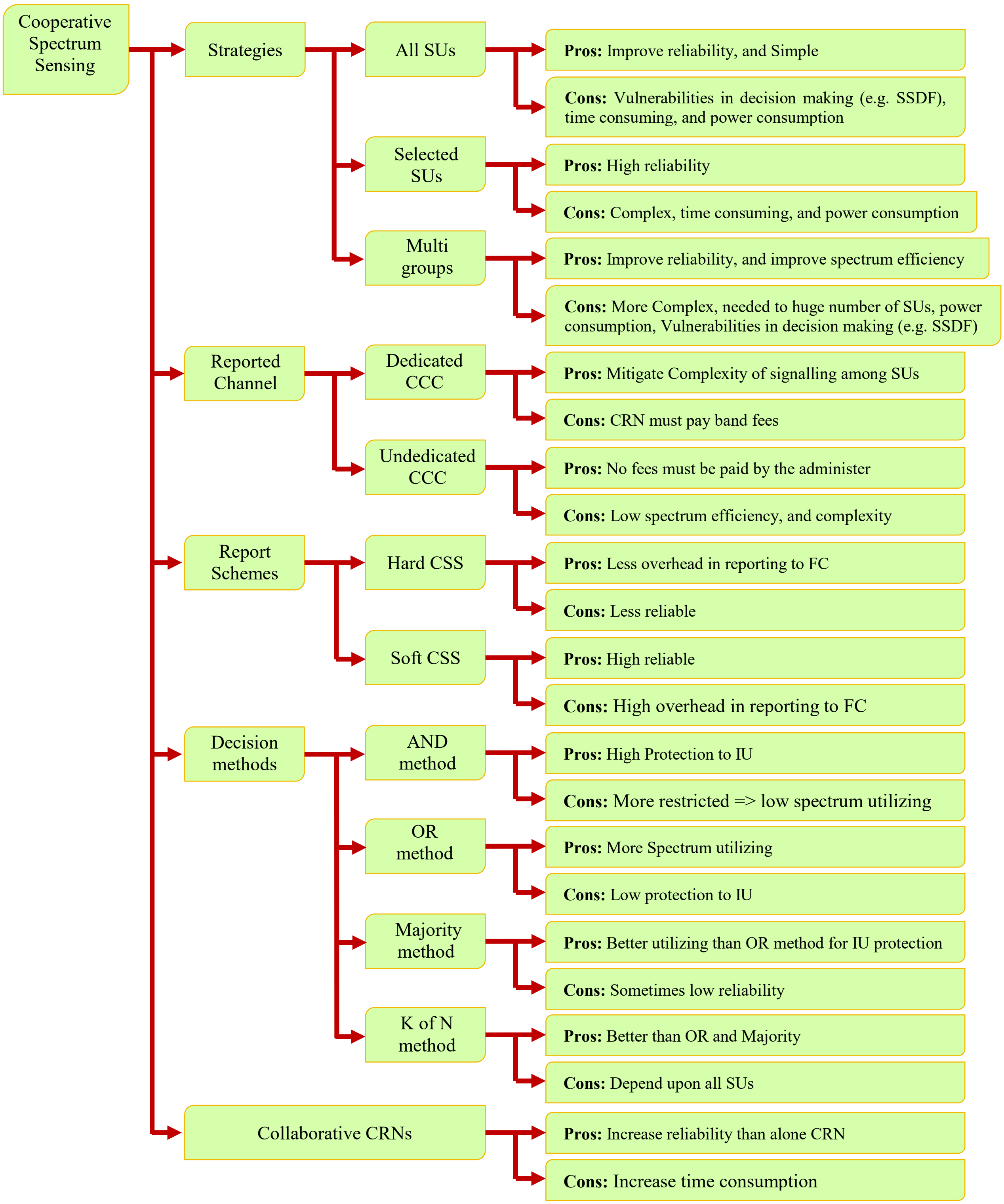

Fig. 10. Cooperative spectrum sensing features.

4.2.4 External Sensing

It is simply defined as the CRN that exploits the information on vacant channels from an external source [180]. The information should be reported continuously to BSs of all CRNs in order to utilize the best channels in case of handoffs. Generally, external sensing methods can be classified into three categories:

- Sensor nodes belong to CRN (or other CRNs in case of cooperative CRNs [29]) spread in the coverage area; thereby, CRN architecture constitutes of two networks: A) Sensor Networks, and B) Operational Networks [180].
- External sensor networks may provide details of vacant channels for certain fees [3].
- Spectrum pooling or official databases have the capability of identifying the incumbent licensed channels on TV bands (-also called TV White Space (TVWS)) [26].

Finally, external sensing may tackle some sensing challenges (explained in the introduction of the current sub-section), and reduce the time required for OBS; thus it will increase spectrum efficiency, and throughput, and reduce the delay of offered services. Consequently, since the SUs will not participate in the sensing task, external sensing will reduce the complexity of SU devices [182]. As a comparison, the merits and demerits of external and local sensing from different perspectives are documented in Table 2.

Table 2 Comparison between local and external spectrum sensing.

		QoS Objectives				**SU Perspective**		**Network Administer perspective**		**Regulator Perspective**		
Sensing Strategy		**Reliability**	**Spectrum efficiency**	**Time consuming**	**Power consumption at SU device**	**Complexity at SU device**	**Dependency on the number of SUs**	**Simplify CRN configuration**	**Additional charge to CRN administer**	**Proposed for Centralized CRN and CRAHN**	**Recommended for IBS in IEEE 802.22 & IEEE 802.11ah**	**Recommended for OBS in IEEE 802.22 & IEEE 802.11ah**
Local (Internal) sensing	**non-cooperative**	Low	Low	Low	High	High	No	No	No	CRAHN	No	No
	Cooperative	High	High	High	High	High	Yes	No	No	Both	Yes	Yes
External sensing		Higher	Higher	Low	Low	Low	No	Yes	No	Both	Yes	Yes Database

4.3 Spectrum Sensing Efficiency

Improving sensing efficiency (or minimizing sensing overheads [97]) is defined as minimizing the total amount of time spent on sensing and detecting spectrum status [185]. Clearly, the highest sensing overheads may lead to degrading the QoS provisioning to CRN users, in addition to impairing spectral efficiency rather than being utilized in data transmitting [34]. In contrast, less frequent sensing may lead to increased P_{md} of the PUs' reappearance in utilized channels and the IUs in other candidate channels. Thus, it is of paramount importance to optimize sensing periods for licensed channels in order to obtain accurate detection probability.

4.3.1 Adaptive Sensing

Spectrum sensing accuracy can be evaluated by minimum sensing periods and frequency of sensing [57]. The crucial challenge in CRN implementation is the stochastic utilizing of the licensed spectrum from PUs, due to the heterogeneity of the PNs and their licensed spectrum bands [189]. Additionally, it is predicted that the licensed spectrum will become more stochastic than before when CRNs are implemented [26]. Therefore, frequent static fix is not suitable for all licensed channels and may lead to losing spectral opportunities in addition to incurring interference with IUs.

Optimizing sensing frequency can be best understood from Fig. 11 and 12 (inspired from [68]). We assumed a CRN attempt to utilize two licensed channels, shown in Fig. 11(a, and b). Although the utilization of these channels shown in the figures is not real, we try to depict the issue of applying the same sensing frequency in both channels. As observed from Fig. 11(c), the proposed sensing frequency led to high interference with PU, and low utilization of available opportunities in Channel 1; whereas in channel 2, it tended to be more satisfactory through achieving high utilization of unused portions and less interference, as illustrated in (Fig. 11(d)). Therefore, for the frequency of sensing we used the same channel (i.e. channel 1) in Fig. 12(a), and the sensing frequency of Fig. 11(d) is repeated in Fig. 12(b). In Fig. 12(c), doubling sensing frequency may bring a better utilization of the licensed channel but it was not needed for the licensed channel in Fig. 11(a) (i.e. channel 1).

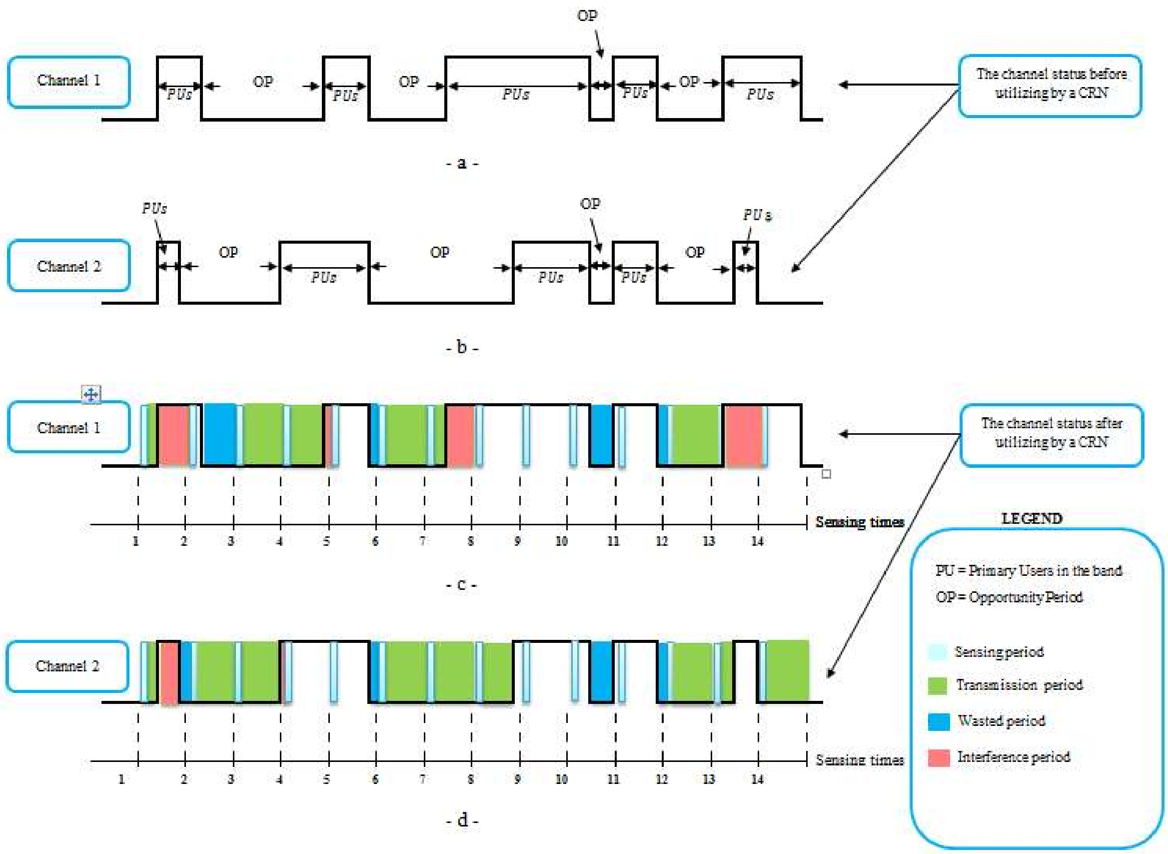

Fig. 11. Impact of exploiting same sensing frequency for two licensed channels (inspired from [68]).

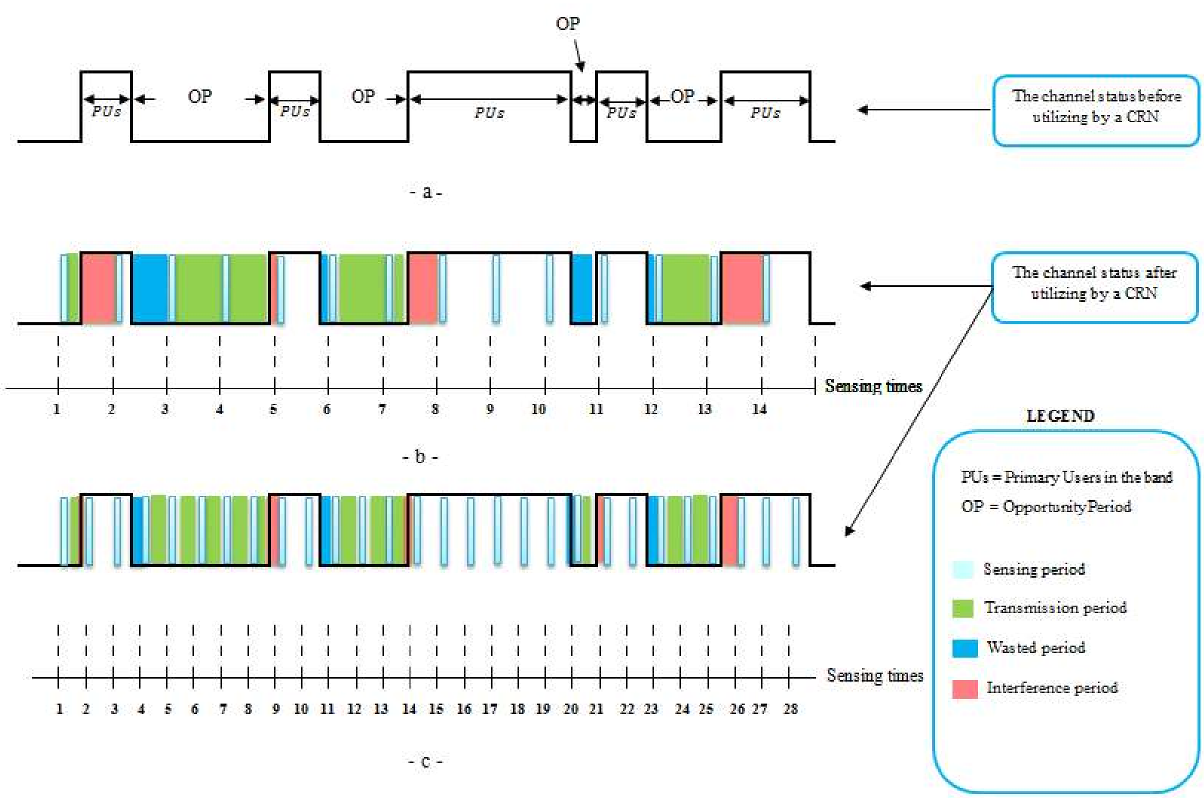

Fig. 12. Impact of sensing frequency for utilizing a licensed channel (inspired from [68]).

In this trend, the authors in [111] proposed a Two-phase (coarse and fine) and Two-period (long and short) Spectrum Sensing (TTSS) scheme, where coarse phase is used to predict the best candidate spectrum bands for fine sensing, and short periods perform at no transmission, whereas the latter is exploited during sessions. Three different schemes for optimizing the duration of spectrum sensing at specific sensing accuracy were proposed in [75]. However, the authors considered utilization of only one channel; therefore, SUs must wait till the channel is unoccupied by PUs. Adaptive sensing, based on a multi-objective scheme, was proposed in [68], where the authors aimed to maximize the utilization of the available spectrum.

Recently, a novel sequential two channels spectrum sensing method was proposed in [51], where the author considered imperfect sensing in optimizing spectrum sensing to achieve maximum throughput. However, power consumption has not considered. A sequential Channel Sensing Probing algorithm in homogeneous channels was used in [52] to optimize the distribution

Table 3 A summary of QoS objectives and procedures of the researches in sub-section (4.3.1).

				QoS Objectives					Cons					
Ref.	**Procedure**		**CRN Architecture**	**Throughput**	**Spectrum efficiency**	**Delay**	**Power Consumption**	**Reliability**	**Sensing overhead**	**Complexity**	**No path loss and**	**Consume power**	**Only One Licensed**	**Homogenous channels**
[51]	Sequential two channels sensing		Centralized	√	-	-	-	√	√	√	-	√	-	-
[52]	Sequential Channel Sensing Probing algorithm		Centralized	√	-	-	-	√	-	√	√	-	-	√
[68]	adaptive sensing scheme Base on multi-objective GA		Centralized	-	√	-	-	√	-	-	√	-	-	-
[75]	Optimizing sensing period schemes based on different objectives (three schemes)	Maximize throughput	Centralized	√	-	-	-	√	-	-	√	-	√	-
		Minimize Delay	Centralized	-	-	√	-	√	-	-	√	-	√	-
		Trade-off between both schemes	Centralized	√	-	√	-	√	-	-	√	-	√	-
[76]	Efficiency-accuracy trade under of specified constant detection threshold		CRAHN	-	√	-	-	√	-	√	√	-	-	-
[85]	DSM considered both PU status and time-variant multipath channels		CRAHN	-	-	-	-	√	√	√	-	-	-	-
[111]	Two-phase (coarse and fine) and Two-period (long and short) Spectrum Sensing		Centralized	-	√	-	-	√	√	√	√	√	-	-

of the throughput. The algorithm was subjected to constraints of tolerance delay and minimum required data rate. To optimize sensing durations in CRAHNs, the authors in [76] proposed an efficiency-accuracy trade-off under a specified constant detection threshold. A novel Dynamic Discrete State-Model (DSM) for characterizing spectrum sensing process in CRAHN was proposed in [85]. However, the model was not tested in terms of complexity and time consumed in the sensing task.

In summary, Table 3 provides further details on the aforementioned articles.

4.3.2 Cooperative Spectrum Sensing for Sensing Efficiency

CSS has been adopted as a QoS provisioning approach, but here it can be exploited to reduce sensing overheads. In this approach, several significant schemes were proposed to optimize sensing efficiency corresponding with two or three QoS objectives. For example, using a coalition game, the authors in [53] proposed a sensing technique capable of maximizing throughput under minimum targets of P_{md} and P_{fa} respectively. Similarly, to maximize throughput, a cluster based CSS was exploited recently in several articles. From the most recent research studies, the authors in [69] proposed fusing the reported data from clusters twice by using two fusion stages within a cluster.

Although the research studies mitigated the congestion at CCC, the scheme suffered from poor performance at a few SUs, and selecting the head of each cluster is still an open research area [39]. Maximizing throughput in CRNs needs to improve the capacity of utilizing the available spectrum; therefore, the authors in [67] proposed a CSS scheme that aims to maximize the capacity within accurate spectrum sensing. Recently, the authors in [67] proposed a spectrum sensing policy that employed recency-based exploration in order that SUs do not need to be instructed from FC which bands to sense. However, the policy may lead to increased complexity of SU devices.

Minimizing consumed energy at SUs (i.e. green energy) by using CSS strategy is another example of optimizing sensing efficiency. For example, a cooperative periodic sensing technique that minimizes power consumption at SU was proposed in [54]. Although the authors considered minimum required P_{md} and P_{fa}, the analysis of fading and path losses were not considered. Power consumption and sensing period optimization method was also proposed in [87], where the authors aimed to minimize power consumption at SU in a diverse cooperative CRN. Recently, an optimal CSS scheme was proposed in [55], where the main aim of the scheme was maximizing energy efficiency without degrading achievable throughput. However, the scheme suffered from poor performance in a few SUs, which is the most common challenge of CSS strategy. Very recently, the authors in [20] surveyed in detail the green energy techniques that have been proposed in the literature. It is worth mentioning that a novel frugal sensing scheme was proposed recently by the authors in [88] as a means of wideband CSS. It is worth mentioning, all the aforementioned efforts are considered for centralized CRN, because of the co-ordination challenges in neighbour discovery in CRAHNs [189].

To sum up, the merits and demerits of the aforementioned sub-section are summarized in Table 4.

Table 4 A summary of QoS objectives and procedures of related works in sub-section (4.3.2).

			QoS Objectives					Cons					
Ref.	**Procedure**	**CRN Architecture**	**Throughput**	**Spectrum efficiency**	**Delay**	**Power Consumption**	**Reliability**	**Sensing overhead**	**Complexity**	**No path loss and**	**Consume power**	**Only One Licensed**	**Homogenous channels**
[49]	Optimum cooperative grouping	Centralized	√	-	-	√	√	√	-	√	-	-	-
[53]	Using coalition game among SUs	Centralized	√	-	-	-	√	√	√	-	-	-	-
[54]	Minimum power consumption at SU at minimum reliability	Centralized	-	-	-	√	√	-	-	√	-	-	-
[56]	Divides SUs into several groups responsible of sensing different channels	CRAHN	-	√	-	-	√	√	√	√	-	-	-
[67]	Cooperative sensing scheme base of faded signal	Centralized	-	√	-	-	√	√	√	-	√	-	-
[69]	Cluster based two stage fusion stages	Centralized	√	-	-	√	√	√	√	√	-	-	-
[86]	Sensing regarding recency-based exploration	Centralized	-	√	-	-	√	√	√	√	-	-	-
[87]	Sensing period optimization to achieve minimize power consumption in a diverse cooperative CRN	Centralized	-	-	-	√	√	-	-	√	-	-	-

4.3.3 Wideband Spectrum Sensing

In contrast to single band (narrow band) sensing, wide band sensing aims to obtain more spectral opportunities over wide spectrum bands in order to achieve higher QoS provision in the offered services [38]. Ideally, CRN should be capable of sensing and utilizing any transmission opportunities in the available spectrum band ranging from 30 kHz to - 300GHz, however, non-permitted bands (e.g. military, security) are excluded [112]. Since CRNs need to continuously determine spectrum opportunities simultaneously over a wide frequency range (e.g. several GHz), several Wideband Spectrum Sensing (WBS) techniques have been proposed in the literature. These techniques have attracted particular attention recently, because they led to merging the periods of IBS and OBS in a single period. Furthermore, detecting the status of multiple channels at the same time will lead to increased opportunities to select the best channels [1]. WBS methods concentrate on reducing the complexity of system design, and these major methods are as follows:

- Multiband Joint detection [57].
- Filter-bank sensing [119].
- Wavelet (WL) detection [120], which can be classified into: a) WL modulus maxima [121]; b) WL multi-scale product [122]; and c) WL multi-scale sum [123].
- Sweep-tune detection [38].

These methods are classified as Nyquist wideband sensing techniques, since they depend primarily on Nyquist sampling [89]. Several evolved WBS techniques were proposed in the literature in order to reduce the operational sampling rate below Nyquist. For that reason, sub-Nyquist WBS techniques have been proposed in the literature to perform sensing at low sampling rates and less complexity than Nyquist WBS techniques. The authors in [38] classified sub-Nyquist WBS techniques into two major categories, as summarized in Fig. 13:

- *Compressive sub-Nyquist WBS techniques*: the authors in [124] utilized compressive sensing to minimize the sampling and signal acquisition rate. However, the technique needed increased robustness towards design imperfection. Therefore, the authors in [90] developed a Quarter Anolog-to-Information Converter (AIC) for improving power consumption. However, design imperfection in addition to model mismatches are major challenges.
- *Multi-channel based sub-Nyquist WBS techniques*: These techniques are classified into: a) **Modulated wideband converter** [125]; b) **Multi-coset sampling** [126]; and c) **Multi-rate asynchronous sub-Nyquist sampling** [127]. Although these techniques solved mismatches (as in Compressive techniques), synchronization and power consumption are their main issues.

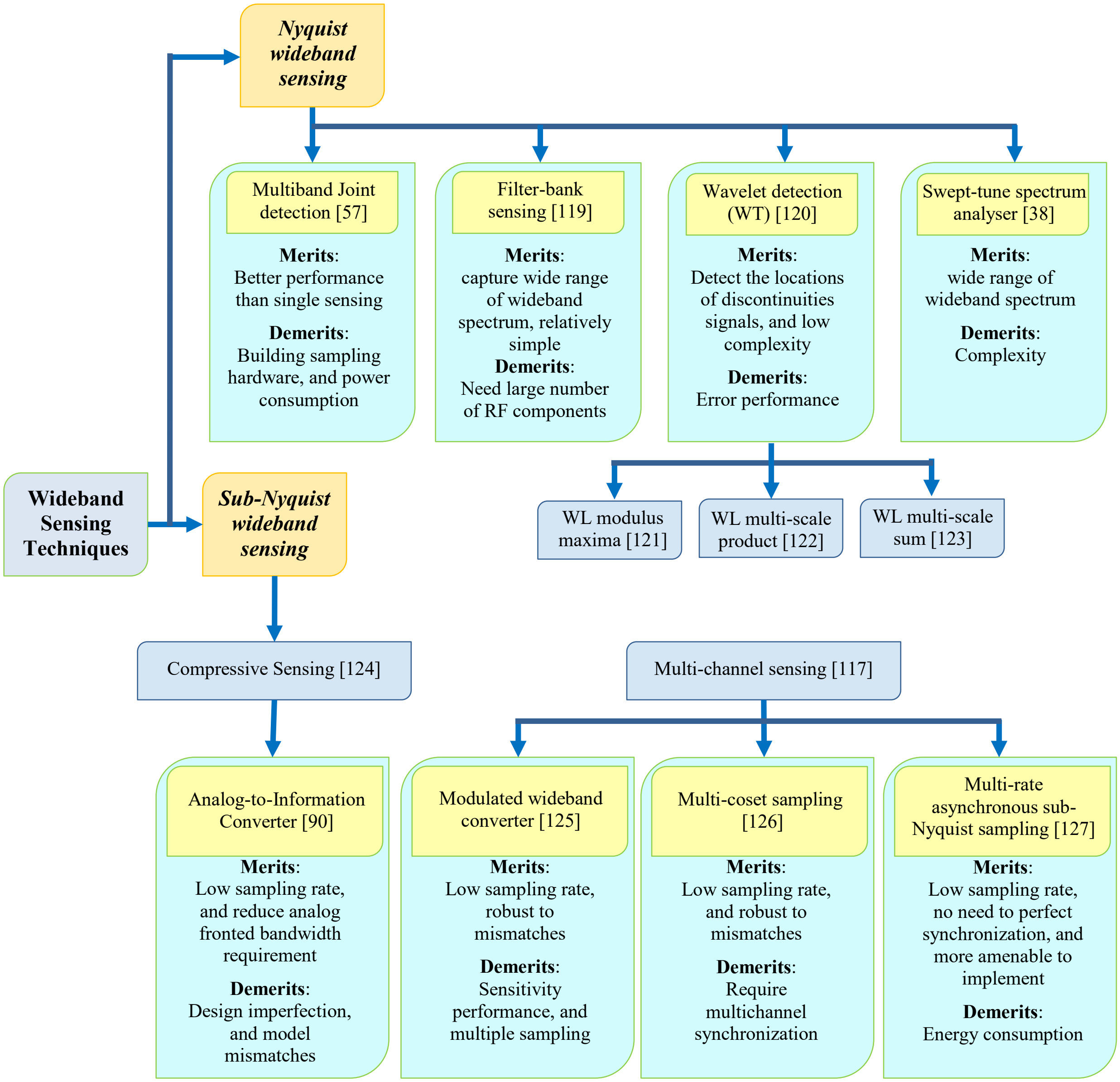

Fig. 13. Merits and demerits of wideband spectrum sensing techniques.

4.4 Challenges in the Spectrum Sensing Component

So far the classifications and influencing factors on spectrum sensing were discussed. Since the spectrum sensing task plays a vital role in the performance of any CRN, sensing strategies and techniques were investigated in depth. However, there is still work to be done. The remaining challenges in the spectrum sensing component can be summarized as follow:

- Sensing at extremely low SNR.

- Optimal threshold setting in heterogeneity spectrum bands.
- Detecting spread spectrum primary signals.
- Imperfect reporting channel.
- Challenges in interference based detection: How to measure interference temperature in the primary.
- Sensing under practical channel conditions taking into consideration, phenomena such as fading, and shadowing.
- Sensing with limited information, and how to utilize the feedback information (in feedback cooperation CRN) efficiently.
- Complexity of implementing robust wide band hardware.

Moreover, although improvements in QoS provisioning are expected by applying Nyquist WBS techniques rather than narrowband sensing, feasible implementation and power consumption are very challenging [89]. These challenges of Nyquist WBS fall under two headline issues:

- *Wideband sensing techniques sampling rate*: according to the Nyquist rate the sampling rate should be at least twice that of signal frequency. For example, if wide band sensing intends to cover 3 GHz bandwidth, the sampling rate must be at least 6 GHz. Consequently practical implementation and signal processing will become a crucial issue [38].
- *Cooperative wideband sensing*: In cooperative wideband sensing, SU should be capable of reporting the detected status of each band to FC [40].

Finally, sensing challenges are related with both incumbent coexistence (i.e. between SUs and PUs) and self-coexistence issues (i.e. among overlapped CRNs). Even though several channel assignment schemes proposed in [173-177] to mitigate self-coexistence problems, but CRNs concept were proposed to compete for spectrum holes without regulation.

5 QoS provisioning approaches in Spectrum Decision Component

The success of safe CRNs and PNs coexistence depends primarily on the channels utilized by CRNs [3]. After the available spectrum opportunities have been identified, CRN needs to identify the best channels in order to select the optimum candidate bands. This procedure falls under the Spectrum Decision component, which can be simply defined as the ability of a CRN to select the best available spectrum to satisfy the QoS requirements on a non-injurious basis to PUs or attacking other existing CRNs [1]. It is very important to distinguish the Spectrum Decision Making (SDM) task from spectrum allocation function which concerns assigning the selected channels (selected by the SDM algorithm) for different users and applications [109].

5.1 Introduction to the Spectrum Decision Elements

A large volume of research has been conducted in the literature to describe the spectrum decision component from different perspectives. As illustrated in Fig. 14, the elements that influence on spectrum band selection can be summarized as follows:

- There are seven aspects influencing channel specifications: a) **Channel identification**: deterministic or stochastic; b) **Channel holding time**; c) **Channel capacity**; d) **Channel range**: The distance that the signal can be transmitted on the selected channel; e) **Channel interference**: Which refers to the maximum tolerated transmission power; f) **Environment conditions**: physical and weather; and g) **Evacuation periods**: Which refers to the time durations that the channel can accept overlapping PU and SU transmission before the transmission is considered as harmful interference (e.g. 2 sec in TV band) [1].
- There are five factors influencing channel selection: a) **Reliability of sensing reports** [143]; b) **Cognitive engine prediction** [128]; c) **SU's remaining energy** (considered in CRAHNs only) [113]; d) **Multi-channel selection** [1139]; and e) **Common Control Channel (CCC) consideration** [190].
- There are two selection strategies in spectrum bands selection: a) **Local**: Refers to the selection that is performed by SU only (considered in CRAHNs related works only) [145]; and b) **Central**: Indicates that the selection is being made by a central node (e.g. BS in centralized CRNs) [191].
- There are six criteria used for channel selection: a) **Interference**: Defined as minimizing the interference among SUs and from SUs to PUs [140]; b) **Throughput**: Refers to selecting the channels that will maximize data rates at SUs [58]; c) **Delay**: Which attempts to reduce the delay in RT applications [77]; d) **Energy efficiency**: Indicates minimizing power consumption at SUs [141]; e) **Cross Layer Decision** (CLD): Which denotes escaping from normal waterfall of ISO model such as a joint route and channel selection approach (considered in CRAHNs only) [192]; and f) **Cluster based selection**: Defined as distributing channel selection among several clusters [193].

- There are six algorithms and theories used commonly in SDM: a) **Game theory** [146]; b) **Graph theory** [142]; c) **Linear programming** [91]; d) **Heuristics** [78]; e) **Evolutionary algorithms** [147]; and f) **Fuzzy logic** [194].
- There are two QoS provisioning approaches in the spectrum decision component: a) **Optimum channel selection**: Refers to selecting of the channels that meet QoS requirements optimally; and b) **Minimize channel selection overheads**: indicates to minimizing the duration needed to complete the optimum decision process, and reducing the complexity of selection [41].
- There are two methods of channel selection for network applications: a) **Optimum channel base application type**: Defined as selecting different channels for Real Time (RT) (e.g. VOIP, TVIP, etc.), and Non-Real Time (NRT) (e.g. texts, emails, etc.) applications respectively [70]; b) **Optimum channel for all applications**: Refers to selecting the best channel for all offered services rather than specific applications [6].
- There are two sources that spectrum band selection may depend on: a) **Prediction techniques**; and b) **Spectrum pooling** [3].

There is no doubt that the QoS in any CRN will deteriorate by increasing and fluctuating of PUs activities as that would cause several channels handoff [31]. Due to sensing and adjusting SUs transceivers to pick a new best available channel, the channel handoff process causes undeniable overheads and delay in SUs activities, resulting in degradation in network reliability through dropping of existing SUs and blocking the incoming users. To overcome this challenge, several methods have been proposed, including: a) **Channels reservation** [195]; b) **Traffic prioritization methods** [196]; c) **Spectrum leasing strategies** [197]; d) **Underlay spectrum access strategy** [198]; e) **Hybrid (Overlay and Underlay) spectrum access strategy** [199]; f) **MIMO Overlay CRNs** [200]; g) **MIMO Underlay CRNs** [201]; and h) **MIMO Hybrid CRNs** [202]. It is important to mention that the selection of spectrum access strategy (Overlay, Underlay or Hybrid) is one of a number of spectrum sharing component functions which may be selected according to the expected performance on the selected channel [203]. Nevertheless, uncoordinated increase the number of CRNs, will affect the existing ones and the newly admitted networks may perform poorly. Therefore, the authors in [26] proposed first network admission algorithm namely CRNAC capable of assigning the maximum number of CRNs in any specific location. The following sub-sections will be dedicated to describing QoS provisioning approaches in this component.

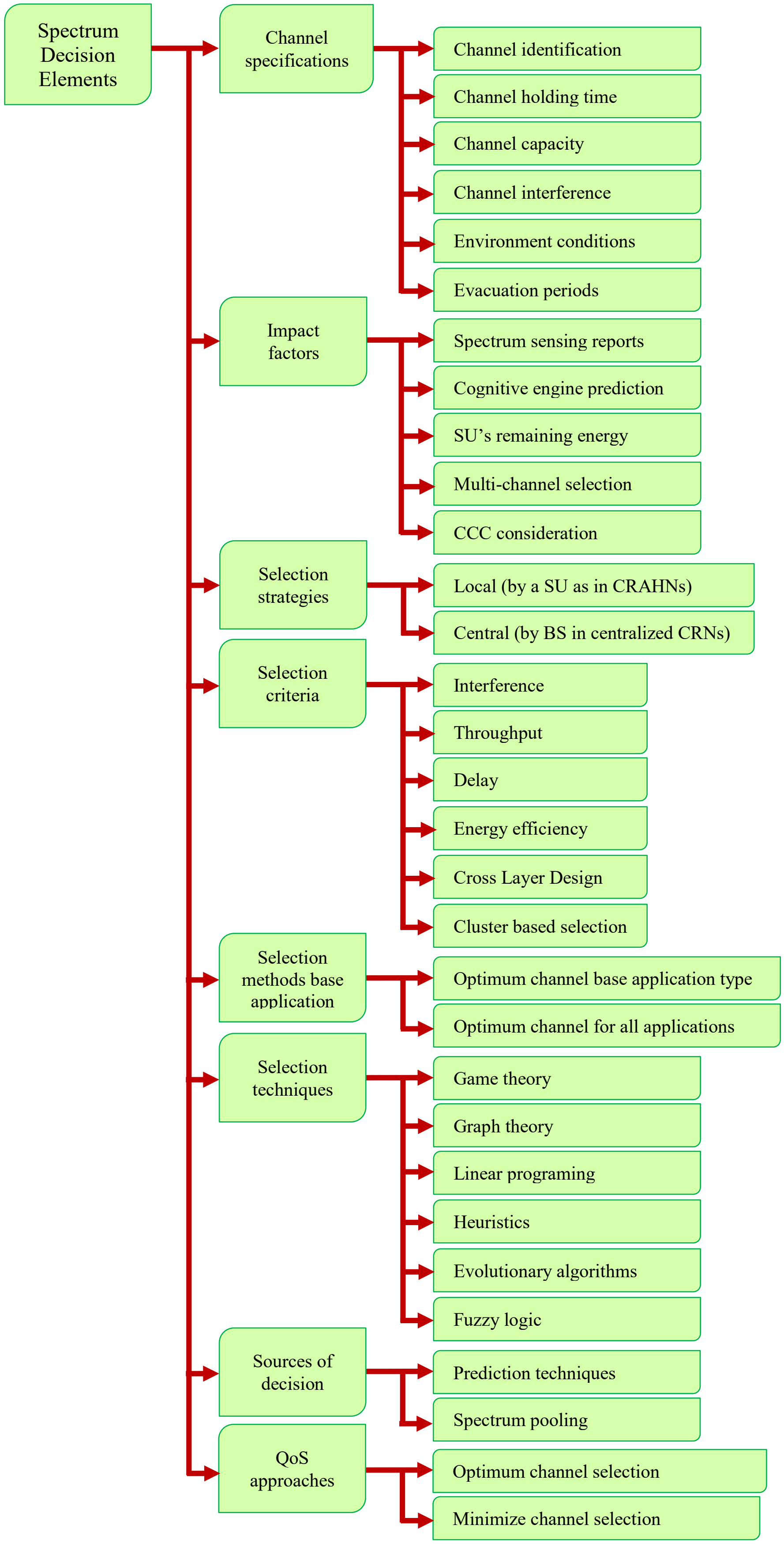

Fig.14. Classification of spectrum decision elements.

5.2 Optimum Channel Selection

A significant improvement in how to select the optimum channel has been proposed in the literature. Up to now, two methods have been adopted in optimum channel selection from: a) **Prediction technique**: Which can be defined as selecting the best channels by predicting the properties of the candidate channels that are reported from the sensing stage [114]; and b) **Spectrum pooling**: defined as selecting the best channels from databases that record the idle channels [137]. The authors in [34] found that selecting the optimum channel will reduce handoffs and power consumption by 50% and 55% respectively. Optimum channel selection needs robust modelling of the license spectrum activities.

It is worth mentioning that, when the best channels are selected, these channels will be allocated to all services or will be grouped into RT and NRT applications respectively, as in [70, 108, 161, 162]. Because channel allocation corresponds to Call Admission Control (CAC), it will be explained in the Spectrum Sharing component. Furthermore, channel selection and packets routing are jointly considered, therefore this will be described under spectrum sharing component.

5.2.1 Optimum Channel Selection Based Prediction Methods

In the literature, there are three steps that the cognitive engine of a CRN must perform in order to predict the activities on any spectrum band, these steps are as follows: 1) Observing; 2) modelling the activities; and 3) applying a prediction model to anticipate the activities [128]. More specifically, the steps can be summarized as follows:

- *Observing*: In this step, the cognitive engine will observe samples of the activities of PUs and SUs (other CRNs) on a certain band. The observation can be performed by using the following tools: antennas, spectrum analyzer, and computer (to analyze the data). Generally speaking, various spectrum occupancy models from spectrum measurement campaigns were proposed. Table 5 summarizes the campaigns [204]-[216] over the past four years; as observed from the table, the measurements covered the frequency range below 3000 MHz, and the occupancy is less than 13% of the total frequency range. In particular, the migration from analogue to digital television broadcasting in a number of countries left specific vacant channels in the TV band [217].
- *Modelling*: Spectrum modelling can be used to increase spectrum sensing reliability to select the best channels for better opportunistic usage, and to remove sensing for more highly efficient resource usage. In the literature, various models have been used to imitate the

spectrum activities, which can be categorized as follows: a) **Statistical models**: Refers to modelling statistical properties for received signals power, spectrum occupancy, and duty cycle; b) **Probabilities models**: Denotes modelling the Cumulative Distribution Function (CDF) or/and Probability Density Function (PDF) for channels' parameters such as: a) signal power; b) duty cycle ; and c) holding time; c) **Markov Chain models**: Indicates modelling two statuses of spectrum occupancy (0, and 1) using one of the MC models, for example Continuous MC (CTMC), Continuous Time semi-MC (CTSMC), and Discrete Time MC (DTMC); d) **Linear regression**: Used in modelling the time, frequency, and space dimensions of the spectrum occupancy such as Laycock-Gott and space methods. Lastly, it is found that spectrum access based on spectrum modelling can increase the utilization of deterministic channels by 3% and the throughput by 10%, and reduce interference to PUs by 30% [33, 46].

Table 5 Most recent spectrum measurement campaigns specifications.

Campaign	City and Country		Frequency Rang (MHz)	Average Duty Cycle (%)	Year of Campaign	Campaign Period (day)
[204]	Kwara State, Nigeria	Rural	50 - 6000	0.18	2016	weekdays
		Urban		5.08		Weekdays
		Urban		1.45		weekends
[205]	San Luis Potosi, Mexico		2401 – 2499	7.00 to 34.00	2016	1
[206]	Dhaka city, Bangladesh		0 – 3000	19.00	2015	1
[207]	Kwara State, Nigeria		48.5 – 880	12.02	2015	1
[208]	Selangor, Malaysia		880 – 960	35.31	2014	1
			1710 – 1880	9.59		
			1885 – 2200	26.08		
			174 – 230	10.92		
			470 – 798	13.36		
[209]	Ruwi, Oman		40 – 3000	13.00	2014	6
[210]	Beijing 1, China		470 - 806	38.00	2014	7
[211]	Kuala Lumpur, Malaysia		470 – 798	27.89	2013	1
[212]	Kampala, Uganda		50 – 1100	37.00	2013	1
[213]	Rio de Janeiro, Brazil		144 – 2690	19.60	2013	90
[214]	San Luis Potosi, Mexico		30 - 910	12.50	2013	1
[215]	Suburb of Pune India		174 - 230	03.55	2013	1
			470 - 806	07.22		
[216]	Hatfield area of Pretoria, South Africa		470 - 854	20.00	2013	42
			935 - 960	92.00		
			1805 - 1880	40.00		

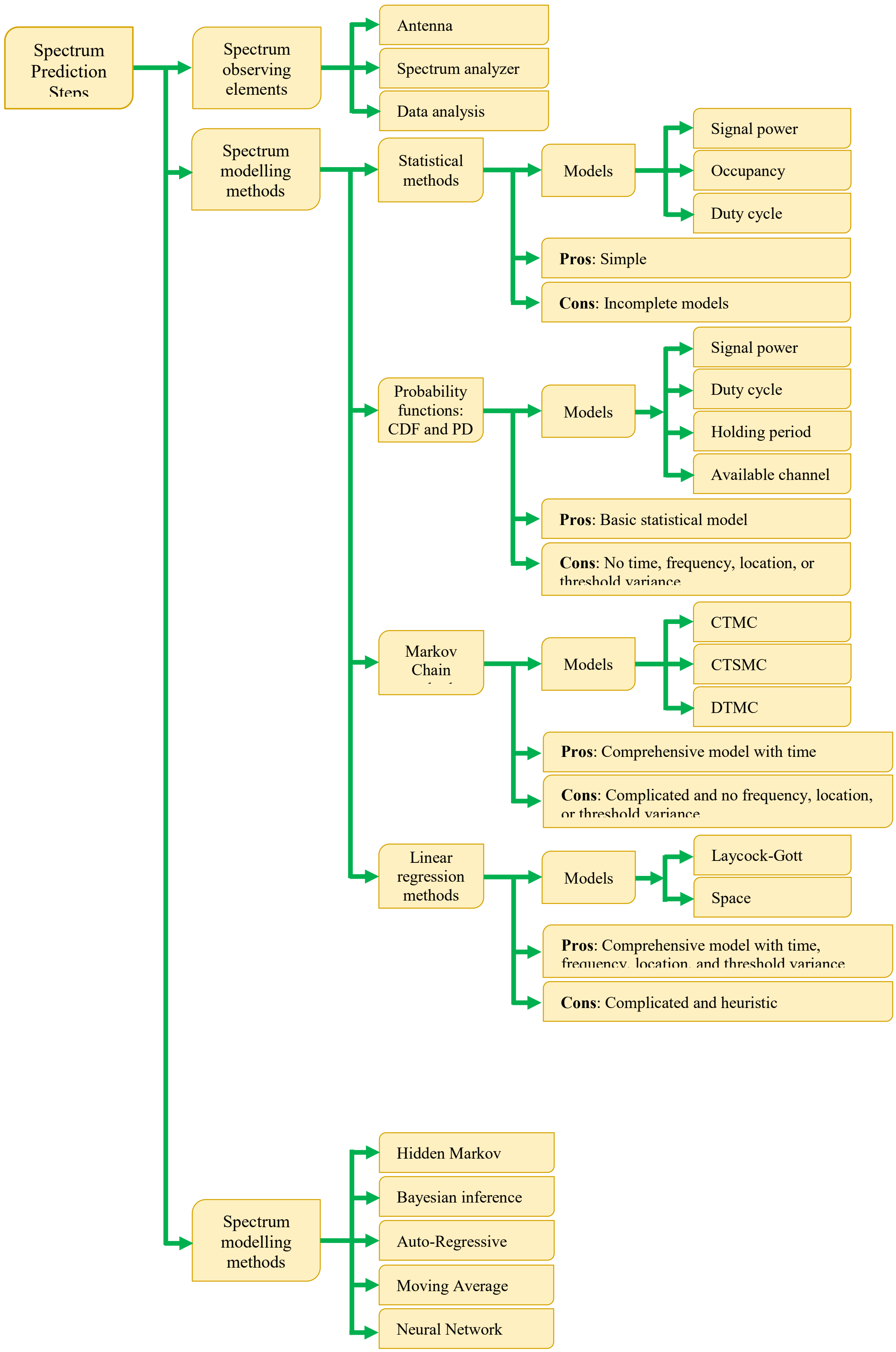

Fig. 15. Spectrum bands prediction steps and features.

- *Predicting*: Spectrum prediction in CRNs is a challenging problem, since it concerns several open research areas such as channel usage prediction [107], PU activity prediction [114], SU activity prediction [26], and channel MAC protocols prediction [150], [218]. In the literature, there are several prediction techniques applied in this area; the most frequently used techniques are: (a) **Hidden Markov Model** (HHM) [151]; (b) **Bayesian inference Model** [219]; (c) **Auto-Regressive Model** [220]; (d) **Moving Average Model** [221]; and (5) **Neural Network** [152]. The prediction model must then be trained using an optimizing algorithm such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA) etc. A summary of the spectrum prediction components is illustrated in Fig. 15.

5.2.2 Optimum Channel Selection based Spectrum Pooling

In September 2010, the Federal Communications Commission (FCC) released a memorandum opinion for eliminating spectrum sensing task from CRN responsibilities [30]. This elimination paved the way for geo-location databases capable of offering information on idle channels. However, these databases have the capability of identifying the vacant channels on the TV band only (i.e. TVWS). Because the PNs are not willing to provide unused portions of their licensed spectrum bands free of charge to any network, it is impossible to make official servers or databases assist the operation of CRNs by providing online information on the utilization in licensed spectrum bands at no cost.

Recently, AIR.U company [222] (which is a collaboration between the declaration network group and various higher education groups from the USA and UK), began to develop a roadmap for Next Generation wireless Networks (NGNs) by utilizing unused TVWS to provide an upgrade of the available broadband network. In July 2013 the AIR.U deployed the first Super Wi-Fi on TVWS on the West Virginia University campus and nearby community, providing access to the internet for students [223]. The range of coverage is up to 5 Km, due to the fact that the propagation path loss and the attenuation by material such as walls are lower in the TV bands (VHF, and UHF) than in traditional Wi-Fi bands (e.g. 2.4 GHz, and 5 GHz) [224]. On November 2013 AIR.U announced the Quick Start Network Programme to accelerate the deployment of the NGN in rural areas exclusively for higher education institutions [225].

5.3 Minimize Channel Selection Overheads

By selection overheads we mean the issues that the selection techniques may suffer from: a) complexity of considered optimizing methods; and b) the time needed to obtain the optimum channel. Regarding the first issue, the author in [128] trained an HMM model using four algorithms: Baum-Welch, Viterbi, PSO, and Memetic (Similar to GA). The model considered two different spectrum bands (heavy and light utilization from PUs). The performance of the model was then compared by considering each algorithm. It was found that PSO predicted the best channels faster than the other algorithms, and was not trapped in a local minimum as the other algorithms might be. However, using floating point operation, the author found that PSO suffered more from complexity than the other algorithms.

In the CRN literature, significant studies have been conducted to reduce the decision period. The majority of methods concentrate on adapting and developing machine learning techniques. For example the authors in [148] combined two crossovers to develop a new version of GA in order to increase converging speed. In the same way, adaptive GA was proposed in [153] the converging period. The authors in [226] proved that adaptive Discrete PSO converged faster compared with normal PSO, and GA.

Moreover, several studies have been published concerning WSS decision making on the status of sub-bands. For example, the authors in [129] designed robust 1-bit compressive sensing to reduce decision complexity. Exponential decay of reconstruction error from binary measurements of sparse signals was investigated in [130]. Very recently, a maximum likelihood of passive and active wideband power spectra scheme was proposed in [112]. However, power consumption is still the main challenge of soft CSS in WBS [42].

5.4 Challenges in the Spectrum Decision Component

The spectrum decision component has attracted great attention due to the fact that the best channels will improve the reliability of the network in terms of call blocking, outage, and dropping probabilities respectively. However, there are many impairments looking for remedy. The most critical challenges that may face in obtaining an optimum selection can be summarized as follows:

- Wide range of spectrum channels to select.
- Dynamic availability of spectrum due to PUs and other SUs activity.
- Long term prediction of each channel’s behaviour.
- Complexity of modelling PUs and SUs activity separately.

- Complexity of considering all QoS objectives; for that reason the majority of articles consider only one or two QoS objectives (e.g. only throughput [227], and throughput and efficient energy [149]).

Undoubtedly, with expected increase in number of CRNs, spectrum decision may become more complicated because of coexisting CRNs activities (-so called SUs activity). Therefore, the authors in [26] presented a novel framework contribute for modelling SUs activity, as result more accurate modelling and anticipating of spectrum bands availability. Nevertheless the key solution of spectrum availability is assigning maximum number of CRNs allowed to operate in any location [26].

6 Conclusion

Developing CRN components is currently experiencing remarkable advances. As it constitutes several QoS approaches to achieving high performance, it has to be robust enough against sporadic spectrum bands utilization. CRN's unique characteristics are sufficient to allow the transformation from inflexible static spectrum management to DSA. However, there is work to be done. Although the literature contains plentiful productive research into QoS approaches, there are many challenges still requiring further research attention. The most vital CRNs' components include: Spectrum, spectrum selection, spectrum sharing, and spectrum management. Spectrum sensing and spectrum selection components have attracted a great deal of attention from scholars, due to fact that they are very important roles to ensure reliable spectrum sharing, since spectrum sensing in CRNs is crucial, to ensure that all important spectrum opportunities are detected in a correct form. Furthermore, spectrum selection is also pivotal to ensuring appropriate bands are selected to satisfy QoS requirements of the services offered.

This paper has been dedicated to presenting the main QoS provisioning approaches based on an extensive study of the most recent literature. So far, these approaches have not been investigated together in all CRN components. Due to the enormous studies in this area, we have separated the paper into two parts. In this part, we focused on the main approaches in spectrum sensing and spectrum decision making components. Spectrum sensing approaches include: sensing accuracy, and sensing efficiency; while spectrum decision making includes: optimum channel selection, and minimizing selection complexity. Furthermore, we explored the solutions and improvements on the most cited articles last four years. Moreover, we identified a significant number of open research issues relating to sensing and selection tasks. In the second part of this paper, we will investigate in depth the QoS provisioning approaches of intranetworking internetworking spectrum sharing and management.

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