

Intuitive effectiveness degree of research methodologies for spectrum sensing in cognitive radio network

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ABSTRACT

The phenomenon of spectrum sensing plays an essential role in cognitive radio network (CRN) that is performed in real-time for better adaptability to dynamic usage of spectrum. However, efficient decision-making is often noted to be affected by dynamic environmental condition, interference, and noise leading to declination in performance. In recent times, there are proposals for various methodologies addressing such issues targeting towards improving spectrum sensing along with machine learning and energy detection approach, which is gaining its pace for technical research implementation. Irrespective of this advancement, ambiguity shrouds regarding the contrast effectiveness associated with these methods and their appropriateness in different situation. Hence, this manuscript presents a comprehensive and yet crisp review work to offer concise assessment of latest methodologies towards spectrum sensing used in CRN ecosystem. The paper has an inclusion of existing techniques, presents their potentials and shortcomings, exhibited evolving trends of research, extracts key gaps and challenges. The prime intention of this review work is towards guiding the future researchers and scholars by facilitating deeper insight towards the recent state of technologies in spectrum sensing.

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1. INTRODUCTION

From the perspective of cognitive radio network (CRN), spectrum sensing can be defined as a mechanism towards identifying and monitoring an unutilized bands of frequency residing within the spectrum of radio frequency [1]. The importance of this mechanism of spectrum sensing plays a crucial role for permitting the unlicensed user (or secondary user) for accessing the frequency bands without influencing the licensed users (or primary users). The process of spectrum sensing is quite essential for cognitive radios as it facilitates identification of this spectrum holes for effective allocation of available resources of spectrum in real-time along with interference mitigation [2]. On the basis of this sensing mechanism, CRN can quickly adapt its devices or nodes (cognitive radio) to the dynamic condition of spectrum thereby permitting more responsive strategy of communication with enhanced flexibility. The reliability, latency, and network throughput can be significantly enhanced by CRN using spectrum sensing by choosing the optimal communication channels. Apart from this, it is also quite eventual that there are various quality-of-service (QoS) demands for various users while they can be catered up by CRN by dynamically choosing an appropriate band of frequency. Finally, utilizing and detecting an underutilized spectrum evidently contributes towards reduced scarcity of spectrum.

However, there are certain noticeable challenges too in this process. The primary challenges are to address the issues of fading, shadowing, interference, and noise. There are various practical reasons for such challenges viz. various environmental factors (terrains and building structures) that can cause obstruction of signals, presence of interference of background noise leading to signal weakening as well as variability in strength of signal. The complete issues render the actual sensing quite unreliable. From real-time scenario, the primary users can utilize the spectrum in a way that it is challenging to even predict and thereby accurate sensing of spectrum in dynamic environment is quite complex. There is also an ongoing issue related to timing where the duration involved in sensing could introduce latency that can generate sub-optima responsiveness as well as degradation of performance especially for time-critical application executed in wireless environment. Even if all the above-mentioned issues are solved, another significant issue is that there is a demand of enormous energy for sensing the spectrum continually. This would be prime limitation for resource-restricted devices in CRN. There are various evolving studies with different techniques for improving CRN operations and spectrum sensing; however, majority of these studies are focused on detection problem overlooking algorithm complexity problems. In order to develop a robust algorithm towards spectrum sensing in CRN, it is essential to consider and model various constraints and environmental parameters demanding usage of signal processing approaches. Inclusion of all these attributes not only make the algorithmic steps look bulky but also induces extensive computational burden over a long run operation in uncertain and unpredictable wireless networks. Considering the scenarios involving different number of cognitive radios, there are higher chances of concurrent sensing phenomenon as well as sensing similar spectrums. Hence, constructing unified and joint decision towards data fusion operation in such cases quite complicated to design and execute. However, the last decade has witnessed an archive of literatures claiming to address multiple set of such challenges with promising result and yet it is quite needed to identify the degree of effectiveness of such research models.

In order to understand the ongoing research challenges, various related work has been studied to understand comprehensively all the methods used for spectrum sensing problems. The recent work carried out by Muzaffar and Sharqi [3] have reviewed existing spectrum sensing methods to find that energy detection is one of the most frequently adopted methods. The authors also added that there is a need for further work towards 5G-based spectrum sensing on CRN. Similar line of discussion is also presented by Jeevangi *et al.* [4]. According to the study carried out by Nasser *et al.* [5], there is a need to mechanism spectrum sensing towards 5G technology with more demands to be met towards searching communication channels and available transmission space, which is currently missing in literatures. Balachander *et al.* [6] have developed a modelling of cooperative sensing of spectrum using a unique design of multiple access technique considering internet-of-things (IoT) scenario hosted in 5G platform. The model is also claimed to be offer significant power controls and energy efficiency. The discussion presented by Sivagurunathan *et al.* [7] has discussed various ongoing challenges in CRN *e.g.*, channel estimation, minimization of interference, while energy consumption is found to be reduced by cluster based methods. An interesting study is carried out by Zhang *et al.* [8] where methods of spectrum sharing between ground network and aerial network has been presented. Apart from beneficial features of existing solution, the study has presented ongoing issues mainly relating to base station position and its influence in spectrum sharing. Existing system has also witnessed increased usage of deep learning approaches towards spectrum sensing as witnessed in work of Zhang and Luo [9] while the work infers the scope and challenges associated with deployment of various deep learning algorithms (convolution neural network, long short-term memory) towards spectrum sensing. Adoption of traditional machine learning model is noted in work of Yu *et al.* [10] where the idea is to analyze the behavior of primary user and apply support vector machine towards selection. Kadjo *et al.* [11] have presented an algorithm for assessment of optimal outcomes of signal considering spatial features by constructing a detector system. The model addresses the problems associated with noncooperative sensing of spectrum under low quality of signal. Toledo *et al.* [12] have discussed about cooperative sensing scheme considering dynamic environment of IoT with an idea to select active nodes for controlling energy consumption.

The insight towards related work suggests evidence of significant study models towards spectrum sensing as well as issues too. Some of the prominent research problems identified are as follows: i) Energy detection scheme is found to be one of the most frequently adopted strategy towards spectrum sensing due to its simpler implementation; however, their performance is not up to the mark when exposed to reduced signal quality; ii) Various learning-based algorithm are also slowly evolving towards improving performance of CRN-based applications; however, one of the potential challenge is still to select the optimal feature from the spectrum; iii) Deep learning based scheme is noted for their noticeable performance; however, this significant performance is only noticeable in higher signal quality condition otherwise there is varying and inconsistent result; iv) There are various innovative studies on improving spectrum sensing for ground network and aerial network system; however, such system is quite dynamic especially in aerial network that acts as an impediment towards ground network system with respect to sharing the spectrum as resources.

Further, there are various review work carried out toward this discussion; however, the point of discussion is often restricted to specific method only. There are few compact discussions of spectrum sensing in CRN.

Therefore, the aim of the proposed system is to present a precise and compact discussion of currently deployed methodologies towards spectrum sensing in CRN-based wireless network system. The discussion carried out in this review study offers a value added contribution as follows: i) The proposed study has reviewed various methodologies of spectrum sensing adopted in CRN-based wireless network with proper structured of its taxonomies followed by identifying their advantages and limitation in each cases, ii) The study also presents briefing of research trend to highlight the most frequently adopted methodology as well as evolving technologies towards spectrum sensing, iii) The study presents highlights of essential learning outcomes from existing CRN-based adopted network system to offer some significant disclosure of issues and ongoing challenges, and iv) Finally, the study contributes towards highlights research gap. The next section briefs of adopted research methodology.

2. METHOD

At present, there are manifold research techniques associated with spectrum sensing under multiple considered environments. This part of the review study is carried out towards considering only the spectrum sensing methodologies and their effectiveness when deployed under CRN-based wireless network system. The idea is to converge all the currently published implementation models under a structured taxonomy in order to review the effectiveness associated with existing techniques efficiently in simplified way. Figure 1 highlights the adopted research methodology to carry out the proposed review work.

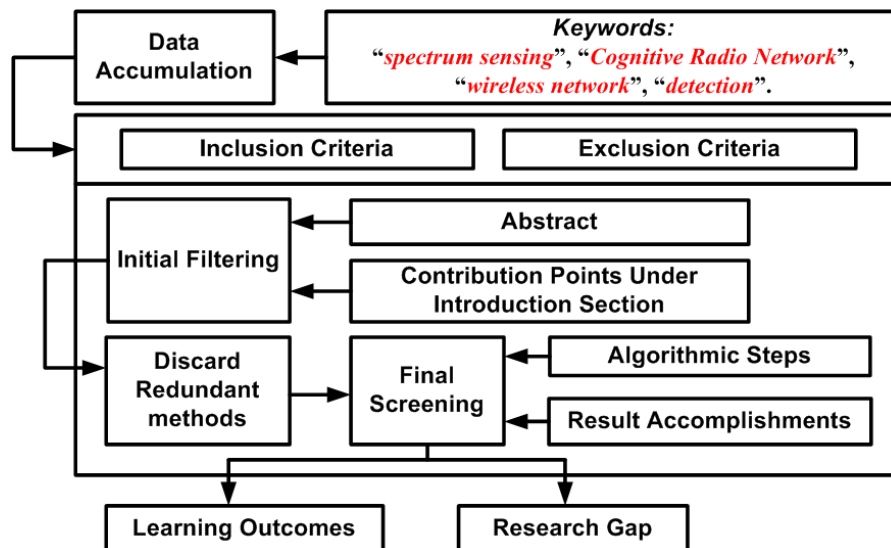


Figure 1. Methodology for studying effectiveness of spectrum sensing in CRN

Referring to Figure 1, it can be noted that first step is towards accumulation of primary information in form of research papers using multiple combination of keywords e.g., “spectrum sensing,” “cognitive radio network,” “wireless network,” “detection,” Upon accumulation of primary data, the next step is to filter them out studying abstract and contribution statement written within introduction section of each study. Redundant study models are identified and discarded which further generate shortlisted manuscript. These final set of manuscripts are then reviewed internally by studying their algorithms and accomplishments in results. All the observations are formed and written structurally in the proposed review work in next section. The complete method is also compliant of certain inclusion and exclusion criteria. The inclusion criteria are i) identification of core implementation methodology, ii) research articles (journals) published between 2020-2024, iii) research articles with distinct clear discussion of experimental environment and briefing of parameters involved in the study. The exclusion criteria are: i) no conference or symposium papers are shortlisted for review process, ii) any paper with missing details of implementation or theoretical papers are not considered in the study. The next section presents discussion of the complete review findings in form of result highlighted in crisp and compact form to gain an insight towards spectrum sensing methods in CRN.

3. RESULTS OF REVIEW

There are different variants of methodology evolved towards improving the performance of spectrum sensing in wireless network considering the involvement of CRN. Each technique has their own methodology and eventually their capability differs from each other. However, overall objective of each technique is found to be quite common which is mainly related to enhance utilization of available spectrum irrespective of any applications owned by user. This section offers insight to all the recently reviewed research model that has contributed towards improvising spectrum sensing.

3.1. Spectrum sensing approaches

Table 1 highlights the current methods towards spectrum sensing. The first spectrum sensing approach found in existing literature is energy detection (ED) scheme which evaluates occupancy level of given spectrum by computing the level of energy present in received signal in wireless network [13]–[19]. The second approach identified is matched filtering (MF) scheme offers optimal performance of detecting spectrums provided the signal of primary user is known [20]–[22]. Majority of this scheme is utilized for determining the availability of particular form of signal using a pattern of known signal. Existing literatures has witnessed another approach known as cyclostationary feature detection (CFD) which targets to leverage the periodicity in order to differentiate noise from multiple types of signals by analyzing the properties of cyclostationary [23], [24]. It has been noted that machine learning (ML) based approaches have been increasingly evolving in various literatures [25]–[29]. The ML approaches are mainly used for detecting and classification of usage of spectrum depending on extracted features from the signal. Existing ML approaches are also highly adaptive and characterized by optimal learning capability with progressive enhancement over time. The next approach is known as cooperative spectrum sensing (CSS) which consists of collaboration with different cognitive radio in order to perform sensing and sharing with a sole motive to improve the detection accuracy [30]–[33]. The existing literatures implementing CSS scheme is meant for enhancing the reliability by minimizing the effects of shadowing and fading effects. Another frequently adopted methodology is distributed spectrum sensing (DSS) where the sensing of spectrum and decision-making is carried out by each node independently followed by aggregation [34]–[36]. Different variants of approaches of DSS attempted in existing system mainly emphasizes towards accomplishing resiliency and scalability towards critical failures owing to its zero dependencies on central node system. Spatial spectrum sensing (SSS) is another existing research method towards managing dynamic spectrum which is mainly found to offer capabilities associated with multipath environment and multiple input multiple output (MIMO) for improving spatial diversity. SSS scheme is mainly found to be implemented towards wireless sensor network, interference management, and dynamic spectrum access [37]–[41]. Another evolving approach is associated with the temporal spectrum sensing (TSS) which is related to the analysis of the time-varying characteristic of spectrum utilization on the basis of occupancy scores in spectrum over time [42]–[45]. Existing TSS approaches are proven beneficial for identifying explicit patterns related to the availability of spectrum. Finally, literatures have also witnessed implementation of hybrid sensing spectrum (HSS) [46]–[49], and geolocation-based spectrum sensing (GSS) methods [50]–[54] to improvise upon sensing capabilities in wireless networks.

Table 1. Summary of current spectrum sensing methods

Method	Authors	Advantages	Limitations
ED	[13]–[19]	Computationally efficient, independent of prior signal information of primary user	Prone to outliers, higher sensitivity to noise
MF	[20]–[22]	Effective for poor signal quality, optimal detection	Dependency of prior knowledge, increased computational complexity
CFD	[23], [24]	Capable of identifying multiple forms of spectrums/signals, robust towards interference/noise	Highly challenging in real-world deployment, involves complex processing.
ML	[25]–[29]	Highly adaptive to varying spectrum, higher detection accuracy	Induce model complexity, demands voluminous labelled data
CSS	[30]–[33]	Improvise the performance, minimize outliers, maximize reliability	Suffers from communication overhead, heavily depends upon participating node integrity.
DSS	[34]–[36]	Higher scalability towards large network, enhanced resiliency towards failure of single point	Information sharing is highly limited; decision complexity associated with aggregation
SSS	[37]–[41]	Higher capacity to access more spectrum, enhanced detection with multipath propagation	Demands sophisticated antennas and hardware, complex processing, maximized cost of deployment
TSS	[42]–[45]	Enhanced efficiency, better pattern recognition, and dynamic spectrum awareness	Highly sensitive to changes in environment, increased computational complexity, demands extensive data
HSS	[46]–[49]	Increased context awareness	Demands accurate location data
GSS	[50]–[54]	Enhanced decision-making	Infrastructure dependence

3.2. Research trend

Table 2 showcases the current trends of research publications on almost all the existing research methodology for spectrum sensing in CRN published between the year 2020-2024. It can be seen that ED techniques ($n_{ED}=55481$) are extensively high on research publications and this can be probably justified by the need of developing or supporting the evolving wireless applications on the basis of specific energy. The next trend of increased number of research publications is observed using methodology of SSS method ($n_{SS}=43443$), DSS method ($n_{DS}=41477$), and HSS method ($n_{HSS}=40491$). When respective methodologies towards SSS, DSS, and HSS are checked it is found that all these methods are well-known for their generalization capabilities with addressing older as well as newer set of challenges. Further, it is noted that much less work is carried out towards considering CFD ($n_{CFD}=132$) and GSS ($n_{GSS}=146$) which could be because of its exclusive restricted application to certain sensing operation. It is also seen that adoption of ML methods ($n_{ML}=3564$) is slowly evolving and increasing in its pace of publication although cumulatively it may be found quite less in current counts of publication trends. The probable reason could be associated with associated scope and limitation associated with ML methods which still needs more improvement; however, ML has undeniably greater scope towards cost-effective spectrum sensing in contrast to other cadre of sensing methods in Table 2.

Table 2. Trends of publications of varied methods of spectrum sensing

Approaches	IEEE	MDPI	Springer	PMC	arXiv	Total
ED	349	59	12622	42414	37	55481
MF	108	10	808	2856	2	3784
CFD	0	2	65	65	0	132
ML	62	12	300	3182	8	3564
CSS	288	55	1327	7597	44	9311
DSS	416	136	9970	30813	142	41477
SSS	982	127	9747	32475	112	43443
TSS	268	52	5842	23184	37	29383
HSS	237	38	6687	33488	41	40491
GSS	0	1	132	13	0	146

3.3. Scope of evolving technique

ML method is one of the promising methods towards deployment of cost-effective spectrum sensing in wireless network. With its capability to identify the complex patterns of signals and getting a deeper insight towards the demands of data transmission, ML can offer its intelligent predictive operation resulting in a proactive measure. Although, less in number of publications in last 4 years, the existing studies using ML discussed in prior sections is found to address some complex set of research problems as exhibited in Figure 2.

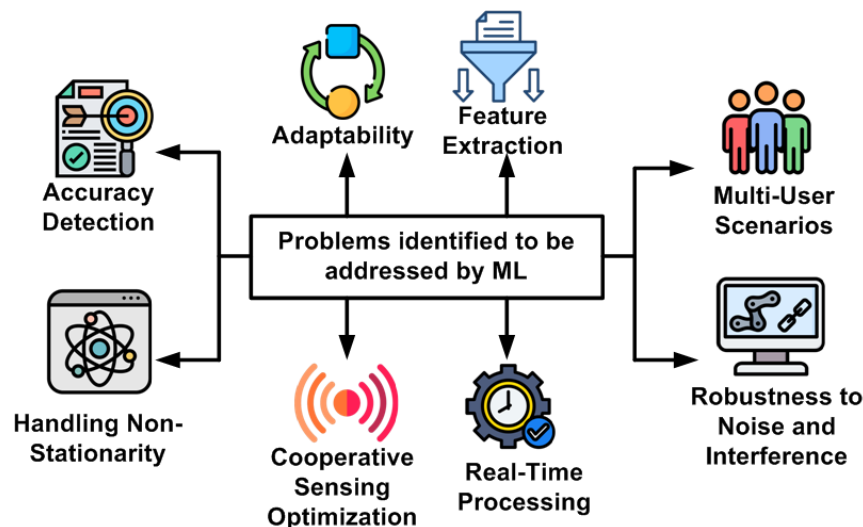


Figure 2. Research problems handled by ML methods

According to Figure 2, the accuracy of detecting signals of primary users can be potentially enhanced especially when exposed to uncertain and complex communication environment. Existing literatures using ML models are also proven to offer a better adaptability to manifold condition of environment and signal characteristic which can progressively finetune detection capability. Another significant capability of ML is towards extraction of potential features from the source spectrum that can minimize the demand of manual engineering of feature and thereby permitting simplification of detection. In compliance of deployment in dynamic environment, ML approaches are also found to handle issues of non-stationarity such as fluctuating environmental factors and user behavior. In presence of multiple number of primary users, ML method can segregate the signals and enhance the classification towards band occupancy. Further, better robustness towards interference and noise is another capability of ML as such models is meant to train for identifying patterns even in under very sub-optimal condition of signal-to-noise ratio. Hence, the detection carried out by ML is quite independent from adverse influence of artifacts. In demand to adhere with various application towards seamless communication, ML method can offer faster processing of spectrum data which supports real-time processing. Finally, ML method is witnessed to support cooperative sensing optimization by fusing data from different users enhancing overall reliability of detection.

3.4. Learning outcomes

It is quite evident that adoption of CRN is proven capable of enhancing the spectrum utilization in wireless network via various discussed methodologies. However, there are still significant amount of challenges that almost every existing research methodologies of spectrum sensing are encountering. Irrespective of various methods, it is still quite a difficult task for offering reliable determination of the primary users especially in dynamic environment. Another technical challenge is associated with developing robust algorithm that enables the secondary users to speedily adapt to fluctuating and varying environment without inducing any communication challenges to primary users. Because of this issue, it is also quite a challenging task to use any form of non-ML methods towards spectrum sensing in order to ensure sufficient bandwidth with minimal loss of packets and reduced delay. Further, with more demands of heterogeneous environment, CRN-based spectrum sensing phenomenon eventually encounters computational challenges towards varying user behavior, sources of interference, and fluctuating condition of signals. However, ML approaches are seen to proactively address these challenges by its sophisticated predictive and analytical operations and yet it too encounters issues towards adaptability over dynamic conditions of network. Another potential trade-off in existing research methodologies associated with spectrum sensing is one hand the solution architecture offered by ML algorithms are quite distributed while other hand, there is a dependency of central entity by the secondary user that degrades the communication performance in large-scale wireless networks. Apart from this, different variants of ML models are characterized by increased computational cost while not much supporting hosting or acting as an underlying architecture towards CRN which uses resource-limited devices. Therefore, it can be stated that ML models have good scope and opportunity towards spectrum sensing operations provided the inherent limitations associated with it as well as identified issues in CRN are bridged. The identified research gaps are as following:

- Massive data dependencies: Although adoption of ML methods is one of the preferred and cost-effective idea in CRN; however, they do have dependencies of large set of annotated data for training their models. The primary impediment in this process is collection of enriched data itself from large spectrum sensing operating environments.
- Ambiguous process of selecting an appropriate feature: Almost all variants of ML methods offer a potential feature extraction method; however, their mechanism varies from each other. Hence, choosing the appropriate feature right from the large data of spectrum is quite ambiguous and challenging with existing ML-based spectrum sensing methods.
- Sub-optimal scalability: Majority of the existing variants of spectrum sensing methodologies were reported to exhibit better sensing performance; however, there is yet lack of concrete evidence related to such model performance when exposed to larger set of spectrums without degrading the task of sensing and detection.
- Induces more computational complexity: Apart from cooperative spectrum sensing, none of the existing sensing methods were shown to identify signal from multiple number of users concurrently for a given large and dense environment of spectrum. Even applying ML methods in such condition will induce more memory saturation state and higher processing time.
- More application specific and less generalization: In spite of large number of research work towards spectrum sensing, there is few studies model to be witnessed with generalization characteristic. It is because of the fact that their problem formulation and modelling is carried out considering controlled research environment on specific assumptions of applications.

4. CONCLUSION

This study has presented discussion associated with various types of spectrum sensing methodologies that are witnessed to be widely adopted in CRN-based wireless network environment. There is undoubtedly significant degree of improvement in existing methodologies; however, this study assists to further crisp down each methodology to give a better insight towards effectiveness of current approaches. Although, there are certain review study discussed on spectrum sensing approaches too, they were not crisp and misses essential findings and research gap in updated time scale. This paper further contributes to showcase the updates taxonomy of all the currently implemented methodology of spectrum sensing along with highlights of research trends, essential learning outcomes, and research gap. The future work will be on the direction towards addressing the identified research gap by developing a novel computational framework harnessing analytical potential of machine learning approaches.

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Keshavamurthy		✓				✓		✓	✓	✓	✓	✓		

C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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