Advancement in Spectrum Sensing Algorithms in Cognitive Radio Architecture

Tejal Shambharkar[1], Ila Sharma[1](✉), and Shikha Maurya[2]

[1] Malaviya National Institute of Technology, Jaipur, India
ila.ece@mnit.ac.in
[2] National Institute of Technology, Patna, India

Abstract. Cognitive Radio Networks (CRNs) consider as one of the advanced and emerging technologies that can be employed in 5G/6G and beyond to satisfy the high data rate demand of wireless communication by reducing the channel scarcity problem. The objective of CRN is to permit the unlicensed/secondary users (SUs) to efficiently utilize the available licensed spectrum without affecting the operations of licensed/primary users (PUs). While implementing CRNs, SUs have to face several challenges such as the detection of PUs as well as resource allocation problems, which occur due to the interference between PU and SU, and between SU and SU. CRN faces problems like inter-symbol interference (ISI) and a lower data rate. Hence to reduce the problem of ISI and to achieve a higher data rate, the Orthogonal Frequency Division Multiplexing (OFDM) technique utilized in CRN. It proves advantageous since it lowers the ISI, pro-vides interoperability, and also improves spectrum sensing. However, OFDM exhibits a spectrum leakage problem. As a solution to this, Filter Bank based Multi-Carrier (FBMC) technique can be employed in the cognitive radio (CR) scenarios. In this paper, we explore different directions and applications where FBMC can be employed with CRNs.

Keywords: Cognitive radio · Spectrum sensing · FBMC

1 Introduction

As the number of wireless communication users continuously increases, each user needs more and more bandwidth. However, the available frequency range is limited. In a study published in early millennium [1], Mitola attempts to reconcile this conflict by introducing the idea of cognitive radio (CR). Primary users (PUs) as well as secondary users (SUs) are the two main entities introduced in CR. When the PUs are not transmitting or receiving data on the licensed spectrum or sections of it [2], SUs can send or receive signals on the licensed spectrum. SUs have ability to access the radio environment and utilize the unused licensed spectrum wisely and passing it over to PUs when they start transmitting [3]. It is needed to obtain information about radio environment and discover spectrum holes in order to run CR systems successfully. There is difficulty in identifying and detecting PU signals in a noisy and hostile channel environment.

Filter bank based multi-carrier (FBMC) is employed in CRN due to having the same flexibility as Orthogonal frequency division multiplexing (OFDM) in terms of using

D. Gupta et al. (Eds.): CVIP 2022, CCIS 1776, pp. 579–588, 2023.
https://doi.org/10.1007/978-3-031-31407-0_43

spectrum holes, but it is less susceptible to rapid time change of the timing offset and channel due to lack of synchronization [4]. In FBMC, there is no need of cyclic prefix (CP) extension and it is more resilient to frequency offsets than OFDM. As a result, FBMC is utilized in a spectrum sensing (SS) process to its lower cost and its excellent performance [2]. It has observed that with small spectral leakage of its prototype filter, the use of FBMC with CR networks can have a significant impact on the Inter-Channel Interference (ICI) caused by timing offset, which reduces the overall information rates of the system and interference between PUs and SUs [5]. Hence it is needed to explore more research and state of art on FBMC based CR methodologies for an efficient CRN.

In this paper, the benefits of FBMC in CR spectrum sensing has been studied. Spectrum sensing is essential functionality in CR to detect the spectrum holes efficiently at small signal to noise ratio (SNR) level. Thus, detection of PUs is the main challenge in CR technology. In literature, there are several techniques available for the detection of PUs in which energy detection based spectrum sensing is one of the most commonly used technique due to its lower computational complexity. However, it cannot detect PUs at low SNR. Therefore, FBMC can be used to detect PUs at low SNR.

The remaining paper is arranged as follows: Basic architecture of CR and its scenarios are discussed in Sect. 2 and Sect. 3, respectively, Sect. 4 discuss different spectrum sensing techniques. Further, advantages of FBMC in CR is discussed in Sect. 5. Some Challenges and future directions are also described in Sect. 6. Finally, conclusions are drawn in Sect. 7.

2 Cognitive Radio Architecture

2.1 Functionality of Cognitive Radio Networks (CRNs):

There are two main qualities of CR, i.e., cognitive capability and configurability. The ability to sense information from the environment is referred to as cognitive capability. Whereas, configurability enables the CR to continuously arrange its parameters in response to the environment [3]. As shown in Fig. 1, a cognitive cycle can be used to describe the basic functions of a CRN.

(a) **Spectrum Sensing (SS).** The fundamental property of SU in CR is to identify the presence of PU in the licensed spectrum and leave the spectrum as soon as PU starts its transmission to prevent the interference with PU. So, SS identifies and distributes available spectrum without interfering with other users

(b) **Spectrum Decision.**: CRs have the ability to choose the best available spectrum for the transmission of SUs in order to fulfill their quality-of-service (QoS) requirements without interfering with PUs.

(c) **Spectrum Sharing.** It is the technique in which CR shares the resources required for SUs.

(d) **Spectrum Mobility.** Whenever PU is available for transmission of data over the channel occupied by SU, SU will vacate that channel immediately so that smooth continuous transmission is sustained.

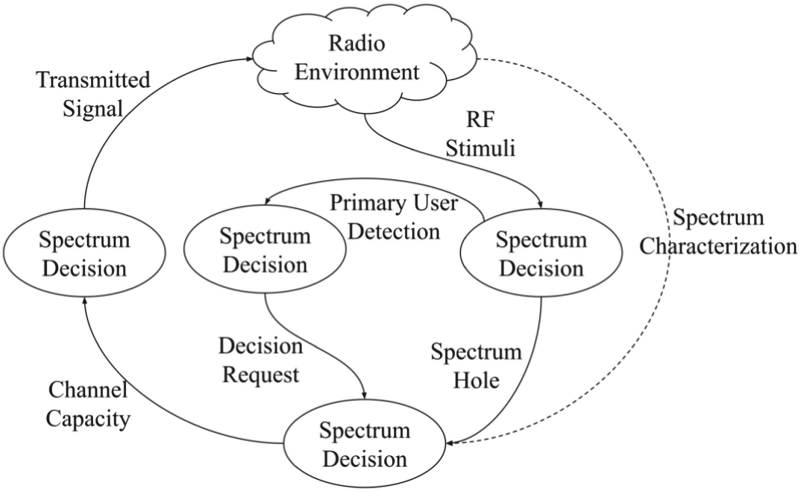
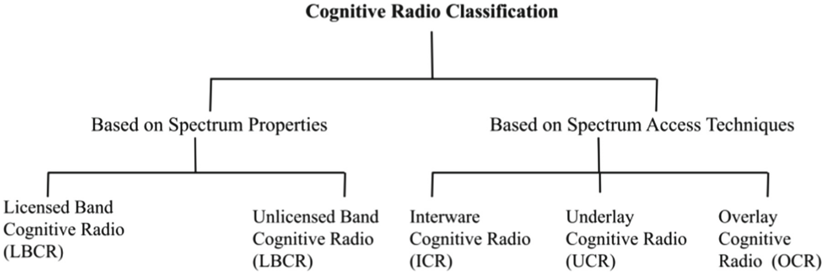


Fig. 1. Cognitive cycle [3]

CR can be mainly classified into two categories: available spectrum property, spectrum access technique.



2.2 CRN Architecture

CRN architecture is made up of primary and secondary networks. A primary network includes one or more PUs and one or more primary base stations (BS). PUs can communicate among each other through BS only. A secondary network includes SUs which communicate with each other either directly or by using base station (BS). The licensed spectrum band can only be accessible by SUs when it is unused by PUs. Secondary BS can be referred to as hub for secondary network. When numerous secondary networks use a shared frequency band, a central network entity called a spectrum broker can correlate their spectrum consumption [4]. The spectrum broker collect data from the secondary network and applies it to spectrum sharing. In CR, SU can temporarily use the unoccupied licensed bands that are known as spectrum hole which belongs to the PUs [6] (Fig. 2).

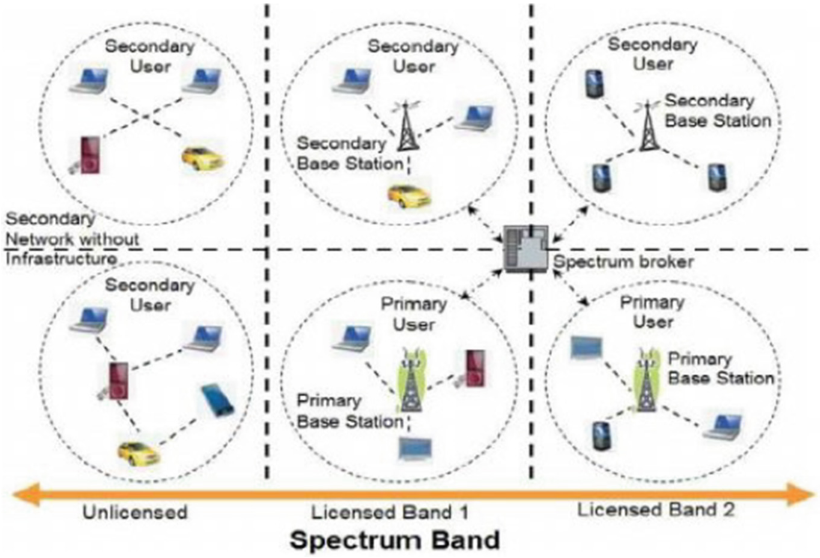


Fig. 2. CRN architecture [7]

3 Spectrum Sensing in Cognitive Radio

In this paper, we are focusing on interweave spectrum access mode of operation. The aim of CR is to increase spectrum efficiency by detecting the presence of spectrum holes and transmitting in it without any interference. Thus, SS is an important feature of CR for the identification of the spectrum holes and make sure that SU does not interfere with PU. SU must detect [8] the spectrum often, while reducing latency period which is spent sensing in order to make optimal use of the available spectrum opportunities. SS as a generic technique is difficult to put together, and particular approaches must be developed based on real applications. Detection of signal is based on two criteria: "probability of detection (Pd) and probability of false alarm (Pfa). Probability of detection denotes the probability of a cognitive radio user declaring that a primary user is present when the spectrum is indeed occupied by a primary user [5]. Probability of false alarm denotes the probability of a cognitive radio user declaring that a primary user is present when the spectrum is free [5]. A false alarm therefore signifies the reduction of the CR throughput (missing the spectrum holes)". Two hypothesis representation for spectrum sensing problem is given by

$$H_0 : Y[n] = W[n] \ (If \ \ PU \ \ is \ absent) \tag{1}$$

$$H_1 : Y[n] = hS[n] + W[n] \ (If \ \ PU \ \ is \ present) \tag{2}$$

where, Y is received signal at SU, S is signal from PU, h is the channel gain and W is additive white Gaussian noise(AWGN) signal. To evaluate the performance, result of test statistic (τ) is compared with predefined threshold value (λ). The result is given as:

$$\tau > \lambda \qquad \text{PU is present}$$

$$\tau > \lambda \qquad \text{PU is absent}$$

SS can be done by detecting the signal strength in the spectrum and for that different signal detection techniques can be used such as matched filter, energy detection, and cyclostationary feature detector [9–12] (Table 1).

Table 1. Features of spectrum sensing techniques [12].

Techniques	Advantages	Disadvantages
Matched Filter based Techniques	Optimal performance Least computation cost and quick sensing	primary user information required High power High complexity
Energy Detection based Techniques	Low complexity Independent of any prior information about primary signal Low computational cost	In noisy environment, can't distinguish between signal and noise
Cyclostationary Feature Detection based Techniques	Robust against noise interference and uncertainty Applicable to low signal to noise ratio	primary user information required High complexity Long sensing time

4 FBMC Based Spectrum Sensing in Cognitive Radio

FBMC has become a much better solution for overcoming the restrictions that exist in OFDM systems because of the lower guard bands between symbols and the absence of CP. When compared to OFDM with a cyclic prefix, FBMC has less spectrum leakage [13]. FBMC can detect multiple number of users having different center frequencies and also users with spectral holes. Farhang first developed the notion of FBMC in [2] for SS.

Cosine Modulated Multi-Tone (CMT), Offset Quadrature Amplitude Modulation (OQAM), and Filtered Multi-Tone (FMT) are three basic FBMC techniques that have been introduced. Unlike OFDM, which sends complex-symbols at constant data rate, it is feasible to accomplish baud rate spacing between consecutive subcarrier channels and retrieve the symbol by inserting delay in-between in phase and quadrature components of QAM signals, which does not have ISI and Inter-Carrier Interference. CMT [14] has a great bandwidth efficiency and the capacity to do blind detection [10] due to the underlying signals' unique structure. Because of CMT's reconstruction characteristic, overlapping neighboring bands may be separated precisely when numerous adjacent bands are utilized for transmission. Another FBMC method, FMT, was first developed for DSL applications [11]. When compared to CMT, it enables neighboring bands to overlap. In FMT, the subcarrier bands do not overlap. As a result, the main distinction between CMT and FMT is how the frequency band is employed. Distinct subcarrier signals in FMT can be split using traditional filtering. The overlapping subcarrier bands in CMT, on the other hand, need be separated by complex filtering design, i.e. FMT, which allows for straightforward and flexible signal processing at the receiver, may be appealing from an implementation standpoint. CMT, on the other side, can provide greater blind detection capabilities and bandwidth efficiency [15].

OQAM divides the channel into a number of sub channels, each of which overlaps exclusively with its neighbors [16].

FBMC contains the following distinct characteristics:

1. Because there is no requirement for a small guard bands and CP, they are adequate to prevent cross-channel interference, OQAM can handle the whole transmission bandwidth [17].
2. FBMC is significantly less susceptible to time offset than OFDM because of small side-lobe [18]. Furthermore, FBMC is less susceptible to frequency offset, indicating greater Doppler Effect resilience.
3. For CR systems high resolution spectrum analysis capabilities of filter banks is use as shown in[19], and filter banks can yield a considerably broader spectrum range than the traditional FFT. As a result, there are fewer unwanted collisions between secondary and primary users.

4.1 FBMC for Spectrum Sensing

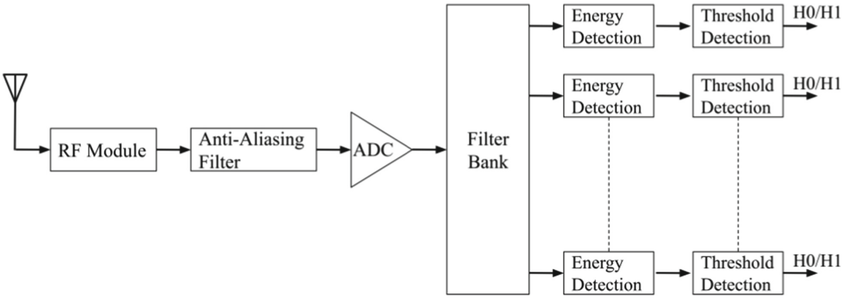


Fig. 3. Basic architecture of spectrum sensing using a filter bank [18].

The fundamental architecture of filter bank [18] for spectrum sensing is shown in Fig. 3. Following the radio frequency (RF) block, an analog to digital converter samples the RF signal, which is then sent to the filter bank [20]. Filter bank consists of analysis and synthesis filter bank. A low pass model filter is shifted to create these filter banks. The overall bandwidth is divided into linear non-overlapping sub-bands using several band pass filters. These sub-band signal is then fed to energy detector for energy detection. Energy detection is a widely used technique due to its lower computational complexity. Each sub-band's power is estimated and evaluated separately. By comparing the energy to a predefined threshold, the signal is recognized and classified as present or not. Energy detection is applied at the sub-band levels at analysis filter banks output, making filter bank based techniques robust and dynamic. The wideband signal is divided into narrowband signal by the analysis filter bank [21]. Challenges and Future Research Directions.

During SS, there should be higher likelihood of exact sensing and fewer chances of false alarm in order to decrease the impact of interference at PUs [22]. Existing sensing approaches have drawbacks. Such as weak signals that are below thermal noise are not detectable by energy detection. If specific signal information is familiar such as operational frequency, bandwidth, pulse shape, type of modulation type and frame structure of the PU, then matched filtering detection techniques with shorter detection times are preferable. The channel responsiveness has a big impact on this method's detection performance. To accomplish this, both the physical and media access control layers must be perfectly timed and synchronized and this adds to the calculations complexity. On the other hand cyclostationary detection is a technique for recognizing PUs transmission that takes use of the received signals' cyclostationarity [23]. The detector can then distinguish among PU, SU, and other interfering signals. However, the success of this strategy is based largely on the number of samples, which rises the complexity. Furthermore, cyclostationary features need a significant amount of computing power, which is not desired in portable systems [24]. Another challenge in SS is to deal with noise uncertainty [15]. The majority of SS approaches employ a fixed threshold that is dependent on the amount of noise. These sensing approaches aren't precise since the noise is unpredictable. In literature [6, 9, 16] different techniques have been suggested in order to deal with uncertainty, such as probabilistic models. Therefore, it is important that the noise must be measured to boost the detection effectiveness of the sensing methods.

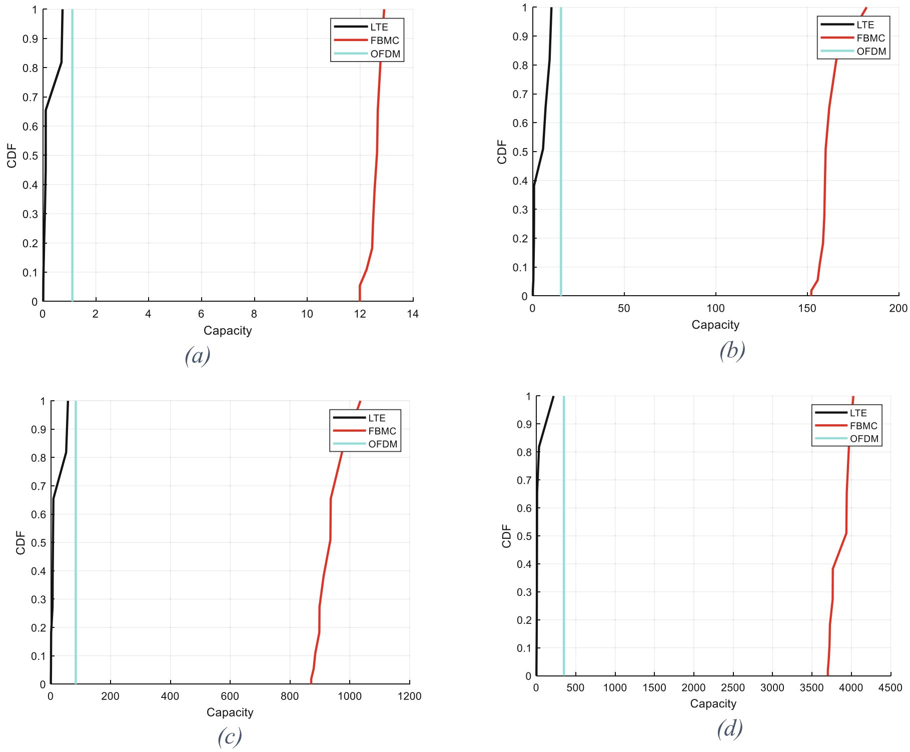
Sensitivity of SS methods is also a challenge. Where compressive sensing techniques are often incorrect, future communication systems are projected to work at lower SNR levels. Only few researchers have studied SS efficiency at lower SNR and it can be explored as a future direction [25].

The following is a simulation of channel capacity against CDF for energy detection using FBMC, as extracted from [18]. Figure 4 (a) shows channels capacity vs. CDF when there is just one PU active and four PU aren't. With 4 unfilled slots, the channel is in very bad condition. Shannon's traditional OFDM capacity in bits/sec is around 1 Shannon. In comparison to FBMC, LTE has a substantially lesser capacity. When FBMC is used, capacity begins to rise dramatically. The capacity attributable to LTE at 50% CDF for FBMC is almost 13 Shannon.

Figure 4(b) depicts the plot when a SU fills the vacant slot, keeping 3 slots open. For all CDF percentiles, OFDM capacity is nearly constant at 20 Shannon in this iteration. The LTE and FBMC capacity increased yet again. At the 50% CDF, Capacity of LTE is 5 Shannon whereas capacity of FBMC is 170 Shannon.

Figure 4(c) the plot for capacity verses during the 3rd iteration, when SU takes up again one slot and two slots are left unfilled. The capacity of the OFDM channel remains constant, but is higher than the preceding iteration i.e. at nearly 80 Shannon. For 50% LTE capacity is 25 while for FBMC it is 950.

Figure 4 (d) depicts plot when SU takes up one gain one slot, implying that not a single slot is left free. Now that all slots are filled, spectrum efficiency improves by large value. Channel capacity for FBMC, LTE, and OFDM has increased significantly. For all % of CDF, capacity of OFDM is constant at 260 Shannon. LTEs capacity at 50% CDF is 60 Shannon, whereas FBMCs capacity is 3990 Shannon.



(a) (b)

(c) (d)

Fig. 4. The channel capacity vs. CDF plot for (a) When just one PU is present and four PU are absent, (b) When one SU takes the vacant slot, three slots remain unfilled. (c) When SU takes up one more slot, leaving two unused (d) When SU takes up one more slot, no slot is left vacant, as all slots are now filled [18].

5 Future Research Direction

1. SS performance can also be enhanced by using FBMC technology. FBMC is considered to be one of the most important technologies for 5G networks when combined with CR. To attain a high spectrum efficiency, FBMC systems make use of the spatial multiplexing gain. A transmitter and receiver are the two fundamental components of a FBMC system. Each element has a variety of antennas [20]. Signal from each antenna is sampled by an independent analog to digital converter to evaluate

the channel availability. FBMC systems are considered to improve detection while decreasing the possibilities of miss-detection and false alarm [25].

2. Energy detection method can be used for SS in filter bank [18]. The threshold in energy detection is a function of noise variance, therefore, noise variance estimation technique can be investigated in wide band spectrum sensing. Basically, fixed threshold is used for all the subbands in the filter bank. If noise variance is estimated in individual subbands, adaptive threshold scheme can be implemented. The adaptive threshold can be implemented for different stages with different spectral resolution in order to increase the probability of detection [26].

6 Conclusion

Spectrum sensing is an important function of CR through which CR is able to properly utilize the spectrum by allowing the SU to operate in the unused licensed band. Different SS methods offer a way of reusing frequency spectrum without interfering with it. Sensing many narrowband channels over a wideband spectrum is a major problem in CRs. FBMC can be used to tackle this challenge. FBMC can efficiently analyses many users with changing center frequencies and spectral dispersion between users. The filter banks provide higher bandwidth efficiency and lower side lobes desirable for spectrum sensing.

References

1. Mitola, J., Maguire, G.: Cognitive radio: making software radios more personal. IEEE Pers. Commun. **6**(4), 13–18 (1999)
2. Farhang-Boroujeny, B.: Filter bank spectrum sensing for cognitive radios. IEEE Trans. Signal Process. **56**(5), 1801–1811 (2008)
3. Wang, F.: Cognitive radio networks and security: a survey. J. Netw. Comput. Appl.1691–1708 (2014)
4. Masonta, M.T., Mzyece, M., Ntlatlapa, N.: Spectrum decision in cognitive radio networks: a survey. IEEE Commun. Surv. Tutor. **15**(3), 1088–1107 (2012)
5. Zhang, H.: Filter Bank based Multicarrier (FBMC) for Cognitive Radio Systems. Networking and Internet Architecture. Thesis, National Conservatory of Arts and Crafts, University of Wuhan (China), (2010)
6. Mitola, J. I.: Cognitive radio. An integrated agent architecture for software defined radio (2002)
7. Anusha, M., Vemuru, S., Gunasekhar, T.: Transmission protocols in cognitive radio mesh networks. Int. J. Elect. Comput. Eng. (IJECE) **5**(6), 1446 (2015). https://doi.org/10.11591/ijece.v5i6.pp1446-1451
8. Budiarjo, I., Nikookar, H., Ligthart, L.P.: Cognitive radio modulation techniques. IEEE Signal Process. Mag. **25**(6), 24–34 (2008)
9. Giannakis, G.B., Tsatsanis, M.K.: Signal detection and classification using matched filtering and higher order statistics. IEEE Trans. Acoust. Speech Signal Process. **38**(7), 1284–1296 (1990)
10. Sharma, I., Singh, G.: A Novel approach for spectrum access using fuzzy logic in cognitive radio. Int. J. Inf. Technol. Comput. Sci. **8**, 1–9 (2012)

11. Ghozzi, M., Dohler, M., Marx, F., Palicot, J.: Cognitive radio: methods for the detection of free bands. Phys. Rep. **7**(7), 794–804 (2006)
12. Wang, B., Liu, K.J.R.: Advances in cognitive radio networks: a survey. IEEE J. Sel. Top. Signal Process. **5**(1), 5–23 (2011)
13. Amini, P., Kempter, R., Chen, R.R., Lin, L., Farhang-Boroujeny, B.: Filter bank multitone: a physical layer candidate for cognitive radios. In: Proceedings of the SDR Forum Technical Conference, pp. 14–18 (2005)
14. Farhang-Boroujeny, B.: Multicarrier modulation with blind detection capability using cosine modulated filter banks. IEEE Trans. Commun. **51**(12), 2057–2070 (2003)
15. Manesh, M.R., Kaabouch, N., Reyes, H., Hu, W.C.: A Bayesian model of the aggregate interference power in cognitive radio networks. In: 2016 IEEE 7th Annual Ubiquitous Computing, Electronics and Mobile Communication Conference (UEMCON), pp. 1–7. IEEE (2016)
16. Weiss, T.A., Jondral, F.K.: Spectrum pooling: an innovative strategy for the enhancement of spectrum efficiency. IEEE Commun. Mag. **42**(3), S8-14 (2004)
17. Salahdine, F., Kaabouch, N., El Ghazi, H.: Techniques for dealing with uncertainty in cognitive radio networks. In: 2017 IEEE 7th Annual Computing and Communication Workshop and Conference (CCWC), pp. 1–6. IEEE (2017)
18. Sheikh, J.A., Mir, Z.I., Mufti, M., Parah, S.A., Bhat, G.M.: A new Filter Bank Multicarrier (FBMC) based cognitive radio for 5g networks using optimization techniques. Wirel. Pers. Commun. **112**(2), 1265–1280 (2020). https://doi.org/10.1007/s11277-020-07101-y
19. Arjoune, Y., Kaabouch, N.: A comprehensive survey on spectrum sensing in cognitive radio networks: recent advances, new challenges, and future research directions. Sensors **19**(1), 126 (2019)
20. Amini, P., Kempter, R., Farhang-Boroujeny, B.: A comparison of alternative filter bank multicarrier methods for cognitive radio systems. In: Proceedings of the SDR Technical Conference and Product Exposition (2006)
21. Cabric, D., Mishra, S.M., Brodersen, R.W.: Implementation issues in spectrum sensing for cognitive radios. In: Conference Record of the Thirty-Eighth Asilomar Conference on Signals, Systems and Computers, vol. 1, pp. 772–776. IEEE (2004)
22. Kumar, A., Sharma, I.: A new method for designing multiplierless two-channel filter bank using shifted-Chebyshev polynomials. Int. J. Electron. **106**(4), 537–552 (2019)
23. Sharma, I., Kumar, A., Singh, G.K.: Adjustable window based design of multiplier-less cosine modulated filter bank using swarm optimization algorithms. AEU-Int. J. Electron. Commun. **70**(1), 85–94 (2016)
24. Wang, H., Wu, B., Yao, Y., Qin, M.: Wideband spectrum sensing based on reconfigurable filter bank in cognitive radio. Future Internet **11**, 244 (2019)
25. Javed, J.N., Khalil, M., Shabbir A.,: A survey on cognitive radio spectrum sensing: classifications and performance comparison. In: 2019 International Conference on Innovative Computing (ICIC), pp. 1–8 (2019)
26. Dikmese, S., Lamichhane, K., Renfors, M.: Novel filter bank-based cooperative spectrum sensing under practical challenges for beyond 5G cognitive radios. EURASIP J. Wirel. Commun. Netw. **2021**(1), 1–27 (2021). https://doi.org/10.1186/s13638-020-01889-w