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A New Filter Bank Multicarrier (FBMC) Based Cognitive Radio for 5G Networks Using Optimization Techniques

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Abstract

Ultra high definition radio, low latency, high bandwidth, machine to machine communication and several emergence application like e-health, IOT etc. will be dominated by 5G in future networks. Therefore there is dire need of more capacity which in turn will demand more efficient spectrum sensing. In this paper we propose a new technique of FBMC spectrum sensing cognitive radio technique in future networks. The proposed technique provides programmability that allows dynamic and real time configuration of the operating channel. The simulation results have been verified in terms of various parameters and found satisfactory results.

Keywords Filter bank · Cognitive radio (CR) · Spectrum sensing · Filter bank multicarrier (FBMC) · 5G · Orthogonal Frequency Division Multiplexing (OFDM) · Channel capacity

1 Introduction

For finding the satisfactory spectrum bands to meet the trade and demand of future forthcoming services is where the major problem facing the future generation wireless communication [1]. In order to overcome this problem, Cognitive radio systems (CRs) are consider the most promising technology that may potentially minimize the problem of spectrum scarcity using dynamic spectrum methods [2]. Joseph Mitola [3, 4] was the first to define the term CR. Cognitive radio (CR) system is a novel method that enables wireless structures to detect the environment, adapts, and learns from the previous journey to enhance the best quality of service. CR system is a promising solution to increase spectrum sensing and utilization. In future wireless communication technology, Cognitive radio systems have smart procedure for scanning the radio spectrum to sense spectral holes. As a result, allocate the same spectrum to secondary users (unlicensed) without creating any unfavorable interference to the primary users (licensed) in broadband spectrum, as spectrum sensing is an essential functioning part of cognitive radios, in detecting spectrum

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access moments and prevailing non-interfered spectrum for dependable communication [5]. Orthogonal Frequency Division Multiplexing (OFDM) among the present multicarrier modulation systems is better all over place. However OFDM experiences huge out-of-band radiation because of high side-lobes of modulated subcarriers [6]. OFDM techniques scarcity high spectral dynamic range and are not appropriate for low-power primary users detection. In CR systems this impact results in high obstruction among Secondary users (SUs) and primary users (PUs). Existing techniques for decreasing this interference have demerits of data transmission rate reduction or high complexity. Advanced Multirate digital signal processing is applied in digital systems where more than one sampling rate is need [2, 6]. Due to the reduced guard bands between the users and lack of cyclic prefix in Filter bank multicarrier (FBMC), FBMC become another solution to overcome the limitations occur in OFDM systems [7, 8]. FBMC limits the leakage of spectrum in caparison to cyclic prefix OFDM systems. FBMC is efficient in identifying multiple users with distinct center frequencies and users with spectral gaps [9]. Various FBMC schemes reported in the literature and initially the concept of FBMC was proposed by Farhang in [6] for spectrum sensing. Other techniques include staggered modulated multi-tone, cosine modulated multi-tone and filtered multi-tone [10, 11].

In this paper we propose a new filter bank multicarrier modulation for enhancing the capacity in cognitive radio networks. Efficient algorithm is designed for spectrum sensing to mitigate the interference and efficient utilization of bandwidth. Five primary users (PU) and one Secondary user (SU) have been used in the proposed work. The SU occupies the slot only in the absence of PU. The optimization problem has been adjusted by the non-linear fractional program and stationary KKT condition is used to derive the optimal values for power allocation coefficients.

The rest of paper is organized as follows Sect. 2 gives a brief description about the filter bank architecture for spectrum sensing Sect. 3 defines resource allocation. The system model is described in Sect. 4. The optimization problem and its solution is described in Sect. 5. Section 6 briefly explains the proposed algorithm. Simulation results along with their description are explained in Sect. 7. Section 8 concludes the paper.

2 Filter Bank Architecture for Spectrum Sensing

Various types of filters have been used in CR systems, but CR based multi-rate filter bank is promising in future generation wireless communication due to its spectral efficiency. Filter bank consists of analysis filter bank and synthesis filter bank. These filter banks are realized by shifting a low pass model filter [12]. Multiple band pass filters split total bandwidth into linear non-overlapping sub-bands. Multicarrier methods were also proposed for spectrum sensing and OFDM multicarrier was first recommended technique for CR [13, 14]. However, due the presence of large side-lobes limits the application of OFDM for CR. Large side-lobes may lead to interference among the different users because of spectral leakage. Furthermore, due to scarcity of high spectral dynamic range of OFDM techniques were not good enough for sensing of low power primary users. Filter bank multiple carrier (FBMC) reduces large side-lobe as compared to cyclic prefixed (CP) OFDM and this become alternate solutions to overcome the limitations of CP OFDM Systems. FBMC is capable of analyzing multiple users efficiently with varying center frequencies and spectral disparity between users precisely with flexibility [6].

By designing prototype filters spectrum efficiency can be enhanced with tolerable sub-band attenuation i.e. filter banks are designed and considered to be an alternate solution for large band spectrum sensing. The length of the prototype filter also needs to be modifying to obtain high efficiency dynamic range of filter banks. Multi-taper method (MT) is one near optimal technique nonetheless MT is computationally high complex [2, 12]. However identical performance can be attained with filter banks adopting extended filters with lower computational complexity [5, 15].

The filter bank architecture for spectrum sensing basic structure is illustrated in Fig. 1. In first Radio frequency (RF) module is followed by wide band analog to digital (ADC) to sample the RF signal [7, 8, 15]. Various structures of filter bank like Multistage Polyphase Filter Bank, DFT and cosine-modulated filter bank (CMFB) can be considered. The complete filter bank structure can be realized by using complex modulated of a single model filter bank. Multiband sensing exploits energy detection methods due to the reduced computational complexity. Methods such as periodogram method and filter bank methods have explored energy detection for spectrum sensing. Due to low computational complexities, Energy detection technique is commonly used technique. Power is calculated at the output of each sub-band independently and examined as the analyzed data. The signal is detected and termed as present or absent by comparing the energy with predefined threshold. Filter bank based techniques are robust and dynamic where energy sensing is implemented at the sub-band level at the output of the analysis filter bank. Analysis filter bank splits the wideband signal into the narrow band signal. The sab-band signal can be expressed as:

$$
\begin{aligned}
H_0 &: y_{\mathrm{k}}[\mathrm{m}] = w_{\mathrm{k}}[\mathrm{m}] \\
H_1 &: y_{\mathrm{k}}[m] = x_{\mathrm{k}}[\mathrm{m}] + w_{\mathrm{k}}[\mathrm{m}]
\end{aligned}
$$

where $x_{\mathrm{k}}[\mathrm{m}]$ represents the transmitted wireless signal, $y_{\mathrm{m}}[\mathrm{m}]$ is the received signal at the kth sub-band (k = 1, 2, 3,…, M), M is the total number of sub-bands. $x_{\mathrm{k}}[\mathrm{m}] = \mathrm{H_k S_k}\,[\mathrm{m}]$, $\mathrm{H_k}$ represents the complex gain of the sub-bands, $\mathrm{S_k}$ [m] is the input signal. $w_{\mathrm{k}}[\mathrm{m}]$ is the noise samples of sub-bands. Energy is detected in similar to traditional manner where noise follows the distribution $w_{\mathrm{k}}[\mathrm{m}] \sim N(0, \sigma^2_{w,k})$ and signal $x_{\mathrm{k}}[\mathrm{m}] \sim N(0, \sigma^2_{w,k})$ with $\sigma^2_{w,k}$ being noise variance and $\sigma^2_{w,k}$ is the signal variance [16]. If the sub-band noise variance is $\sigma^2_{w,k}/\mathrm{M}$ and

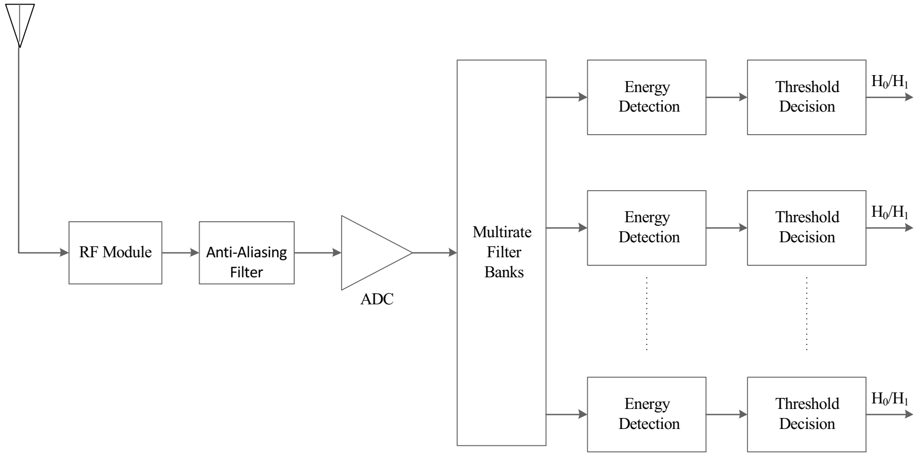


Fig. 1 Filter bank architecture for spectrum sensing

$\sigma^2_{w,k}$ is the noise variance of the wideband channel. The test statistic energy at the output of individual sub-bands is considered as:

$$Y_k = \frac{1}{L}\sum_{m=0}^{L-1} y_k[m]^2 \tag{1}$$

where L is the number of samples in each sub-band and $L = \frac{N_s}{M}$ M is number of sub-bands for detection and N_s is total number of samples received. Two hypotheses are formulated for the presence and absence of primary user signal is given as:

$$y_k[\mathrm{m}] \sim \mathrm{N}\left(\sigma^2_{w,k}, \frac{1}{L}\sigma^4_{w,k}\right); \quad \text{for “}H_0\text{” hypothesis}$$

$$y_k[\mathrm{m}] \sim \mathrm{N}\left((\sigma^2_{x,k} + \sigma^2_{w,k}, \frac{1}{L}\left(\sigma^2_{x,k} + \sigma^2_{w,k}\right)^2\right); \quad \text{for “}H_1\text{” hypothesis}$$

To perform energy detection even in low SNR, the number of samples for each stage needs to be large enough and at each stage the minimum number of samples required can be calculated using the given relation:

$$\mathrm{N}_{min} = 2\left[Q^{-1}\left(p_{fa}\right) - Q^{-1}\left(p_{\mathrm{d}}\right)(1 + \mathrm{SNR})\right]^2 \mathrm{SNR}^{-2} \tag{2}$$

where p_{fa} is probability of false alarm and p_{d} is the probability of detection:

$$p_{fa} = Q\left(\frac{\lambda - \sigma^2_w}{\sqrt{1/N_s\sigma^2_w}}\right) \tag{3}$$

$$p_d = Q\left(\frac{\lambda - (\sigma^2_w + \sigma^2_s)}{\sqrt{1/N_s(\sigma^2_w + \sigma^2_s)}}\right) \tag{4}$$

where σ^2_x is the signal variance.

The threshold λ is obtained from Eq. (3) and the value of λ is calculated using the knowledge p_{fa} and σ^2_w (noise variance) of the received signal is given as:

$$\lambda = \left(Q^{-1}\left(p_{fa}\right)\sqrt{1/N_s\sigma^2_w}\right) \tag{5}$$

The presence and absence of an active signal is determined by comparing test statistics with a predetermined threshold.

3 Resource Allocation

Cognitive Radio (CR) is a dependable technology in increasing the spectral efficiency of secondary users by permitting them to access the unoccupied licensed spectrum bands belonging to the primary users [16, 17]. A developing trend in general and for 5G networks is to focus on more and more energy efficient transmission in wireless communication [18, 19] and the burst of increasing wireless application has lead the demand of large radio bandwidth. CR has ability to meet the ever-increasing demand of large radio spectrum by allowing the SUs (unlicensed) to utilize the unoccupied channel (licensed) by primary users. The unlicensed users are not allowed to access free spectrum of PUs in fixed bandwidth management policy, which results a low performance of frequency spectrum for future generation (5G) communication [17].

Wireless spectrum for communication is a sparse communication resource few MHz slab of frequency band can be very expensive. In the Year 2014 in India, the auction for 2G spectrum was held by department of telecom (DOT) under the government of India in the frequency range of 900 MHz and 1800 MHz. In the said auction DOT earned 612 billion Indian rupees (USD 8.5 billion). Reliance JIO (4G) has acquired 269.9 MHz of spectrum for ₹13,672 crore (USD 19.1 billion approx.) [20]. This sharp increase of wireless spectrum is due swift blossoming of wireless data networks. On the other side, worldwide footage of spectrum utilization time of licensed wireless range by licensed users is only about 5 to 10 percent [2]. That means, this expensive valuable resource remains under-utilized most of the time. This is the main reason which led to exploit the concept of CR technology utilizing which the wireless networks can smartly sense and explore the spectrum holes (unused band of spectrum) of the PUs at a particular location and time instant [21–25].

4 Proposed System Model

We are considering the system in which CR consists of five Primary users (PUs) and Secondary system with one SU as shown in Fig. 2. D is the distance between PUs and SUs and Rp and R_s are the radius of the Primary system (PS) and Secondary system (SS) cell. PUs are allocated a fixed line slot, and SU occupies the slot only in the absence of PU. The PUs and

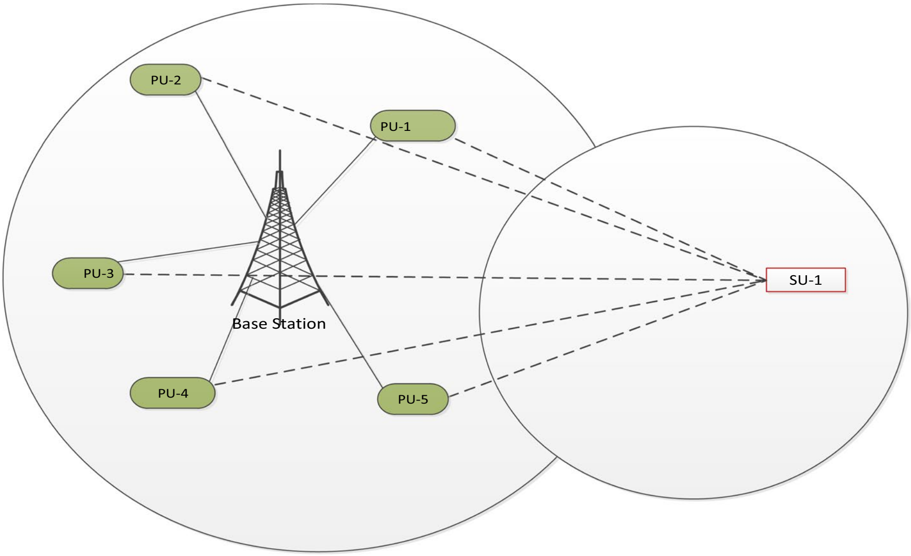


Fig. 2 Shows the resource allocation between PU and SU

SUs share the adjacent frequency bands. The absences of PUs lead to the spectrum hole and may have one or multiple clusters. Thus SUs occupy L subcarriers. The goal of a secondary user in the system model is to maximize the channel capacity regarding bits/second by allocating power to the empty slot (absence of PU). The signal received at primary user is given as:

$$Y_{PU} = \frac{1}{L}\sum_{m=0}^{L-1} y_k[m]^2 \tag{6}$$

where m = 1, 2, 3,4,5, implies that we are using five position for PU in the network. The *m*th position SU linearly processes the received symbol using weighting matrix '$\mathrm{w_m}$' and transmits: $\mathrm{T_m} = \mathrm{Y_m}\,\mathrm{w_m}$ to access link, in the second time slot.

Thus the signal received in the second time is actually the signal received by SU:

$$\mathrm{Z_{SU}} = \mathrm{h^{m}_{CU}}\,\mathrm{T_m} + w_k[\mathrm{m}] \tag{7}$$

The aggregate power constraint at *mth* PU and SU is given by:

$$\sum_{\mathrm{m}=1}^{\mathrm{M}} \mathrm{E}\left\{\mathrm{E_r}\left(\mathrm{Y_m}\,\mathrm{Y^*_m}\right)\right\} \le \mathrm{P}^{m}_{\mathrm{b}} \tag{8}$$

$$\sum_{\mathrm{m}=1}^{\mathrm{M}} \mathrm{E}\left\{\mathrm{E_r}\left(\mathrm{Z_m}\,\mathrm{Z^*_m}\right)\right\} \le \mathrm{P^{m}_{PU}} \tag{9}$$

where $\mathrm{P}^{m}_{\mathrm{b}}$ is the power of base station and $\mathrm{P^{m}_{PU}}$ is the power for mth primary user. In order to define the optimization problem, we take into consideration their total channel Capacities of the contour i.e., PU and SU. Total system throughput will be same as

$$C_{Tout} = \sum_{\mathrm{m}=1}^{\mathrm{M}} R_m \tag{10}$$

where $R_{m,k} = \sum_{m=1}^{M}\left(C_{PU}, C_{SU}\right)$.

where C_{PU} represents throughput of PU and C_{SU} represents throughput of SU. Both C_{PU} and C_{SU} follow the normalized and modified Shannon Hartley capacity formulae in the unit of capacity known as Shannon.

$$C_{PU} = \log_2\left(1 + \frac{h^m_{PU}(h^m_{PU})^H Y_m (Y_m)^H}{\mathrm{n_m}}\right) \tag{11}$$

$$C_{SU} = 1 + \left(\frac{h^m_{SU}(h^m_{SU})^H Z_m (Z_m)^H}{\mathrm{n_m}}\right) \tag{12}$$

The total power consumption for PU and SU is as follows:

$$P_{PU} = \sum_{m=1}^{M} p_{PU} \text{ subject to } \sum p_{PU} \le 1 \tag{13}$$

$$P_{SU} = \sum_{m=1}^{M} p_{SU} \text{ subject to } \sum p_{SU} \leq 1 \tag{14}$$

where P_{SU} is the total power for secondary user, p_{PU} and p_{SU} are power allocation coefficients for PU and SU respectively.

Thus the total power consumption ($\mathrm{P}_{\mathrm{total}}$) in the contour is given as:

$$\mathrm{P}_{\mathrm{total}} = \mathrm{P}_{\mathrm{PU}} + \mathrm{P}_{\mathrm{SU}} \tag{15}$$

The energy efficiency will thus be same as:

$$\mathrm{EE} = \frac{C_{Tout}}{P_{Total}} \tag{16}$$

5 Optimization Problem

The optimization problem is formulated as follows:

$$\overset{max}{P_{PU,}P_{SU}} C_{Tout} \tag{17}$$

$$\overset{max}{P_{PU,}P_{SU}} EE \tag{18}$$

Subject to following constraints:P1:

$$\sum_{m=1}^{M} P_{PU} \leq P_{PU} \tag{19a}$$

$$\sum_{m=1}^{M} P_{SU} \leq P_{SU} \tag{19b}$$

$$p_{PU} \leq 1 \tag{19c}$$

$$p_{SU} \leq 1 \tag{19d}$$

$$\sum_{m=1}^{M} P_{SU} h_{PU} \leq I_{th}^{PU} \tag{19e}$$

$$\sum_{m=1}^{M} P_{SU} h_{SU} \leq I_{th}^{SU} \tag{19f}$$

where $C_{Tout} = \sum_{m=1}^{M} R_m$ is the total system throughput and I_{th}^{PU} and I_{th}^{SU} are interference threshold for m^{th} PU pair and SU link.

5.1 Frame Work For Optimal Solution Using FBMC

P1 is the Fractional Programming (FP) problem with non-concave Fractional objective function and non-linear constraints, and it is difficult to find the optimal solution. Thus P1 is transformed into subtractive problem as:

P2:

$$\text{Max}\left(C_{Tout} - \lambda\left(p_{PU} + p_{SU} + \mu_m C_{Tout}\right)\right) \tag{20}$$

$$\text{S.T.} \quad (C_{PU}, C_{SU}) \tag{20a}$$

where $\lambda=(\lambda_1,\lambda_2,\lambda_3,\ldots,\lambda_m)$ is the langragian multiplier vector and μ_m Is the langragian multiplier associated with m^{th} power constant on both link. The langragian function can be expressed as

$$\begin{aligned} L = \sum_{m=1}^{M} \left[\log_2\left(1 + \frac{h_{PU}^m (h_{PU}^m)^H Y_m (Y_m)^H}{\mathrm{n_m}}\right)\right] + \log_2\left(1 + \frac{h_{SU}^m (h_{SU}^m)^H Z_m (Z_m)^H}{\mathrm{n_m}}\right) \\ + \mu_m P_{Total} \sum (p_{PU} - P_{PU}) \sum (p_{SU} - P_{SU})] \end{aligned} \tag{21}$$

By using KKT, we can solve the concavity of the problem and get an optimal solution.

$$\text{After solving } \frac{\partial L}{\partial p_{PU}} = 0 \text{ and } \frac{\partial L}{\partial p_{SU}} = 0$$

Using KKT condition (Karush–Kuhn–Tucker), we can get optimal solutions as:

$$p_{PU} = \mu_m \left[\sum_{m=1}^{M} \frac{(P_{Total}\mu_m + h_{PU}^m Y_m - n_m)}{\sum P_{PU}} \right] \tag{22}$$

$$p_{SU} = \mu_m \left[\sum_{m=1}^{M} \frac{(P_{Total}\mu_m + h_{SU}^m Z_m - n_m)}{SU} \right] \tag{23}$$

Equation (22) and (23) represents the energy efficient equations for power allocation, depending on user dependent matrices $\mathrm{Y_m}$ and $\mathrm{Z_m}$. Increasing $\mathrm{Y_m}$ and $\mathrm{Z_m}$ will increase the weights leading to water filling phenomenon for channel capacity.

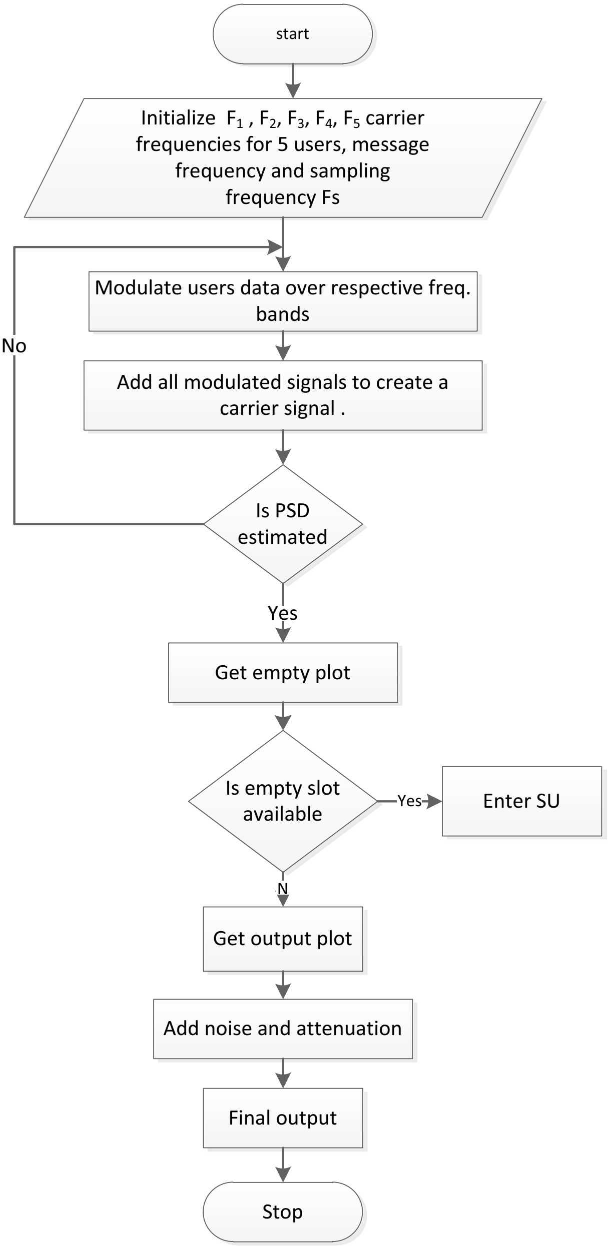
6 Algorithm and Flowchart

Flowchart as shown in Fig. 3 followed by Pseudo code for spectrum sensing:

Pseudo code for channel capacity

```
Step1
    Initialize $F_1$, $F_2$, $F_3$, $F_4$, $F_5$
    $Y_1 = 1, Y_2 = Y_3 = Y_4 = Y_5 = 0$
    QAM.Mod($Y_1, Y_2, Y_3, Y_4, Y_5$)
    $N_T, N_R, P_{PU}, P_{SU}, P_b$
Step 2
    $Y = Y_1 + Y_2 + Y_3 + Y_4 + Y_5$
    $P_{XX}$ = Periodiogram
    SNR = 0;
    $F_r$ $I = 1$: length($P_{XX}$)
    SNR = SNR + 2
    Switch (OFDM)
    Update power allocating coefficients using equation (22) & (23)
    if $P_{PU} \leq 1$ & $P_{SU} \leq 1$
    Calculate
    Channel capacity using equation (11) and (12)
    Switch (LTE)
    Update power allocating coefficients using equation (22) & (23)
    if $P_{PU} \leq 1$ & $P_{SU} \leq 1$
    Calculate
            Channel capacity using equation (11) and (12)
    Switch (FBMC)
    Update power allocating coefficients using equation (22) & (23)
    if $P_{PU} \leq 1$ & $P_{SU} \leq 1$
    Calculate
            Channel capacity using equation (11) and (12)
Step 3
    Make SU entry
Step 4
    Go to step 2
Step 5
    If all slots occupied
    End
```

Fig. 3 Flowchart for spectrum sensing



7 Results and Discussion

Figure 4 shows the channel capacity versus CDF when only one PU is present and four PU are absent. The channel is in worst condition with four empty slots. Conventional OFDM capacity in bits per second (Shannon) is almost 0.08 (Shannon). However capacity due to LTE and FBMC is utilized for positions of PU. The LTE is having much

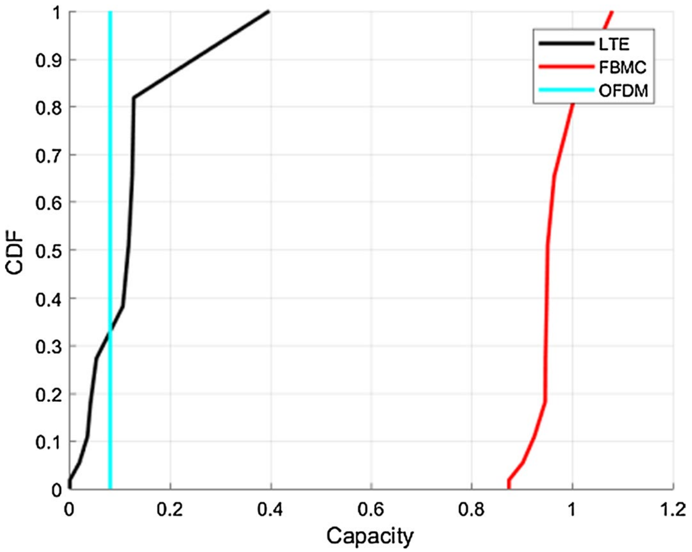


Fig. 4 CDF versus capacity for P A A A A

smaller capacity as compared to FBMC. When FBMC is employed, capacity starts increasing drastically. At the 5th percentile CDF level capacity due to LTE is 0.01 (Shannon) while FBMC increases the capacity to approximately 0.88 (Shannon). Similarly for 50th percentile CDF level capacity for LTE is 0.18 (Shannon) and for FBMC it is almost 0.9 (Shannon).

Figure 5 shows the channel capacity versus CDF when one SU occupies the empty slot leaving three slots empty. Again OFDM capacity is almost constant for all percentiles of

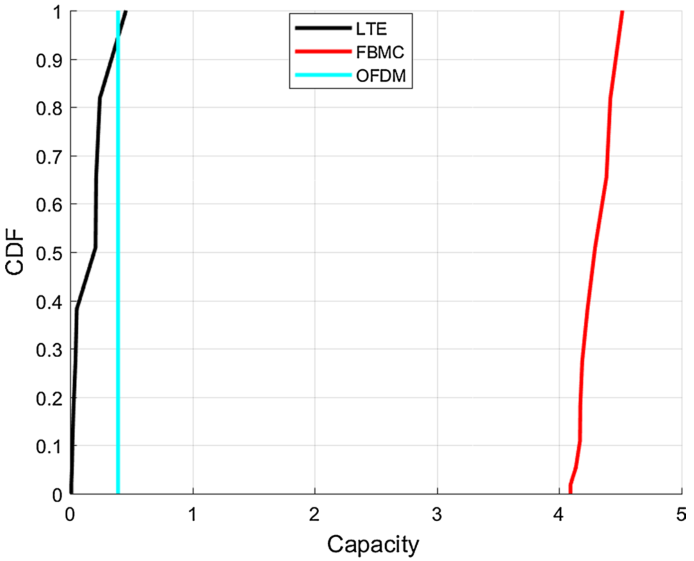


Fig. 5 CDF versus Capacity for P P A A A

CDF. However in this iteration capacity increases to 0.3 (Shannon). Again we can see the LTE and FBMC capacities varying. At 5th percentile CDF level capacity due to LTE is almost negligible and the proposed FBMC increases the capacity to almost 4.05 (Shannon). Similarly at 50th percentile CDF level capacity due to LTE is 0.25 (Shannon) and capacity due FBMC is 4.2 (Shannon).

Figure 6 shows the channel capacity versus CDF for third iteration i.e. when SU occupies one more slot leaving two slots empty. Channel capacity again set increased for OFDM, LTE and FBMC. OFDM channel capacity is again constant but more than previous iteration. OFDM channel capacity is almost 6.0 (Shannon). FBMC again significantly increased the capacity as compared to LTE for all percentiles of CDF. For 5th percentile of CDF level channel capacity due to LTE is only 1.0 (Shannon) while FBMC increases capacity to about 62.0 (Shannon). Similarly for 50th percentile CDF level capacity due to LTE is 9.0 (Shannon) while due to FBMC it is 68.0 (Shannon).

Figure 7 shows the channel capacity versus CDF when SU occupies three slots, leaving only one slot empty. There is more improvement in channel capacity with the occupation of one more slot. OFDM capacity is again constant for all percentiles of CDF. OFDM capacity is almost equal to 18.0 (Shannon). For 5th percentile CDF level capacity is almost 2.0 (Shannon) while for FBMC capacity is approximately 130 (Shannon). For 50th percentile CDF level capacity due to LTE is almost 20.0 (Shannon) while for FBMC it is 140 (Shannon).

Figure 8 shows the channel capacity versus CDF when SU occupies one more slot i.e. no slot is left empty now, since all slots sets occupied. This is the case where efficient resource allocation takes place. There is a significant increase in channel capacity for OFDM, LTE and FBMC. OFDM capacity is almost constant and is equal to 30.0 (Shannon) for all percentile of CDF. The LTE capacity for 5th percentile CDF is approximately 10.0 (Shannon). While for FBMC users capacity improved to 450.0

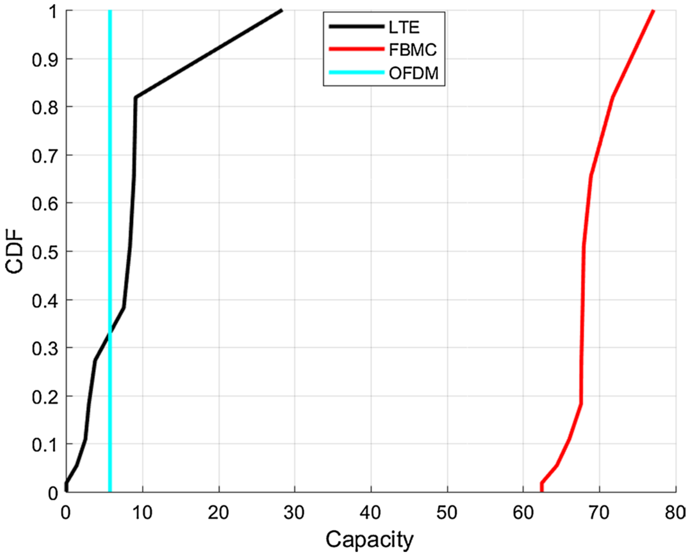


Fig. 6 CDF versus Capacity for P P P A A

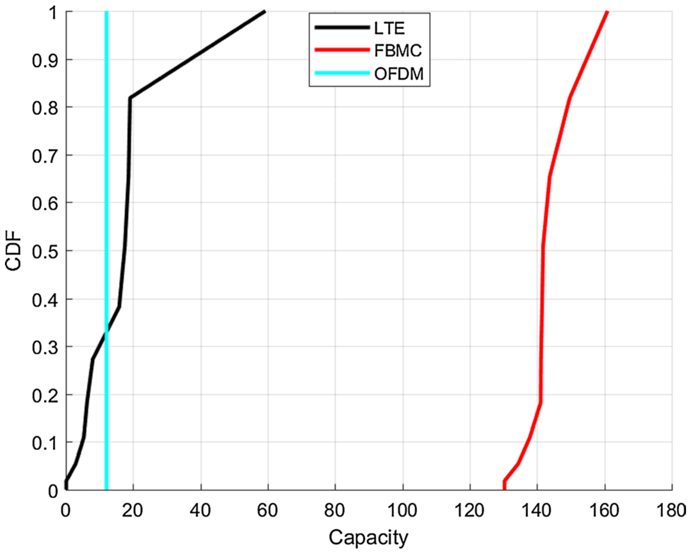


Fig. 7 CDF versus Capacity for P P P P A

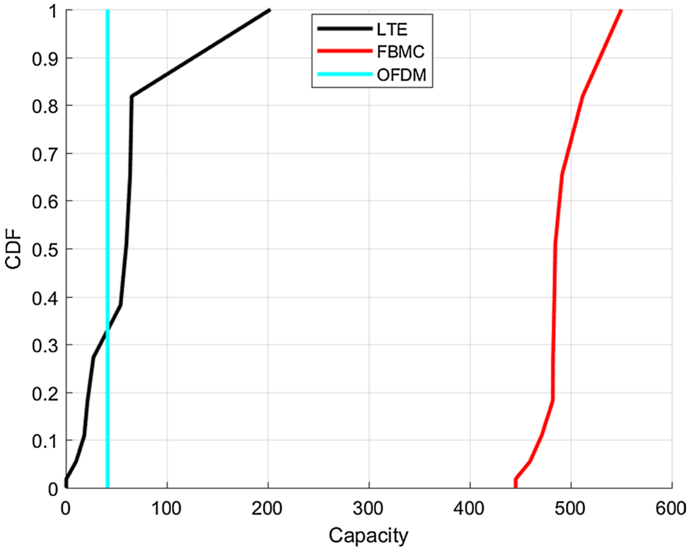


Fig. 8 CDF versus Capacity for P P P P P

(Shannon). Similarly for 50th percentile CDF level LTE capacity is 60.0(Shannon) while FBMC capacity is 490.0 (Shannon).

8 Conclusion

In this paper an understanding and integration of Cognitive Radio with the 5G wireless networks to fulfill the demand and challenges of future 5G networks has been presented. The proposed technique can prove to be intelligent and be able to use network resources in an efficient manner. The optimization principle has been mathematically integrated with the cognitive radio for 5G networks. Since the work proposed in this paper integrates the cognitive radio with the 5G networks using optimization techniques, therefore it will prove ideal candidate for deploying the 5th generation wireless networks with IOT platform for smart cities. Moreover the proposed technique will also act as benchmark for further research of using bio inspired optimization techniques for efficient integration of cognitive radio with the future 5G networks.

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