CrossMark

Performance analysis of FBMC-CR through optimization: tradeoff between various performance parameters in the cognitive radio environment

A. S. Kang[1] · Renu Vig[1]

Abstract This paper provides the detailed simulation analysis of Filter Bank Multicarrier Cognitive Radio for doing tradeoff between the parameters of cognitive radio for achieving optimum performance. An attempt for tradeoff between different transmission-radio environment parameters has been done as this leads to an increase in spectrum efficiency by decreasing the spectral leakage which provides optimal performance. The optimization-tradeoff between different radio environment parameters is necessary for prediction and planning of future wireless communication systems. Transmission, reception and radio environment parameters play a key role in the performance enhancement of FBMC cognitive radio.

Keywords FBMC · Cognitive radio · Filter Bank · Multicarrier

1 Introduction: role of cognitive radio in next generation wireless communication

A cognitive radio is essentially a software defined radio running under the control of an intelligent software package called a "cognitive engine". The term cognitive radio (CR) was first defined by Joseph Mitola III [1–3]. According to Mitola, CR technology is the "intersection of personal wireless technology and computational intelligence, "where CR is defined as a smart radio that would be self-aware, RF-aware, user-aware, with a lot of high-fidelity knowledge of the radio environment". Cognitive radios are aware of their surrounding environment and bandwidth availability, and are able to dynamically tune the spectrum usage on the basis of location, nearby radios, time of day and other factors. This provides for better use of the spectrum as well as reduced power consumption. Various devices will be able to detect other radios around them and work together to optimize the use of spectrum, allocate resources, and ultimately communicate with their peers [4]. Cognitive radio offers new opportunities for the wireless industry and consumers to cope with the ever increasing mobile data traffic. Cognitive technologies can significantly enhance the overall utilization of spectrum, by allowing sharing in bands where it was earlier not possible [5].

2 Drivers of the present problem

A fundamental problem facing the future wireless communication systems is where to find the suitable spectrum bands to meet the demand of future services [6]. In order to overcome this problem and improve spectrum utilization, cognitive radio concept has evolved. To build a highly adaptive radio technology that learns from the environment to best serve its user, multi rate signal processing techniques need to be developed for different functionalities of cognitive radio [7,8].

2.1 Role of FBMC over OFDM in cognitive radio physical layer

Multi rate systems and filter banks have played an important role in source coding and compression for contemporary communication applications [9,10]. Multi rate DSP is applied in digital systems where more than single sampling rate is the requirement [11]. Filter Bank Multicarrier (FBMC)

✉ A. S. Kang
   askang_85@yahoo.co.in

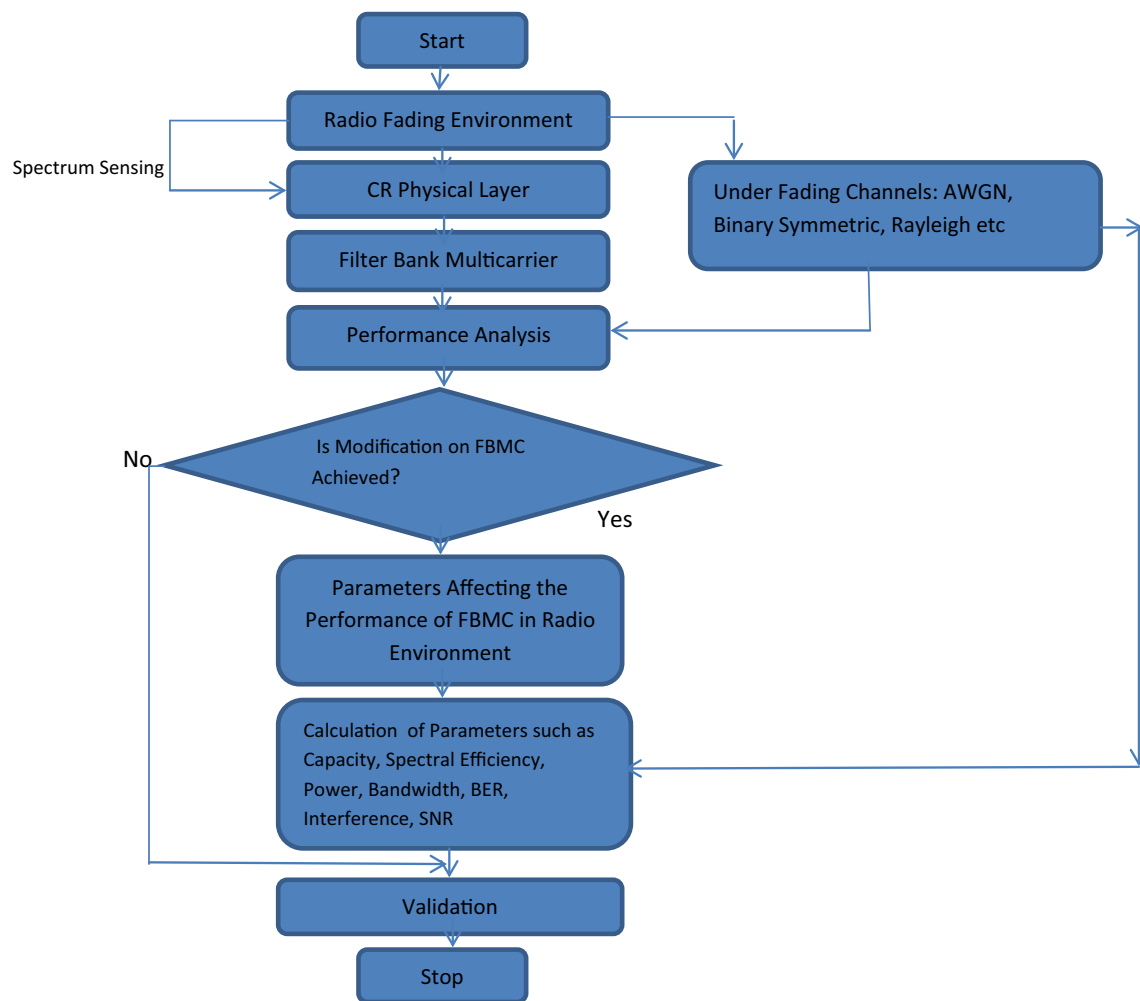[1] Department of ECE, UIET, Panjab University, Chandigarh, India

Fig. 1 Optimization-tradeoff between different radio environment parameters for future wireless cognitive radio

has advantages over OFDM such as reduced guard bands between users and improved spectral efficiency due to lack of Cyclic Prefix and reduced synchronization requirements due to very good spectral containment. Hence, this Filter Bank Multicarrier Technique is used in spectrum sensing in cognitive radio. Various applications of multi rate signal processing are in the field of Communication Systems, Speech & Audio Processing Systems, Antenna & Radar Systems. Advanced techniques on multi rate signal processing can be applied for digital information processing due to the advantages like lesser computational requirements, less storage for filter coefficients, less finite arithmetic effects, low requirement of filter order in multi rate application, less sensitivity to filter coefficient length [12]. Filter Bank Multicarrier System (FBMC) with offset quadrature amplitude modulation (OQAM) can achieve smaller inter symbol interference (ISI) and Inter Carrier Interference (ICI) without using the CP by utilizing well designed pulse shapes that satisfy the perfect reconstruction conditions [13, 14]. Moreover, the problem of

the spectral leakage can be solved by minimizing the side lobes of each sub carriers which leads to high efficiency (in terms of spectrum and interference). Filter Bank Multicarrier (evolving OFDM-OQAM) techniques have been recommended to replace conventional OFDM multicarrier technique for CR transmission [15] (Fig. 1).

3 Flowchart for present study: $Lp = KM + 1$ (performance analysis of modified FBMC)

A Flowchart has been prepared for study of effect of sub channels M on prototype filter length Lp for FBMC cognitive radio has been discussed. The distinctive feature of the FBMC design technique has ability to provide improved frequency selectivity through the use of longer and spectrally well shaped prototype filters. In the present case, more emphasis has been laid on the $Lp = KM, KM - 1 - D, KM +$
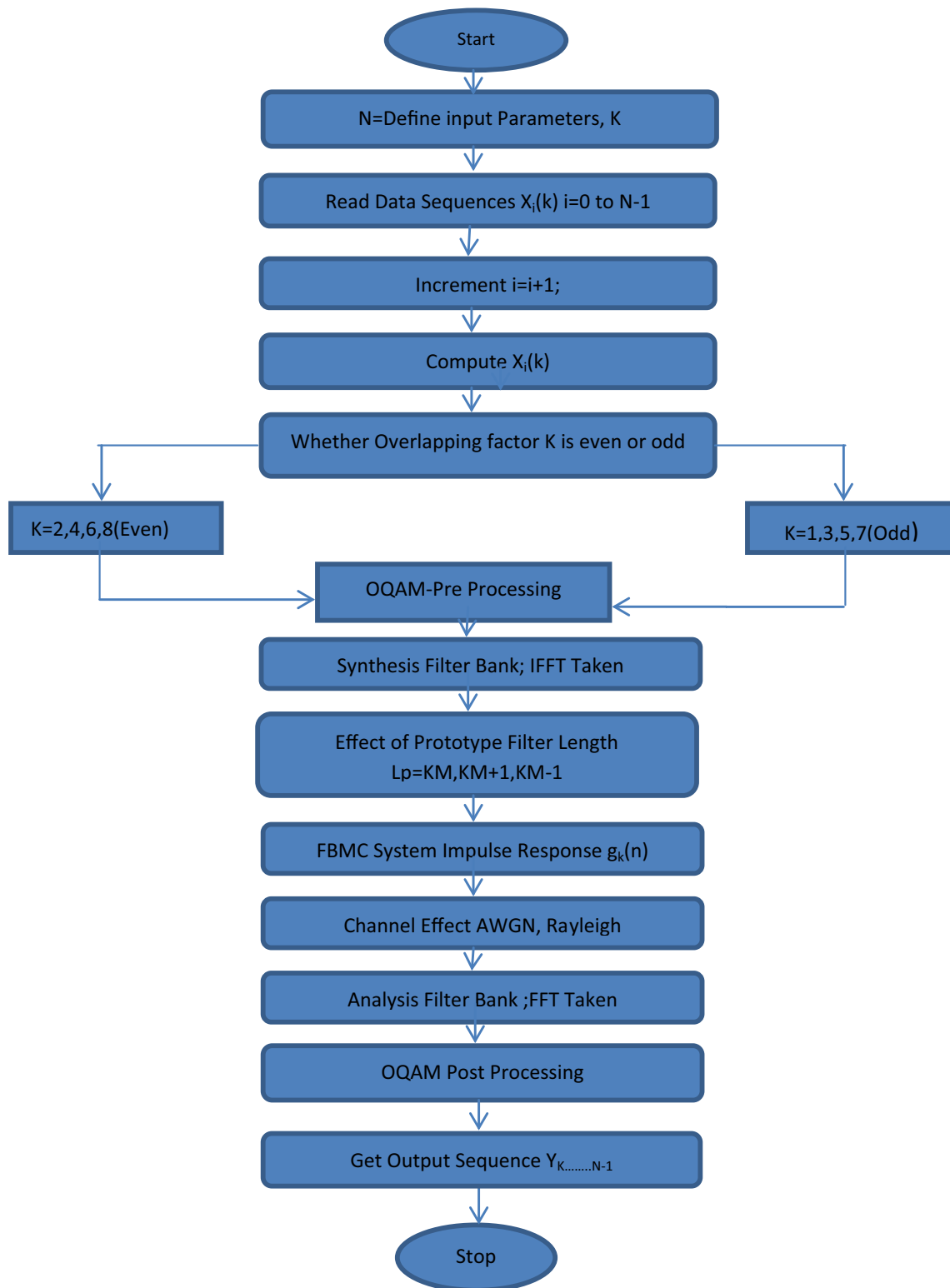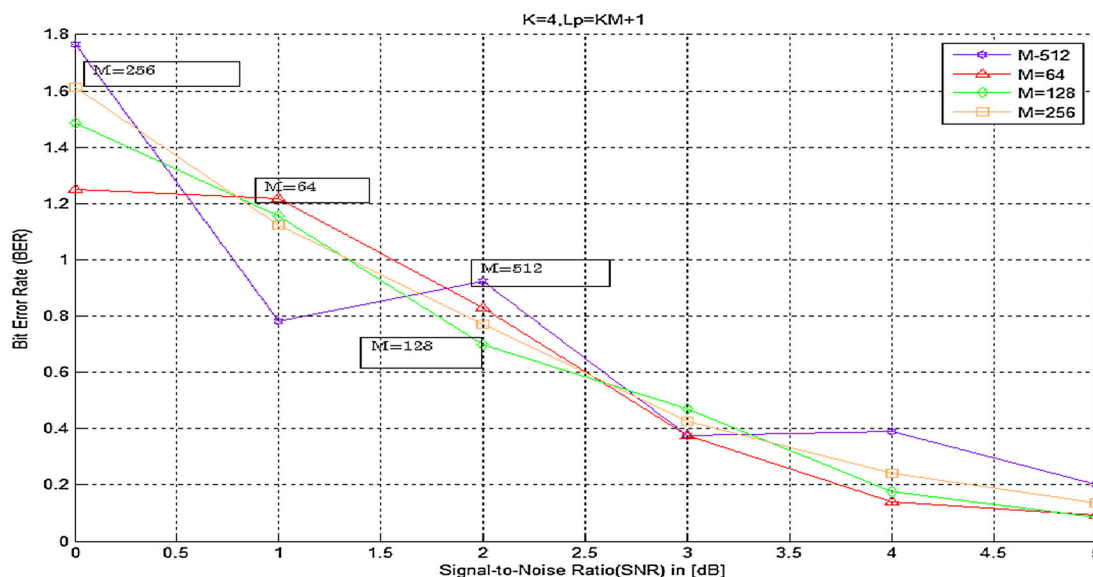
Fig. 2 Flow diagram of FBMC
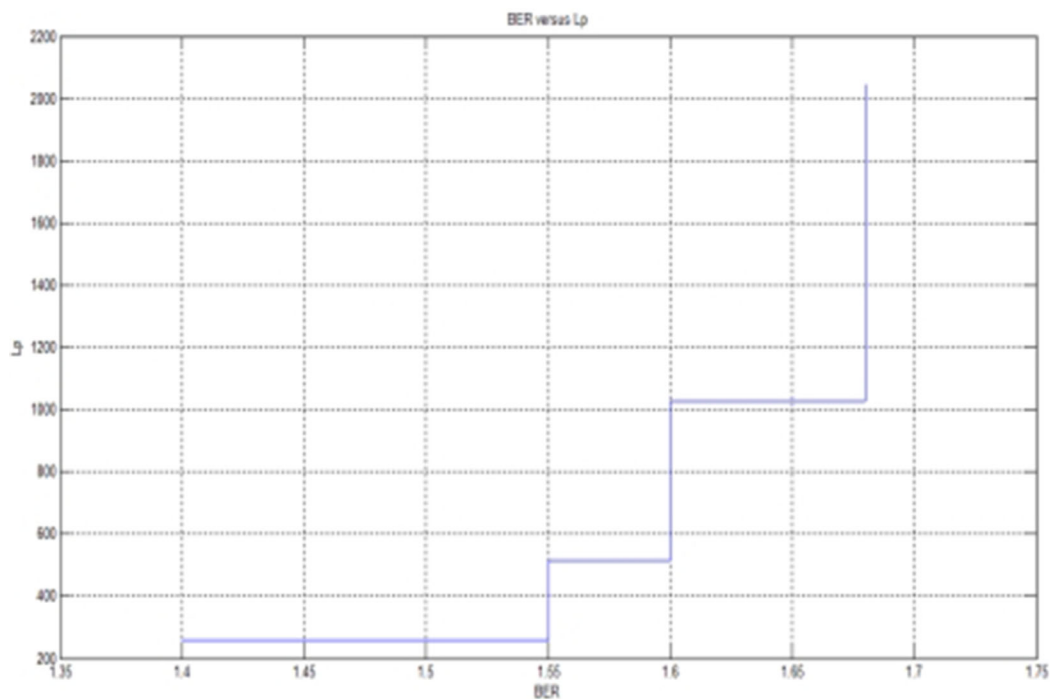
Fig. 3 BER versus SNR at K = 4, Lp = KM + 1

Fig. 4 Staircase Plot between Lp and BER

3.1 Results and discussion

Different graphic plots have been obtained between the various parameters namely number of sub channels M, bit error rate (BER), signal to noise ratio (SNR), prototype filter length Lp = K × M + 1 at a fix value of Overlapping factor K = 4. The spectrum sensing is performed by measuring the signal strength at the outputs of the subcarrier channels at the receiver. The cognitive radio system is able to transmit over the direct link more than that when the direct link is blocked for all subcarriers in the source side. The impact of the present
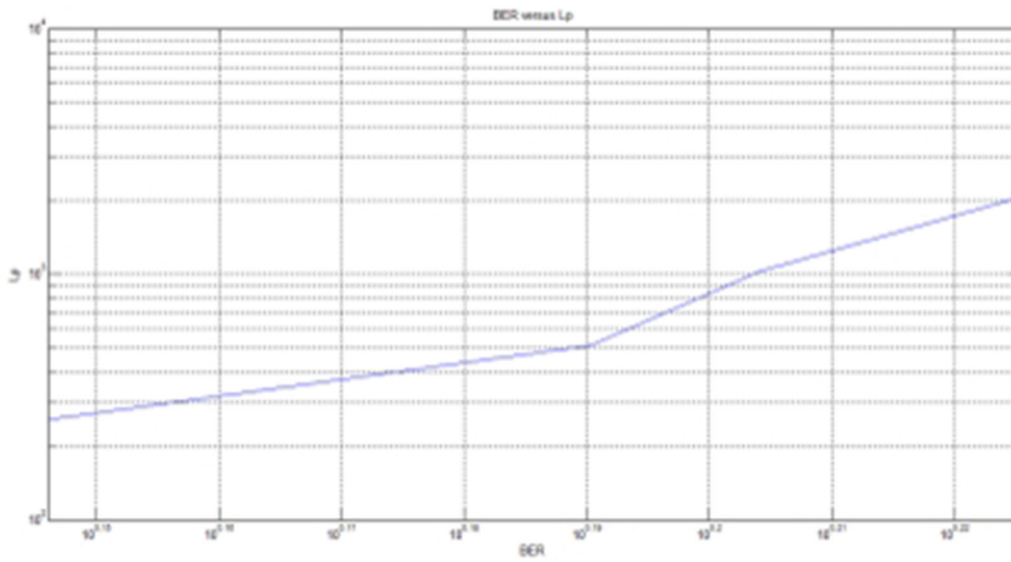
1 − D as a specific prototype filter length, under the assumption of Group Delay D of filter as zero in all the cases (Fig. 2).

Fig. 5 Loglog plot between Lp and BER
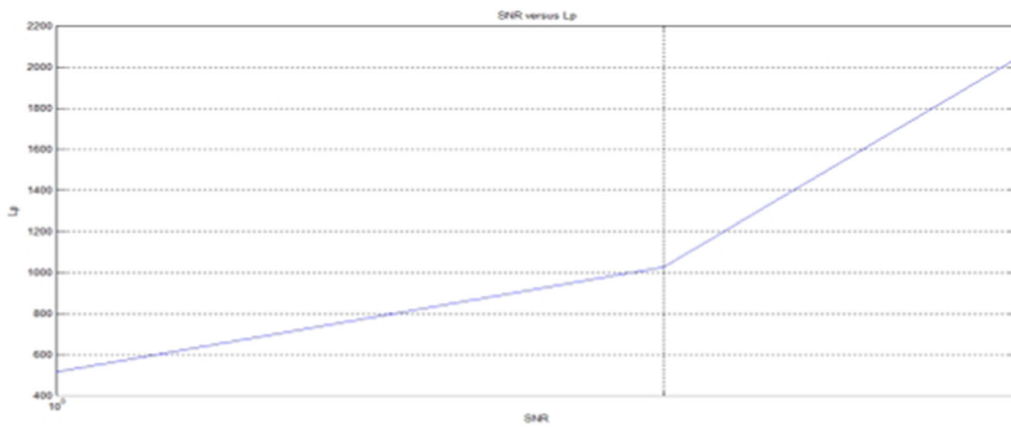

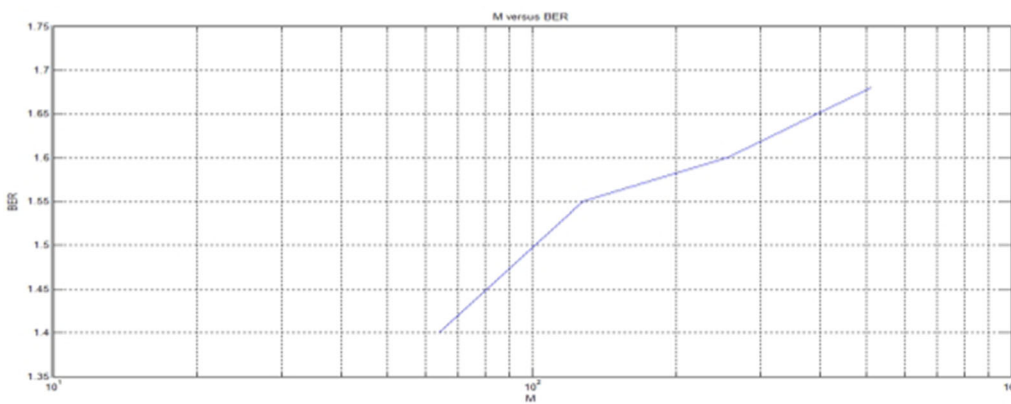**Fig. 6** Plot obtained between SNR and Lp
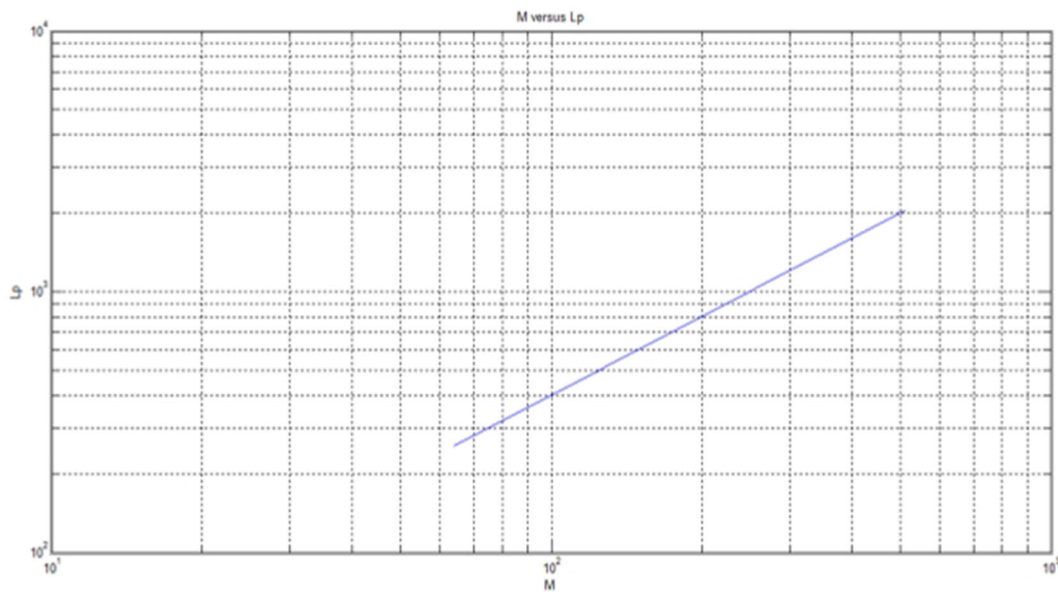

Fig. 7 Plot obtained between M and BER
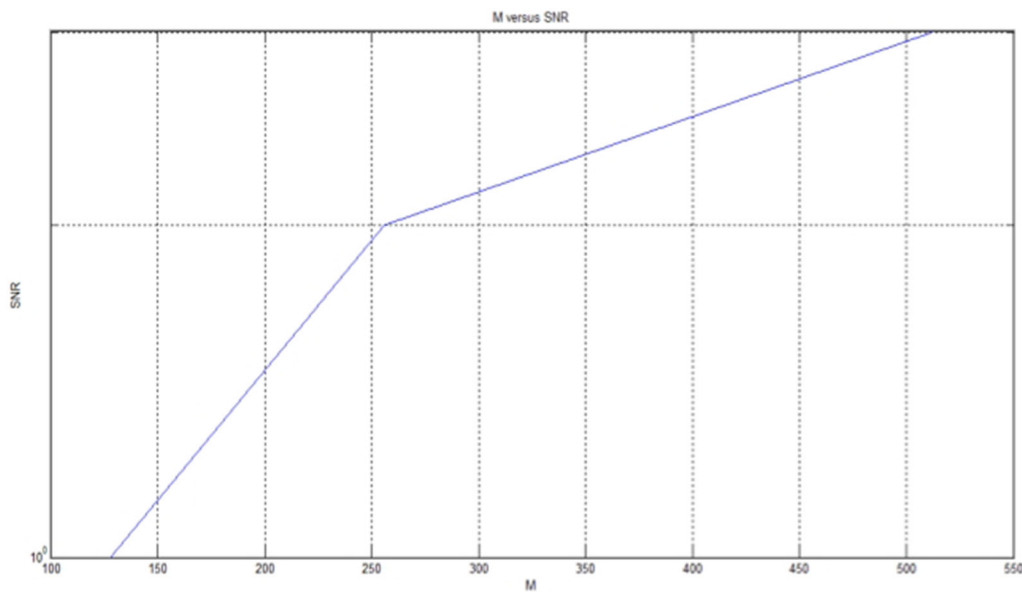
Fig. 8 Plot obtained between M and Lp

Fig. 9 Plot obtained between M and SNR

study of FBMC CR is highlighted through the role of number of sub channels. Readjustment of various parameter levels leads to optimization between different radio environment parameters under varying strategic conditions. The computational complexity of the FBMC cognitive radio is studied under the effect of K, M and Lp. For FBMC system, the prototype filter coefficients are assumed to be matching the Physical Layer for Dynamic Spectrum Access (PHYDAS) coefficients with overlapping factor K = 4 (optimum). Actually, the entire process here involves the three steps. fixing

the subcarriers, matching the subcarriers and re-adjusting the assigned subcarriers as per the system requirement on an average basis. For optimization and tradeoff sake, the number of subcarriers is taken to be greater than 64. The literature survey on FBMC shows that the different subcarriers are adjusted in such a way that the interference to the primary user by secondary users is kept to a minimum. Moreover, the impact of different constraint values on the system performance is investigated. This section formulates a problem to select and match some subcarriers for transmission
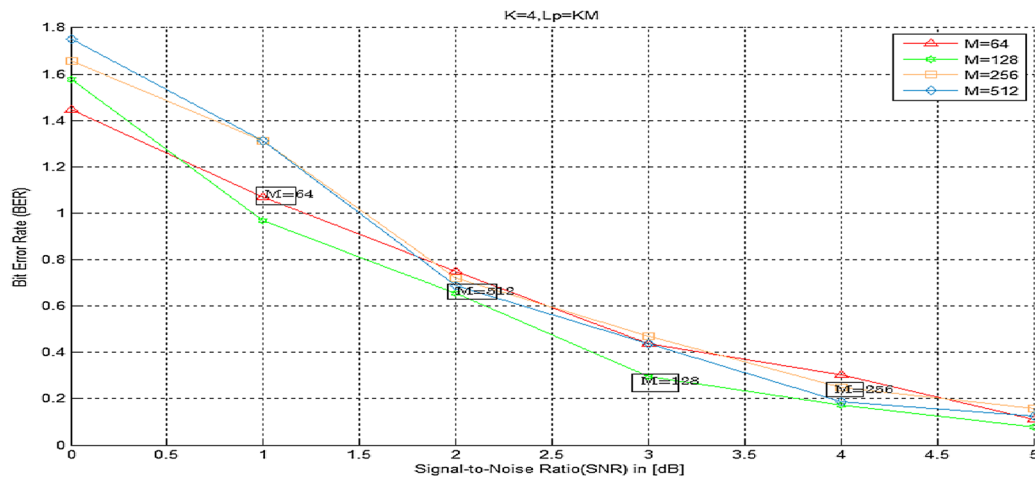
Fig. 10 Plot between BER and SNR at K = 4, Lp = KM with M = 64, 128, 256, 512
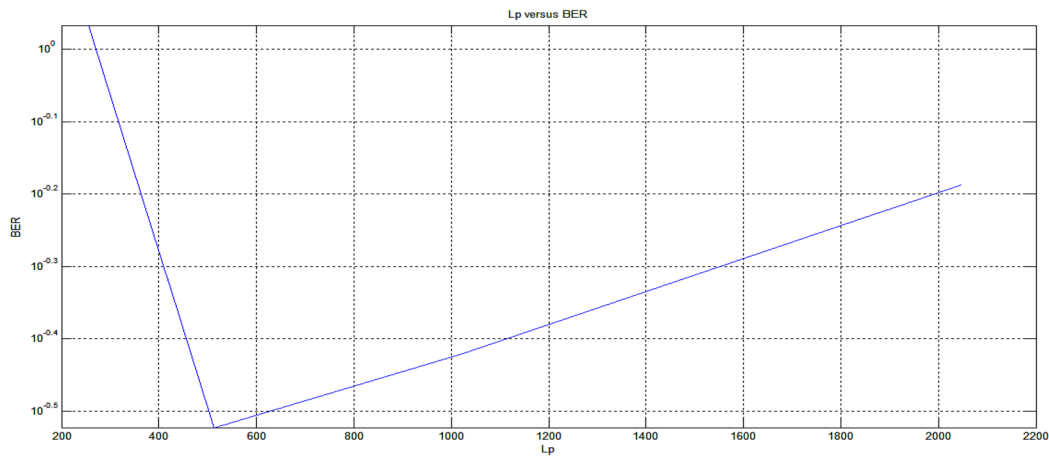

Fig. 11 Plot between Lp and BER

and use the rest only for direct transmission. The FBMC CR in physical layer is a potential candidate for future wireless communication system. A Bandwidth of 10 MHz (within a useful BW range of 6–10 MHz) with M = 64, 128, 256, 512 subcarriers has been taken into consideration in the present scenario. The subcarriers are allocated sequentially to the users with optimum results. In Fig. 3 BER is found to be decreasing with increasing values of SNR. A staircase plot between Lp and BER has been shown in Fig. 4. Plots between various performance parameters have been depicted in Figs. 5, 6, 7, 8 and 9.

3.2 Results and discussion: Lp = KM

Figure 10 shows BER versus SNR plot at different values of M. The trend for M values has been clearly shown here. At M = 64, BER = 1.45 at SNR = 0 dB, BER = 1.1 at

SNR = 1 dB, BER = 0.75 at SNR = 2 dB, BER = 0.45 at SNR = 3 dB, BER = 0.3 at SNR = 4 dB, BER = 0.1 at SNR = 5 dB. It is very clear that at higher values of M initial values of BER are found to be higher than 1.45 at SNR = 0 dB. The values of SNR chosen are well within the range (−5 to +30 dB) as per specifications of IEEE 802.22 Standard for FBMC cognitive radio. Figure 11 shows the plot between Lp and BER which shows that beyond Lp = 500, BER is found to rise to a value $10^{-0.2}$ till Lp = 2000. Figure 12 shows plot between Lp and SNR which clearly shows SNR decrease beyond Lp = 10^3. Figure 13 shows the plot between M and BER which indicates that beyond M = 10^2, BER increases to $10^{-0.2}$. Figure 14 shows with M more than 10^2, Lp becomes more than 10^3. In Fig. 15, SNR decreases to 2 dB beyond M = 10^2. Various performance parameters have shown that with increasing BER, SNR is found to decrease and vice versa.
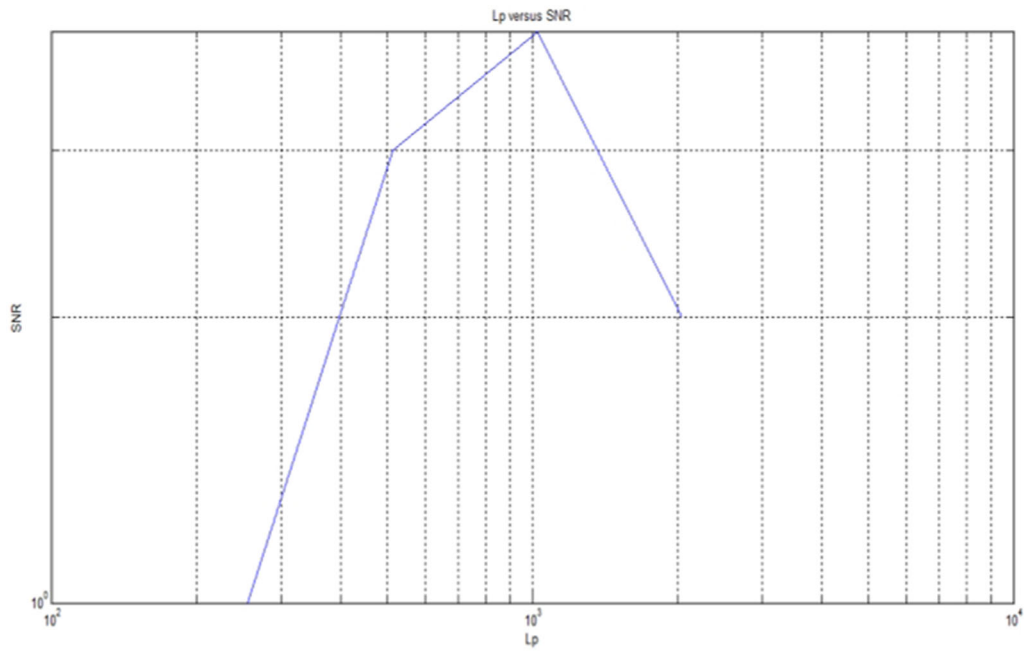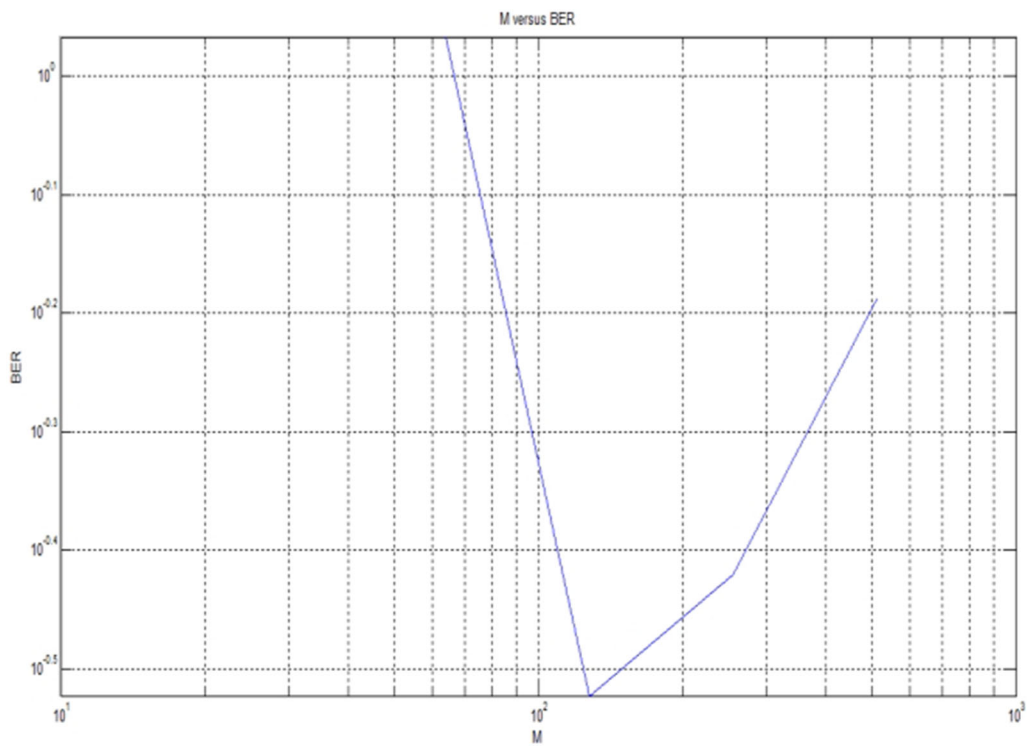
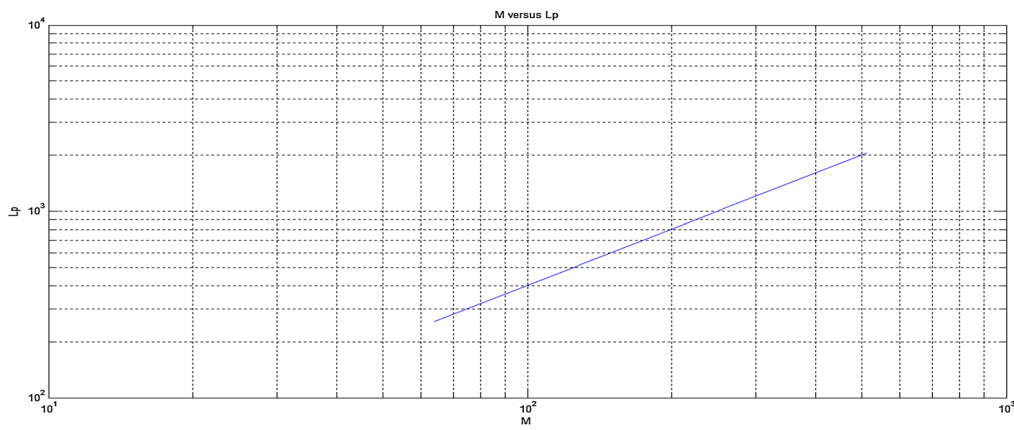**Fig. 12** Plot between Lp and SNR

Fig. 13 Plot between M and BER
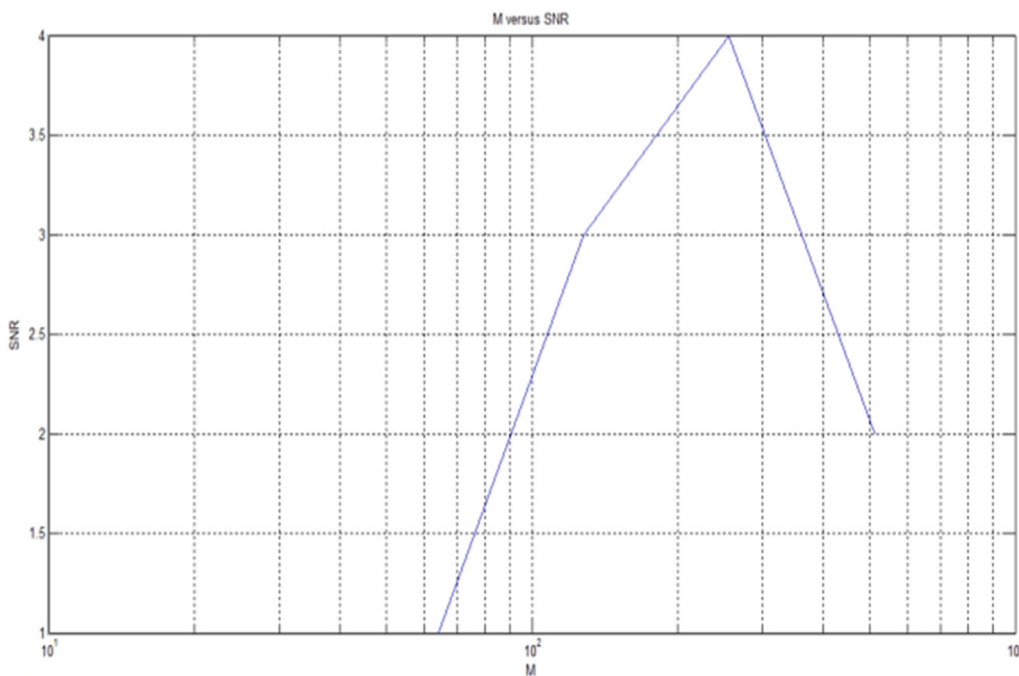
Fig. 14 Plot between M and Lp

Fig. 15 Plot between M and SNR

3.3 Lp = KM − 1

The plots obtained between various parameters, number of sub channels M, BER, SNR, prototype filter length Lp = K × M + 1 at a fix value of overlapping factor K = 4 here (Figs. 16, 17, 18, 19, 20, 21, 22).

Below are the Matlab graphs obtained between various performance parameters namely, channel capacity, spectral efficiency, BER, Eb/No, interference, power, bandwidth for performance analysis of FBMC cognitive radio (Figs. 23, 24, 25, 26, 27, 28, 29, 30, 31).

The spectral efficiency $\quad \eta = P \cdot R_{av}G/B \quad$ (1)

where P is the peak data rate taken as 15.36×10^6 and $R_{average}$ is the modulating and coding scheme average factor while B represents the Channel Bandwidth = 6, 7, 8, 9, 10 MHz in the useful range as per the PHYDAS (Physical Layer for Dynamic Spectrum Access) Specifications D5.1 [14]. The well known formula for calculating Channel Capacity C, as per Shanon Hartley Theorem, is stated as

$C = Blog_2(1 + SNR)Bits/ sec /Hz \quad$ (2)

Table 1 shows the BER values computed in FBMC CR Simulink model using AWGN channel at different values of Eb/No. At a decimation factor 1/3 in FIR decimation filter
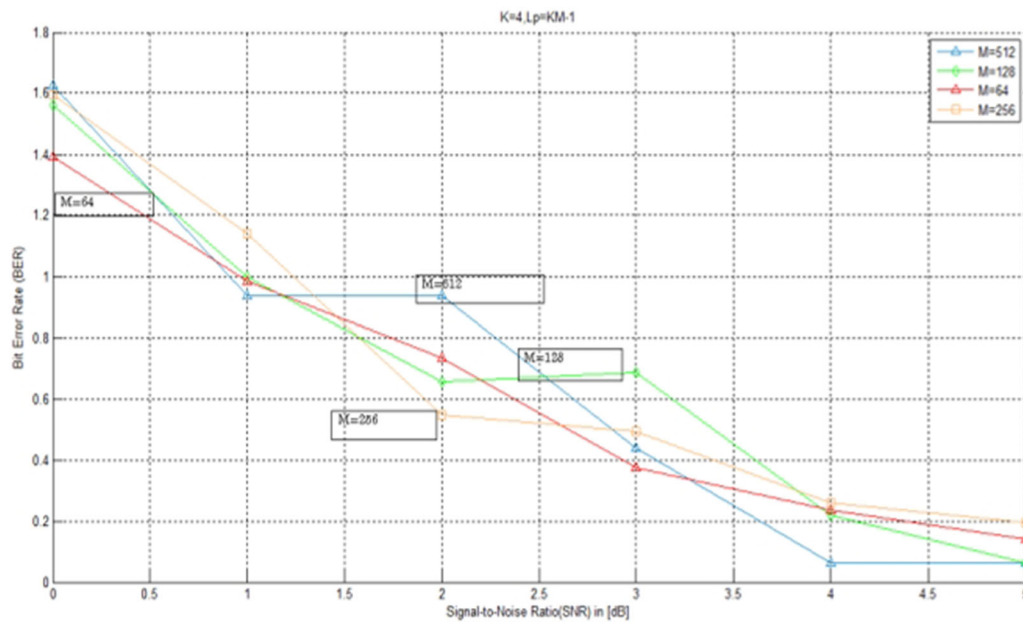
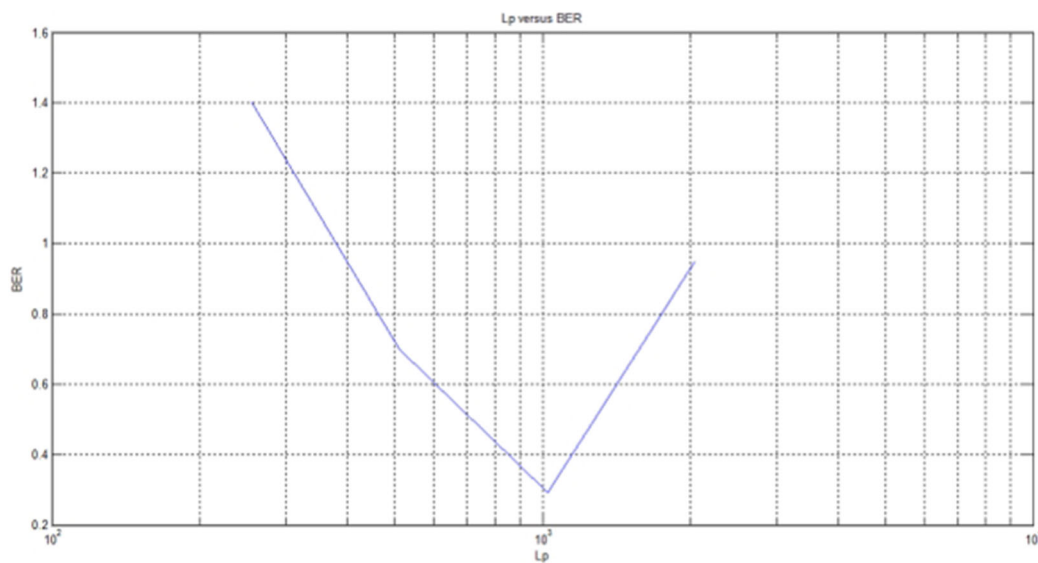**Fig. 16** BER versus SNR plot at K = 4, Lp = K × M − 1

Fig. 17 Plot between Lp and BER

and interpolation factor of 3 in FIR interpolation filter, it has been found that BER comes out to be 0.1223 approximately. While for the same model at a decimation factor 1/2 and interpolation factor of 2, the BER comes out to be around 0.01235. At a decimation factor of 1/8 and interpolation factor of 8, BER calculated through Simulink model is approx 0.01224.

Table 2 shows the calculated values of AWGN channel capacity for FBMC-CR system under the effect of varying Eb/No (dB) as 12, 13, 14, 15, 16 for different values of BW =

6, 7, 8, 9, 10 MHz when sample time Ts = 1/4000 (Figs. 32, 33, 34, 35, 36, 37, 38, 39, 40; Tables 3, 4, 5, 6, 7, 8).

3.4 OFDM: BER-SNR performance analysis

4 Evaluation of experimental environment and future scope of work

The comparative BER performance analysis of FBMC CR based Simulink model under binary symmetric channel
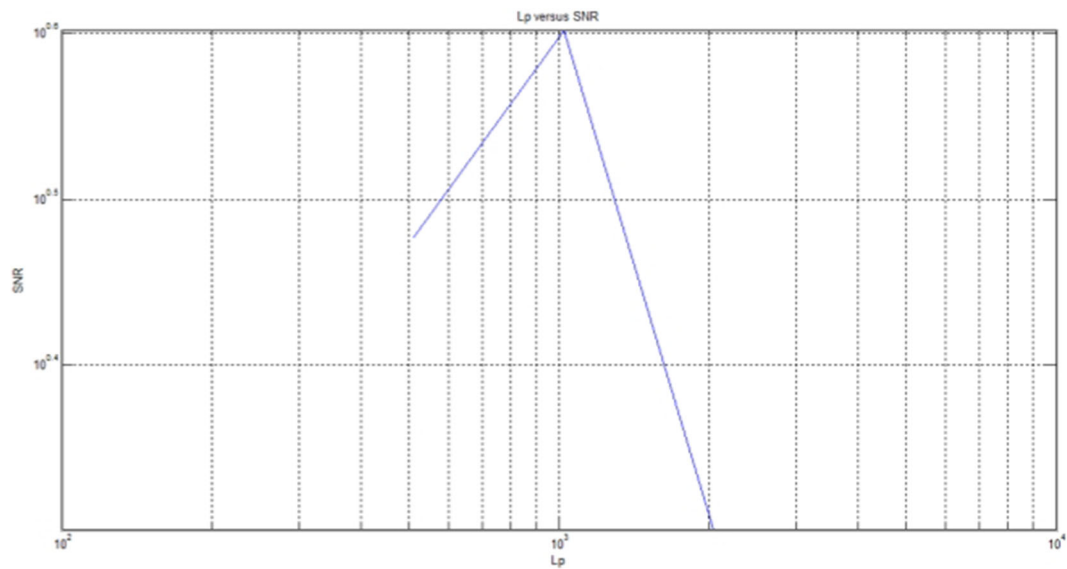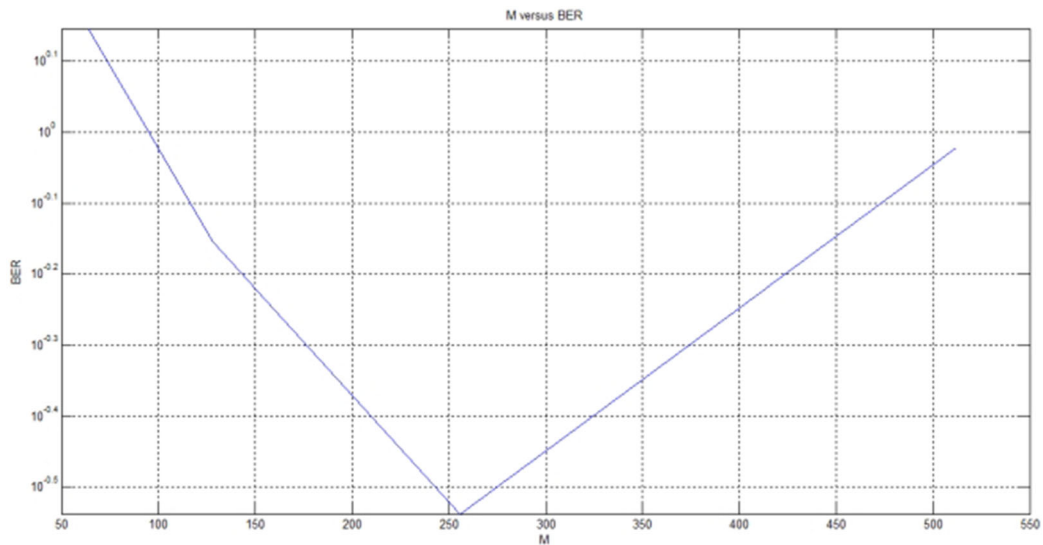
Fig. 18 Plot between Lp and SNR

Fig. 19 Plot between M versus BER

(BSC) with different error probabilities and under the effect of band filter and Two Channel Synthesis Sub band filter with AWGN channel in between has been shown in Table 9. The study is useful to improve the performance of CR system under different signal impairments, channel modulation techniques for Physical layer CR. The computer modeling and simulation of interference analysis by using different techniques in Physical layer CR wireless environment has led to the improvement in terms of gain for channel capacity and spectral efficiency with minimum BER and least power requirements. Better utilization of available spectrum rf bandwidth is possible by reduction of multiple access interference, a major factor in system capacity and quality of communication at a minimum power level. The proposed CR simulators can be used for capacity, coverage and quality analysis. It works on a trade-off algorithm of chan-
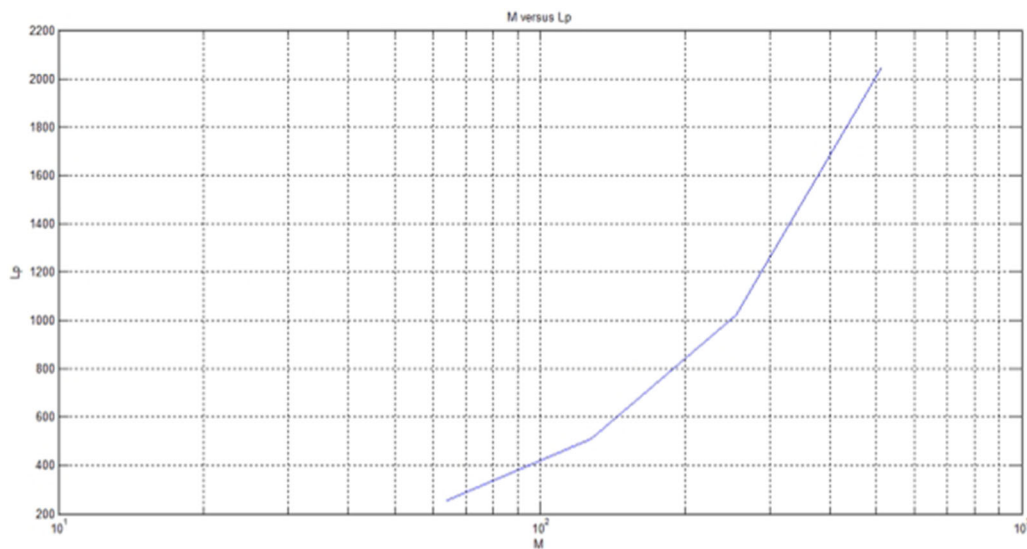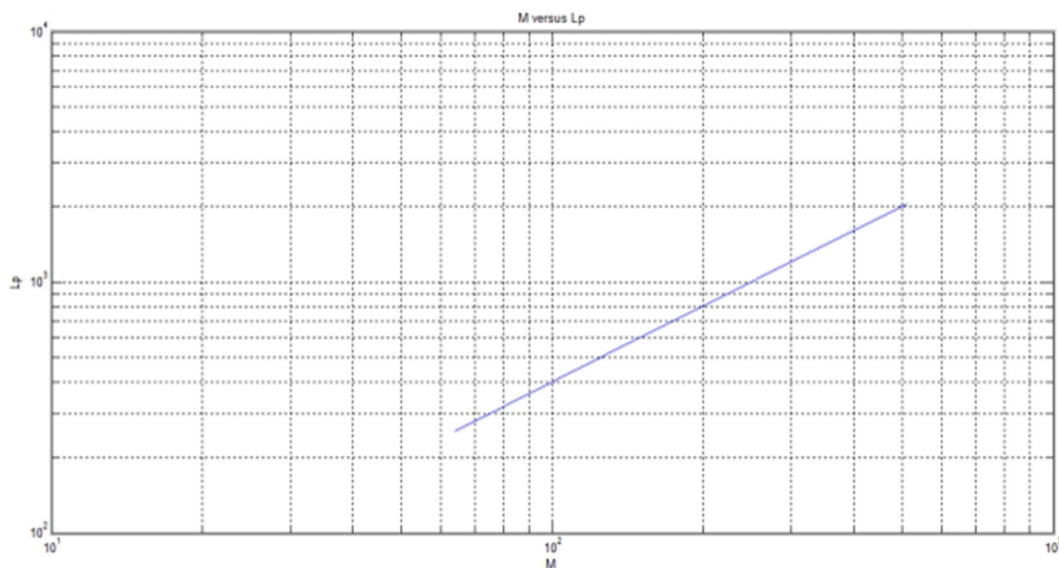
Fig. 20 Plot between M and Lp

Fig. 21 Plot between M and Lp

nel capacity, spectral efficiency, BER, power, interference, bandwidth, SNR (Eb/No), overlapping-factor/prototype filter length, number of sub channels used, power spectral density, interpolation, decimation, single channel/multi channel sub band processing through multirate filter banks in a TMUX configuration. So, this study is useful for CR wireless network planning, optimization with various mobile services. Rayleigh, Rician, Nakagami, Weibull fading channels are available to replace AWGN and binary symmetric channel models to simulate the system under mobility radio channel. The performance higher than optimal can be achieved by incorporating more influential parameters of interest in sys-

tem level simulation models using adaptive signal processing approach. Attempts should be made to develop newer models of CR on lab view, system view within SNR range for cognitive radio operation −5 to +40 dB. Radio Spectrum Management at Physical Layer CR still may not provide sufficient Bandwidth. Spectrum sensing in cognitive radio under media access control layer of OSI Model can be done as spectrum sensing cognitive radio enhancement to ProToMAC (Proactive Transmit Opportunity Detection at MAC Layer). The work can be extended to develop algorithms which further enhance the network coverage and higher interference suppression in a cognitive radio network.
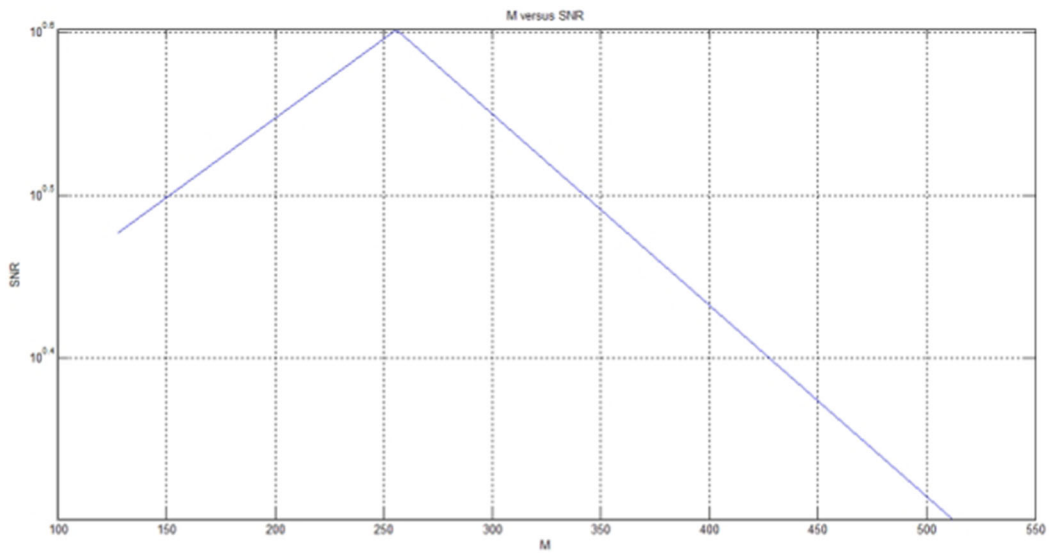
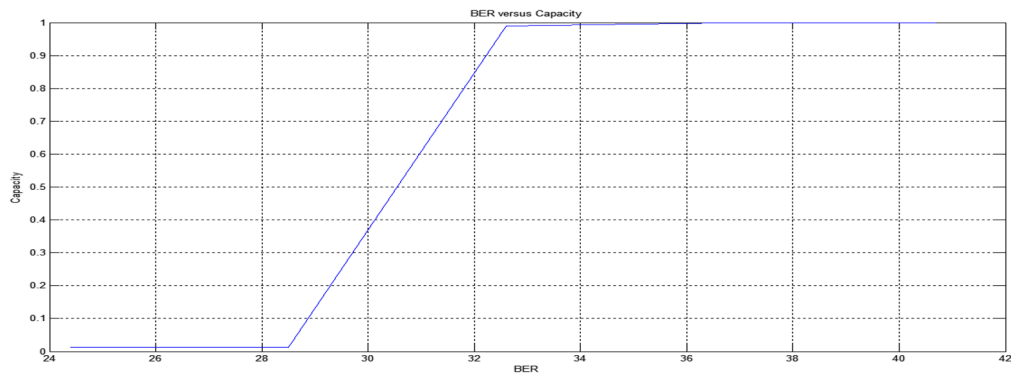**Fig. 22** Plot between M and SNR

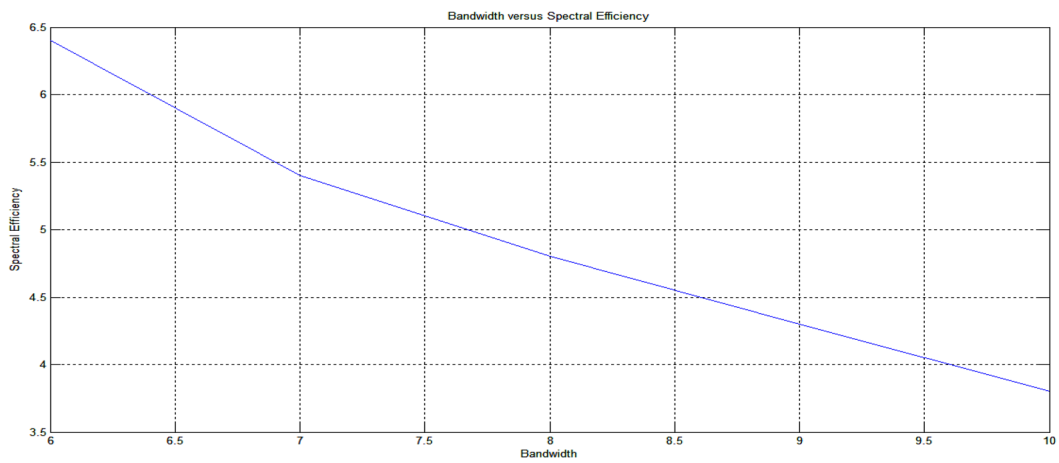**Fig. 23** BER versus capacity

Fig. 24 Bandwidth versus spectral efficiency
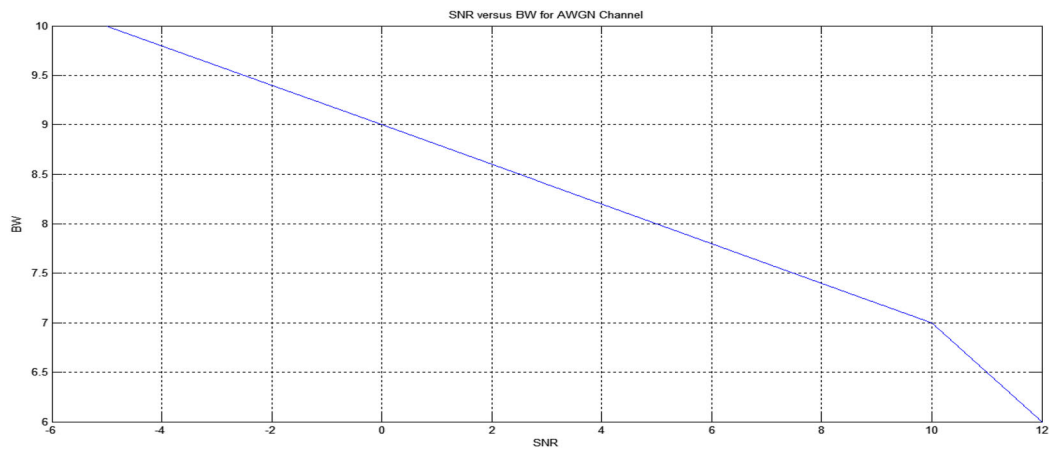
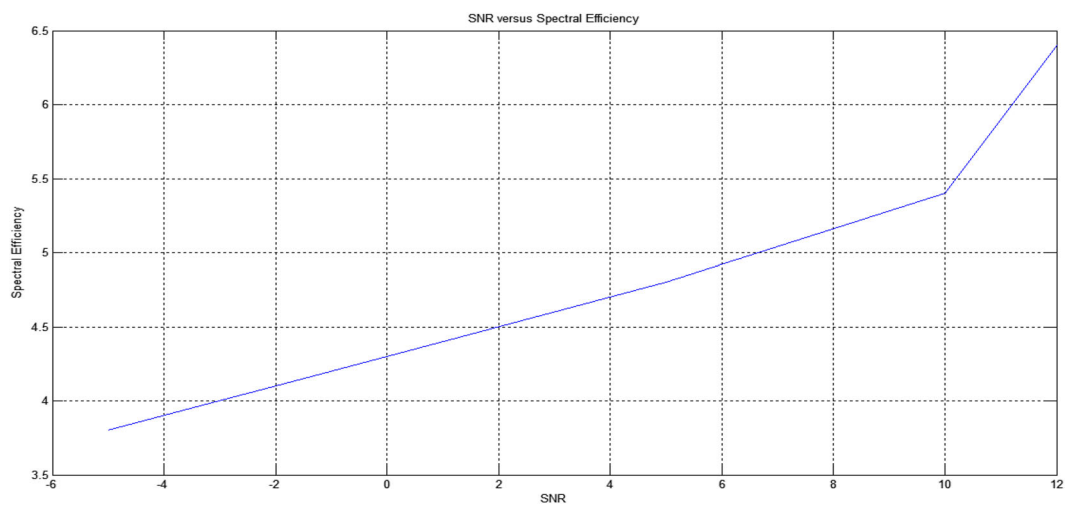**Fig. 25** SNR versus bandwidth

Fig. 26 SNR versus spectral efficiency
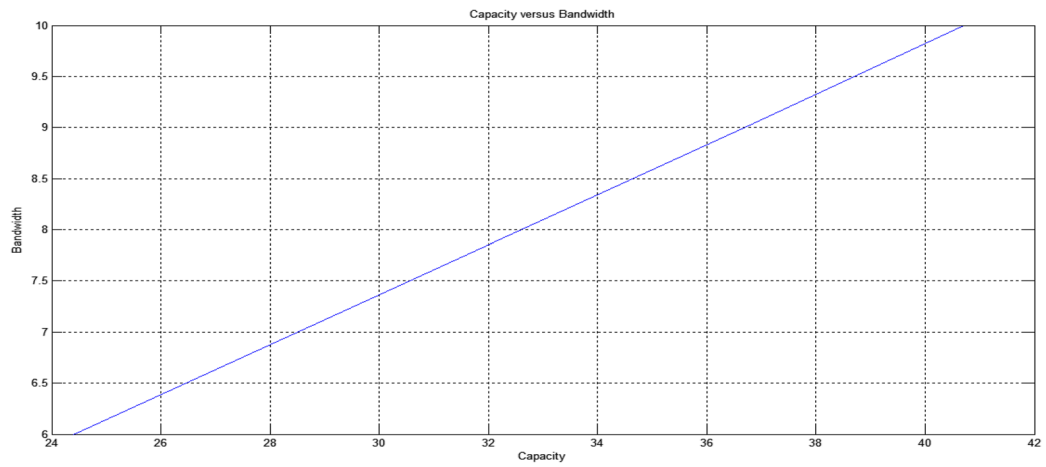

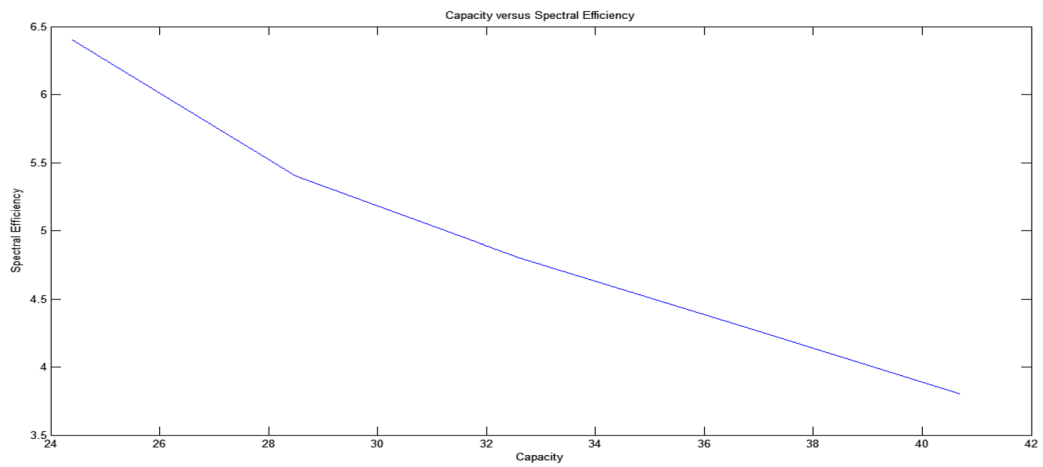**Fig. 27** Capacity versus bandwidth

Fig. 28 Capacity versus spectral efficiency
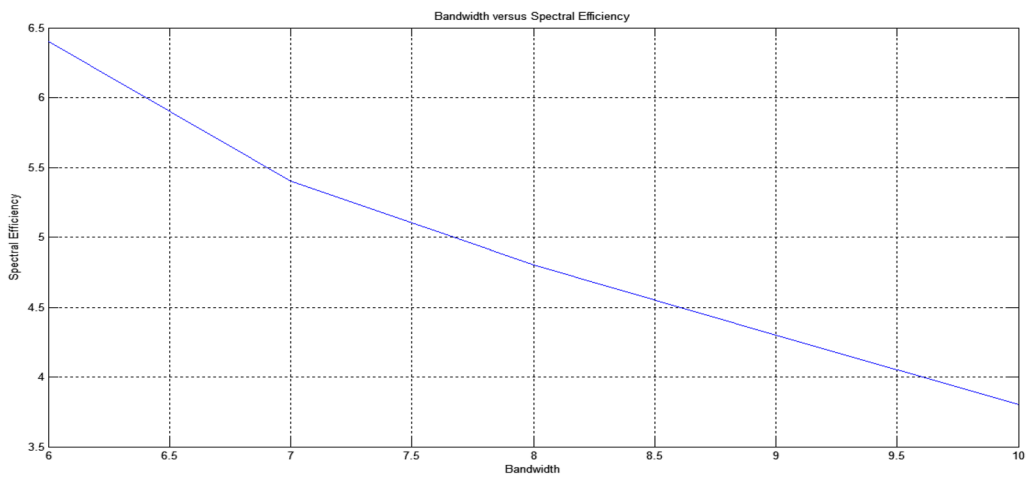

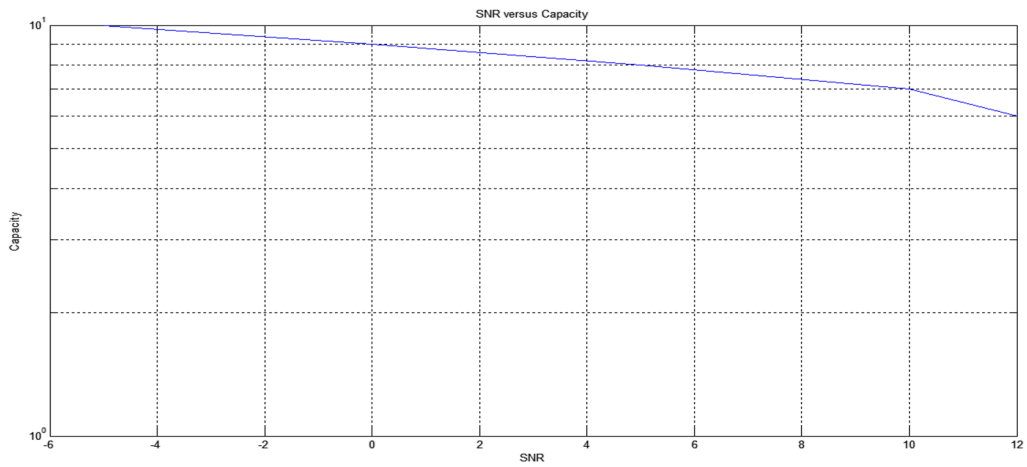**Fig. 29** BW versus spectral efficiency
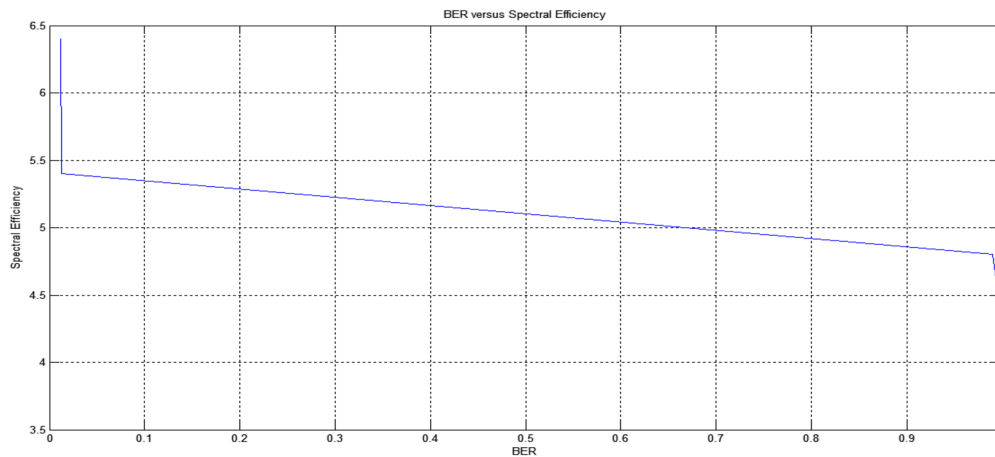

Fig. 30 SNR versus capacity plot

Fig. 31 BER versus spectral efficiency

Table 1 BER values computed in FBMC CR Simulink model using AWGN channel at different values of Eb/No

BER computed from FBMC CR Simulink model using AWGN channel	Eb/No (SNR)
0.01223	12
0.01236	10
0.99	5
1.0	0
1.0	−5

5 Conclusion

This BER versus SNR plot clearly depicts that in Filter Bank Multicarrier approach, followed for AWGN Channel State Estimation purpose shows that at SNR = 0 dB, BER is at peak while with increase in SNR beyond 0 dB, BER consistently remains minimal i.e. approximately zero which is good trend from efficient communication signal processing and Nyquist pulse shaping point of view. In this section, the problem of capacity maximization and Spectral Efficiency Enhancement for FBMC-CR multi-user resource allocation based on channel type is considered. Maximization of system capacity, based on available error-free instantaneous estimated channel state information at the transmitter, is the goal. Moreover, it is shown, through Monte Carlo simulations, that numerical results absolutely coincides the analytical computations.

Table 2 The calculated values of AWGN channel capacity for FBMC-CR system under the effect of varying Eb/No (dB) as 12, 13, 14, 15, 16 for different values of BW = 6, 7, 8, 9, 10 MHz when sample time Ts = 1/4000

Eb/No (dB)	AWGN channel capacity (MHz)	Bandwidth (Hz)
12	24.475	6×10^6
12	28.554	7×10^6
12	32.633	8×10^6
12	36.712	9×10^6
12	40.792	10×10^6
13	24.683	6×10^6
13	28.797	7×10^6
13	32.911	8×10^6
13	37.025	9×10^6
13	41.139	10×10^6
14	24.876	6×10^6
14	29.023	7×10^6
14	33.169	8×10^6
14	37.315	9×10^6
14	41.461	10×10^6
15	25.056	6×10^6
15	29.232	7×10^6
15	33.408	8×10^6
15	37.585	9×10^6
15	41.761	10×10^6
16	25.224	6×10^6
16	29.429	7×10^6
16	33.633	8×10^6
16	37.837	9×10^6
16	42.041	10×10^6

Fig. 32 BER performance analysis of OFDM at SNR = 50

Fig. 33 BER performance analysis of OFDM at SNR = −5

Fig. 34 BER performance analysis of OFDM at SNR = 20
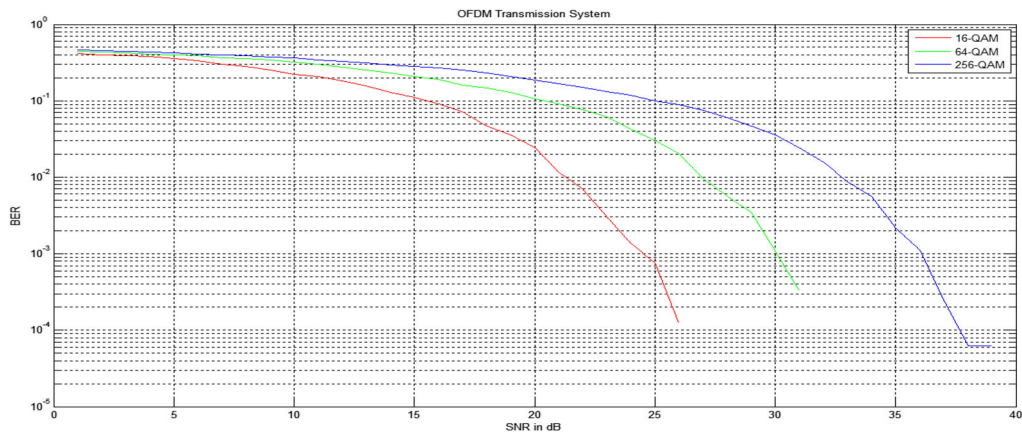
Fig. 35 BER performance analysis of OFDM at SNR = 10
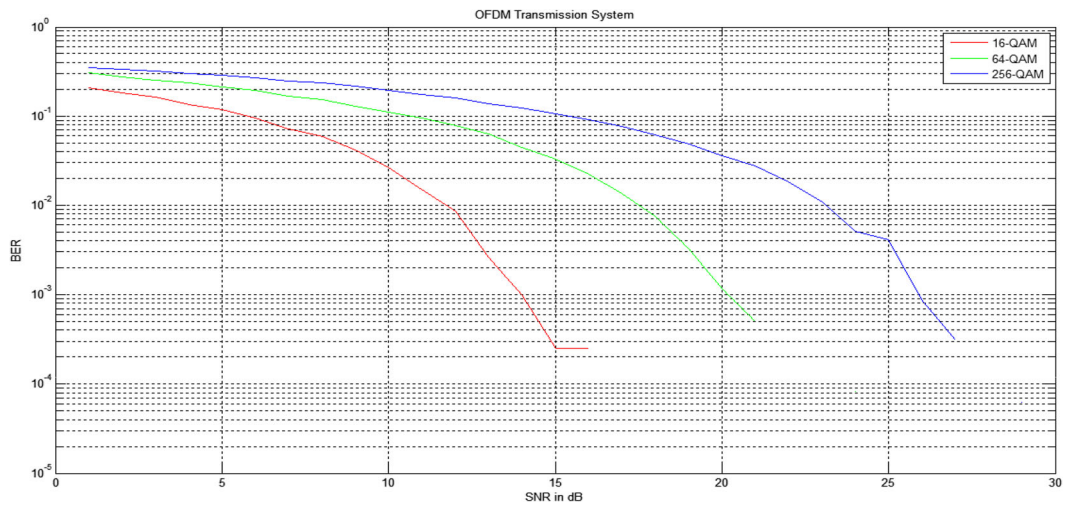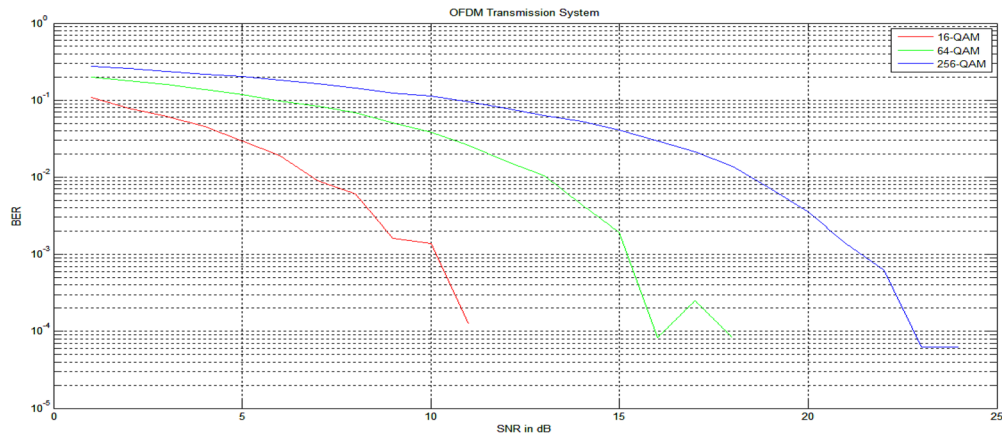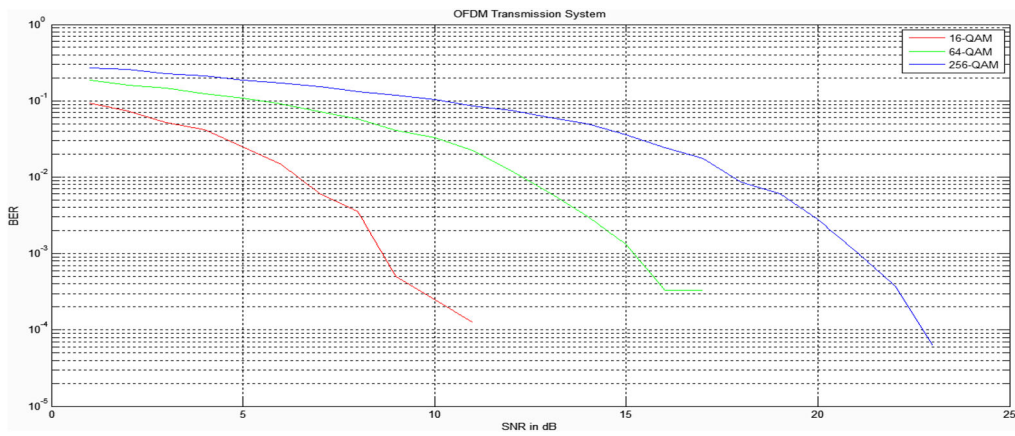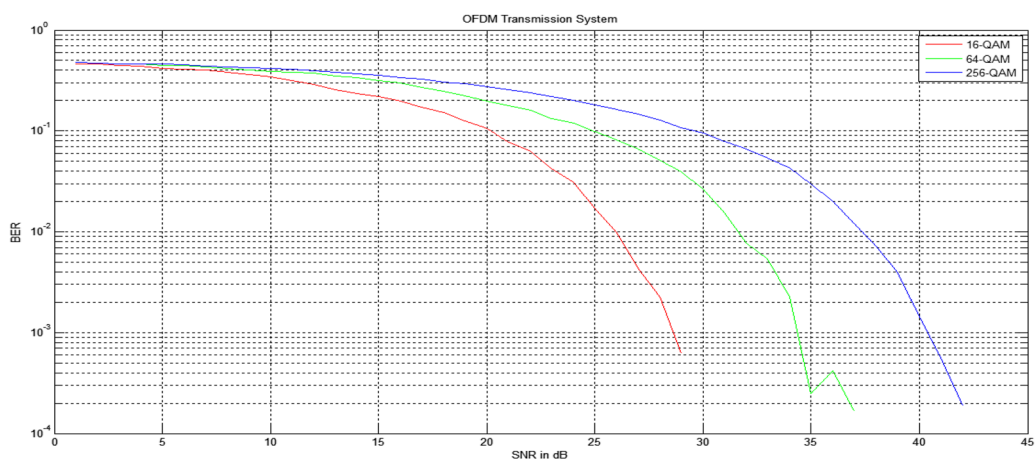

Fig. 36 BER performance analysis of OFDM at SNR = 5
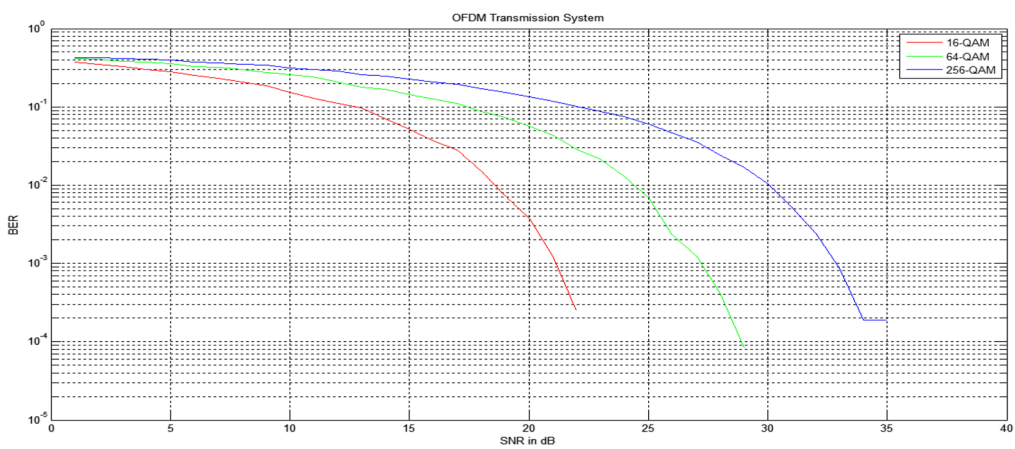

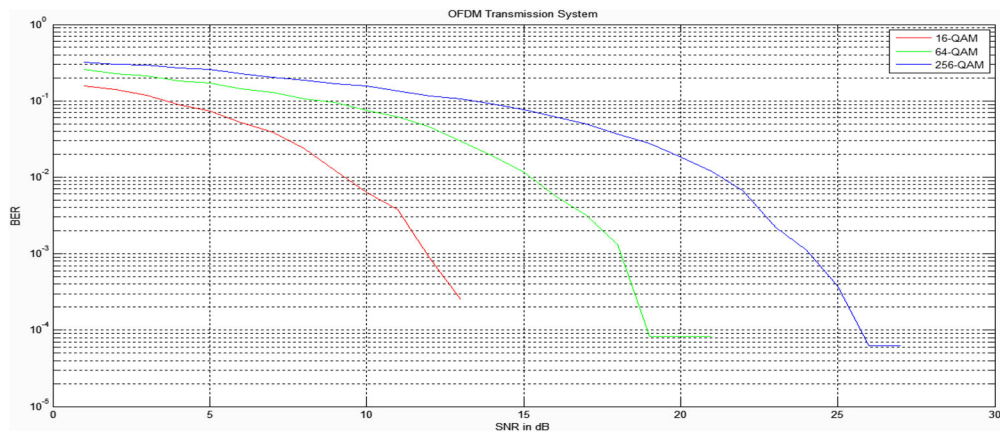**Fig. 37** BER performance analysis of OFDM at SNR = −10

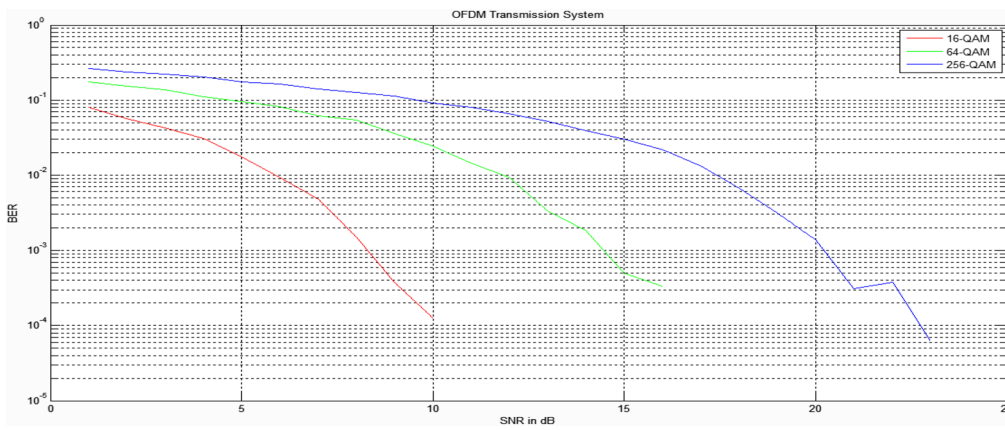**Fig. 38** BER performance analysis of OFDM at SNR $= -20$

Fig. 39 BER performance analysis of OFDM at SNR $= -50$
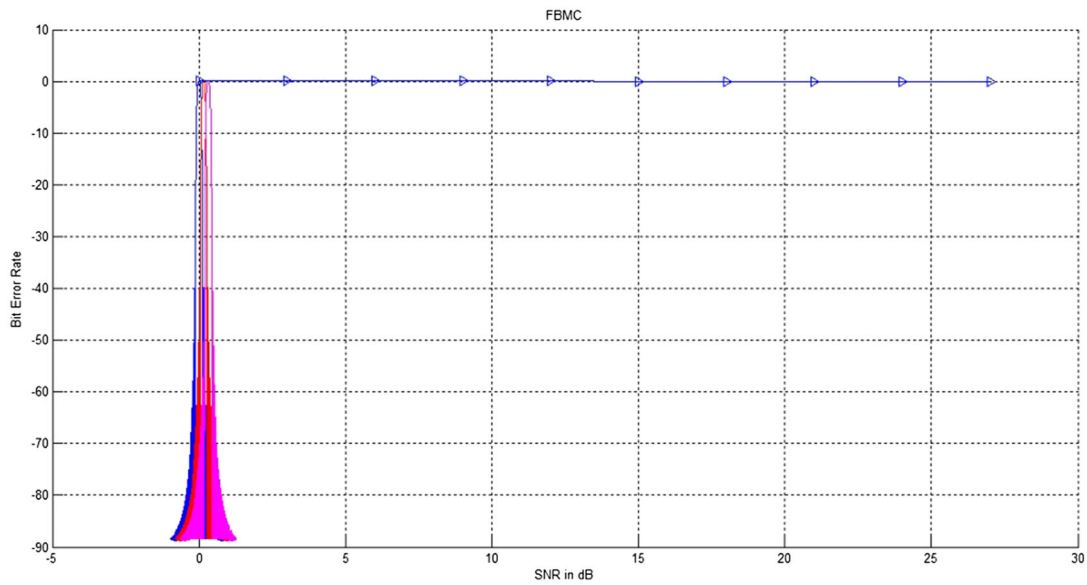
Fig. 40 BER versus SNR plot for FBMC in AWGN channel state estimation

Table 3 Spectral efficiency computation at P = 15.36, gain factor = 10 at variable R$_{avg}$ for useful BW range in cognitive radio

Bandwidth (Hz)	Spectral efficiency with P = 15.36; R$_{avg}$ = 1/4; gain factor G = 10	Spectral efficiency with P = 15.36; R$_{avg}$ = 1/8; gain factor G = 10	Spectral efficiency with P = 15.36; R$_{avg}$ = 1/16; gain factor G = 10
6×10^6	6.4	3.2	1.6
7×10^6	5.4	2.7	1.35
8×10^6	4.8	2.4	1.2
9×10^6	4.3	2.1	1.06
10×10^6	3.84	1.9	0.96

Table 4 Spectral efficiency computation at P = 15.36, gain factor = 20 at variable R$_{avg}$ for useful BW range in cognitive radio

Bandwidth (Hz)	Spectral efficiency with P = 15.36; R$_{avg}$ = 1/4; gain factor G = 20	Spectral efficiency with P = 15.36; R$_{avg}$ = 1/8; gain factor G = 20	Spectral efficiency with P = 15.36; R$_{avg}$ = 1/16; gain factor G = 20
6×10^6	12.8	6.4	3.2
7×10^6	10.8	5.4	2.7
8×10^6	9.6	4.8	2.4
9×10^6	8.6	4.26	2.13
10×10^6	7.68	3.84	1.92

Table 5 Spectral efficiency computation at P = 15.36, gain factor = 50 at variable R$_{avg}$ for useful BW range in cognitive radio

Bandwidth (Hz)	Spectral efficiency with P = 15.36; R$_{avg}$ = 1/4; gain factor G = 50	Spectral efficiency with P = 15.36; R$_{avg}$ = 1/8; gain factor G = 50	Spectral efficiency with P = 15.36; R$_{avg}$ = 1/16; gain factor G = 50
6×10^6	32	16	8
7×10^6	27	13.5	6.75
8×10^6	24	12	6
9×10^6	21.5	10.6	5.31
10×10^6	19.2	9.6	4.82

Table 6 Spectral efficiency computation at P = 15.36, gain factor = 50 at variable R$_{avg}$ for useful BW range in cognitive radio

Bandwidth (Hz)	Spectral efficiency with P = 15.36; R$_{avg}$ = 1/4; gain factor G = 100	Spectral efficiency with P = 15.36; R$_{avg}$ = 1/8; gain factor G = 100	Spectral efficiency with P = 15.36; R$_{avg}$ = 1/16; gain factor G = 100
6×10^6	64	32	16
7×10^6	54	27	13.5
8×10^6	48	24	12
9×10^6	43	21	10.5
10×10^6	38	19	9.5

Table 7 Rayleigh channel capacity calculations for OFDM at varying SNR for CR useful BW = 6−10 MHz

SNR	Rayleigh channel capacity (MHz)	Bandwidth
5	4.668	6×10^6
10	6.248	6×10^6
20	7.933	6×10^6
50	10.245	6×10^6
5	5.44	7×10^6
10	7.289	7×10^6
20	9.255	7×10^6
50	11.952	7×10^6
5	6.225	8×10^6
10	8.331	8×10^6
20	10.577	8×10^6
50	13.660	8×10^6
5	7.003	9×10^6
10	9.372	9×10^6
20	11.899	9×10^6
50	15.368	9×10^6
5	7.781	10×10^6
10	10.413	10×10^6
20	13.222	10×10^6
50	17.075	10×10^6

Table 8 BER computation for OFDM transmission using Rayleigh fading channel at varying SNR values

BER computed for OFDM transmission using Rayleigh channel	At SNR value
For 16 QAM, $10^{-0.55} < \text{BER} < 10^{-3.8}$; For 64 QAM, $10^{-0.55} < \text{BER} < 10^{-3.2}$; For 256 QAM, $10^{-0.55} < \text{BER} < 10^{-3.5}$	-5
For 16 QAM; $10^{-0.42} < \text{BER} < 10^{-3.6}$; For 64 QAM, $10^{-0.43} < \text{BER} < 10^{-4.4}$; For 256 QAM; $10^{-0.43} < \text{BER} < 10^{-3.7}$	-10
For 16 QAM; $10^{-0.90} < \text{BER} < 10^{-3.6}$; For 64 QAM, $10^{-0.75} < \text{BER} < 10^{-4.3}$; For 256 QAM; $10^{-0.50} < \text{BER} < 10^{-4.5}$	-20
For16 QAM; $10^{-0.50} < \text{BER} < 10^{-4.8}$; For 64 QAM, $10^{-0.45} < \text{BER} < 10^{-3.6}$; For 256 QAM; $10^{-13} < \text{BER} < 10^{-3.9}$	-50
For 16 QAM; $10^{-0.45} < \text{BER} < 10^{-0.35}$; For 64 QAM; $10^{-0.46} < \text{BER} < 10^{-38}$; For 256 QAM; $10^{-0.45} < \text{BER} < 10^{-36}$	5
For 16 QAM; $10^{-0.65} < \text{BER} < 10^{-4.6}$; For 64 QAM; $10^{-0.75} < \text{BER} < 10^{-4.0}$; For 256 QAM; $10^{-1} < \text{BER} < 10^{-4}$	10
For 16 QAM; $10^{-1} < \text{BER} < 10^{-3.8}$; For 64 QAM; $10^{-0.90} < \text{BER} < 10^{-4.3}$; For 256 QAM; $10^{-0.75} < \text{BER} < 10^{-4.6}$	20
For 16 QAM; $10^{-0.65} < \text{BER} < 10^{-3.9}$; For 64 QAM; $10^{-0.65} < \text{BER} < 10^{-3.2}$; For 256 QAM; $10^{-0.65} < \text{BER} < 10^{-4.3}$	50

Table 9 Computed BER for different FIR decimation and interpolation factors in case of BSC and AWGN channel with Two Channel Analysis FB & Two Channel Synthesis FB Sub band processing employed

Channel (BSC/AWGN)	Initial seed value	Error probability	FIR decimation and FIR interpolation factor taken	BER computed at five different simulation runs	Average computed BER
BSC	71	0.05	1/3;3	0.2783, 0.2725, 0.2899, 0.2841, 0.2896	0.28288
BSC	71	1.0	1/2;2	0.9706, 0.9706, 0.9804, 0.9804, 0.9804	0.97640
BSC	71	0.1	1/3;3	0.4299, 0.4525, 0.4525, 0.448, 0.4389	0.44436
BSC	71	0.1	1/8;8	0.2088, 0.2049, 0.2008, 0.2008, 0.2008, 0.2049	0.2442
BSC	71	0.01	1/5;5	0.0476, 0.03617, 0.03665, 0.03665, 0.03665	0.03874
AWGN (Two Channel Analysis FB & Two Channel Synthesis FB sub band processing)	67	_	1/3;3	0.004065, 0.004065, 0.004107, 0.004148, 0.004148	0.011573

6 Impact of study

The present study has its deep impact on the design and development of FBMC systems in cognitive radio under ubiquitous pervasive environment [16–20].

References

1. Schaich, F. (2010). Filterbank based multi carrier transmission (FBMC) evolving OFDM: FBMC in the context of WiMAX. In *Proceedings of European wireless conference (EW)* (pp. 1051–1058), Lucca, Italy.
2. Lélé, C., Javaudin, J., Legouable, R., Skrzypczak, A., & Siohan, P. (2008). Channel estimation methods for preamble-based OFDM/OQAM modulations. *European Transactions on Telecommunications*, *19*(7), 741–750.
3. Du, J., & Signell, S. (2008). Pulse shape adaptivity in OFDM/OQAM systems. In *Proceedings of international conference on advanced Infocomm Technology*, China.
4. Kozek, W., & Molisch, A. (1998). Nonorthogonal pulseshapes for multicarrier communications in doubly dispersive channels. *IEEE Journal on Selected Areas in Communications*, *16*(8), 1579–1589.
5. Trigui, I., Siala, M., Affes, S., Stephenne, A., & Boujemâa, H. (2007). Optimum pulse shaping for OFDM/BFDM systems operating in time varying multi-path channels. In *Proceedings of IEEE global telecommunications conference* (pp. 3817–3821), USA.
6. Du, J., & Signell, S. (2007). Classic OFDM systems and pulse-shaping OFDM/OQAM systems. Technical Report. KTH—Royal Institute of Technology, pp. 1–32.
7. Bolcskei, H., Duhamel, P., & Hleiss, R. (1999). Design of pulse shaping OFDM/OQAM systems for high data-rate transmission over wireless channels. In *Proceedings of IEEE international conference on communication (ICC)* (Vol. 1, pp. 559–564), Canada.
8. Haas, R., & Belfiore, J. (1997). A time-frequency well-localized pulse for multiple carrier transmission. *Wireless Personal Communications*, *5*(1), 1–18.
9. Strohmer, T., & Beaver, S. (2003). Optimal OFDM design for time-frequency dispersive channels. *IEEE Transactions on Communications*, *51*(7), 1111–1122.
10. Martin, K. W. (1998). Small side-lobe filter design for multi tone data communication applications. *IEEE Transactions on Circuits and Systems II: Analog and Digital Signal Processing*, *45*(8), 1155–1161.
11. Amini, P., Kempter, R., Chen, R. R., Lin, L., & Farhang-Boroujeny, B. (2005). Filter bank multitone: A physical layer candidate for cognitive radios. *Software defined radio technical conference (SDR 2005)*, California, 14–18 November 2005.
12. Amini, P., Azarnasab, E., Akoum, S., Mao, X., Rao, H., & Farhang-Bouroujeny, B. (2007). Implementation of a cognitive radio modem. In *Software defined radio technical conference*, Denver, CO, 5–9 November 2007.
13. Renfors, M. PHYDYAS:D5.1 Report. Tampere University of Technology, Finland.
14. Phydas Report. (2009). Prototype filter and filter bank structure optimization (pp. 1–102).
15. Zhao, O., & Sadler, B. M. (2007). A survey of dynamic spectrum access. *IEEE Signal Processing Magazine*, *24*(3), 79–89.
16. Kang, A. S., & Vig, R. (2014). Comparative performance analysis of modified FBMC prototype filter under strategic conditions. *European Journal of Scientific Research*, *125*(3), 362–369.
17. Kang, A. S., & Vig, R. (2015). Computer aided BER performance analysis of Filter Bank Multicarrier based cognitive radio under binary symmetric radio fading channel. *Springer Journal of Wireless Personal Communication*, *81*(2), 15.
18. Kang, A. S., & Vig, R. (2016). Comparative performance evaluation of modified prototype Filter Bank Multi Carrier cognitive radio under constraints of Lp, K, N and D. *The Computer Journal*, *59*(3), 1–13.
19. Kang, A. S., Vig, R., et al. (2016). Comparative analysis of Energy Detection spectrum sensing of cognitive radio under Wireless Environment using SEAMCAT. *International Journal of Advanced Computer Science and Applications, 7*(1), 493–498.

20. Kang, A. S., & Sharma, V. (2016). Effect of prototype filter length on PAPR reduction and side lobe tail attenuation on autocorrelation in FBMC cognitive radio. *International Journal of Advanced Information Systems & Technology*, *51*, 38–48.

A. S. Kang did his B.Tech. in Electronics & Communication from Guru Nanak Dev University Amritsar in 2007 followed by M.Tech. Degree in Electronics & Communication Engg from Panjab University Chandigarh with University Merit Certificate in 2009. Thereafter he joined Dr. B.R. Ambedkar NIT Jalandhar for a short period and later joined Panjab University as Asstt Prof. in ECE in 2009. He has been pursuing his Ph.D. in the field of cognitive radio communication from Department of UIET, Panjab University Chd from February 2011 onwards. He has to his credit 07 IEEE and 01 Elsevier Conference Publication till date. Also, he has 26 paper publications at various international journals of repute from countries of India, USA, UK, Russia, Germany, Pakistan and Portugal including Springer. He has one publication at Panjab University Research Journal (Sciences) and has guided several M.Tech. Thesis Dissertations in the field of Communication Signal Processing. He has qualified the first National Mathematics Olympiad, New Delhi in year 2000. He has been an External Reviewer for Proposal Title Analysis, Design and Implementation of Nyquist Pulses in Next Generation Wireless Communication Systems submitted to the 2014 Initiation into Research (National Fund for Scientific & Technological Development (FONDECYT) of the Chilean National Commission for Scientific and Technological Research (CONICYT), CHILE, Aug 2014. He has attended many refresher and short term courses in the field of DSP and Communication throughout India from 2006 till date. He has even participated actively in "India–France Technology Summit" organized by DST, Govt of India, New Delhi 2014. He is a Life Member of IETE (New Delhi), IAENG (Hong Kong), MBSA (UK), MISEIS (Canada), MSDIWC (USA), MISOC (Switzerland), MIACSIT (Singapore), MISA (North Carolina, USA), Associate Member of Institute of Research Engineers & Doctors (New York, USA).

Renu Vig holds B.E. in Electronics and Comm Engg followed by M.E. and Ph.D. degrees from Punjab Engg College, Chd (PANJAB UNIV CHD). She worked as an Engg Educator at various reputed institutions namely NITTTR Chd, PEC Chd for the past more than 25 years. At present she is working as Professor of Electronics & Communication at Department UIET, Sc-25 PU Chd with an Additional Charge of Director, UIET. She has to her credit many paper publications in International journals of repute beside a large number of Publications in IEEE International Conferences held in India and abroad. She has guided several M.E./M.Tech. student Dissertations in joint collaboration with CSIO Chandigarh and many students are enrolled and registered for their Ph.D. work under her Dynamic Leadership and Guidance. She has been awarded with Sir Thomas Medal by IE, India for her meritorious research work. She has been a source of motivation and courage to all the young scientists working in the field of Wireless & Mobile Communication, Digital Signal Processing, Image Processing, Neural Network Fuzzy logic based Intelligent approach, Data Communication and Computer Networks. She has even authored a text book on the Principles of Electronics. Her Current research areas include Communication Signal Processing and Cognitive Radio Communication with special emphasis on wireless sensor networks.