

Filter Bank Multicarrier Modulation Techniques for 5G and Beyond Wireless Communication Systems

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Abstract — Higher data rates, higher mobility, lower latency, and better quality of service are the prime requirements for future communication systems. It is expected to provide connectivity to the Internet of everything, time-sensitive/time-engineered application, and service to high-fidelity holographic society. Its performance in terms of data rate, latency, synchronization, security, and reliability will be much better compared to 4G and 5G mobile communication systems. This paper investigates the performance of the pulse shaping-based filter bank multicarrier (FBMC) modulation technique used in 5G mobile communication systems. Simulation results show that the FBMC system has a better performance compared to the conventional orthogonal frequency division multiplexing (OFDM) system in terms of many parameters such as achievable channel capacity, signal to noise ratio, time, and frequency response, out of band leakage, etc.

Keywords — Division Multiplexing, Filter Bank Multicarrier, Modulation Technique, Novel orthogonal Multiple Access Technique, orthogonal frequency, spectrum Efficiency.

I. INTRODUCTION

As per the Edholm's law of bandwidth, mobile data rate has been doubled in every 18 months during the past 30 years. Mobile communication has undergone tremendous change from the First Generation (1G) that offered mobile voice calling services that was launched in the year 1980 and services offered by it was analog in nature. Since then, after every 10 years a new generation of the mobile communication has been introduced in the market [1]. The Second Generation (2G) digital cellular services launched in 1990 as Global System for Mobile Communication (GSM) commercially achieved a great success in the market. It captured a huge market as it provided convenience service for voice, short texting (messages) and data services with low data rate transmission capability [2].

With the advent of spread spectrum communication technology, Code Division Multiple Access (CDMA) brought a revolutionary change in the mobile industry when introduced as Third Generation (3G) mobile communication system in 2001. Represented by Wideband Code Division Multiple Access (WCDMA), CDMA2000 and Time Division Synchronous Code Division Multiple Access (TD-SCDMA), it supported high speed data access with data rate of several megabits per second.

The first mobile broadband services proposed by Third Generation Partnership Project (3GPP) as Long Term Evolution (LTE) network was launched as Fourth Generation

(4G) mobile communication system in December 2009 [3]. It combined the concept of Multiple Input Multiple Output (MIMO) with orthogonal frequency Division Multiplexing (OFDM) 4G promoted mobile internet services and provided services to smartphones. Table I enumerates different generations of mobile communication with types of services offered [4].

With the introduction of Fifth Generation (5G) mobile communication services in April 2019, we stepped into another era of mobile communication that has attracted unprecedented attention of the people from the globe [5]. While the previous generations of mobile communication were mainly focused on providing services to people as consumer and improving its network capacities, services provided by 5G shifted its focus from human to things, from consumers to vertical industries. It aimed to provide communication services to Machine to Machine (M2M), Device to Device (D2D) and Internet of Things (IoT). It provided countless inter-connectivity among machine, things, and people [6]. 5G provided a wide variety of services from traditional mobile broadband to industry 4.0, Virtual Reality (VR), Augmented Reality (AR), IoT, automatic driving, and many more. When COVID-19 pandemic brought unprecedented challenge to human life and affected the social and economic condition of the globe, the role of network and digital infrastructure proved a boon to the society [7]. It supported many services such as smart healthcare including remote surgery and Ultra Violet (UV) disinfection of hospitals, online education, remote working, unmanned delivery, robot-assisted services, supply chain management, driverless vehicles, social services, etc. and keeping families connected and system running smoothly [8].

Though presently 5G is still in its infancy stage and is on its way of being deployed commercially across the globe, in order to fulfil the future requirements of Information and Communication Technology (ICT), it is time to think beyond 5G or more precisely on Sixth Generation (6G) of mobile communication systems [9-10]. Following the past trends, 6G is expected to be introduced in the market place by 2030 that will be aimed at lifestyle and societal changes as its main driving characteristics [11]. It is expected to provide connectivity to Internet of everything, time sensitive/time engineered application and service to high-fidelity holographic society. Its performance in terms of data rate, latency, synchronization, security and reliability will be much better compared to 4G and 5G mobile communication systems [12]-[14].

TABLE I: MOBILE COMMUNICATION GENERATIONS

Generations	Based on	Year	Services Offered	Type
1G	Frequency-division multiple access (FDMA)	1980	Voice Calling	Analog
2G	Time-division multiple access (TDMA)	1990	Voice, messages, and data	GSM, Digital
3G	Code-division multiple access (CDMA)	2001	Voice, high speed data	Digital WCDMA CDMA2000, TD-SCDMA
4G	Orthogonal frequency division multiple access (OFDMA)	2009	Smart phone services	Digital, MIMO
5G	OMA & NOMA	2019	M2M, D2D and IoT	VR, AR, IoT, Massive MIMO, Automatic driving
6G		2030 Expected	Ultra-Reliable Low Latency Broadband Communication	Tactile Internet, Holographic, Extended Reality, Intelligence

TABLE II: COMPARISON OF 4G, 5G AND 6G COMMUNICATION SYSTEMS

Key Performance Indicator	4G	5G	6G
Peak Data Rate	300 Mbps	20 Gbps	1 Tbps
User Experience Rate	10 Mbps	100 Mbps	1 Gbps
Spectral efficiency	1.90 bits/ Hz	7.8 bps/Hz	10 time that of 5G
User Plane Latency	50 ms	4 ms	2.5 μ s
Control Plane Latency	50 ms	20 ms	1 ms
Connection Density	10 ³ devices/k m ²	10 ⁶ devices/km ²	10 ⁷ devices/km ²
Mobility	350 km/h	500 km/h	1000 km/h
Peak Spectral Efficiency	3.75 bps/Hz (Downlink) 2.75 bps/Hz (Uplink)	30 bps/Hz (Downlink) 15 bps/Hz (Uplink)	3 times Higher
Signal Bandwidth	10-30 MHz	100 MHz	1 Ghz
Positioning Accuracy	30 m	10 m	10 cm
Frequency Band	Low Band: 600-800 MHz Mid Band: 2.1-2.6 GHz	Low Band: 600-800 MHz Mid Band: 2.5-3.7 GHz Upper Band: 25-39 GHz Future Plan-100 GHz	THz
Wavelength	50 cm-10 cm	1-10 mm	Sub mm
Coverage Area	1-2 Km	50-80 km	Much Larger than 5G

Table II exhibits comparison of 6G with 4G and 5G mobile Communication systems. The future generation of mobile communication has to optimize on three important thrust areas such as: spectrum efficiency, energy efficiency and power efficiency [15]. Spectrum efficiency is the rate of data transmission over a given bandwidth, whereas energy efficiency is the measure of energy consumption by the system, which includes both hardware and software involved in data processing. On the other hand, power efficiency is the measure of power required for signal transmission [16], [17].

II. MODULATION TECHNIQUES

In 4G mobile communication system orthogonal frequency division multiplexing (OFDM) has been widely used. It was proposed by 3GPP as long-term evolution (LTE) / LTE advanced network. OFDM technique suffered from spectral efficiency, due to use of cyclic prefix (CP), high peak to average power ratio (PAPR), inter carrier interference (ICI) and high out of band (OOB) leakage due to rectangular pulse shaping. In order to maintain orthogonality, OFDM required different users to be fully synchronized otherwise there would

be interference among adjacent subbands [18]. Synchronization of signals cannot be guaranteed in the case of IoT and wireless sensor network (WSN) enabled services as billions of sensors are generating data. Hence, OFDM is unable to meet the new demands required by 5G and beyond new radio (NR) networks [19].

TABLE III: NOVEL OMA AND NOMA BASED MODULATION TECHNIQUES

Modulation Techniques based on Novel OMA	Modulation Technique based on Pulse Shaping	Filter bank Multicarrier (FBMC)
		Generalized Frequency Division Multiplexing (GFDM)
Modulation Techniques based on Novel NOMA	Modulation Technique based on Subband Filtering	Universal Filtered Multicarrier (UFMC)
		Filtered OFDM (f-OFDM)
Modulation Techniques based on NOMA	Modulation based on other Techniques	Guard interval discrete Fourier Transform Spread OFDM (GI DFT-s-OFDM)
		Spectrally Pre-coded OFDM
Modulation Techniques based on NOMA	Power-Domain NOMA	Multiple Antenna Based NOMA
		Cooperative NOMA
Modulation Techniques based on NOMA	Code Domain NOMA	Cognitive Radio Inspired NOMA
		Low Density Spreading CDMA (LDS-CDMA)
Modulation Techniques based on NOMA	NOMA Multiplexing in Multiple Domain	Low Density Spreading OFDM (LDS-OFDM)
		Sparse Code Multiple Access (SCMA)
Modulation Techniques based on NOMA	NOMA Multiplexing in Multiple Domain	Pattern Division Multiple Access (PDMA)
		Building Block Sparse Constellation Multiple Access (BOMA)
Modulation Techniques based on NOMA	NOMA Multiplexing in Multiple Domain	Lattice Partition Multiple Access (LPMA)

To address these challenges new types of modulation techniques have been proposed for 5G and beyond NR networks. Novel orthogonal multiple access (OMA) technique that is based on OFDM with some modifications have been suggested by many researchers. But novel OMA techniques can support only limited number of users due to restrictions in the number of orthogonal resource blocks and put a limit on spectral efficiency and capacity of the networks. In order to address the above issues and to support a massive number of heterogeneous users' non-orthogonal multiple access (NOMA) techniques have also been investigated by many researchers for NR networks [20].

As depicted in table-3, novel OMA based techniques are further classified based on Pulse Shaping, Subband Filtering and other Techniques. Whereas NOMA techniques have been put under power-domain, code domain and multiple domain based techniques. NOMA can be integrated with existing

multiple access technique, perform multiplexing within one of the time/frequency/code domains and hence support more users in the same resource block [21]. At the cost of additional interference and complexity, NOMA will improve network capacity by supporting more users in the same resource block.

A. OFDM System Characterization

In this technique, time domain signals are generated by multiplication of subcarriers with data symbols and that is expressed by (1).

$$x_k = \sum_{n=0}^{N-1} X_n e^{j2\pi k n / N} \quad (1)$$

Here, X_n is the data symbol for the n -th subcarrier. In order to ensure that subcarriers are orthogonal to each other, spacing of subcarriers by inserting cyclic prefix and frequencies are carefully selected. The condition of orthogonality is satisfied as per (2).

$$\frac{1}{T} \int_0^T m(t) n(t) dt = 0 \quad (2)$$

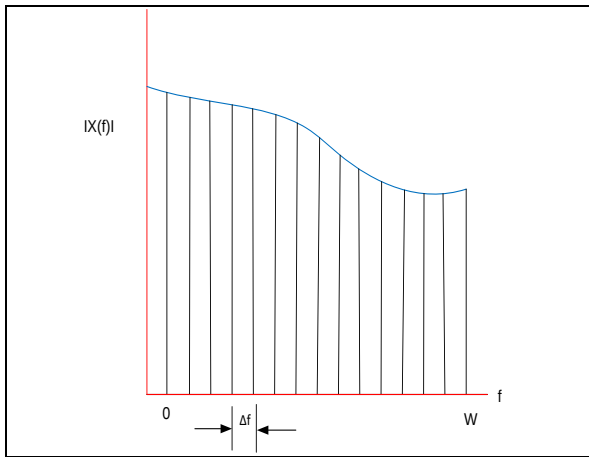


Fig. 1. Subdivision of bandwidth in OFDM modulation.

Fig. 1 shows subdivision of bandwidth in the OFDM systems. The given frequency band is subdivided into smaller bands known as subcarriers.

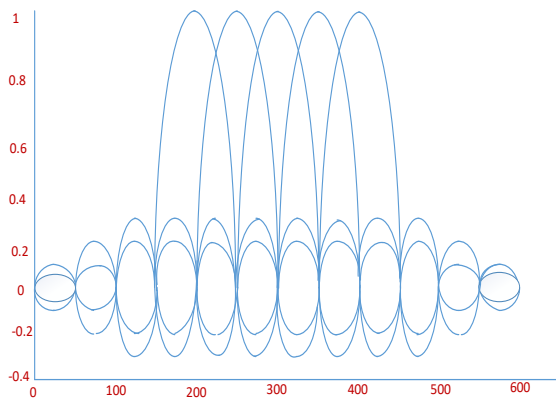


Fig. 2. OFDM subcarrier arrangement.

As depicted in Fig. 2, the adjacent subcarriers are overlapping to each other in the frequency domain and do not

create interference as they maintain orthogonality among themselves.

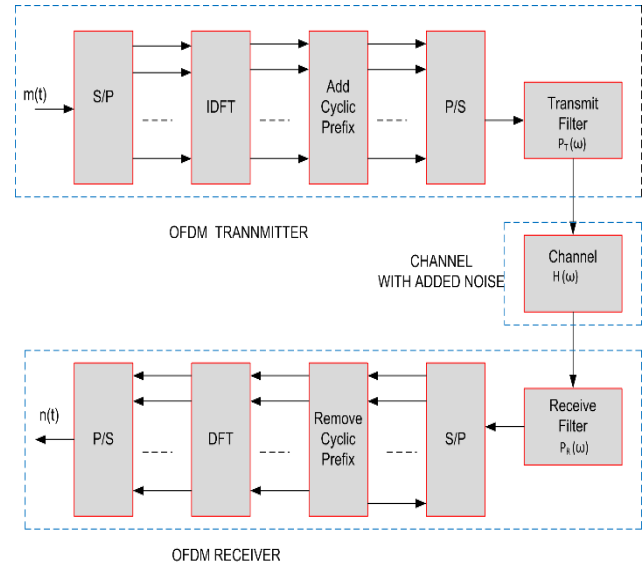


Fig. 3. Orthogonal Frequency Division Multiplexing System.

Fig. 3 depicts the OFDM used in 4G Mobile Communication System. The QPSK/QAM digitally modulated baseband signal is subjected to IDFT operation then cyclic prefix is added to reduce out of band leakage and inter carrier interference (ICI). After D/A conversion passband modulation is done before transmitting the signal through the channel. In the receiver opposite action is taken that was done during transmission process.

B. Novel OMA Technique Based on Pulse Shaping

In the present paper, Filter Bank Multi-carrier (FBMC) has been investigated in detail that are based on pulse shaping novel OMA techniques used in 5G NR networks. FBMC does not require to maintain orthogonality among subcarriers hence power loss can be minimized. By using nonrectangular pulse shaping out of band leakage can also be reduced. When compared to OFDM, FBMC is able to increase robustness to synchronization errors and isolate subcarriers through filtering at the cost of slight decrease in efficiency.

III. FILTER BANK MULTICARRIER

Filter bank multi-carrier (FBMC) has many advantages over OFDM system, and it is considered to be one of the suitable waveforms for future communication. FBMC uses a bank of frequency localized filter, synthesis filter bank at transmitter and analysis filter bank at the receiver. It can accept asynchronous data and separate non-adjacent subbands perfectly in frequency domain hence is more robust to carrier frequency offset. It has higher spectral efficiency as cyclic prefix is not required to be added while transmitting long data packets. Like OFDM, FBMC also maintains orthogonality by either perfect reconstruction (PR) or nearly perfect reconstruction (NPR) among subbands in real domain by using a real valued low pass prototype synthesis and analysis filter banks. In real time perfect reconstruction is very difficult to meet where time varying or non-uniform spectrum splitting is required.

In this paper, a new type of FMBC known as imperfect reconstruction FMBC (iPR- FMBC) is proposed that does not require orthogonality condition to be satisfied still signal can be recovered using signal processing algorithm at the cost of moderate computational complexities. Its performance is superior to FMBC with PR constraint and OFDM. It supports more flexible subband allocation in multi carrier communication systems.

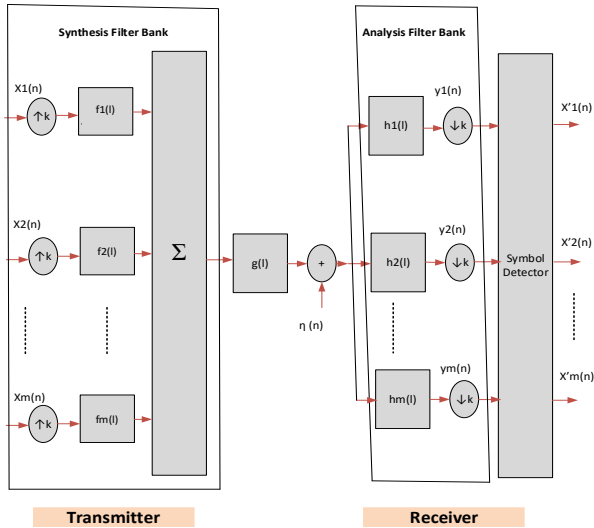


Fig. 4. Filter Bank Multicarrier System.

Fig. 4 depicts the block diagram of transceiver using FBMC technique. Here synthesis filter, $f_m(l)$ as represented by (3) and analysis filters, $h_m(l)$ represented by (4) are realized from common prototype low pass filter.

$$f_m(l) = h_m(l) \exp \left\{ j \frac{2\pi}{M} \left(m - \frac{1}{2} \right) \left(1 + \frac{M+1}{2} \right) \right\} \quad (3)$$

$$h_m(l) = f_m^*(N_f - 1 - l) \quad (4)$$

where, M is the number of subbands, P is the sampling factor, N_f is the filter tap indices. We have taken for our analysis a critically sampled complex valued filter bank with $P = M$ and have not considered either an oversampled ($P < M$) or an under sampled ($P > M$) filter banks.

We have used offset Quadrature Amplitude Modulation (OQAM) with same signal density as OFDM but without cyclic prefix (CP). For the condition of complex orthogonality represented by (5) has to be satisfied in order to fulfill the Balian–Low theorem. Where $x_{l1,k1}(t)$ and $x_{l2,k2}(t)$ are transmitted basis pulses.

$$\{x_{l1,k1}(t), x_{l2,k2}(t)\} = \delta_{(l2-l1), (k2-k1)} \quad (5)$$

But in our work, we have used a less strict real orthogonality condition that satisfies (6).

$$R\{< x_{l1,k1}(t), x_{l2,k2}(t) >\} = \delta_{(t2-t1), (k2-k1)} \quad (6)$$

Here the prototype filter is first designed with $p(t) = p(-t)$ that is orthogonal for a time spacing of T and frequency spacing of $F = 2/T$ with total time-frequency spacing of 2 seconds. Then the time-frequency spacing is reduced by a

factor of 2 for both time and frequency spacing making it equal to 0.5. This will induce interference which can be shifted to purely imaginary domain by the phase shift given by (7).

$$\varphi_{m,n} = \frac{\pi}{2}(m+n) \quad (7)$$

But it has been ensured that only real valued information symbols are transmitted with time-frequency spacing of 1 second for complex symbol.

Fig. 5 shows effect of overlapping factor on the frequency response for the prototype FBMC filter. For the simulation, 1024 number of sub channels, 2 OQAM samples per symbol, with 4, 3, 2 overlapping factor have been considered. It is evident from the figure that for larger value of overlapping factor, signal to noise ratio (SNR) is high and bandwidth occupied is low. But SNR decrease with the reduction in the overlapping factor. The optimum value of overlapping factor is 6 for the prototype low pass finite impulse response FBMC filter considered in this work.

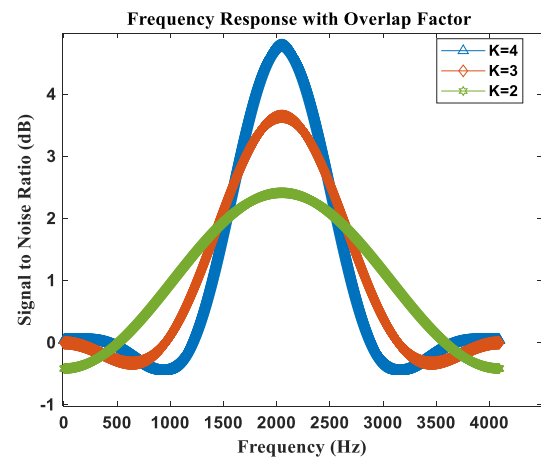


Fig. 5. Frequency Response with Overlap Factor.

A. Time and Frequency Response of Prototype Filters

Time and frequency response of prototype rectangular, PHYDYAS and Hermite filters have been plotted using Matlab at sampling rate of 30.36 MHz and subcarrier spacing of 30 KHz.

Fig. 6 depicts the time response of prototype filters that include rectangular, PHYDYAS with overlapping factor of 4 and Hermite filters with overlapping factor 8. As evident from the figure PHYDYAS filter perform better than Hermite and rectangular filters. But Hermite filter has better performance response than rectangular filters.

Similarly, Fig. 7 shows the frequency response of prototype filters that include rectangular, PHYDYAS with overlapping factor of 4 and Hermite filters with overlapping factor 8. It is evident from the figure that frequency response of PHYDYAS filter is better in terms of spectrum efficiency with less out of band (OOB) leakage.

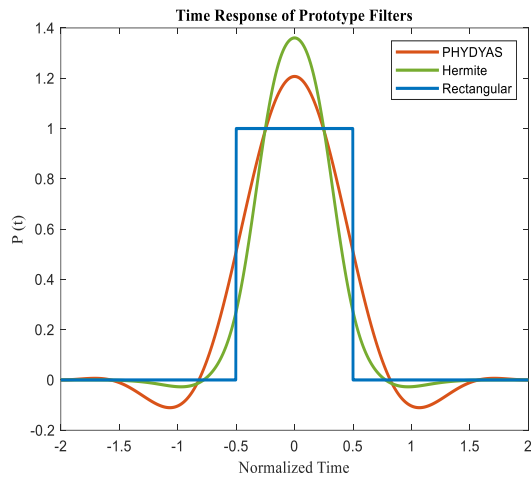


Fig. 6. Time Response of Prototype Filters.

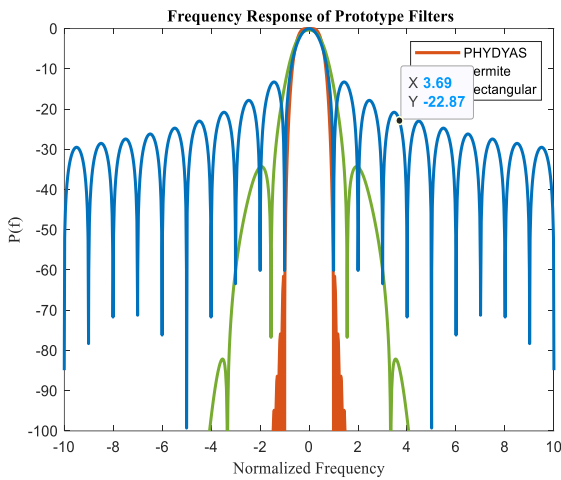


Fig. 7. Frequency Response of Different Type of Filters.

B. Channel Estimation and Performance Measurement

In order to compare performance of FBMC over OFDM Matlab simulations have been carried out with the input parameters as reflected in Table IV. It has been observed that for the same transmitted power data transmission rate of FBMC is better than OFDM. FBMC requires smaller guard band as compared to OFDM as it has higher signal to interference ratio (SIR). We require higher SIR due to different power levels when compared to channel induced interference.

TABLE IV: SNR AND BER RESPONSE

S. No	Description	Value
1	Number of sub carriers	16
2	Sampling Rate	30 KHz
3	Sample Spacing	30 KHz
4	Modulation Type	OQAM
5	Modulation Order	512
5	Transmit Power (Watt)	1.0
6	SNR (dB)	0.0
7	Bit Rate for OFDM	4032000
8	Bit Rate for FBMC	4320000

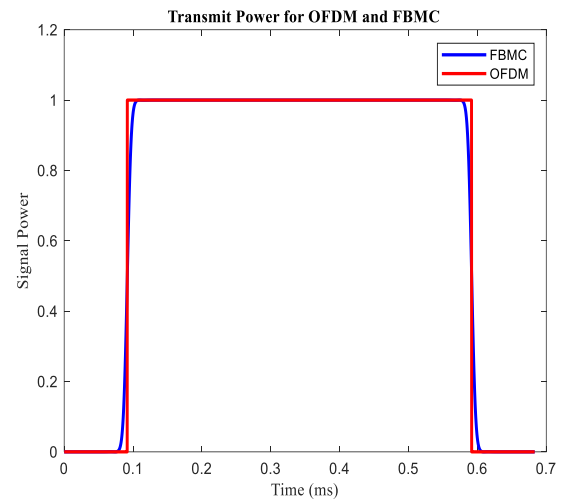


Fig. 8. Transmit Power of OFDM and FBMC

As evident from Fig. 8 and 9 performances of FBMC is better than OFDM both for transmit power and power spectral density. FBMC has less OOB, high data transmission rate with same SNR and transmit power.

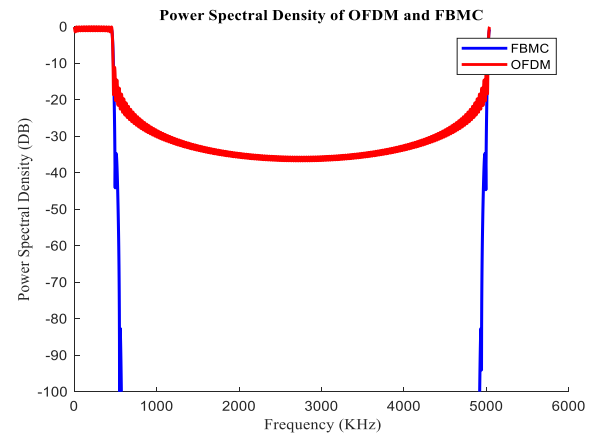


Fig. 9. Power Spectral of OFDM and FBMC.

The achievable capacity and throughput for both FBMC and OFDM has been computed using Gaussian inputs and the ergodic channel capacity as enumerated in (8).

$$C = E_x \{ \log_2 (1 + |x|^2 \text{SNR}) \} \quad (8)$$

where E_x is the ensemble average of the random variable and x is the channel gain vector. Calculation of signal to interference ratio (SIR) for OQAM signal is not easy like that of for QAM modulation technique. As we take real part of the signal along with phase compensation technique for OQAM. In the case of OQAM technique final SIR is expressed as in (9).

$$SIR_j^{OQAM} = \frac{[\tilde{\mathbf{f}}_j]_{j,j}}{\text{tr}\{\tilde{\mathbf{f}}_j\} - [\tilde{\mathbf{f}}_j]_{j,j}} \quad (9)$$

In order to maximize the SIR optimal subcarrier spacing has to be considered so that (10) is satisfied.

$$\frac{\alpha_t}{\alpha_f} \approx \frac{\tau_{rms}}{v_{rms}} \quad (10)$$

where α_t is the time localization, α_f is the frequency localization, v_{rms} is Doppler spread and τ_{rms} is the RMS delay spread.

IV. RESULTS AND DISCUSSION

Available capacity for 1.6 MHz FBMC and OFDM LTE system has been calculated using Matlab simulation. For simulation following parameters as depicted in Table V have been considered.

As evident from Fig. 10 and 11 the achievable capacity of FBMC is far better than that of OFDM under the similar parameters.

TABLE V: SIMULATION PARAMETER FOR CHANNEL ESTIMATION

Description / Modulation Type	FBMC	OFDM
No of subcarriers	90	80
No of symbols	30	20
Subcarrier spacing (KHz)	40	40
Sampling rate	30000*15*12	30000*15*12
Intermediate frequency first subcarrier (Hz)	30000*25	30000*25
Pilot Spacing in Frequency Domain	6	4
Pilot Spacing in Time Domain	6	4

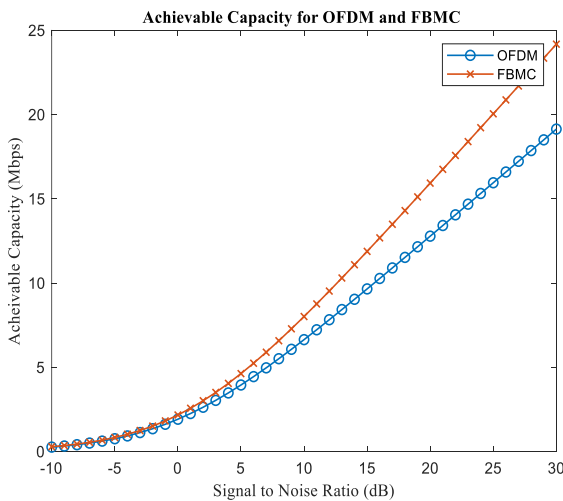


Fig. 10. Achievable Capacity for OFDM and FBMC.

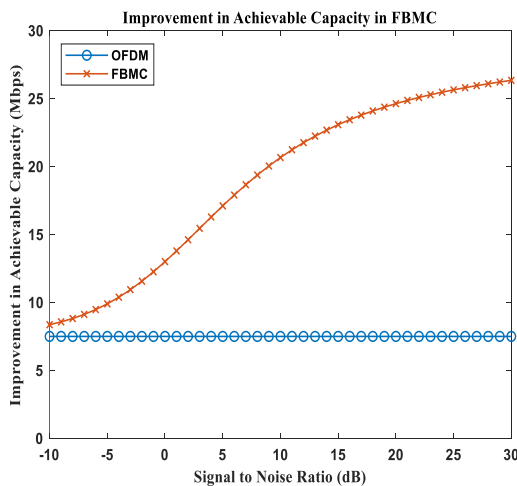


Fig. 11. Improvement in Achievable Capacity in FBMC.

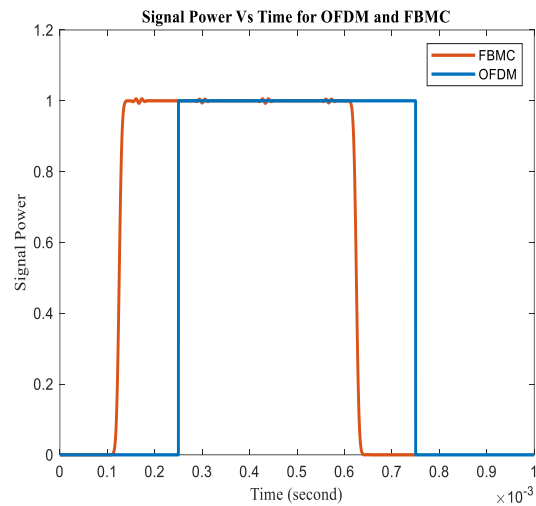


Fig. 12. Signal Power Vs Time for FBMC and OFDM.

Fig. 12 depicts the signal transmit power for FBMC and OFDM modulation techniques for 5 ms of time duration. It clearly indicates that transmit signal power is almost same for both the techniques.

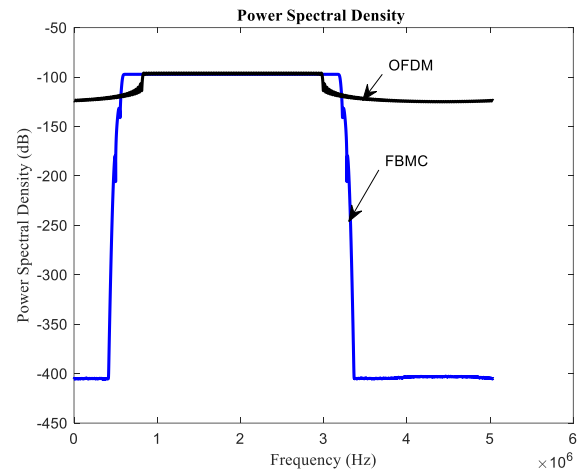


Fig. 13. Signal Power Vs Time for FBMC and OFDM.

Power spectral density for FBMC and OFDM modulation techniques have been shown in Fig. 13. It indicates that distribution of power is better for FBMC than OFDM modulation techniques over the same frequency spectrum.

V. CONCLUSIONS

Mobile communication has undergone tremendous changes from the first Generation that offered voice calling services. Though presently 5G is still in its infancy stage, it is time to think beyond 5G or more precisely on 6G of mobile communication systems. Services offered by 6G is aimed at lifestyle and societal changes with improved performance in terms of data rate, latency, synchronization, security, and reliability. In the present work performance of pulse shaping based FBMC modulation technique has been investigated. Results obtained shows that FBMC system performs much better in terms of many parameters such as achievable channel capacity, signal to noise ratio, time, and frequency response, out of band leakage, etc.

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