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Analysis of Multi Carrier Modulation Techniques for 5G Physical Layer Communications Estimation of KPI

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The more enchanting Multicarrier Communication (MCM) techniques like Fifth Generation (5G), Long Term Evolution (LTE) and Fourth Generation (4G) are the enhancing techniques that contribute the progress of wireless communication systems. The most effective way to save resources in 5G is to make efficient use of all existing discontinuous spectrums, which maximizes Spectrum Efficiency (SE). A valid comparison of many 5G MCM techniques is made in this work, namely Universal Filter Multi Carrier (UFMC), Filter Bank Multi Carrier (FBMC) and Orthogonal Frequency Division Modulation (OFDM). Various Key Performance Indicators (KPI) such as Bit Error Ratio (BER), Signal to Interference Ratio (SIR), Power Spectral Density (PSD) and ratio between Peak Power and Average Power, Throughput, and Spectral Efficiency (SE) are evaluated and compared under various realistic channels. UFMC Modulation technique is compatible with existing channel estimation and detection techniques and further improves SE. The SE of FBMC has been improved by 2% with Hermite filter when compared to PHYSDAS, RRC prototype filters. It has been observed that FBMC offered better SIR, Throughput, also a complex design of filter reduced BER and PAPR.

Keywords: BER, Power spectral density, Prototype filter, SIR, Spectral efficiency

Introduction

End user data rates and increased traffic capacity are prime driving parameters for the demand of traditional Mobile Broad Band applications.[1,2] The data traffic is expected to increase from hundred to thousand times in next 10 years.[3,4] To suffice this traffic, 3GPP started to embrace 5G requirements leading to an emerging agreement with a non-backward consistent, modern radio access technology at the same time as component in 5G.[5] To provide higher datarate and ease of access, segregation of non-contiguous spectrum is required. This can be addressed by looking into other multi-carrier wave form that gives improved leakage performance for adjacent channels while not affecting Spectral Efficiency.[6–9] Orthogonal Frequency Division Multiplexing (OFDM) is the predominant Multi-Carrier Modulation (MCM) system in wireless designs, especially for less than 6 GHz transmission.[10] Drawbacks with this are, Cyclic Prefix (CP) insertion that causes SE loss, and rectangular pulse shape that causes frequency leakage. At the outset to overcome inter and intra-cell interferences, orthogonality is required. Filter Bank Multicarrier (FBMC) modulation differs from OFDM with its filter characteristics. It reduces the Inter carrier Interference, Inter Symbol Interference by using OQAM mapper with proper filter. Following the IFFT stage, a Poly Phase Network (PPN) is also used as a filter processing unit.

Prototype Filters

Three prototype filters such as PHYDYAS, Hermite, and Root Raised Cosine (RRC) filters are introduced for better localization with reduced ICI and ISI in FBMC. PHYDYAS filter provides improved localization with a transmitter and receiver using simple equalization technique. PHYDYAS filter and Quadrature Amplitude Modulation (QAM) modulation combination process presents orthogonality without using cyclic prefix to improve SE and channel capacity.[11] The Hermite filter is created by combining linearly isotropic Hermite pulses with a strong weight Hermite pulse to create a filter through the lowest dispersion product.[12] RRC is used as filter in the transmitter and receiver. The performance of pulse shaping filter depends on roll-

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off factor (α).[13] The better RRC filter performance can be obtained with only more roll off-factor and lengthy filter, but this may be expensive.

MCM techniques such as OFDM, FBMC, UFMC, FBMC with QAM and FBMC with OQAM[14,15] has been focused in this work. Each subcarrier in FBMC has been filtered by a time-frequency prototype filter. PHYDYAS, Hermite, RRC has been designed within frequency domain, for evaluation of Out-of-Band (OOB) leakage. The BER of FBMC, UFMC, and OFDM has been investigated[16] using typical, EVU, and ETU channel models. By varying carrier frequency offsets and FFT size, the efficiency of the MCM is evaluated by comparing to that of OFDM, UFMC, and FBMC-QAM techniques. In each Physical Resource Block (RB), the interference distribution is evaluated after demodulation in terms of SIR. SE could be increased by varying the modulation order, overlapping factor and type of filter for each carrier.

In this paper the Key Performance Indicators (KPI) such as SE, Power Spectral Density, Peak to Average Power (PAPR) and Throughput for each MCM are compared. Furthermore, performance of 3GPP channel models is evaluated with respect to BER in order to achieve awareness into receiver robustness to realistic channel conditions. The 5G-MCM along with their associated transmitter-receiver, detailed comparison of the waveforms w.r.t KPI parameters such as PSD, PAPR, SE, Throughput and BER and Receiver of OFDM, UFMC and FBMC are discussed with their characteristics in the following sections.

Materials and Methods

MCM Techniques

MCM is one of the data transmission methods which transmit data across different carriers which are typically near to each other. It has several benefits that include resistance to narrow band fading, interference immunity and multipath effects. It is extensively employed for data transmission because this has been a spectral efficient technique and robust signal waveform to real-world channel environments.

Orthogonal Frequency Division Multiplexing (OFDM)

In OFDM technique, data is carried by large number of orthogonal subcarriers that are closely spaced. Although sidebands from each carrier overlap, subbands receive data with no interference because they are orthogonal to each other. OFDM transmitter and receiver system block diagram is presented in Fig. 1. Serial to Parallel converter transforms serial binary input data to parallel binary data. The IFFT block receives parallel data. By maintaining the orthogonality of the OFDM with IFFT, the parallel data is transformed into a time domain signal. Cyclic Prefix (CP) is appended to IFFT block for synchronization.

The received signal Y_k is given by Eq. 1

$$Y_k = r_{N+NC,N} F_N^H X_k \qquad \ldots (1)$$

where, X_k is the transmitted signal, $r_{N+NC,N}$ is the CP-Insertionmatrix, F is the DFT matrix and Y_k is the received signal.

High PAPR is not preferable spectral parameter for 5G communications. The special features of 5G when compared to 4G are Internet of Things (IoT),[17] very large wireless data rate connectivity upto10 Gb/s and reduced latency. These applications cannot be implemented by OFDM technique. Hence the new techniques such as UFMC and FBMC have been introduced.

Filter Bank Multicarrier (FBMC)

FBMC transceiver block diagram is presented in Fig. 2. OFDM has the similar principle of operation except cyclic prefix is replaced by PPN. PPN technique adds a set of digital filters with fewer computations. Orthogonality must be ensured for all carriers in OFDM, whereas FBMC only requires orthogonality for neighboring sub-channels. Without an OFDM cyclic prefix, the arrangement of filter banks through OQAM modulation leads highest bit rate.[18,19]

N numbers of input signals are utilized to generate N numbers of outputs using array of N numbers of filter processes. If the inputs of these N filters are connected, based on each filter characteristics, the

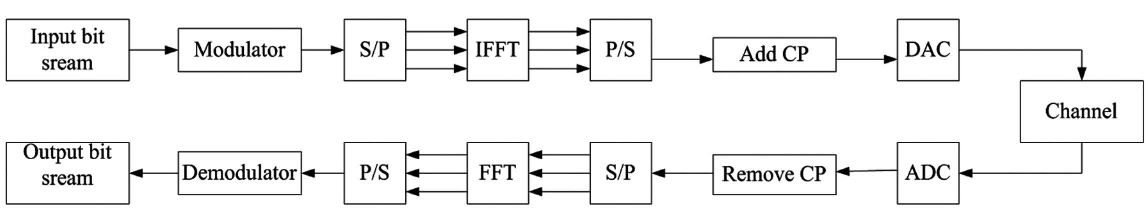

Fig. 1 — OFDM transmitter & receiver

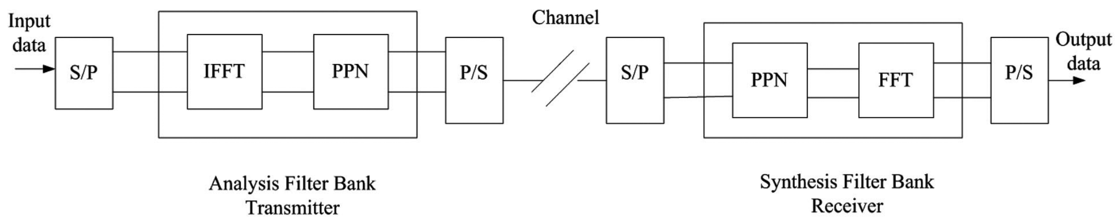

Fig. 2 — FBMC transmitter & receiver

system can be considered as an analyzer to the input signal and this type of filter bank is called Analysis Filter Bank (AFB). When filter array is considered with added outputs thena distinct signal is synthesized, and this filter bank is named as Synthesis Filter Bank (SFB).[20]

The prototype filter is designed using frequency sampling technique. In the frequency response, there are $P = 2K - 1$ non-zero samples in this approach. The coefficients of frequency domain pulse response are computed and expressed[21,22] for K = 2 as shown in Table 1

The IFFT output is transformed to serial form by using P/S convertor followed by accumulation of serial data. This process of P/S conversion and accumulation is known as overlap and-sum. After completion of transient period, at any given time, number of samples being added are 2K out of the KN-IFFT output samples. Therefore, the FBMC signal in the time domain is given by

$$Y_k = F_N^H H S_k + \sum_{m=1}^{2k-1} Q_{-mN/_2} F_N^H H S_{k-m} + Q_{+mN/_2} F_N^H H S_{k+M} \quad \ldots (2)$$

Here, samples between the m block delay is given by Qm and H represents matrix of prototype filter, 2 × (2K − 1) +1 FBMC-OQAM filtered symbols adds those overlaps in a given time is represented in Eq. 2.

The adjacent carriers are filtered by prototype filter in the FBMC-OQAM, results in intrinsic interference whereas intrinsic interference in the FBMC-QAM between the even-odd numbered carriers can be neutralized by the two orthogonal prototype filters.[23,24]

A symbol Yk for FBMC-QAM can be given by

$$Y_k = F_N^H H S_k^0 + \sum_{m=1}^{k-1} Q_{-mN} F_N^H H S_{k-m}^0 + Q_{+mN} F_N^H H S_{k+m}^0 + \Omega F_N^H\, H S_k^1 + \Omega \sum_{m=1}^{k-1} Q_{-mN} F_N^H H S_{k-m}^1 + Q_{+mN} F_N^H H S_{k+m}^1 \quad \ldots (3)$$

where, block-wise interleaving is denoted by matrix Ω. The data on even and odd carrier is modeled by S_{k+m}^0 and S_{k+m}^1 matrices

Table 1 — Prototype filter coefficients Frequency domain

K	H0	H1	H2	H3	σ^2 (dB)
2	1	$\sqrt{2}/2$	—	—	−35
3	1	0.911438	0.411438	—	−44
4	1	0.971960	$\sqrt{2}/2$	0.235147	−65

Universal Filtered Multi Carrier (UFMC)

The UFMC transmitter and receiver block diagram is presented in Fig. 3. Here, the overall bandwidth has been divided into a few subbands first. Every subband has some number of subcarriers. Data bits are given to each subband.[25] After that the data bits are given to symbol mapper which assigns symbols to bits. The S/P converter transforms the data bits to parallel. The output of S/P converter is given to N-point IFFT. Here the IFFT function as a modulator. It is very difficult to design modulators for each and every subcarrier. The IFFT output is serialized by using a P/S converter, and the output is filtered with a Chebyshev filter of length L.[26] The output of each filter is added, and the filter output is transmitted through the channel.

The received data from the channel is fed into the S/P converter and then demodulated after passing through the 2N-point FFT. After that the output of FFT is given to frequency domain equalizer per sub-carrier. The output of equalizer is given to Parallel to Serial (P/S) converter which converts all the parallel data streams into single stream. The single stream is passed through symbol demapper that transforms the symbols to bits and original data is retrieved. UFMC has higher spectral efficiency compared to OFDM because of the absence of cyclic prefix insertion as in case of OFDM. It uses the entire spectrum because there is no repetition of the same bits.[27] UFMC has fewer side lobes than OFDM and FBMC which in turn decreases the interference on adjacent subcarriers.[28]

The transmit vector X in the time-domain is given by a length of $1 \times N_{FFT} + L - 1$ for a multicarrier symbol. The subband filtered components when superimposed[27] having user k are represented by

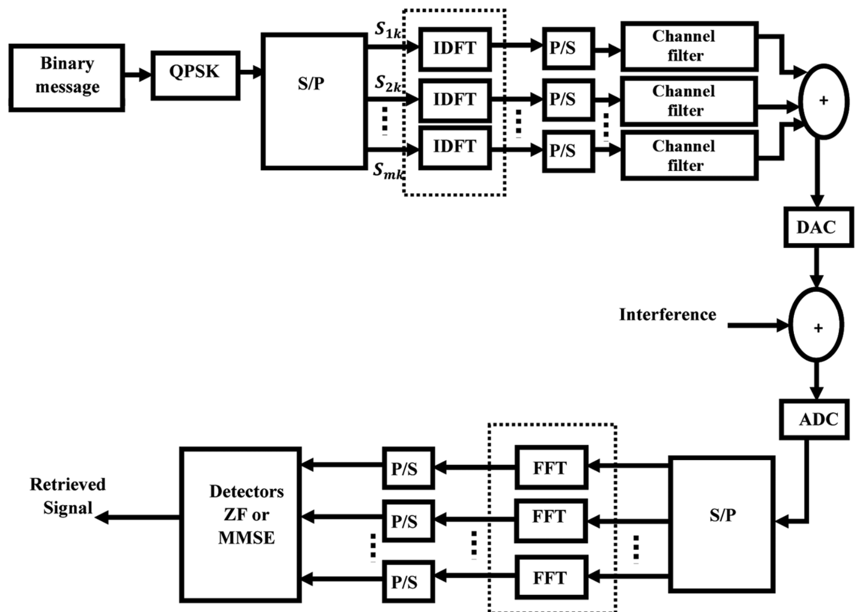

Fig. 3 — UFMC transmitter and receiver

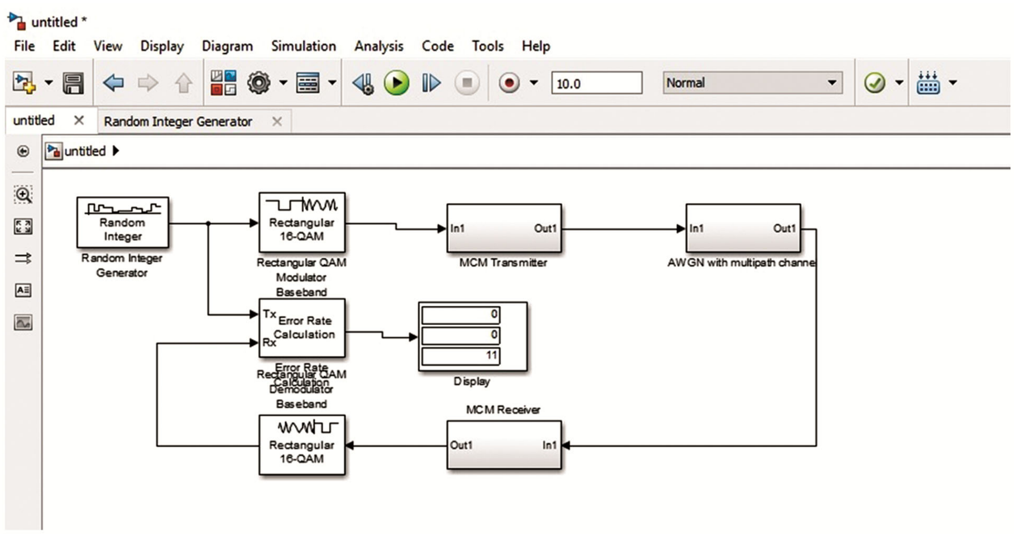

Fig. 4 — Experimental setup

$$X_K = \sum_{i=1}^{B} C_{i,k} F_{i,k} X_{i,k} \qquad \dots (4)$$

where, data vector is given by $X_{i,k}$ in block I with size $1 \times ni$, $C_{i,k}$ represents filtering matrix with size $(N_{FFT} + L - 1) \times N_{FFT}$, IFFT matrix $F_{i,k}$ is of size $NFFT \times ni$ with appropriate frequency mapping.

Simulation Setup

Multi Carrier Modulation (MCM) has been discussed in the previous section. KPI for various MCM techniques are computed by considering LTE Standards for OFDM, FBMC and UFMC. The numbers of subcarriers considered for the proposed work are 10, as shown in Table 2. However, maximum numbers of subcarriers are allowed to 1200. The simulation setup shown in Fig. 4 and specifications for the performance evaluation of various MCM techniques as given in Table 2 are defined using MATLAB/Simulink.

The signal to be transmitted is modulated with QAM modulation by varying their modulation in the order of 4, 16, 64, and 56. Constellation points or symbols of modulated signal are transmitted using DFT/FFT of different lengths. For OFDM, CP is added to each symbol for the synchronization after computing FFT/DFT. At the OFDM receiver symbols

Table 2 — Simulation setup

Parameters	Values
FFT Size	256, 512, 1024, 2048
Overlapping Factor (K)	2, 3, 4, 6, 8 (K = 4 Optimum)
Number of Sub Bands	10
Bits per Sub Carrier	2, 4, 6
Length of filter	43, 63, 83
Modulation order	QAM (4, 16, 64, 256)
size of sub band	20

are demodulated. For FBMC, FFT symbols are passed through the various prototype filters such as PHYDYAS, Hermite, RRC. PHYDYAS filter is designed with various lengths of overlapping factor (K) in the order of 2, 4, 6, and 8. Orthogonality is maintained for FBMC with PHYDYAS, RRC and Hermite protype filters. The transmitted signal is recovered in the FBMC receiver.

In the UFMC, IDFT signal is transmitted with Channel filter. A group of symbols /subbands are transmitted with one channel filter. Similarly, all subabands are transmitted through different channel filters. The length of channel filter and bits per subcarrier is varied as given in Table 2. The transmitted signal is recovered in the UFMC receiver. KPI parameters of various MCM techniques are initialized and computed using MATLAB to analyze Multi Carrier modulation techniques & 5G physical layer.

MCM KPI Indicators and Simulation

Various KPI parameters, such as Power Spectral Density (PSD), will be computed in this section to emphasize the FBMC parametrization impact on Out-of-Band (OOB) leakage. SE, BER and PAPR are to be computed for various 5G Candidate Waveform techniques

Power Spectral Density (PSD)

The PSD specifies power of various frequencies present in the signal, allowing us to determine the power range at which the signal frequencies operate. For a MCM technique the spectral location is essentially linked to the reuse of spectrum and the co-existence of different services.

Spectral Efficiency (SE)

When MCM techniques are constructed to meet especially lower OOB radiation constraint, a small number of guard carriers on either side of the band permit approximately zero OOB radiation. UFMC SE is determined by FFT size and its modulation efficiency. And it is determined by the coding rate, order of modulation and active numbered RBs. SE is measured in bits per second per Hertz and is independent of burst duration. In case of OFDM system the SE is given by

$$\eta_{OFDM} = \frac{N}{N+N_C}\eta \qquad \ldots (5)$$

Here, η is the efficiency of Modulation. In the instance of UFMC the spectral efficiency be contingent on the transient state period of shaping filter, i.e for UFMC SE is given by

$$\eta_{UFMC} = \frac{N}{N-1+L}\eta \qquad \ldots (6)$$

In the case of FBMC SE is expressed in number of symbols transmitted. Let M be the number of Symbols transmitted then SE is given by

$$\eta_{FBMC-QAM} = \frac{M}{K+M-1}\eta \qquad \ldots (7)$$

Signal to Interference Ratio (SIR)

In the case of an MCM transmission, the SIR can be calculated using matrix notation.[29] SIR is like signal-to-noise ratio (SNR), but interference is considered as co-channel interference since it is part of radio transmitters.

Peak to Average Power (PAPR)

PAPR is specified as the square of peak amplitude to average power ratio calculated for burst m is given by

$$PAPR = \frac{max(y_b(k)^2)}{E(y_b(k)^2)} \qquad \ldots (8)$$

PAPR can be obtained by computing Complementary Cumulative Probability Density Function (CCDF) and it is given by

$$CCDF_{PAPR}(\gamma) = pr_{[b]}(PAPR[m] > \gamma) \qquad \ldots (9)$$

For the parameters mentioned in Table 2, the PAPR of OFDM is 8.883dB, UFMC is 8.2379 dB, and FBMC is 8. 123dB. Lower PAPR can be obtained by FBMC when the FFT size is reduced from 1024 to 256.

BER (Bit Error Rate)

The errors in the transmission system are given by BER. Data signal is generated, modulated with QPSK, and transmitted using OFDM/UFMC/FBMC techniques.[30] The modulated signal is allowed to pass through various fast fading channels like Vehicular-A, Vehicular-B and doppler models such as Jakes and Uniform. At the receiver BER can be computed.

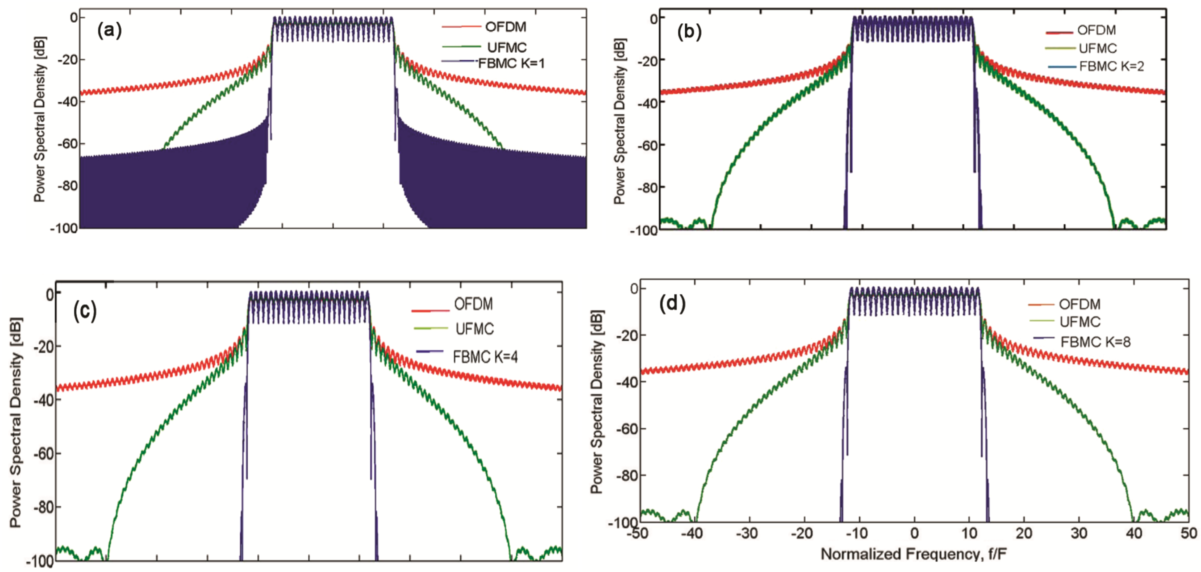

Fig. 5 — PSD of OFDM/UFMC/FBMC with overlapping factor: (a) k = 1, (b) k = 2, (c) k = 4, (d) k = 8

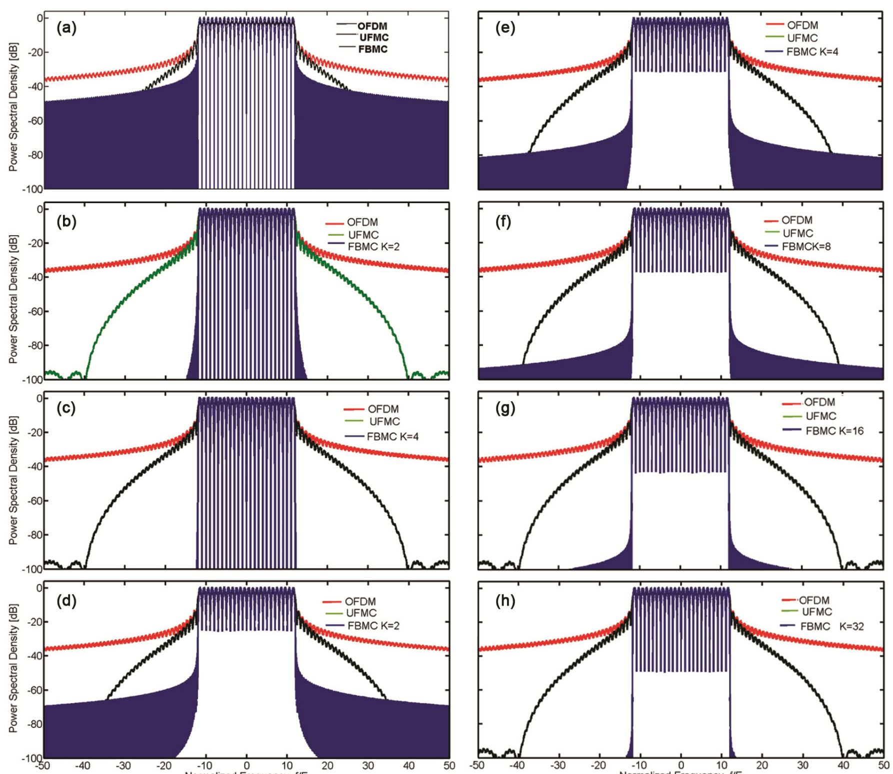

Fig. 6 — PSD of OFDM/UFMC/FBMC with PHYDYAS filter overlapping factor: (a) k = 1, (b) k = 2, (c) k = 4, (d) k = 2; with RRC filter (e) k = 4, (f) k = 8, (g) k = 16, (h) k = 32

Results and Discussion

Techniques of 5G MCM such as FBMC, UFMC, and OFDM are compared and presented under a common structure. Various KPI parameters, such as SIR, SE, PSD, PAPR, Throughput, and BER are evaluated for noisy channel conditions.

Hermite, PHYDYAS and RRC filters have been incorporated in FBMC and compared with UFMC, OFDM. The PSD of MCM techniques[27] such as OFDM, UFMC, and FBMC is computed and shown in Figs 5 & 6. By incorporating various overlapping factors for k =1, 2, 4 & 8 with Hermite filter in the

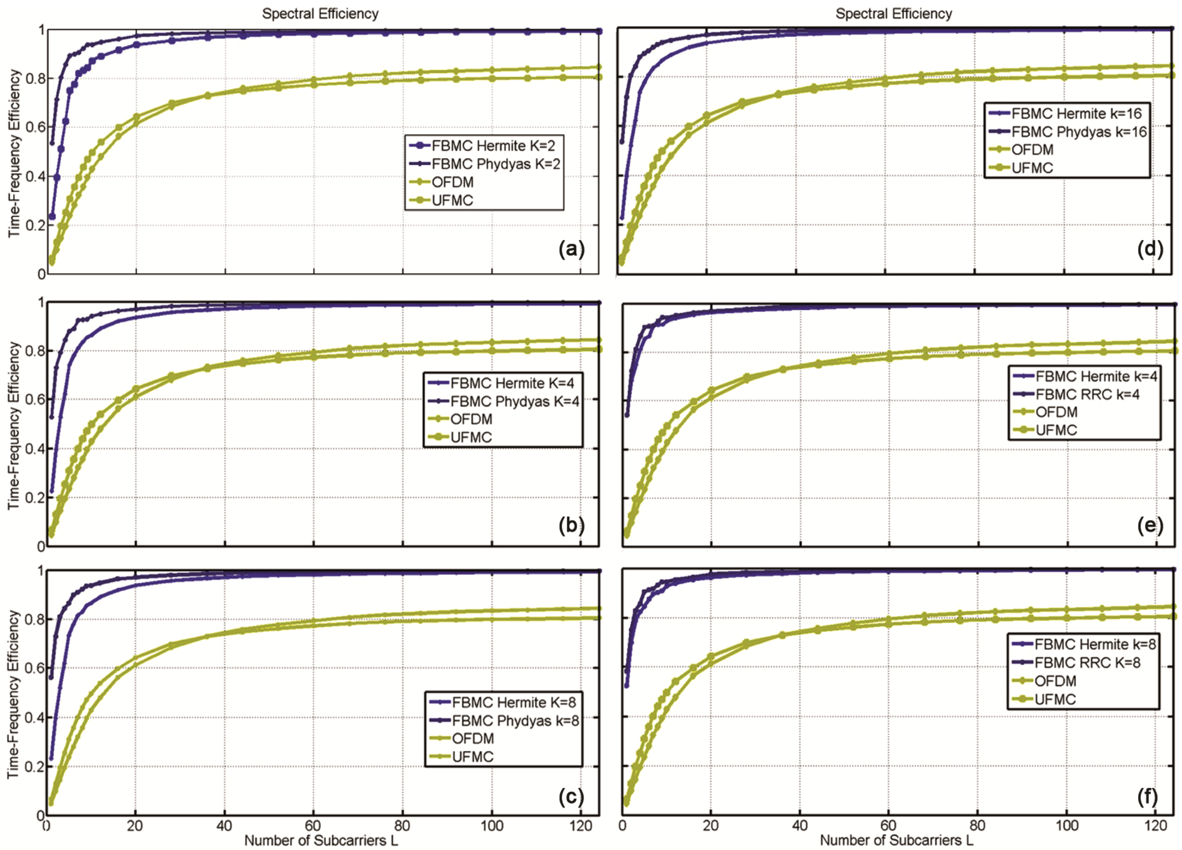

Fig. 7 — Spectral efficiency of OFDM, UFMC, FBMC with overlapping factor: (a) k = 2, (b) k = 4, (c) k = 8, (d) k = 16 with Hermite & PHYDYAS filter; (e) k = 4, (f) k = 8 with Hermite & RRC filter

FBMC, PSD is computed and compared with UFMC, OFDM and plotted in the Fig. 5 (a, b, c, d). From Fig. 5 it is clear that FBMC-Hermite filter with larger overlapping factor has a smaller OOB leakage when matched to OFDM, UFMC. The performance of various Prototype filters such as RRC and PHYDYAS are also observed and lower OOB leakage is obtained only for larger value of k. Lower OOB leakage is obtained for k = 8, 16, 32 (Fig. 6 (f–h)). For PHYDYAS filter PSD is also computed by incorporating RRC filter with different values of k such as 1, 2, 4, 8, 16, and 32 as plotted in Fig. 6 (a–h). When compared to UFMC and OFDM, the finest spectral location is achieved using FBMC-PHYDYAS filter with overlapping factor K = 4 and FBMC-RRC filter with overlapping factor K=32.

SE is computed for MCM techniques and plotted with various filters of FBMC like Hermite, PHYDYAS and RRC as shown in Fig. 6. OFDM achieves maximum spectral efficiency with more subcarriers i.e. at L = 100, which is shown in Fig. 7(a), whereas FBMC with PHYDYAS, Hermite filter also achieves maximum spectral efficiency even at L = 2. The maximum spectral efficiency obtained with a smaller number of subcarriers for FBMC as compared to UFMC and OFDM for various values of k (4, 8, and 16) as shown in Fig. 7 (b–d). SE is also computed for FBMC-RRC filter and compared with OFDM, UFMC as shown in Fig. 7 (e & f).

The noise is approximated to zero for one symbol at receiver with subcarrier position time-position of k, SIR is evaluated for channel Matrix H and plotted in Fig. 8.

Various prototype filters are incorporated in FBMC such as Hermite, PHYDYAS, RRC and SIR is computed as shown in the Table 3. These prototype filters are designed with the Quadrature Amplitude Modulation (QAM) and OQAM (Offset Quadrature Amplitude modulation). The resulting SIR is better for Hermite-QAM. SIR is evaluated for FBMC-Hermite QAM and compared with the OFDM, UFMC as shown in Table 4. FBMC Hermite – QAM is better in terms of SIR compared to OFDM, UFMC Techniques.

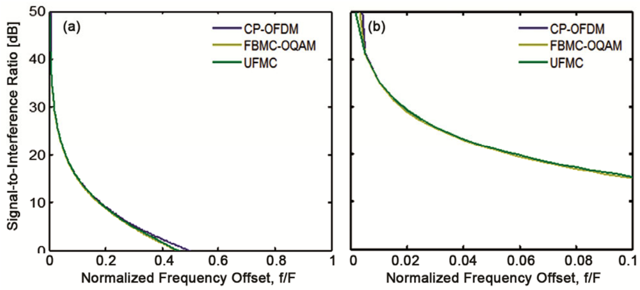

Fig. 8 — SIR of OFDM, UFMC, FBMC: (a) frequency offset = 1 Hz; (b) frequency offset = 0.1 Hz

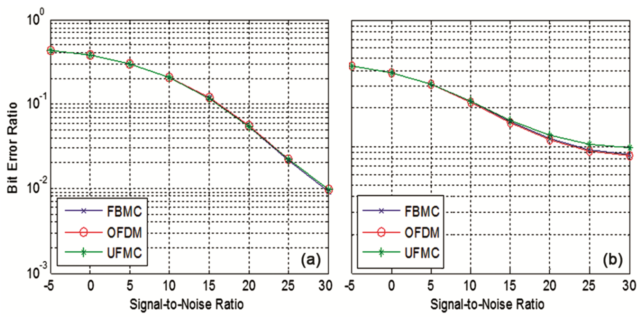

Fig. 9 — BER V/S SNR Characteristics with: (a) Vehicular Channel-A, Jakes Doppler; (b) Vehicular Channel-B, Uniform Doppler Model

Table 3 — SIR (dB) for various prototype

MCM	SIR (dB)
OFDM	66.39
UFMC	69.87
FBMC Hermite QAM	117.58

Table 4 — SIR (dB) forvarious MCM techniques Filters of FBMC

Type of prototype filter	QAM	OQAM
Hermite	117.58	101.86
PHYDYAS	88.31	65.20
RRC	58.90	45.60

The signal is demodulated with the help of one tap-Equalizer. Finally, BER is computed and plotted as shown in Fig. 9. BER of 0.01 is obtained for Channel model of Vehicular-A, with Doppler model of Jakes with SNR = 30 dB and shown in Fig. 9a at 30 dB of Signal to Noise ratio with Channel model of Vehicular-Band Doppler model of Jakes for 0.01 of BER is obtained which is shown in Fig. 9b

Conclusions

Major challenge for future 5G networks is making effectual utilization of entire existing discontinuous spectrum for various network deployments. Air interfacing technologies of 5G must be compliant and competent of matching different services to save resources and to maximize SE, PSD. As a result, physical layer modulation flexibility and frequency localization are critical requirements. A nondiscriminatory comparison of various 5G MCM (UFMC, FBMC-QAM, OFDM) is considered in a conventional structure. BER, SE, PAPR, PSD and Throughput are evaluated. UFMC Modulation offers better SE, pulse shaping function provides strength to approach with ease synchronization compared to OFDM. In addition, UFMC maintains backward compatibility with frequently used and popular OFDM algorithms (MIMO detectors, channel estimation). FBMC also provides better SE, SIR and lower BER and PAPR. Prototype filter type offers a substantial impact on both performance and equalization complexity. UFMC improves on OFDM while maintaining backward compatibility, whereas FBMC-OQAM outperforms with better PSD, SE, SIR, BER, and offers strength against both asynchronous communication and greater delay spread channel conditions.

Enhanced KPI parameters can be obtained for FBMC by changing intercarrier spacing. Less PAPR in FBMC compared to OFDM UFMC, supports small packet size. In broadcast transmission, having no guard period results in efficiency gain of higher packet size. This can be achieved by a complex FBMC transceiver which can be implemented using embedded digital and analog filtering functions.

Conflict of Interest

We have no conflicts of interests associated with thispublication. As a corresponding author, I confirm that the manuscript has been read and approved for submission by all the named authors.

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