Comparative Study of Modulation Techniques for 5G Networks

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Abstract. Fifth Generation (5G) communication systems applications are expected to use or require lower latency, higher data rates, and efficient spectrum usage which are impacted by the adopted modulation scheme. Thus, proper selection and usage of efficient modulation scheme is crucial. Orthogonal Frequency Division Multiplexing (OFDM) suffers from high peak to average power ratio, which results in low efficiency of power amplifier and increases the battery consumption. Moreover, the OFDM spectrum has high out of band side lobes or side lobe leakage causing problem of low spectral efficiency. So, to overcome some of these drawbacks new modulation techniques for 5G communication systems such as Generalized Frequency Division Multiplexing (GFDM), filtered – OFDM (f-OFDM), Universal Filtered Multi-Carrier (UFMC), Filter Bank Multi-Carrier (FBMC) are considered. In this paper, we perform the comparative study of UFMC and FBMC in terms of Spectral Efficiency (SE) and Power Spectral Density (PSD). Simulations were done to evaluate the performance variation that can be achieved by varying the parameters of these modulation techniques, such as filter length, burst duration and overlapping factor. Our simulation results show that, FBMC has better SE for large burst durations whereas UFMC is better for small burst durations. In terms of PSD, FBMC has lower side lobe than UFMC. This implies that FBMC is more preferable to minimize the inter symbol interference and inter carrier interference.

Keywords: 5G · FBMC · UFMC

1 Introduction

Wireless communications have become an essential tool for our life. Starting from the First-Generation wireless networks (1G), there has been an exponential growth in number of users and their applications. Fifth generation mobile networks or 5th generation wireless systems are the proposed next telecommunications standards beyond the current Fourth Generation (4G/IMT -Advanced Standard). 5G planning aims at higher capacity than current 4G, allowing a higher density of mobile broadband users, and supporting device-to-device, more reliable, and massive machine communications. 5G research and development also aims at lower latency than 4G equipment and lower battery consumption, for better implementation of the Internet of Things (IoT). In addition to providing simply faster speeds, it is predicted that 5G networks also will

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need to meet new use cases, such as the IoT, as well as broadcast-like services and lifeline communication in times of natural disaster [1].

Owing to a broad range of applications spanning from wireless regional area networks to machine type communications, future wireless networks have challenging objectives such as very high spectral and energy efficiency, very low latency and very high data rate, which require more effective physical layer solutions [1]. In this context, the vision and overall objectives of future wireless networks for 2020 and beyond have been defined by the International Telecommunication Union (ITU); and standardization activities for 5G wireless networks have been started through discussions about scenarios and requirements by Third Generation Partnership Project (3GPP) [2].

Orthogonal Frequency Division Multiplexing (OFDM) is the core of the physical layer of 4G wireless networks and fulfills the requirements and challenges of 4G scenarios. Despite of its proven advantages, OFDM has some shortcomings that make it difficult to address the scenarios foreseen for future 5G wireless networks. In OFDM, every symbol requires a Cyclic Prefix (CP). The insertion of CP reduces the spectral efficiency and prevents obtaining a low latency by shortening the symbols. Furthermore, OFDM is very sensitive to time and frequency synchronization errors and has high Out-of-Band (OOB) emission due to rectangular pulse shaping. Thus, OFDM can fulfill the requirements of 5G wireless networks in a limited way [3].

In recent years, several waveform proposals have been presented to overcome the above limitations of OFDM. These proposals can be categorized into two main classes: Cyclically-Prefixed OFDM (CP-OFDM) and non-CP-OFDM. The proposals in the first class, such as filtered OFDM (f-OFDM) and windowed OFDM (W-OFDM) [3], attempt to resolve the aforementioned problems by keeping the orthogonality. The proposals in the second class initially dismiss orthogonality to obtain better temporal and spectral characteristics, thus, causes a major paradigm shift in the context of waveform design, which may yield some backward compatibility issues [4]. Thus, in order to overcome these drawbacks, new modulation techniques such as f-OFDM, Filter Bank Multicarrier (FBMC), and Universal Filtered Multicarrier (UFMC) were suggested as novel modulation techniques of 5G wireless networks.

The comparative analysis of FBMC with OFDM, and UFMC with OFDM in terms of Power Spectral Density (PSD) and Spectral Efficiency (SE) was done in [5–7]. However, the sensitivity of the performance metrics on the parameters of these modulation techniques was not done so far. In this paper, however, we perform the comparative study of UFMC and FBMC in terms of SE and PSD. We will also analyze the performance of these modulation techniques by varying their parameters. The result of this research will play a significant role in selecting efficient modulation scheme for the upcoming 5G wireless networks.

This paper has two contributions. These are (1) we evaluate the dependency of the performance metrics of FBMC and UFMC on their parameters. We identify the parameters that strongly influences the performance of these modulation techniques. (2) We show the advantage of employing different modulation techniques for different applications to enhance the performance. The characteristics of the communication systems, such as burst duration, can influence the performance of these modulation techniques.

This paper contains four sections. A brief Introduction is given in Sect. 1. UFMC and FBMC system model details are discussed in Sect. 2. Sections 3 and 4 will deal with simulation results and conclusion, respectively.

2 Candidate 5G Modulation Techniques

Various types of modulation techniques have been proposed to address the new challenges that 5G networks are expected to solve, such as pulse shaping, filtering, and pre-coding to reduce the out-of-band (OOB) leakage of OFDM signals. Filtering is the most straightforward approach to reduce the OOB leakage and with a properly designed filter, the leakage over the stop-band can be greatly suppressed. Pulse shaping can be considered as a type of subcarrier-based filtering that reduces overlaps between subcarriers even inside the band of a single user. Thus, FBMC is an example of 5G modulations based on pulse shaping, whereas UFMC is an example of 5G modulations based on sub band filtering.

(1) **Filter Bank Multicarrier** (**FBMC**): FBMC is an OFDM-like modulation format wherein subcarriers are passed through filters that suppress signal side lobes, making them eventually strictly band limited. FBMC is usually either coupled with Quadrature Amplitude Modulation (QAM) or with Offset QAM (OQAM) modulation formats. But, to achieve the best spectral efficiency OQAM is usually applied to make FBMC real-domain orthogonal in time and frequency domains. By adding generalized pulse shaping filters, the FBMC technique overcomes the limitations of OFDM which delivers a well localized sub channel in both time and frequency domain. The filter bank used at the transmitter side is called synthesis filter bank and that used in receiver side is called analysis filter bank [8].

As shown in Fig. 1, the input signal is first converted from serial to parallel (S/P) form and then passed through synthesis filter bank and then it is converted back to serial form after coming out of synthesis filter bank. Whereas at the receiver side, Fig. 2, after the signal passes through the channel it is converted to parallel form by serial to parallel converter and passed through analysis filter bank. Finally, when the output signal is obtained it is again converted to serial form by parallel to serial (P/S) converter.

(2) **Universal Filter Multicarrier** (**UFMC**): In UFMC, the sub bands are equal in size, and each filter is a shifted version of the same prototype filter. OFDM is applied within a sub band for this modulation. Since the bandwidth of the filter in UFMC is much wider than that of the modulations based on the pulse shaping, the length in time domain is much shorter. Therefore, interference caused by the train of the filter can be easily eliminated by adopting a zero-padding (ZP) prefix with a reasonable length.

The UFMC transmitter and receiver block diagrams are shown below in Figs. 3 and 4, respectively. UFMC employs the full band of subcarriers (N) divided into sub bands. Each sub band has a fixed number of subcarriers and not all sub bands need to be employed for a given transmission. The modulation technique processes these sub bands individually and each sub band consists of fixed number of subcarriers. The narrowband and closely spaced individual sub bands undergoes N-point Inverse Fast Fourier Transform (IFFT) to get time domain of each sub band from Frequency

Domain of each sub band. An N-point IFFT for each sub band is computed, inserting zeros for the unallocated carriers [6].

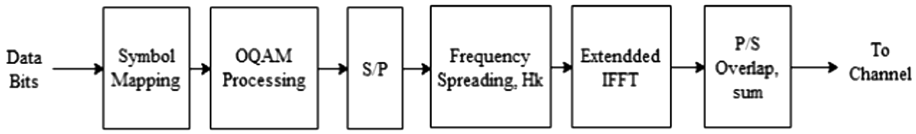

Fig. 1. Filter Bank Multicarrier Transmitter Block Diagram

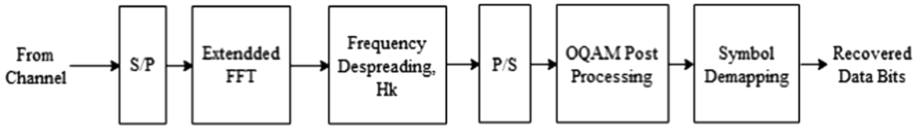

Fig. 2. Filter Bank Multicarrier Receiver Block Diagram

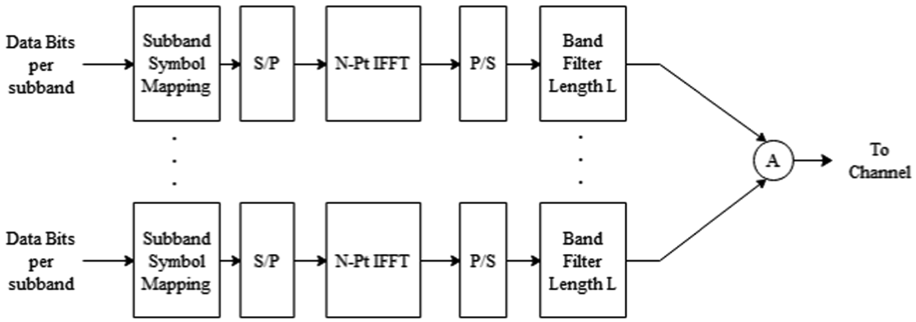

Fig. 3. Universal Filter Multicarrier transmitter block diagram

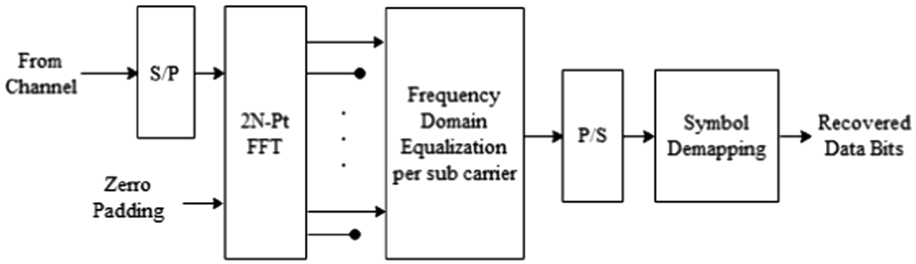

Fig. 4. Univeral Filter Multicarrier receiver block diagram

The UFMC receiver performs 2N point FFT on the data obtained from the channel. A guard interval of zeros is added between successive IFFT symbols. This prevents inter symbol interference (ISI) due to transmitter filter delay. Discard even subcarrier points to get N length frequency domain receive signal. FFT block is used to process the received signal and converts data received in time domain into frequency domain. Equalization detects the transmitted data. The Symbol de mapping is performed to the frequency domain equalization to get the original data bits [6].

3 Performance Analysis

3.1 Comparison of Spectral Efficiency of UFMC and FBMC

The term spectral efficiency is used to describe the rate of information being transmitted over a given bandwidth in specific communication systems. Spectral Efficiency may also be called bandwidth efficiency. Since frequency spectrum is limited, it has to be utilized efficiently. A given bandwidth is said to be used effectively if maximum information can be transmitted over it. The spectral efficiency of UFMC and FBMC modulation schemes is given by [9]:

$$\eta_{UFMC} = \frac{mxN_{FFT}}{N_{FFT} + L - 1} \tag{1}$$

$$\eta_{FBMC} = \frac{mxS}{S + K - \frac{1}{2}} \tag{2}$$

Where: NFFT = number of FFT; S = duration of burst; m = bits per subcarrier; K = Overlapping factor; L = filter length.

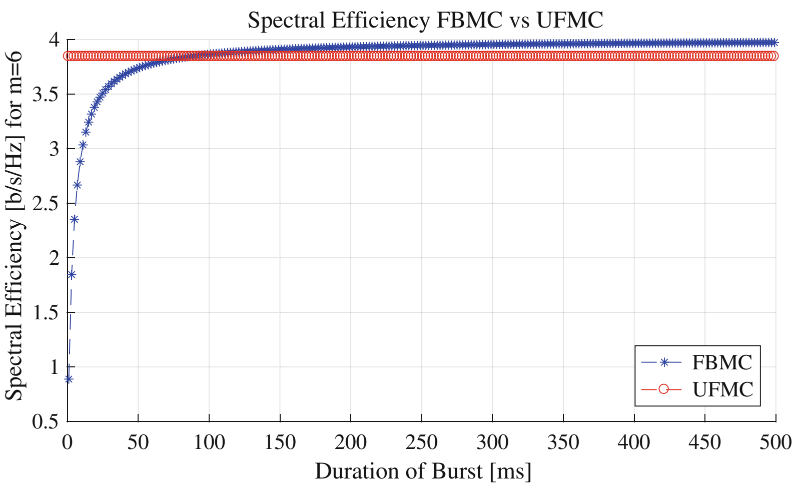

Fig. 5. Spectral Efficiency of FBMC and UFMC with filter length equal to 43.

We now show the spectral efficiency of the UFMC and FBMC for different value of number of FFT (NFFT), duration of burst (s), bits per subcarrier (m), overlapping factor (K), and filter length (L).

Figures 5 and 6 show the spectral efficiency of UFMC and FBMC with number of FFT 1024, bits per subcarrier and overlapping factor equal to four, and with the burst duration of up to 500 ms and with filter length equal to 43 and 23, respectively.

In Fig. 5, the spectral efficiency of UFMC is constant (around 3.85b/s/Hz) throughout the burst duration. Whereas the spectral efficiency of FBMC increases rapidly with burst duration till 70 ms. After around 70 ms, the spectral efficiency of FBMC increases gradually with larger value than UFMC.

Everything being the same, decreasing the filter length from 43 to 23, in Fig. 6, increases the spectral efficiency of both FBMC and UFMC near to 3.95b/s/Hz.

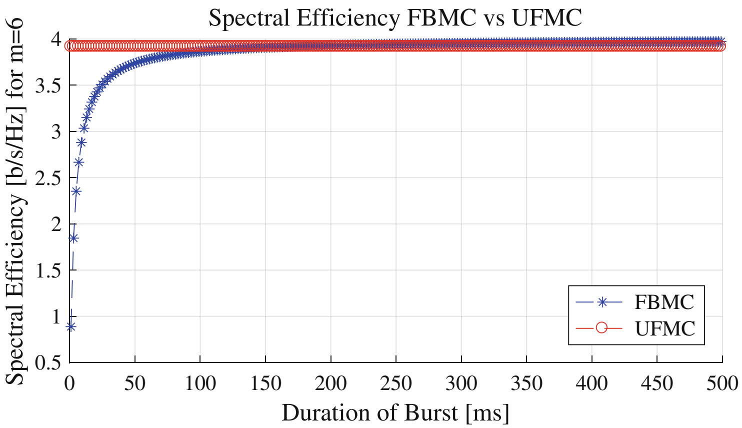

Fig. 6. Spectral efficiency of FBMC and UFMC with filter length equal to 23.

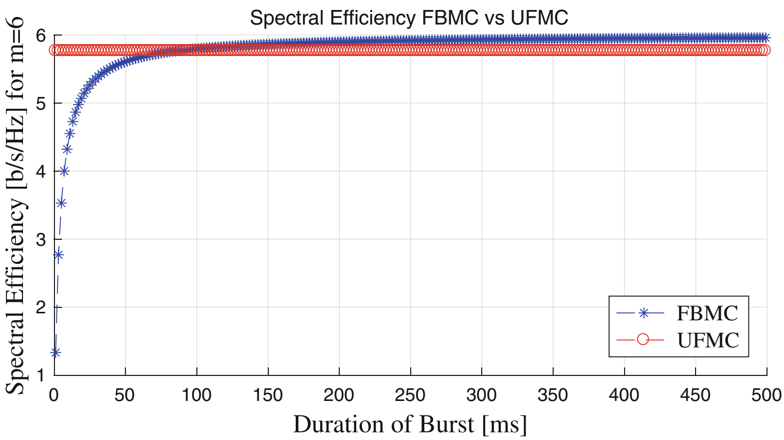

Fig. 7. Spectral efficiency of FBMC and UFMC with bits per subcarrier (m) = 6

Where FBMC still increases gradually beyond this value, showing its efficiency being larger than UFMC.

Figures 7 and 8 show the spectral efficiency of UFMC and FBMC for burst duration of up to 500 ms, overlapping factor equal to four, filter length equal to 43, bits per subcarrier, m = 6 and number of FFT 1024 and 512, respectively.

Increasing the bits per sub carrier from 4, in Figs. 5 and 6, to 6, in Figs. 7 and 8, the spectral efficiency of both FBMC and UFMC increases up to around 5.7b/s/Hz and beyond. As Fig. 7 shows, the spectral efficiency of FBMC is larger than UFMC and continues to increase after burst duration of 100 ms. But, when we decrease the number of FFT value from 1024 to 512 as in Fig. 8, the spectral efficiency of FBMC increases rapidly and copes with UFMC at around 40 ms with an efficiency value of 5.52b/s/Hz. Moreover, the spectral efficiency of UFMC has decreased from 5.7b/s/Hz in Figs. 7, 6 and 5.52b/s/Hz in Fig. 8 with decreasing value of number of FFT. However, the spectral efficiency of FBMC is same, at around 5.7b/s/Hz with decreasing the number of FFT.

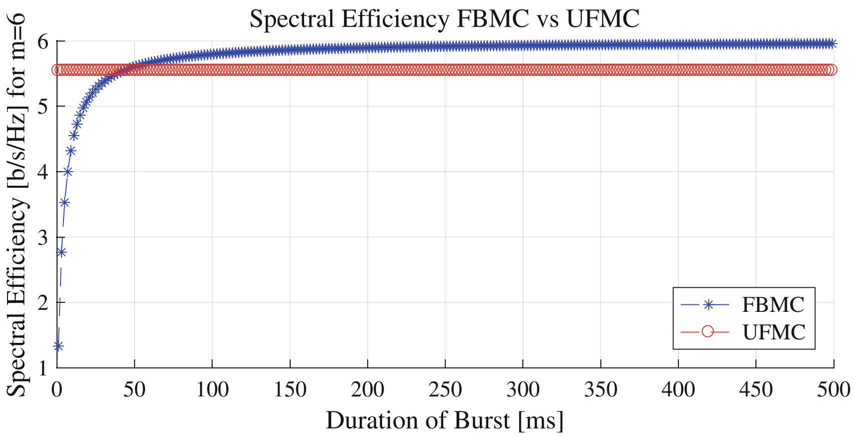

Fig. 8. Spectral efficiency of FBMC and UFMC with number of FFT 512.

Figure 9 is the spectral efficiency of FBMC and UFMC for burst duration of up to 500 ms with number of FFT 512, filter length 43, Bits per subcarrier equal to 6, and with overlapping factor increased to six.

By increasing the overlapping factor from 4 to 6, in Fig. 9, the spectral efficiency of FBMC is lower than 5.7b/s/Hz. Whereas, UFMC has the same spectral efficiency in both cases.

From the output results, shown in Figs. 5, 6, 7, 8 and 9, we see that the spectral efficiency of FBMC increases rapidly for the first few intervals of the burst duration and then, it increases smoothly with the burst duration until it attains the spectral efficiency of UFMC. After that, it looks constant for some range of burst duration like UFMC. Then, it increases beyond this constant value. However, the spectral efficiency of UFMC is constant throughout the burst duration.

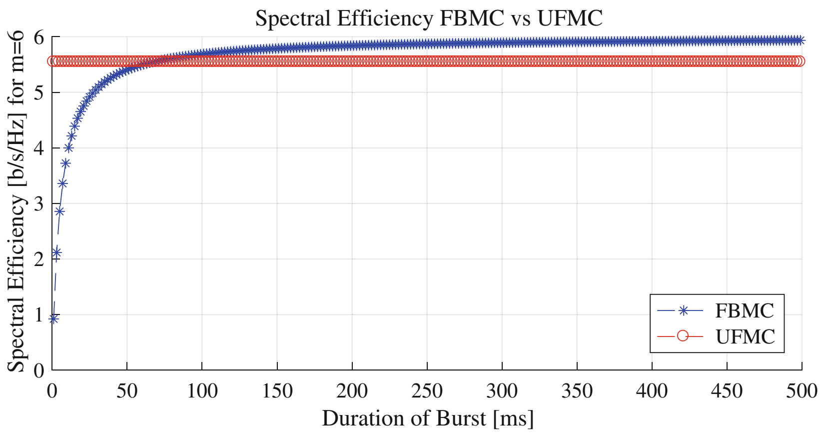

Fig. 9. Spectral efficiency of FBMC and UFMC with overlapping factor = 6

UFMC has better spectral efficiency for small value of burst durations than FBMC. But, for larger burst durations the spectral efficiency of FBMC is better. To effectively use these modulation techniques, apply UFMC for small burst duration communication applications and FBMC for larger burst duration purposes. By decreasing the filter length, by increasing bits per sub carrier, and by increasing the number of FFT the spectral efficiency of UFMC can be enhanced. By increasing bits per subcarrier, by decreasing overlapping factor, and by increasing burst duration the spectral efficiency of FBMC can also be improved.

In order to validate the spectral efficiency results shown in Figs. 5, 6, 7, 8 and 9, we also performed a plot for the well-known 4G-modulation technique, OFDM, using parameters that resulted best performance in UFMC and FBMC. Thus, we used number of FFT 512, bits per subcarrier equal to 6 and overlapping factor equal to four, and with burst duration of up to 500 ms and filter length equal to 43.

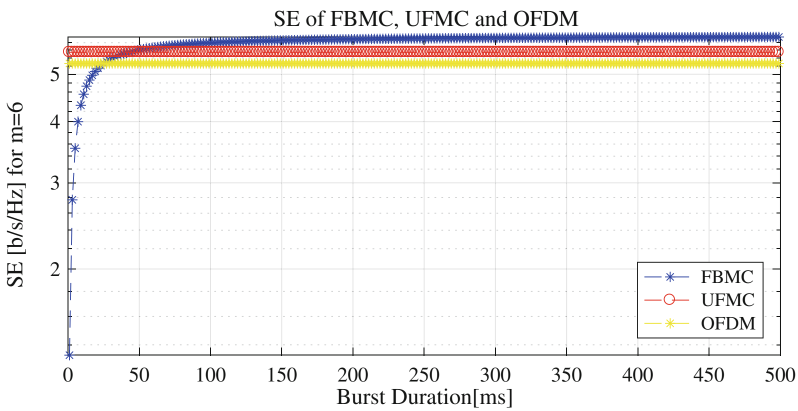

Fig. 10. Spectral Efficiency of FBMC, UFMC and OFDM

As Fig. 10 shows, the spectral efficiency of UFMC and OFDM is constant throughout the burst duration, around 5.7b/s/Hz and 5.2b/s/Hz, respectively. However, the spectral efficiency of FBMC increases rapidly with burst duration till 50 ms. After around 50 ms, the spectral efficiency of FBMC increases gradually with larger value than UFMC and OFDM.

As our result shows OFDM has low spectral efficiency than both UFMC and FBMC. This is due to the wide frequency guards and the cyclic prefix used by OFDM. Unlike OFDM, UFMC and FBMC do not use cyclic prefix, which results in the increase in spectral efficiency. Thus, the spectral efficiency of FBMC and UFMC is very efficient and OFDM is rather inefficient.

3.2 Power Spectral Density of FBMC

To compromise the Bit error rate (BER) and peak-to-average power ratio (PAPR) for both UFMC and FBMC modulation techniques, 15 dB signal-to-noise ratio (SNR) value is considered for comparison and 4QAM is used for FBMC whereas, 16QAM is used for UFMC as a mapping scheme. In addition, the system parameters, as shown in Table 1, are considered initially to simulate the FBMC for the PSD unless and otherwise stated.

Table 1. Simulation Parameters

Parameters	Values
Overlapping symbols K	4
Number of FFT points NFFT	1024
Guard bands on both sides	212
Number of symbols	100
Bits per subcarrier (4QAM)	2
Signal to noise ratio SNR	15 dB

As shown in Fig. 11, the PSD of FBMC occupies its band width within the frequency range of between nearly −0.3 and 0.3. But, the power spectral density outside of this range is not necessary because it is considered as out of bound and leads to inter symbol interference.

Figure 12 shows, the PSD of FBMC with number of FFT decreasing from 1024 to 512.

As shown in Fig. 12, the PSD of FBMC occupies its bandwidth within the frequency range of between nearly −0.1 and 0.1. But, the PSD outside of this range is not necessary because it is considered as out of bound and leads to inter symbol interference. Compared to the result in Fig. 11 with NFFT = 1024, the bandwidth of this spectral density and the power occupied within this bandwidth is smaller. However, out-of-band leakage is lower than that of Fig. 11. Therefore, it has an efficient PSD than with the number of FFT equal to 1024.

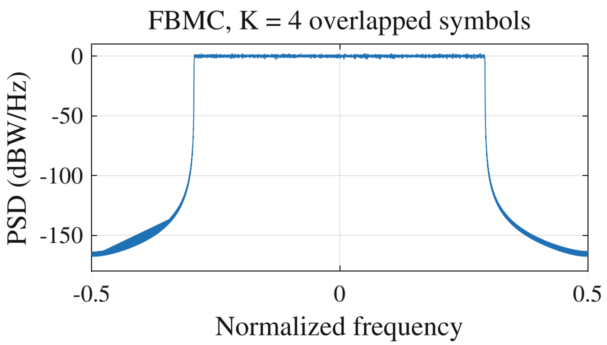

Fig. 11. Power spectral density of FBMC with NFFT = 1024

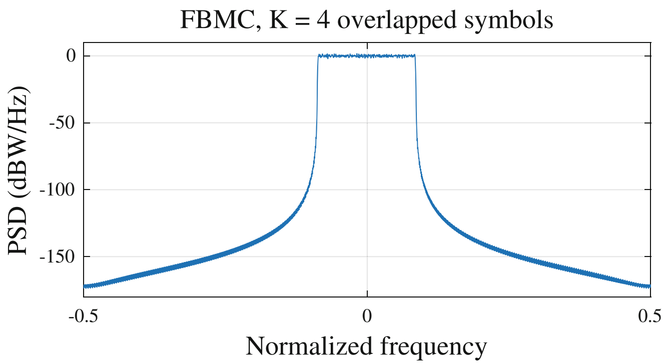

Fig. 12. Power Spectral Density of FBMC (Number of FFT = 512)

Figure 13 shows the PSD of FBMC with number of FFT 512, overlapping symbol equal to four, and with decreasing the guard band from 212 to 112.

As shown in Fig. 13, the PSD of FBMC occupies its band width within the frequency range of between nearly −0.4 and 0.4. The bandwidth and the power occupied within this bandwidth is higher, when we compare with guard band of 212. However, the gap between the graph of the power spectral density outside of this bandwidth range and the normalized is increasing. This shows that it is highly affected by the ISI than with guard band 212. Therefore, it has less efficient PSD than with guard band 212.

The PSD of FBMC with overlapping symbol equal to three is shown in Fig. 14. As shown in Fig. 14, the PSD of FBMC occupies its bandwidth within the frequency range of between nearly −0.3 and 0.3. The bandwidth of this spectral density and the power occupied within this bandwidth is the same with the overlapping symbol equal to four. However, the out-of-band leakage is higher than that of Fig. 13. This shows that it leads to higher ISI than with overlapping symbol equal to four. Therefore, it has less efficient PSD than with overlapping symbol equal to four.

Figure 15 shows the PSD of FBMC with number of FFT equal to 512, guard bands on both sides equal to 212, and overlapping symbol equal to two.

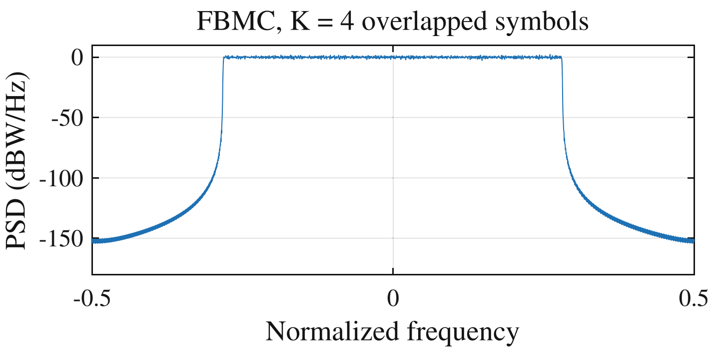

Fig. 13. Power Spectral Density of FBMC with number of FFT = 512 and guard band 112.

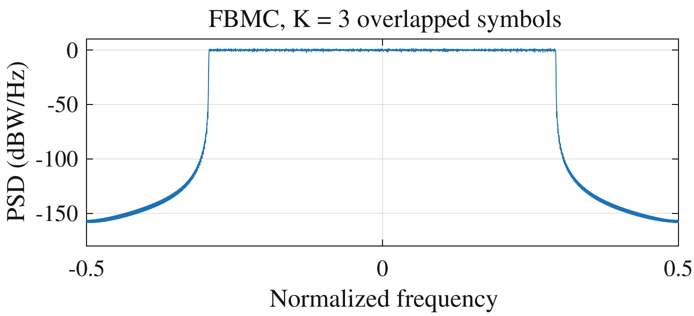

Fig. 14. Power Spectral Density of FBMC with overlapping symbol equal to 3

As shown in Fig. 15, the PSD of FBMC occupies its bandwidth within the frequency range of between nearly −0.1 and 0.1. The bandwidth of this spectral density and the power occupied within this bandwidth is smaller, when we compare it with the overlapping symbol equal to three and four. And also, the out-of-band spectral leakage increases with decreasing overlapping symbol. This shows that it is extremely affected by ISI than with the overlapped symbol equal to three and four. Therefore, it has very less efficient PSD when we compare it with the overlapping symbol equal to three and four. The out-of-band spectral leakage increases, which increases ISI, with decreasing overlapping symbol.

3.3 Power Spectral Density of UFMC

Simulation result of the PSD of UFMC for various values of sub bands and sub-carriers is demonstrated.

Figure 16 shows the PSD of UFMC for 72 subcarriers with 6 sub bands and 12 sub-carriers. Thus, the overall band is divided into 6 sub bands, each sub band having 12 subcarriers with less side lobes. The required bandwidth range is covered between

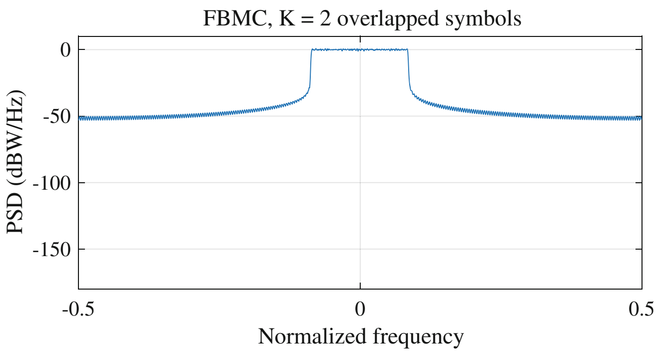

Fig. 15. Power Spectral Density of FBMC with number of FFT = 512

the normalized frequency of −0.1 and 0.1. Outside of this range of frequency is unwanted because it leads to inter symbol interference.

Figure 17 shows the PSD for 162 subcarriers. That is, the overall band is divided into 9 sub bands, each sub band having 18 subcarriers with less side lobes. The required bandwidth range is approximately covered between the normalized frequency of −0.2 and 0.2. Outside of this range of frequency is unwanted because it leads to ISI. This result shows that the bandwidth and the power occupied at this bandwidth is higher than that of 72 sub carries. And also, out-of-band spectral leakage is higher as compared to the UFMC with 72 subcarriers. So, it is more affected to inter symbol interference than 72 sub carries.

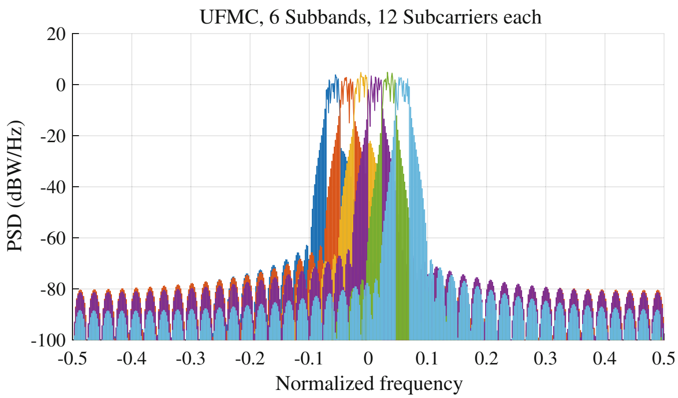

Fig. 16. Power Spectral Density of UFMC with 6 sub bands

Figure 18 shows the power spectral density of UFMC with 15 sub bands and 30 sub-carries.

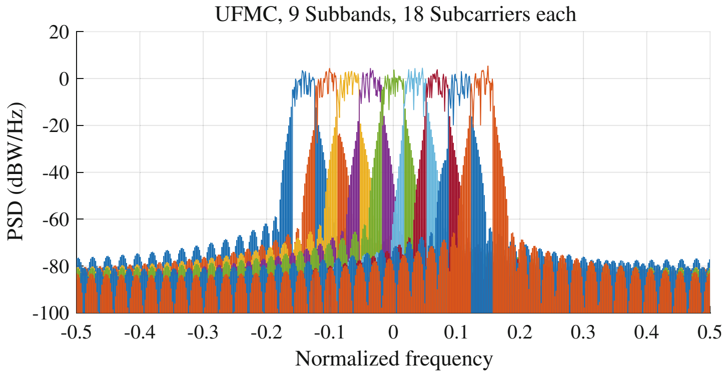

Fig. 17. Power Spectral Density of UFMC with 9 sub bands

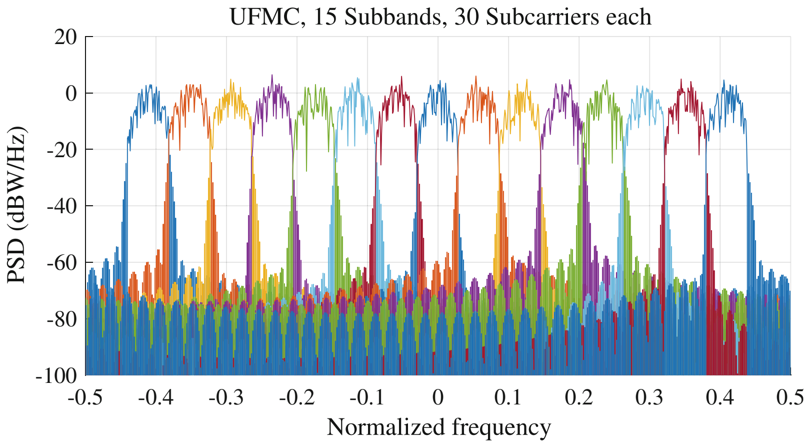

Fig. 18. Power Spectral Density of UFMC with 15 sub bands

Figure 18 shows the PSD of UFMC for 450 subcarriers. The overall band is divided into 15 sub bands, each sub band having 30 subcarriers with less side lobes. The required bandwidth range is approximately covered between the normalized frequency of −0.45 and 0.45. Then, outside of this range of frequency is unwanted because it leads to inter symbol interference. This result shows that the bandwidth and the power occupied at this bandwidth is higher than that of 72 and 162 sub carries. Furthermore, the out-of-band spectral leakage has increased when we compare it with the 72 and 162 sub carries. So, it is more affected by inter symbol interference than 72 and 162 sub carries. Therefore, its power spectral density is less efficient compared to the 72 and 162 sub carriers.

3.4 Power Spectral Density Comparison of UFMC and FBMC

Generally, the PSD of FBMC in Figs. 11, 12, 13, 14 and 15 shows that with decreasing number of FFT, the out-of-band spectral leakage reduces. But, it decreases with the bandwidth. With decreasing the guard bands, the out-of band spectral leakage reduces. The bandwidth also increases. And with decreasing the overlapping factor the out-of-band spectral leakage increases which leads to higher ISI. The bandwidth also reduces with decreasing overlapping symbol.

Figures 16, 17 and 18 shows the PSD of UFMC with increasing number of sub bands and sub carriers. It shows that with increasing the number of sub bands and sub carriers, the out-of-band spectral leakage increases. And also, the range of frequency occupied by the transmitted signal has increased. This shows that, the amount of power within the bandwidth increases with increasing the number of sub bands and sub-carriers.

If the out-of-band spectral leakage is low, the Modulation's spectral density is efficient. From our result, FBMC has lower out-of-band spectral leakage than UFMC. Therefore, the spectral density of FBMC is greater than that of the UFMC. Hence, FBMC is more preferable to minimize the inter symbol interference and inter carrier interference.

By reducing the number of sub carriers, the PSD of UFMC can be improved. In other words, the inter symbol interference and inter carrier interference becomes lesser because, the UFMC has lower out-of-band spectral leakage.

By decreasing the number of FFT and increasing guard band with overlapping symbols equal to four, the inter symbol interference and inter carrier interference of FBMC can be more minimized because, the FBMC out-of-band spectral leakage reduces. The bandwidth occupied by the signal also reduces.

Taking values of the OFDM parameter that results the best PSD performance we compared the output of PSD of UFMC and FBMC with OFDM. The number of FFT equal to 2048, guard band = 924, number of sub carrier = 200, filter length = 43 and bits per subcarrier = 2 (i.e. 4QAM symbol mapper) the PSD of OFDM is as shown in Fig. 19.

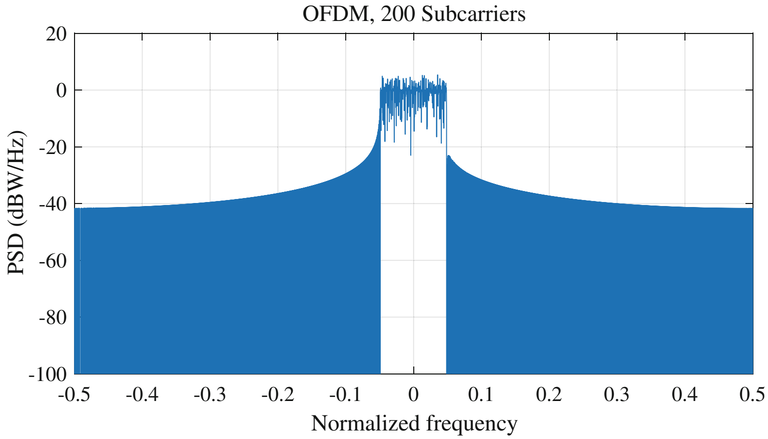

Fig. 19. Power Spectral Density of OFDM with 200 subcarriers

Figure 19 shows the PSD of OFDM for 200 subcarriers. The required bandwidth range is approximately covered between the normalized frequency of −0.05 and 0.05. This result shows that the bandwidth and the power occupied at this bandwidth is lesser than that of UFMC and FBMC with lesser sub carriers and number of FFT. Furthermore, the out-of-band spectral leakage of OFDM is higher when we compare it with the other modulation techniques. So, OFDM is more affected by inter symbol interference making its power spectral density less efficient.

Thus, this drawback of OFDM is addressed by UFMC and FBMC with efficient PSD result as depicted in Sects. 3.2 and 3.3 of this paper.

4 Conclusions

In this paper, we have performed comparison of candidate 5G modulation techniques (UFMC and FBMC) in terms of their spectral efficiency and power spectral density. The results found depicted that both can overcome the limitation of OFDM in its SE and PSD performance to meet the requirement set for 5G. Thus, both can be applied to 5G communication applications. Specifically, since UFMC has better SE for small burst duration than FBMC, it can be applied to applications requiring small burst duration. On the other hand, FBMC can be applied to communication systems where larger burst duration is required.

In terms of their PSD, FBMC has lower out-of band spectral leakage than UFMC, which results the spectral density of FBMC to be greater than that of the UFMC. From these finding we conclude that FBMC is more preferable to minimize the inter symbol interference and inter carrier interference, which are the requirement of 5G systems. Thus, FBMC is more preferable to 5G scenarios than UFMC.

In the future, we will further extend this work by comparing more Modulation techniques such as OFDM, f-OFDM, GFDM. The comparative study can be further extended by considering more parameters such as peak-to-average power ratio, delay and computational complexity of the modulation techniques.

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