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Spectral Efficiency Analysis of Multicarrier Scheme for 5G Communications

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Abstract: Filter bank multicarrier (FBMC) system is the one of the favorable waveform candidates to satisfy the demands of future cellular and wireless communication networks. FBMC use prototype filters with lower side lobe and faster spectral decay, which enables it to have the advantages of reduced out-of-band energy and theoretically higher spectral efficiency (SE) compared to conventional multicarrier scheme i.e., orthogonal frequency division multiplexing (OFDM). These systems also have the ability to facilitate aggregation of non-adjacent bands to acquire higher bandwidths for data transmission. They also support asynchronous transmissions to reduce signaling overhead to meet the ever increasing demand of high data rate transmission in future wireless networks. In this paper, we discuss the fundamental difference between multicarrier scheme such as FBMC and conventional OFDM system along with a comparison between the two techniques and also evaluated the computational complexity of OFDM and FBMC systems.

Key words: FBMC, OFDM, computational complexity and SE.

I. INTRODUCTION

4G wireless communication network is currently massively rolled-out but it is also known that it will quickly reach its limits. The higher peak data rates have been increasing extremely over the past few years. To achieve this requirement is to use wide bandwidth but wideband signals are susceptible to frequency selective fading from the multipath fading channels. Single carrier transmission systems are not well suitable for this case. The multicarrier modulation(MCM) techniques is the one of most important techniques that can vanish the fading effect by converting wideband signals into number of narrowband signals, so frequency selective fading very effectively handled[1,7].

Orthogonal Frequency Division Multiplexing (OFDM) is MCM techniques used n various existing systems, such as WiFi, IEEE 802.11 standards, Wimax (Worldwide Interoperability for Microwave Access), Long Term Evolution (LTE), and LTE-advanced etc [2-3]. OFDM is more popular due to robustness to multipath fading, its high spectral efficiency (SE) due to the closely spaced orthogonal subcarriers and its ability to avoid both inter symbol interference (ISI) by using sufficient guard time and inter-carrier interference (ICI) by appending a cyclic prefix (CP) in the guard interval. OFDM suffers from remarkable spectral leakage due to rectangular pulses uses and it has poor frequency localization techniques. Therefore, OFDM requires a large guard bands to preserve nearby channels and also decay in SE of the system. FBMC system is one of the promising candidate waveforms to satisfy the requirements of future wireless communication and networks. FBMC system employ prototype filter and it is well localized both in time and frequency that enables to increasing SE and better spectral containment [5-8]. In this paper, we discuss the fundamental difference between multicarrier scheme such as FBMC and conventional OFDM system along with a comparison between the two techniques and also evaluated the computational complexity of OFDM and FBMC systems. Despite various advantages over conventional OFDM systems, there are also some open challenges in FBMC that needs attention to make it viable for practical applications. In this work, the primary research objective is to address some of the critical challenges in FBMC systems to make it a strong waveform candidate for future wireless networks. The first challenge is related to the SE of the FBMC system. Although, FBMC has higher SE compared to conventional OFDM system is use prototype filter that ensures ISI and ICI are avoided without the use of CP. However, FBMC systems suffers from long filter tails which may reduce the SE of the system. These long tails results from the fact that transmit filtering affect the localization of FBMC system in time domain. This reduces the actual efficiency of the system due to the filter transients when passing the transmit signal through the polyphase filter. The transmission efficiency η can be dropped by the following proportion.

$$\eta = \frac{M}{M+K-1}$$

where M is the number of symbols per transmission block and K is the length of each prototype filter. Although, this overhead can be negligible for long transmission blocks. However, this overhead can be significant when the transmitted data is divided into shorter blocks.

II. OFDM vs. FBMC

FBMC is an OFDM based multicarrier scheme that uses offset QAM for modulating each sub-carrier and utilizes a specially designed filter in time and frequency domain. The ability to achieve superior SE and robustness against multipath frequency selective fading channels without CP,

the FBMC uses a specially designed prototype filter as compared with OFDM system [9]. In OFDM, the baseband discrete signal can be written as

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$$x[i]=\frac{1}{\sqrt{N}}\sum_{n=0}^{N-1}\sum_{m=-\infty}^{\infty}s_{m,n}\,g[i-mN]\,e^{j\frac{2\pi}{N}ni}$$

(1)

where the subcarrier index represented as n, the data transmitted on the nth subcarrier of the mth OFDM symbol is expressed as sm,n which is a quadrature modulated symbol, N represent the total number of subcarriers, the power normalization is denoting by factor $\frac{1}{\sqrt{N}}$, and g is the rectangular window function that separates the sub-channels, with its time domain coefficients defined as

$$g[i]=\begin{cases}\frac{1}{\sqrt{T}} & if\ |i|\le\frac{T}{2}\\ 0 & if\ |i|>\frac{T}{2}\end{cases}$$

(2)

where $T=\frac{1}{\Delta f}=NT_s$ is the OFDM symbol duration, Ts is the sampling interval and Δf is the subcarrier spacing. To eliminate the ISI and ICI, a CP of length Lcp is added to the OFDM symbol whose length is equal or greater than the channel delay spread. Although use of CP ensures ISI and ICI, however, the SNR is reduced factor is defined as $\alpha=\frac{N}{N+L_{cp}}$.

Contrary to OFDM, each subcarrier in a FBMC system is modulated with a real-valued symbol to satisfy the orthogonality requirement. To maintain the same data rates of OFDM system without CP, the FBMC system transmit symbol every half symbol duration i.e. T /2, this called as FBMC/OQAM system [13]. The performance at the transmitter side is complex data symbol sm,n in (1), is divided into real/in-phase $\left(s^{I}_{m,n}\right)$ and imaginary/quadrature phase $\left(s^{Q}_{m,n}\right)$ components. If T represents complex OFDM symbol duration with no CP, then τ0 = T/2 represent the symbol duration of the real FBMC/OQAM symbol. However, the subcarrier spacing υ0 in FBMC/OQAM is same as OFDM i.e., υ0 = Δf. Thus for FBMC/OQAM system have τ0υ0 = 1/2. The transmitted symbol carried by one complex-value of OFDM symbol with duration T, whereas in FBMC/OQAM system carried by two real-valued transmitted symbols with duration T/2. Hence, the SE of FBMC/OQAM is same as that of OFDM without CP. The distribution of symbol for FBMC/OQAM is illustrated in Fig.1

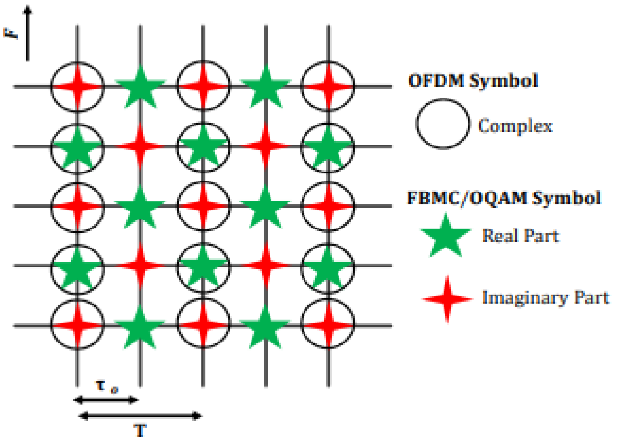


Figure 1: Symbol distribution of OFDM & FBMC/OQAM

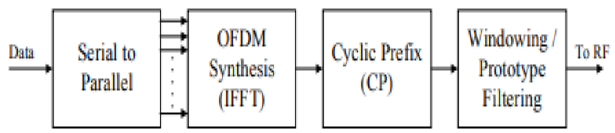
The FBMC/OQAM transmit signal is expressed as

$$x[i]=\sum_{n=0}^{N-1}\sum_{m=-\infty}^{\infty}a_{m,n}\,g\left[i-m\frac{N}{2}\right]e^{j\frac{2\pi}{N}n\left(i-\frac{D}{2}\right)}e^{j\phi_{m,n}}$$

(3)

where $a_{m,n}$ is the real-valued symbol which is either the real or the imaginary part of the input QAM symbol i.e., $a_{m,n}\in\left\{s^{I}_{m,n},s^{Q}_{m,n}\right\}$. While g[i] represent the well localized prototype filter and the length of filter D = KN – 1 this delay depends on D/2. The phase term φm,n is to ensure that the phase shift of ±π/2 is between adjacent PAM symbols along the time and frequency axis and is given as φm,n = π/2 (m + n). With the help of prototype filters, the ISI and ICI are avoided without the use of CP. This enables FBMC to achieve higher SE compared to OFDM system.

An alternate approach for implementing FBMC/OQAM system is to shifts the prototype filter instead of offset QAM symbols [13]. The advantage of this method is to avoid mapping complex QAM symbols into offset-QAM symbols [14]. The key differences between OFDM and FBMC systems can be explained using a top level block diagram as follows



Waveforms	A	B	C
CP-OFDM	√	√	√
FBMC	√		√

Figure 2: differences between OFDM and FBMC Systems

It can be seen that OFDM require a cyclic prefix (CP) in its guard interval to combat ISI and ICI terms and also windowing operation is required to suppress the high side lobes in frequency domain. Whereas, FBMC can avoid ICI and ISI terms without the use of CP due to the use of per subcarrier filtering (prototype filtering) as shown in Fig. 2. The use of well localized prototype filters enables FBMC/OQAM system to have lowered out of band radiation (OoBR) with compared to OFDM system. To observe the spectral leakage, we considered a fragmented spectrum consisting of 2048 subcarriers. Where transmission is done on two sub-bands of 512 subcarriers i.e., subcarrier 257-768 and subcarrier 1281-1792. Whereas no transmission is done on the remaining subcarriers.

The Fig. 3 illustrated that the decreases in the interference level which having different size of guard band between the sub-bands of transmission and non-transmission. Therefore, guard band of 1% of the total bandwidth i.e., 2048 subcarriers, the interference level are significantly decay in FBMC where as slight enhancement is achieved in OFDM.

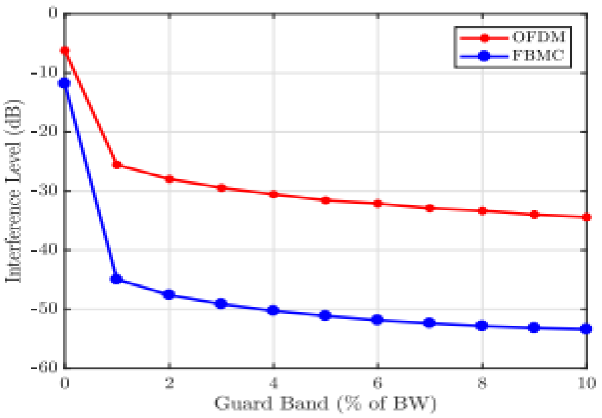


Figure 3: OFDM and FBMC Systems Transmit spectrum

Hence, the low OoBR in FBMC system makes it a potential candidate waveform for future wireless communication applications that have avoid adjacent channel interference (ACI) requirements. Despite several advantages, FBMC is more computationally complex than conventional OFDM. The computational complexity of any multicarrier scheme can be evaluated by calculating the number of real multiplications involved in computing a length-N complex-valued output sequence. In OFDM, the computational complexity comes from the IFFT and FFT operations and its complexity can be written as

$$C_{OFDM} = 2\times\left[N\log_2 N - 3N + 4\right]$$

(4)

The complexity of FBMC can be calculating the synthesis filter bank (SFB) multiplications at the transmitter and analysis filter bank (AFB) at the receiver. Therefore, the complexity of the FBMC can define as

$$C_{FBMC} = 4\times\left[2N + N\log_2 N - 3N + 4 + 2KN\right]$$

(5)

Fig. 4 shows that the FBMC is several times more complex than conventional OFDM system. It can also be noticed that the complexity of FBMC depends slightly on overlapping factor K of the prototype filters. It's worth mentioning that the average bit energy in OFDM is reduced when a CP is introduced in OFDM symbols. The average bit energy reduces with the increase in CP length, resulting in the SNR reduction. To carry out a fair comparison between OFDM and FBMC/OQAM schemes, we have to consider this SNR reduction factor in OFDM. However, FBMC/OQAM does not incur such SNR reduction as it doesn't require a CP. However, FBMC/OQAM suffers from long filter tails which may reduce the SNR of the system.

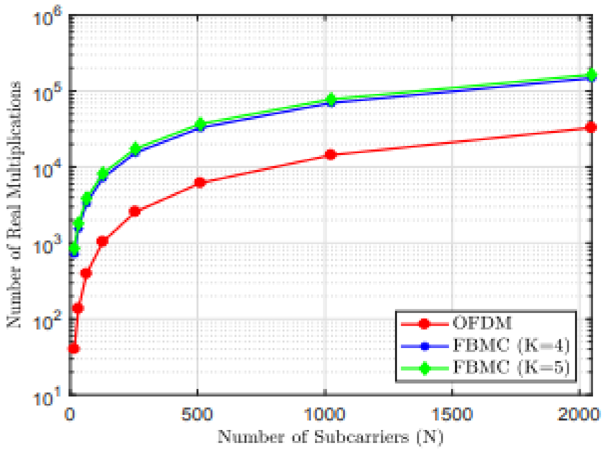


Figure 4: OFDM and FBMC Systems Computational Complexity

These long tails results from the fact that transmit filtering affect the localization of FBMC/OQAM system in time domain. Fig. 5 show

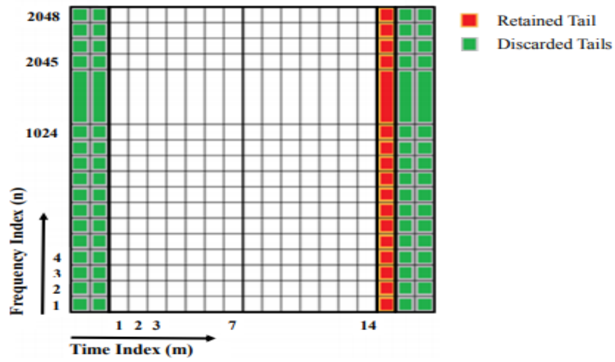


Figure 5: FBMC/OQAM transmits filter output (K=6)

s that FBMC/OQAM transmits filter output (K − 1) N more samples. The overhead of the system will now be (K − 1)/M, which can be very high with large filter overlapping factor K or/and small block size M. As a solution, the front and end elements of block could be cut out to improve the SE. However, if we discard all the filter tails without any further compensation algorithm, this will lead to the performance degradation in terms of signal to interference ratio. Therefore, there is a trade-off between the performance and the SE. The overhead in OFDM and FBMC systems due to the use of CP and filter tails respectively can lead to a decrease in SE of the system.

The spectral efficiency (SE) of FBMC expressed as in general form

$$\eta = \delta(\Lambda)\alpha\beta \quad (6)$$

where $\delta(\Lambda) = \frac{1}{|\det(L)|}$ is the lattice density i.e., the density of the subcarriers in time-frequency (T-F) plane and det(L) = T.F defines the determinant of the lattice geometry L [15].

In (6), the lattice density of OFDM without CP and FBMC is 1, the variable α is the SNR reduction factor in OFDM, where as β is the SNR reduction factor in FBMC system. The values of α and β for OFDM and FBMC systems are tabulated in Table 1, where T is the length of OFDM symbol without CP, L_{cp} is the length of cyclic prefix, M is the number of symbols per FBMC block (Note that each block can be considered as a sub frame in a LTE frame structure which has 14 symbols per sub frame.

Table 1: Spectral Efficiency Reduction Factors

	α	β
OFDM without CP	1	1
OFDM with CP	$\frac{T}{T+L_{cp}}$	1
FBMC/OQAM without Tunc	1	$\frac{M}{M+K-1}$
FBMC/OQAM with Trunc	1	$\frac{M}{M+1}$

In this case each FBMC block can be considered as a sub frame of M symbols per block) and K is the length of the overlapping factor of the filter. Assuming the length of CP as normal mode in the LTE standard i.e., approximately 7% of the OFDM symbol duration (T) and the overlapping factor is assumed to be K = 5.

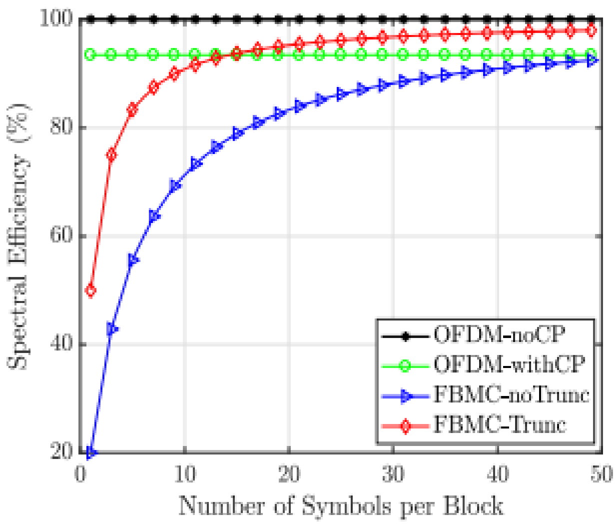


Figure 6: SE of OFDM and FBMC Systems

The SE analysis of OFDM and FBMC, with and without CP and tail cutting is illustrated in Fig. 6. The SE of OFDM has maximum without CP, since there is no overhead in the system. If a CP is added to OFDM symbols we can see that the SE of the system reduces to around 93%. If we compare the results with FBMC system, we can see that without tail truncation, the SE of the system is very low for short block size. However, if we discard all the filter tails except one, observe that the SE of the FBMC system surpasses the CP based OFDM system when M ≥ 14. The SE of the FBMC system can be further improved if we are able to discard all the filter tails. However, discarding all tails can lead to performance degradation since orthogonality of the system will be affected.

III. CONCLUSION

FBMC system is alternative waveform candidate to replace OFDM scheme to satisfy the requirements of future wireless communications and networks. Due to FBMC offers the advantage of shaping subcarrier signals with waveform that is well localized both in time and frequency domains. Despite various advantages, some key challenges in FBMC systems have been identified that needed attention to make it viable for future wireless applications.

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