A New Framework in Filter Bank Multi Carrier Modulation with OQAM

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Abstract - *Major requirement in flexible allocation of available time- frequency resources is seen as a major difficulty in conventional multi-carrier modulation systems with rapid use of wireless communication systems. This lead to further modifications in windowing or filtering techniques involved in multi-carrier modulations. In addition, a different modulation technique called Filter Bank Multicarrier(FBMC) is deployed along with Doubly Selective Channel Estimation which offers better spectral properties. A comparison of OFDM with FBMC is made and thus identified two key observations for future mobile systems. In addition, Offset Quadrature Amplitude Modulation(OQAM) is mainly focused because of its higher spectral efficiency. A unifying framework discussion and performance evaluation of FBMC and OFDM systems are provided and necessary comparisons of Bit Error Rate and Power Spectral Densities are made using simulation results.*

Key Words: **FBMC, OQAM, OFDM, Windowing, filtering.**

1.INTRODUCTION

The requirement of future mobile systems(5G) mainly resides on larger range of user cases from low latency communication to machine type communication by providing flexible allocation of available time-frequency resources. This allocation is difficult in conventional OFDM systems because of its poor spectral properties. Thus we alternatively employ new waveform derivatives like windowed OFDM, Universal Filtered Multi Carrier (UFMC) [1]. Another prominent scheme with much better spectral properties that employs pulses in both time as well as frequency is Filter Bank Multi Carrier(FBMC) along with Offset Quadrature Amplitude Modulation(OQAM) [2]. Although there exist many variants in FBMC, our main focus is on OQAM as it provides much better spectral efficiency. More arguments like lower delay spread or decreasing cell size and spatial filtering through beamforming can become even more noteworthy for future mobile communication because of more densification in network that may lead to increase of propagation path loss.

In many aspects FBMC behaves similar to OFDM, but some become a little bit challenging because of occurrence of imaginary interference [3] or Multiple Input Multiple Output(MIMO). Although drawbacks occur in combining FBMC and MIMO, the most effective method has been sought out i.e.) spreading of data symbols in either time or frequency domain thereby enhances to eliminate imaginary interference that occur. This might require some additional processing [4]. For multicarrier systems, one tap channel is been used for modelling transmission over time-variant multi-path channels which often simplifies the equalization. Minimum Mean Square Error[MMSE] method of estimation is more commonly used to estimate doubly selective channel estimation. Only one OFDM symbol in time is considered which also requires clustered pilots. To accurately estimate all elements of doubly selective channel, a compact matrix description is incorporated with very few pilots.

Thus for proper modulation and multiple access scheme in future mobile systems, two main key observations has been kept forward: (i) To more efficiently support may user requirements and characteristics of channel, allocation of flexible time-frequency is made. (ii) Majorly in very dense heterogeneous network providing lower delay spread by significantly utilizing MIMO and higher carrier frequencies.

Hence the above two observations efficiently make FBMC as more feasible option for future mobile systems as it provides better localization in time as well as frequency resources and also guarantees simple one tap equalizer is sufficient to provide lower delay spread thereby reducing the necessary of complicated receiver structures. The important contributions of this paper can be summarized as follows:

- We compare bit error probability and power spectral density of various existing systems with FBMC and put-forth the betterment of FBMC than other modulation techniques.
- A doubly selective channel estimation is been proposed which does not require clustered pilot plots for estimation.

2. SYSTEM MODEL

Generally, the pulses through which the information is transmitted commonly occupy only a smaller bandwidth which might overlap in time and frequency. Mathematically, u(t) the transmitted signal of multicarrier system under time domain is given by,

$$u(t) = \sum_{l=0}^{L-1} \sum_{m=0}^{M-1} g_{l,m}(t) x_{l,m} \quad \text{.............................. (1)}$$

Where $x_{l,m}$ is the transmitted symbol at l subcarrier position and k time position.

The basis transmitted pulse $g_{l,m}(t)$ of the above expression is given by,

$$g_{l,m}(t) = s(t-kT) e^{j2\pi lF(t-kT)} e^{j\theta_{l,k}} \quad \text{....................... (2)}$$

With s(t) as prototype filter of time and frequency shifted version and also T and F denotes time spacing and frequency spacing respectively and $\theta_{l,k}$ denotes the phase shift.

The received symbols after transmission through a channel are decoded by received signal r(t) through basis pulses $g_{l,m}(t)$ is given by,

$$w_{l,m} = \langle r(t), g_{l,m}(t) \rangle = \int_{-\infty}^{\infty} r(t) g_{l,m}^{*}(t)\, dt \quad \text{........... (3)}$$

Which corresponds to matched filter that maximizes the SNR in AWGN channel.

To simplify the notation mainly for CP-OFDM and also its derivatives, we simply use same transmit and receive pulse.

Some fundamental limitations do occur for multicarrier systems as stated in Balian–Low theorem [6] that all the following mathematical properties are satisfied at the same time i.e.) having maximum symbol density TF=1, time localization $\sigma_t<\infty$ and frequency localization $\sigma_f<\infty$. Generally, in OFDM, frequency localization is not satisfied as the prototype filter is based on rectangular pulse function. So in addition, Cyclic Prefix (CP) is added such that it sacrifices spectral efficiency and thereby gaining high robustness in frequency selective channels. In contrary, FBMC satisfies the condition with least real orthogonality condition such that only real valued symbols $x_{l,m} \in R$ are transmitted.

This constitutes for the idea of designing a prototype filter of time frequency spacing TF=2 based on hermite polynomials [7] and thus time frequency spacing is reduced to TF=1/2. The imaginary interference created can be eliminated by considering only the real part.

3. MULTICARRIER MODULATION

3.1 CP-OFDM:

One of the most prominent technique applied in Wireless LAN and long term evolution(LTE) CP-OFDM greatly reduces the computational complexity as it employs rectangular transmit and receive pulses. But the rectangular pulses are not been localized in frequency domain that leads to high Out Of Band (OOB) emission as depicted in fig. (1) which stays as greatest drawback of CP-OFDM. In addition to that the cyclic prefix tries to simplify the equalization in frequency selective channels thereby reducing its spectral efficiency.

Furthermore, to minimize the OOB emission, the 3rd Generation Partnership Project(3GPP) in recent surveys consider windowing and filtering [8]. The windowed OFDM is always referred as WOLA i.e.) Weighted OverLap and Add [8]. Here at the transmitter side, the edges of rectangular pulses are replaced by smoother function and the nearby WOLA symbols overlap in time. The receiver side also thereby applies windowing with an exception that overlap and add operation is executed in same WOLA symbol thus the inter-band interference is minimized with the fact that CP must account for both transmitter and also at receiver.

The filtered based OFDM proposes two methods namely Universal Filtered Multi-Carrier(UFMC) [9] and filtered OFDM (f-OFDM). The UFMC implies sub-band wise filtering and Zero Padding (ZP) or conventional CP guarantees the orthogonality. The sub band wise filtering is employed at both transmitter and receiver so that at time-frequency spacing of TF=1.14, the orthogonality is satisfied. In order to improve the spectral efficiency, the time-frequency spacing is reduced to TF=1.09 thereby allowing very least interference. The f-OFDM utilizes all subcarriers belonging to specific user case. For a better comparison, the same time-frequency spacing TF=1.09 is considered and thereby increasing the length of transmit and receive filters thereby minimizing the self- interference.

3.2 FILTER BANK MULTI CARRIER MODULATION

FBMC is an advanced technique of OFDM where no cyclic prefix is used. This results in greater spectral efficiency and increase the capacity of the system. Each subcarrier of multicarrier signals are filtered and thus reducing side lobes. Thus FBMC is analyzed with filter bank at both transmitter and receiver where it is called as 'synthetic filter bank' at transmitter and 'analytic filter bank' at receiver.

Difference between OFDM and FBMC lies in the choice of TF (time frequency spacing). In conventional OFDM, p(t) is a rectangular pulse of height one and width T while the pr(t) is also a rectangular pulse of height one but width is reduced to Tfft<T where Tfft=1/B. In FBMC, T=Tfft=1/B, however pr(t) and pt(t) are greater than T.

3.3 FBMC-QAM

Although there is no unique definition for FBMC-QAM, we consider time frequency spacing TF=2 to satisfy all desired properties thereby sacrificing its spectral efficiency. The prototype filter for FBMC-QAM is based on hermite polynomial [10] Hn(.) given by,

$$s(t) = \frac{1}{\sqrt{T_0}} e^{-2\pi \left(\frac{t}{T_0}\right)^{\wedge}2 \sum_{i=[0,4,8,12,16,20]} m_i H_i\left(2\sqrt{\pi}\frac{t}{T_0}\right)} \text{……….(4)}$$

Where the coefficients are given by,

m_0 =1.412692577 m_{12} =-2.2611.10^{-9}

m_4 =-3.0145x10^{-3} m_{16} =-4.4570x10^{-15}

m_8 =-8.8041x10^{-6} m_{20} =-1.8633x10^{-16}

These hermite pulses exhibit symmetries as it has same shape in time and frequency.

Another prominent prototype filter is PHYDYAS [11] which is given by,

$$s(t) = \begin{cases} \dfrac{1 + 2\sum_{i=1}^{O-1} n_i \cos\frac{2\pi t}{OT_0}}{O\sqrt{T_0}} & if \ \dfrac{-OT_0}{2} < t \leq \dfrac{OT_0}{2} \\ 0 \end{cases} \text{…..(5)}$$

The coefficient n_i depends on overlapping factor O. considering O=4, the coefficients are given by,

n_1=0.97195983 n_2=√2/2 n_3=0.23514695

Thus on comparison between hermite and PHYDYAS filter, PHYDYAS has much better frequency localization but poor time localization and also poor time frequency localization.

3.4 FBMC-OQAM:

FBMC-OQAM is more closely related to FBMC-QAM but has similar spectral density like OFDM which has no Cyclic Prefix. In this, the time-frequency spacing is greatly minimized to T=T_0/2 and F=1/T_0 such that TF=0.5 but the fact that only real part of the symbol is transmitted. The name Offset-QAM is only because the real part of the symbol is matched to the first time slot and the second slot is matched with the imaginary part. Loss of complex orthogonality is the major drawback in FBMC-OQAM. Furthermore, FBMC promotes efficient separation of subsequent blocks by single guard symbol thereby enhancing better time-frequency localization. This implies particularities for some MIMO techniques, such as space-time block codes or maximum likelihood symbol detection as well as for the channel estimation.

3.5 Coded FBMC-OQAM:

In order to straightforwardly employ all MIMO methods and channel estimation techniques known in OFDM, we have to restore complex orthogonality in FBMC-OQAM. This can be achieved by spreading symbols in time or frequency. Although such spreading is similar to Code Division Multiple Access (CDMA), employed in 3G, coded FBMC-OQAM is different in the sense that no rake receiver and no root-raised-cosine filter is necessary. Instead, we employ simple one-tap equalizers which is possible as long as the channel is approximately flat in time (if we spread in time) or in frequency (if we spread in frequency). Because wireless channels are highly under-spread, such assumption is true in many scenarios. Furthermore, the good time-frequency localization of FBMC allows the efficient separation of different blocks by only one guard symbol and no additional filtering is necessary. Another advantage can be found in the uplink. Conventional FBMC-OQAM requires phase synchronous transmissions $\theta l,k = \pi/2(l + k))$ which is problematic in the up-link (but not in the down-link). In coded FBMC, this is no longer an issue because we restore complex orthogonality. The main disadvantage, on the other hand, is the increased sensitivity to doubly-selective channels. This, however, was not an issue in our measurements. In some the authors utilize Fast Fourier Transform (FFT) spreading, while others employ Hadamard spreading. The latter can be implemented by a fast Walsh Hadamard transform, which reduces the computational complexity and requires no multiplications; we thus prefer it over FFT spreading. Comprehensive overview of such Hadamard spreading approach and investigate the effects of a time-variant channel is provided. Both, FBMC and OFDM, have the same Bit Error Ratio (BER), validating the spreading approach. However, FBMC has much better spectral properties.

4. DOUBLY SELECTIVE CHANNEL ESTIMATION

The transmission over doubly selective channel is given by the relation [5]

$$y = Dx+n \quad \ldots\ldots(6)$$

where x represents the transmitted data symbols, y gives the received symbol with n as Gaussian noise. The transmission matrix D is given by [5]

$$D = Q^H HG \quad \ldots\ldots(7)$$

Where H is the time-variant convolution matrix

Generally, in doubly-selective channel the estimation of channel impulse response H seems [13] to be problematic as the number of active subcarriers is often lower than Fast Fourier transform(FFT) i.e.) $L<N_{FFT}$. Computational complexity is also another major aspect. This huge computational burden may be caused even if one is accurately able to estimate the impulse response. The sampled time- variant transfer function is interpolated, delivering an estimate of the full time-variant transfer function. This is possible because of high correlation in time and frequency. The weighting factor has a major influence on the channel estimation accuracy. Interference cancellation is also very important for the channel estimation process because the LS channel estimates at pilot positions are corrupted by interference. By cancelling this interference the channel estimation accuracy can be improved.

5. RESULTS AND DISCUSSION

The BER curves for both FBMC and CP-OFDM are presented for 200 channel realizations and N= 1000 symbols per-subcarrier for each channel realization. The bit error rate performance of OFDM and FBMC was analyzed and the results show that coded FBMC-OQAM has better performance than OFDM systems.

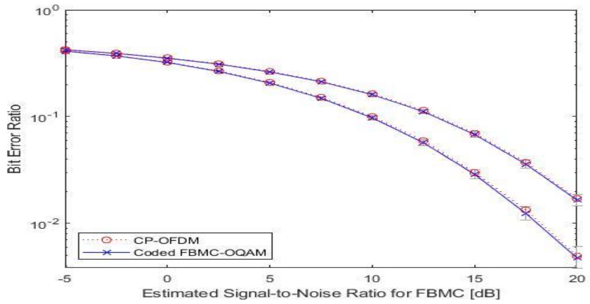

Fig.1. Bit Error performance of OFDM vs FBMC

In Fig.2. the power spectral density of both FBMC and CP-OFDM are depicted for a system with 5 MHz of bandwidth. FBMC has better spectral properties compared to CP-OFDM. Windowing(WOLA) and filtering (UFMC,f-OFDM) can improve the spectral properties but FBMC still performs much better and has additional advantage of maximum symbol density.

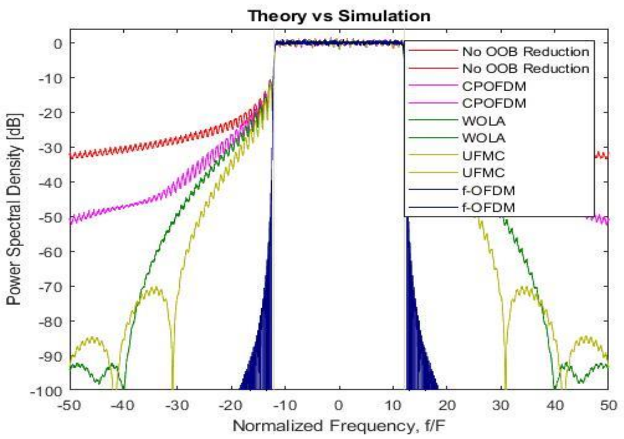

Fig.2. Power Spectral Density

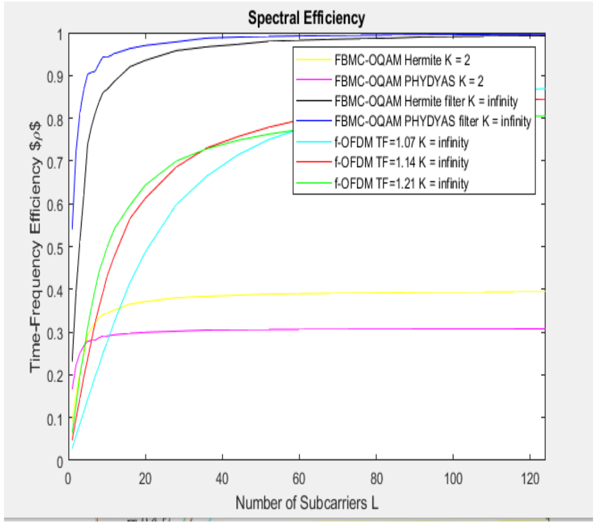

Fig.3. Spectral efficiency

The time-frequency efficiency depends on the number of subcarriers and the number of time symbols

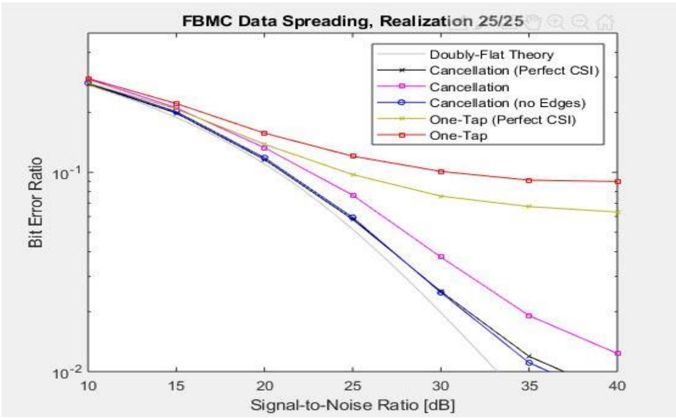

Fig.4. BER over SNR for FBMC using auxiliary symbols

In Fig.4. we employ four auxiliary symbols per pilot plot, guaranteeing that the channel induced interference at pilot position is relatively low and also the auxiliary symbol power is close to zero. Here the performance is better because the additional pilot symbol is taken from the auxiliary symbols and not from data symbols.

Compared to Fig.4. the BER is slightly worse in Fig.5. because of spreading and the fact that the additional pilot power is taken from the data symbols. However, the spreading method gas a lower overhead and thus a higher data rate.

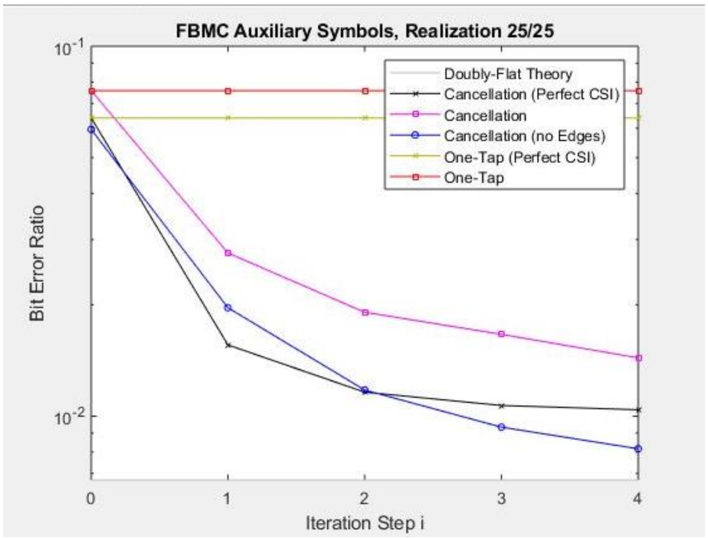

Fig.5. BER for FBMC based on data spreading approach

6. CONCLUSION

OFDM based multicarrier techniques like WOLA, UFMC and f-OFDM provide relatively higher spectral efficiency if they have higher number of subcarriers. Though not all possible use cases tend to provide higher number of subcarriers in future mobile communication systems there evolved FBMC systems where for a small number of subcarriers, it becomes much more efficient than OFDM, mostly if the transmission band is shared between different use cases. Many challenges like MIMO and channel estimation have been dealt with FBMC and thus in addition one tap equalizers are deployed which are much more sufficient in many practical cases if the subcarrier spacing is matched to the channel statistics. In highly doubly selective channels, we can switch from an FBMC-OQAM transmission to an FBMC-QAM transmission, thus deliberately sacrificing spectral efficiency but gaining robustness. This leads to an even higher SIR than in CP-OFDM. While it is true that the computational complexity of FBMC is higher than in windowed OFDM, both methods require the same basic operations, allowing us to reuse many hardware components. Thus FBMC based on auxiliary symbol method outperforms OFDM in terms of BER and FBMC data spreading method has an additional advantage of higher data rate.

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