Performance Evaluation of FBMC with optimal subcarrier spacing for 5G & beyond Communications

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***Abstract*—In 5G New Radio (NR) Release 15, the 3rd Generation Partnership Project (3GPP) Physical Layer Modulation for downlink and uplink communications, the Cyclic Prefix OFDM (CP-OFDM) is used. A wide range of potential use cases will describe future wireless networks. In order to achieve this, time-frequency resources must be dynamically assigned, which is difficult for traditional Orthogonal Frequency Division Multiplexing (OFDM). Therefore, OFDM improvements like filtering or windowing are needed. On the other hand, a multicarrier method like Filter Bank Multi-Carrier (FBMC) can be employed. Several prototype filters, including Hermite, PHYDYAS, and Root Raise Cosine (RRC), are used in this work to develop the framework for FBMC. Time-frequency efficiency will be determined for each user in the same band by adjusting the subcarrier spacing. The performance of the Signal to Interference Noise Ratio (SIR) is calculated for FBMC using varying subcarrier spacing and compared with different multicarrier transmission methods such as f-OFDM (filtered OFDM), CP-OFDM, UFMC (Universal Filter Multi Carrier), Weighted Overlap and Add (WOLA). FBMC outperforms CP-OFDM, UFMC, f-OFDM, and WOLA in terms of Signal-to-Interference-plus-Noise Ratio (SIR), especially when subcarrier spacing is short (15 kHz, 30 kHz), where spectral leakage is most noticeable. The PHYDYAS filter performed better than the other ones, reducing inter-carrier interference and increasing spectral efficiency by 20–30% even in asynchronous transmission scenarios. Furthermore, FBMC improved bandwidth economy by maintaining excellent performance without requiring a cyclic prefix. According to these findings, FBMC is a strong contender for upcoming 5G upgrades and 6G networks that require flexible waveform design, low out-of-band emissions, and support for a variety of service classes, such as mMTC, URLLC, and non- orthogonal transmissions.**

***Index Terms*—time-frequency resources, prototype filters, Filter Bank Multi-Carrier (FBMC), subcarrier spacing, Signal to Interference Noise Ratio (SIR).**

I. INTRODUCTION

Future wireless and cellular communication systems have many potential uses, including massive Machine Type Communications (mMTC), ultra-reliable low-latency communication (URLLC), and enhanced Mobile BroadBand (eMBB), particularly in areas like industrial automation and vehicle networks [1–3]. In order to meet these various and demanding needs, spectrum usage must be extremely flexible and efficient, which frequently calls for improvements in multicarrier modulation techniques.

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Orthogonal Frequency Division Multiplexing (OFDM), which is widely used in 4G and 5G networks because its simplicity and robustness, provides effective spectrum to usage but has substantial out-of-band emissions and poor adaptability to changing spectral environments [4-6]. Various alternative systems have been proposed to overcome these restrictions, including filtered-OFDM (f-OFDM), windowed-OFDM (W-OFDM), universal filtered multicarrier (UFMC), and filter bank multicarrier (FBMC) [7–9]. Because of its superior spectral containment, removal of cyclic prefix, and enhanced robustness in asynchronous environments, FBMC with Offset Quadrature Amplitude Modulation (OQAM) has shown considerable promise among these [10–12]

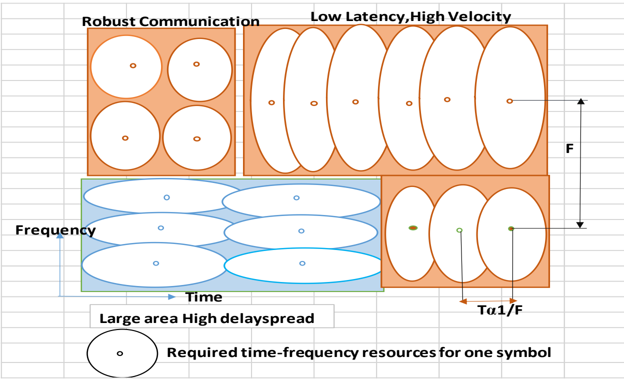


Figure.1. flexible assignment of future wireless system [11]

Several investigations have reviewed OFDM and FBMC in an array of channel conditions, with an emphasis on implementation complexity, inter-symbol interference (ISI), and spectral efficiency [13–17]. Additionally, previous research has investigated how prototype filters, like Root Raised Cosine (RRC), Hermite, and PHYDYAS, affect FBMC's performance [18–20]. The impact of subcarrier spacing optimization on the Signal-to-Interference Ratio (SIR) of various FBMC filter types, especially in scenarios that are pertinent to real-world implementation, like environments with high interference and different guard band sizes, is still largely unknown. The majority of current research ignores filter-specific performance under adaptive subcarrier configurations, which is crucial for dynamic spectrum access in applications like as eMBB, mMTC, and URLLC.

In order to bridge this gap, the best subcarrier spacing in FBMC systems using several prototype filters is evaluated in this paper. We compare performance to various multicarrier schemes including CP-OFDM, f-OFDM, W-OFDM, and UFMC and examine the effects of spacing on SIR. According to these results, FBMC is an interesting choice for flexible waveform designs in the future since it can achieve nearly optimal performance with simple one-tap equalizers when subcarrier spacing is carefully specified. The main objective of this research is to assess the effects of subcarrier spacing on the Signal-to-Interference Ratio (SIR) for various multicarrier waveforms, with a focus on FBMC under various prototype filters. The key objective is SIR-based interference analysis to guide waveform and filter selection in real-world deployment environments, even though associated issues like spectral efficiency and latency are essential.The rest of this paper is organized as follows: The primary multicarrier methods and prototype filters are introduced in Section 2, the simulation framework and SIR analysis are presented in Section 3, and the subcarrier optimization process and performance evaluation will be addressed in Section 4.

II. MULTICARRIER COMMUNICATIONS

The information is transmitted in the form of pulses for multicarrier system, where the pulses overlap in frequency and time. Due to the small bandwidth of the pulse, the frequency selective channels transform to many flat subchannels with less interference. An equalizer with just one tap is adequate, when the signal is transmitted in the presence of Gaussian noise with maximum likelihood symbol detection.

The time domain multi carrier system transmitted signal s(t) is given as

$$s(t) = \sum_{k=0}^{K-1} \sum_{l=0}^{L-1} g_{l,k}(t) x_{l,k} \quad (1)$$

Where $x_{l,k}$ is the transmitted symbol, l is subcarrier position, k represents time position. L denotes the number of subcarriers and K represents the number of multicarrier symbols while transmitting basis pulse. $g_{l,k}(t)$ is basis pulse which is expressed as

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

The basis pulse of prototype filter $p(t)$ is shifted with time spacing (T) and frequency spacing (F) and phase shift of $\theta_{l,k}$.

The signal is transmitted through Additive White Gaussian Noise (AWGN) Channel, then the signal can be retrieved from the received signal, which is denoted by the symbol r(t).

$$y_{l,k}(t) = < r(t), g_{\,l,k}(t) > = \int_{-\propto}^{\propto} r(t) g_{l,k}^{*}(t) dt \quad (3)$$

The similar basis pulse is used in the receiver to maximizes the Signal to Noise Ratio (SNR)

The Balian-Low theorem [20] states that the desired properties for the existence of multi carrier systems may not be fulfilled at the same time: i.e

- Orthogonality $< g_{l1,k1}(t), g_{l2,k2}(t) > = \delta_{(l_2-l_1)(k_2-k_1)}$
- Time-localization $\sigma_t < \propto$
- Frequency- localization $\sigma_f < \propto$
- Maximum symbol density $TF = 1$

δ denotes the Kronecker delta function. Time localization σ_t, and frequency localization σ_f are defined as

$$\sigma_t = \sqrt{\int_{-\alpha}^{\alpha} (t - \bar{t})^2 |p(t)|^2 dt}\ \sigma_f \quad (4)$$

$$= \sqrt{\int_{-\alpha}^{\alpha} (f - \bar{f})^2 |P(f)|^2 df} \quad (5)$$

The basis pulse $p(t)$ is normalized to get energy with mean time

$$\bar{t} = \int_{-\alpha}^{\alpha} t |p(t)|^2 dt \quad (6)$$

And mean frequency is given as

$$\bar{f} = \int_{-\alpha}^{\alpha} f |P(f)|^2 df \quad (7)$$

$|p(t)|^2$ and $|P(f)|^2$ represents Probability Density Function (PDF).

The Balian-Low theorem states that one of the desired characteristics can be neglected while implementing the multicarrier systems. Different multi carrier transmissions are compared and shown in Table.1. which indicates Filtered/windowed OFDM and CP-OFDM provide full bi-orthogonality with good time localization, while FBMC variants offer superior frequency localization. FBMC-QAM allows full complex-domain bi-orthogonality at the expense of pilot flexibility, while FBMC-OQAM is restricted to real-domain orthogonality.

CP-OFDM

The common multicarrier transmission is called CP-OFDM technique used in 4G, Wireless LAN, and LTE. In CP-OFDM the computational complexity can be reduced because of transmit and receive pulses.

The prototype filter of transmitter and receiver can be expressed as

$$p_{TX}(t) = \begin{cases} \frac{1}{\sqrt{T_O}} & ; \quad if \left(-\frac{T_O}{2} + T_{CP}\right) \le t \le \frac{T_O}{2} \\ 0 & ; \quad otherwise \end{cases} \quad (8)$$

$$p_{RX}(t) = \begin{cases} \frac{1}{\sqrt{T_O}} & ; \quad if -\frac{T_O}{2} \le t \le \frac{T_O}{2} \\ 0 & ; \quad otherwise \end{cases} \quad (9)$$

Localization: $\sigma_t = \frac{T_O + T_{CP}}{2\sqrt{3}}; \sigma_f = \propto$ (10)

Bi-Orthogonal: $T = T_O + T_{CP}; F = \frac{1}{T_O}$ (11)

T_O signifies the time scaling parameter determined by the required time spacing and subcarrier spacing.

Important time-domain pulse shapes and associated parameters are introduced by equations (8)– (11). Equations (8) and (9), which define the normalized transmit and receive pulse shapes over periods involving T_O (symbol time) and T_{CP} (cyclic prefix duration), respectively, are represented by the symbols $p_{TX}(t)$ and $p_{RX}(t)$. Equation (10) specifies the temporal localization σ_t, while σ_f indicates the frequency localization, which for rectangular pulses is unlimited (∞). The time-frequency spacing in bi-orthogonal systems is given by equation (11) where the subcarrier spacing is $F = 1/T_o$and the symbol duration is $T = T_O + T_{CP}$.

Because of the poor frequency domain localization of rectangular pulses, there is a lot of Out of Band (OOB) emission in CP-OFDM. Additionally, the CP reduces spectral efficiency but makes receiver equalization for frequency-selective channels simpler. 3GPP considered windowing [21] and filtering [22], [23] to reduce OOB emission in OFDM with Weighted Over Lap and Add (WOLA) i.e windowed OFDM scheme[24-25].

A smoother function (windowing) replaces the borders of the rectangular pulse at the transmitter, and adjacent WOLA symbols overlap in time. Windowing is also used by receivers to prevent inter band interference, however overlapping and adding operations are performed within the WOLA symbol. F. Schaich.et.al [26] proposed two methods to implement f-OFDM (filtered-OFDM). Initially, Universal Filtered Multi-Carrier (UFMC) employs a Dolph-Chebyshev window-based subband-wise filtering technique. The filter design includes 12 subcarriers per subband, having a time-frequency spacing that is orthogonal of $TF = 1.07$ which is same as in LTE. By choosing $TF = 1.14$, orthogonality is ensured for a time-frequency spacing. By decreasing the spacing of time-frequency to $TF = 1.09$, with slight self-interference (≈65 dB) spectral efficiency can be enhanced. The f-OFDM scheme is the 3GPP's second filter-based OFDM technique. A Hann window is multiplied by a sinc pulse (perfect rectangular filter) for generating f-OFDM. The same time-frequency spacing as UFMC but with longer filter lengths allow f-OFDM to experience the same self-interference(65 dB).

Additionally, windowing and filtering could reduce significant OOB emissions from CP-OFDM at the expense of reduced spectral efficiency. Moreover, FBMC continues to provide lower OOB emissions than filtering and windowing.

FBMC-OQAM

The desired properties of Balian-Low theorem, can be satisfied by replacing the strict the complex orthogonality condition $g_{l1,k1}(t), g_{l2,k2}(t) = \delta_{(l_2-l_1)(k_2-k_1)}$ with less real strict condition $\mathbb{R}\{g_{l1,k1}(t), g_{l2,k2}(t)\} = \delta_{(l_2-l_1)(k_2-k_1)}$. FBMC-OQAM can be implemented with the following filters as given in next sub section.

TABLE I
COMPARISON OF MULTI CARRIER TRANSMISSION OVER AWGN CHANNEL

S.No.	Multi carrier transmission	Maximum pilot density	Time localization	Frequency localization	Bi-Orthogonal
1	CP-OFDM	Yes	Yes	No	Yes
2	filtered/Windowed OFDM	No	Yes	Yes	Yes
3	FBMC-OQAM	Yes	Yes	Yes	Real only
4	FBMC-QAM	No	Yes	Yes	Yes

Hermite polynomials

Hermite filter can be designed by

1. Design a prototype filter based on Hermite polynomials Hn(·)[27]

$$p(t) = \frac{1}{\sqrt{T_O}} e^{-2\pi\left(\frac{1}{T_O}\right)^2} \sum_{i=\{0,4,8,12,16,20\}} a_i H_i \left(2\sqrt{\pi}\frac{t}{T_O}\right) \quad (12)$$

For which the co-efficients can be

$$a_o = 1.412692577 \qquad a_{12} = -2.2611X10^{-9} \quad (13)$$
$$a_4 = -3.0145\,X10^{-3} \qquad a_{16} = -4.4570X10^{-15} \quad (14)$$
$$a_4 = -8.8041X10^{-6} \qquad a_{16} = 1.8633X10^{-16} \quad (15)$$

With $p(t) = p(-t)$

2. Real orthogonal can be obtained by taking time-frequency spacing factor of two i.e , $T = T0/2$ and $F = 1/T0$.
3. The phase shift of the induced imaginary interference is shifted with

$$\theta_{l,k} = \frac{\pi}{2}(l + k) \quad (16)$$

Orthogonal : $T = T0;\ F = 2/T0 \rightarrow TF = 2$ (17)

Localization : $\sigma_t = 0.2015\,T_O;\ \sigma_f = 0.403\,T_O^{-1}$ (18)

PHYDYAS prototype filter

The PHYDYAS prototype filter is another important filter [28], designed by a basis function

$$p(t) = \begin{cases} 1 + 2\sum_{i=1}^{O-1} b_i cos\left(\frac{2\pi t}{OT_0}\right); & if\ \frac{-OT_O}{2} < T \leq \frac{OT_O}{2} \\ 0 & ;\ otherwise \end{cases}$$

(18)

The calculation of co-efficient b_i [19] depends on the overlapping factor O.

Let $O = 4$ then the co-efficients b_i is expressed as

$$b_1 = 0.97195983 \qquad b_2 = \frac{\sqrt{2}}{2} \qquad b_3 = 0.23514695 \quad (19)$$

Orthogonal: $T = T_O;\ F = 2/T_O \rightarrow TF = 2$ (20)

Localization: $\sigma_T = 0.2745\,T_O;\ \sigma_f = 0.328\,T_O^{-1}$ (21)

The PHYDYAS filter provides stronger frequency-localization but not as good as time-localization than the Hermite prototype filter.

RRC Filter

The frequency domain representation of the signal transmitted by the RRC filter is provided by [29]

$$P(f) = G(f) = \sqrt{|X_{rc}(f)|}e^{-j2\pi f T_O} \quad (22)$$

With $G(f) = P^*(f)$ where T_O is a delay.

And in the time domain $p(t)$ is given by

$$p(t) = \frac{1}{\sqrt{T_O}} \frac{sin\frac{(\pi t(1-\beta))}{T_O} + \frac{4\beta t}{T_O} cos\frac{(\pi t(1+\beta))}{T_O}}{\frac{\pi t}{T_O}\left(1 - \left(\frac{4\beta t}{T_O}\right)^2\right)} \quad (23)$$

Where β is the Roll-off factor

Orthogonal: $T = T_O;\ F = 2/T_O \rightarrow TF = 2$ (24)

Localization: $\sigma_T = 0.2745\,T_O;\ \sigma_f = 0.328\,T_O^{-1}$ (25)

III. SIGNAL TO INTERFERENCE RATIO COMPUTATION

The SIR of FBMC-OQAM can be computed from the receiving symbol at $l^{\,th}$ subcarrier position, $k^{\,th}$ time position, and set noise to zero, then the received signal is expressed as [30]

$$y_{l,k} = g_{l,k}^H\, H\, G\, x = \left((G\,x)^T \otimes g_{l,k}^H\right) vec\{H\} \quad (26)$$

By combining all basis pulse vectors to form a transmit matrix $G \in \mathbb{C}^{N\times LK}$, and transmit symbol vector $x \in \mathbb{C}^{LK\times 1}$ is represented as

$$G = [g_{0,0} \ \cdots \ g_{L-1,0} \ \ g_{0,1} \ \cdots \ g_{L-1,K-1}], \quad (27)$$

$$x = [x_{0,0} \ \cdots \ x_{L-1,0} \ \ x_{0,1} \ \cdots \ x_{L-1,K-1}]^T \quad (28)$$

The impulse response of channel matrix is $H \in \mathbb{C}^{N\times N}$ and the operator $vec\{.\}$ is used to simplify the operation. To determine SIR in the FBMC-OQAM case

Let $\Gamma \in \mathbb{C}^{LKXLK}$ and it is given by

$$\Gamma = (G^T \otimes g_{l,k}^H) R_{vec\{H\}} (G^T \otimes g_{l,k}^H)^H , \quad (29)$$

Where Γ is decomposed with the following equation

$$\Gamma = \Omega\Omega^H \quad (30)$$

Where Ω is auxiliary matrix. $\Omega \in \mathbb{C}^{LKXLK}$Then compute

$$[\breve{\Omega}_i]_{u,v} = [\Omega]_{u,v} \frac{|[\Omega]_{i,v}|}{[\Omega]_{i,v}},$$

$$\breve{\Gamma}_i = \Re\{\Omega_i\}\Re\{\Omega_i\}^H$$

Finally, SIR can be computed as

$$SNR_i^{OQAM} = \frac{[\breve{\Gamma}_i]_{i,i}}{tr\{\breve{\Gamma}_i\} - [\breve{\Gamma}_i]_{i,i}} \quad (31)$$

IV. Effect of Optimal subcarrier spacing while computing SIR

Within the same band, FBMC may efficiently support various subcarrier spacing. Subcarrier spacing needed to be designed so that [31-32]

$$\frac{\sigma_t}{\sigma_f} = \frac{T_{rms}}{V_{rms}} \quad (32)$$

Where time-localization σ_t and frequency localization σ_f

Two use cases are considered in the proposed work i.e., user1 with subcarrier spacing $F_1 = 15kHz$ and user2 with subcarrier spacing $F_2 = 120\ kHz$. These two different subcarrier spacings are included to transmit the signal for various channel conditions. Low latency transmissions are improved by the larger subcarrier spacing. Low subcarrier spacing improves bandwidth efficiency while also making the system more robust to delays.

V. Results

A baseband multicarrier system model was used in MATLAB to carry out the simulations. PHYDYAS, Hermite, and RRC filters were used to analyze each waveform, including CP-OFDM, WOLA, UFMC, f-OFDM, and FBMC, under various subcarrier spacings (15 kHz, 120 kHz, and 480 kHz) and guard band ratios. SIR was calculated by averaging 1000 Monte Carlo runs in an AWGN channel and calculating the ratio of the intended signal power to adjacent subcarrier interference. A 96-tap length and an overlapping factor of 4 were used for implementing FBMC filters. To ensure equity, the same modulation (QAM), symbol durations, and total bandwidth were employed for all waveforms.

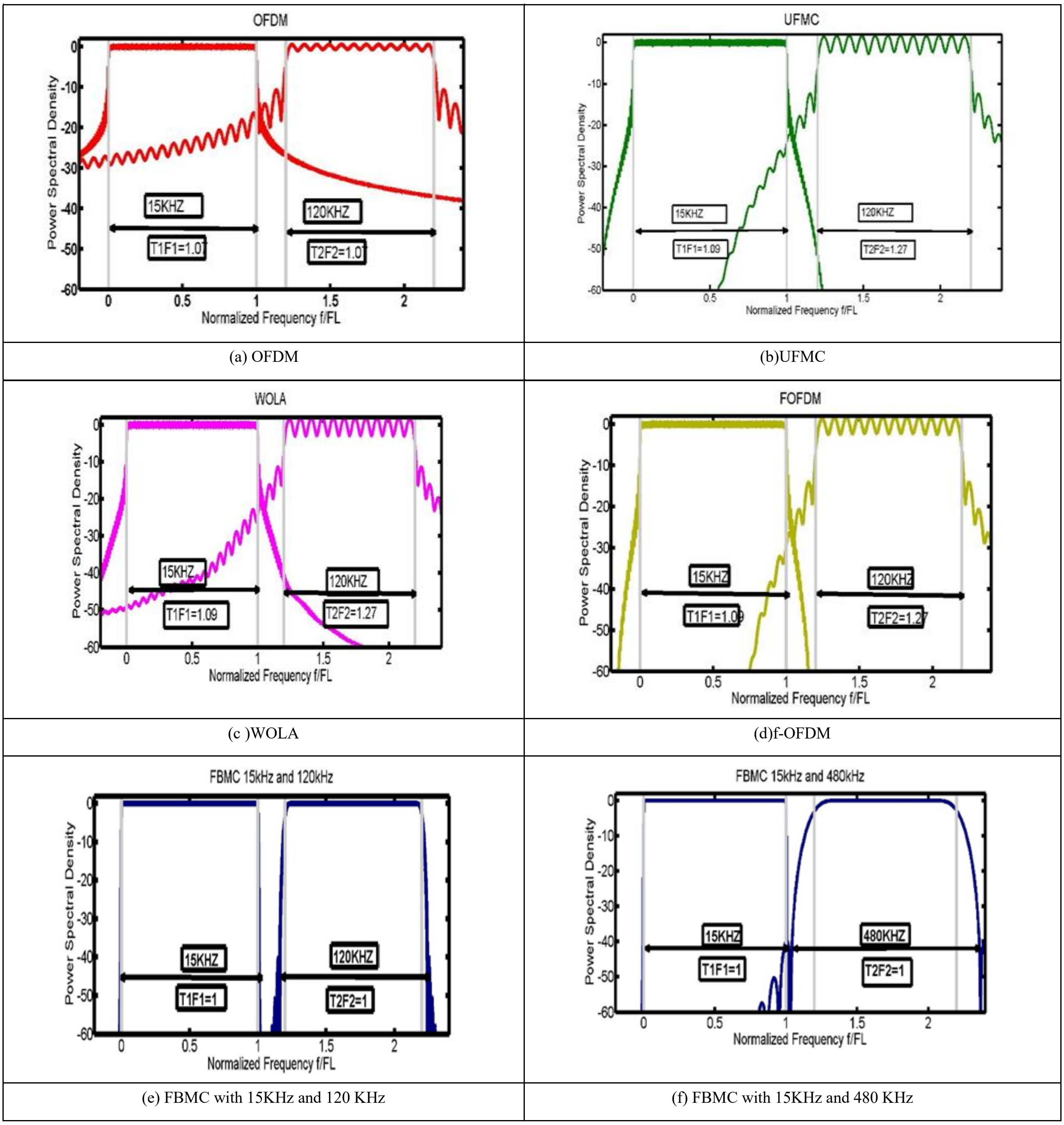
The transmitted signal from user1 is characterized by G1 with Number of subcarriers $L1 = 96$ with $F_1 = 15kHz$ subcarrier spacing resulting transmission bandwidth of $F_1L_1 = 1.44MHz$. Similarly, the transmitted signal from user2 is characterized by G2 with Number of subcarriers $L2 = 12$ with $F_2 = 120kHz$ subcarrier spacing resulting transmission bandwidth of $F_2L_2 = 1.44MHz$. Furthermore, User G2 frequency is shifted by $F_1L_1 + F_G$. A guard band of $F_G = 0.2F_1L_1$ is used between user1 and user2. A time-frequency spacing is used in WOLA, f-OFDM, and UFMC to lower the OOB, $T_1F_1 = 1.09$ for user1, $T_2F_2 = 1.27$ for user2 are assumed. FBMC with Hermite, OFDM, UFMC, WOLA, f-OFDM, PHYDYAS, and RRC with two users are calculated and presented in the Figure.2. (a) (b), (c), (d), (e), and (f)

The overall spectral performance of several multicarrier waveforms at different subcarrier spacings is shown in Figures 2.a through 2.f, highlighting their use for future wireless systems. While UFMC (Figure 2.b.) exhibits some improvement through sub-band filtering, OFDM (Figure 2.a.) suffers from excessive out-of-band emissions (OOBE), which get larger with increasing subcarrier spacing. However, residual side lobes still exist, particularly at higher spacings. WOLA (Figure 2.c.) still shows leakage under large spacing, although time-domain windowing helps with smoother roll-off. Though f-OFDM (Figure 2.d.) is sensitive to spectral overlap, it provides moderate suppression by subband filtering. However, at both 15 kHz and 480 kHz spacings, FBMC (Figures 2.e and 2.f) exhibits excellent spectrum confinement with negligible side lobes, showing its efficiency in minimizing leakage and maintaining orthogonality for high-bandwidth, interference-sensitive systems.

For 2-user case SIR can be given as

$$SIR_{total-2\,user} = \frac{L_1K_1 + L_2K_2}{||\Re\{G_1^H G_2\}||_F^2 + ||\Re\{G_2^H G_1\}||_F^2}$$

Where $||.||_F$ operation represents Frobenius norm.The $\Re$ in the above equation disappears for CP-OFDM, WOLA, UFMC and f-OFDM because it operates in complex domain. More interference may be experienced by nearby subcarriers than by distant ones. Figure.2(a) to 2(d) shows that if guard band is more then there is a less interference.



(a) OFDM | (b)UFMC

(c)WOLA | (d)f-OFDM

(e) FBMC with 15KHz and 120 KHz | (f) FBMC with 15KHz and 480 KHz

Figure.2. PSD of multicarrier transmission

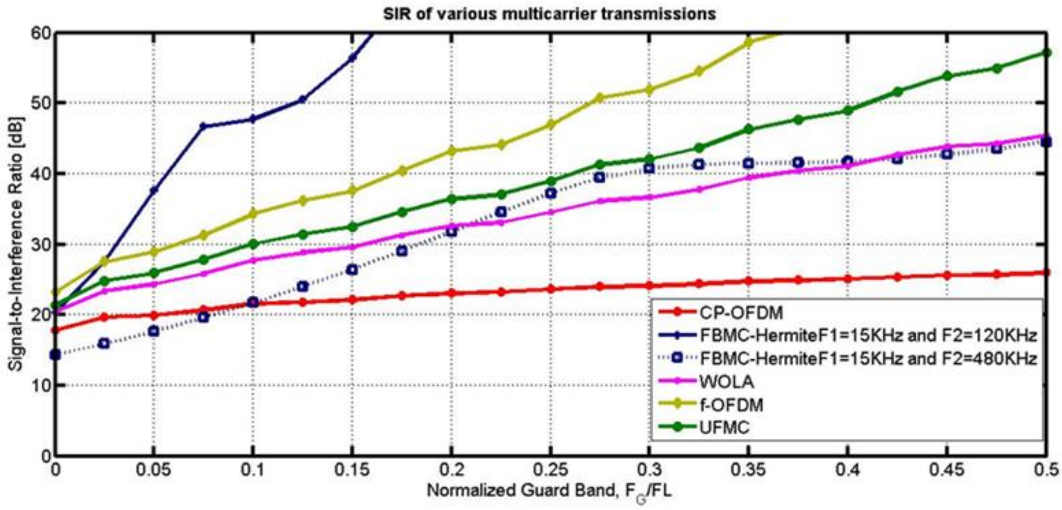


Figure.3. SIR characteristics of Multi carrier transmission techniques with FBMC-Hermite

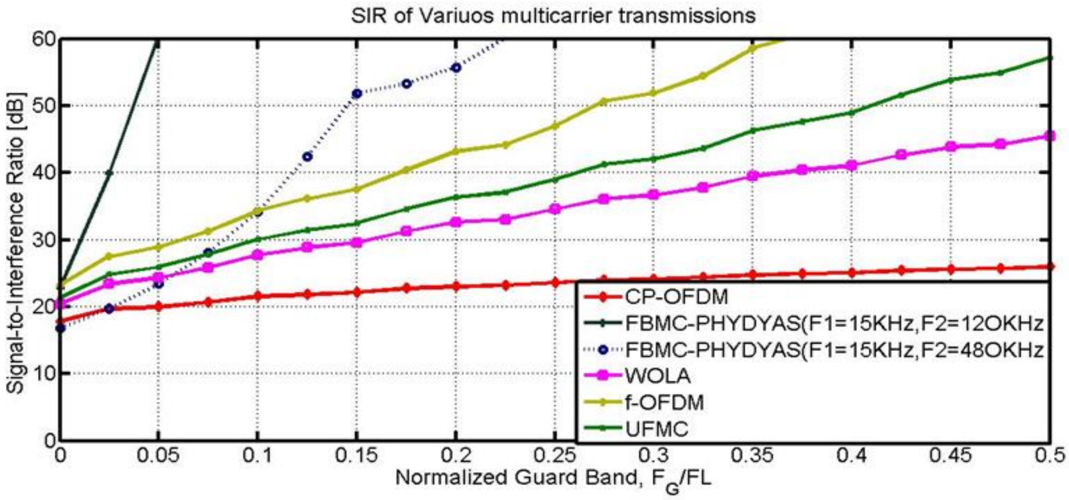


Figure.4. SIR characteristics of Multi carrier transmission techniques with FBMC-PHYDYAS

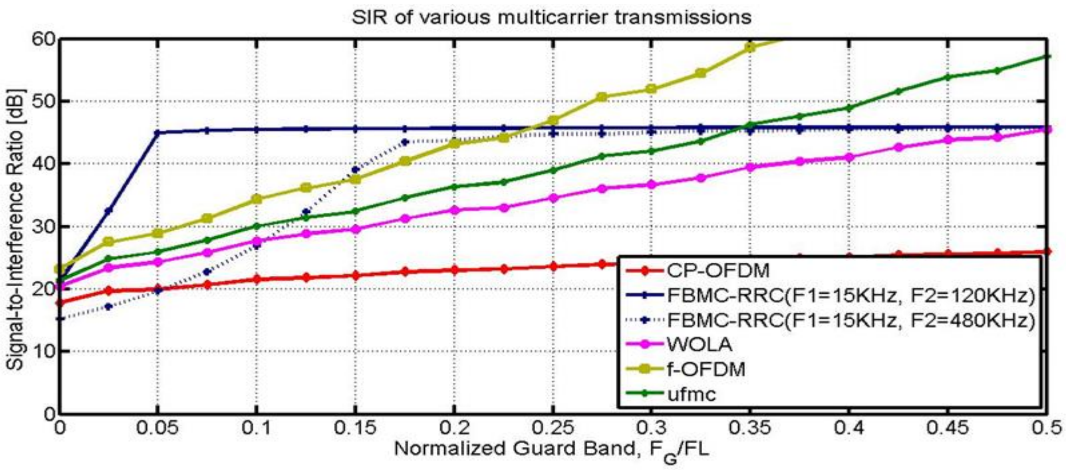


Figure.5. SIR characteristics of Multi carrier transmission techniques with FBMC-RRC

TABLE II
SIR FOR DIFFERENT F_G/F_L RATIOS

S.No	SIR (dB)	CP-OFDM	WOLA	UFMC	f-OFDM	FBMC-Hermite	FBMC-PHYDYAS	FBMC-RRC
1	$F_G/F_L = 0.05$	20	24	27	29	38	60	45
2	$F_G/F_L = 0.1$	22	28	30	34	48	60	45
3	$F_G/F_L = 0.17$	22	30	32	38	60	60	45

After receiving the signal SIR is calculated for various multicarrier transmission techniques with proposed optimal SIR is computed for FBMC with proposed 2 usecases with different prototype filters. FBMC usecase1 with $F1 = 15\ KHZ$ and $F2 = 120\ KHZ$, FBMC usecase2 with $F1 = 15\ KHZ$ and $F2 = 480\ KHZ$. For these usecases Hermite, PHYDYAS, RRC prototype filters are incorporated in FBMC, and computed SIR is shown in Figure 3 to 5. and it reveals that FBMC works significantly better than other systems in every scenario, with PHYDYAS and Hermite filters reaching up to 60 dB SIR at broader guard bands. While WOLA performs marginally better than CP-OFDM, which consistently yields the lowest SIR across all scenarios, UFMC and f-OFDM exhibit moderate gains.

FBMC - PHYDYAS with $F1 = 15KHZ$ and $F2 = 120KHZ$ achieves $60dB$ of SIR with least subcarrier spacing of $\frac{F_G}{F_L} = 0.05$. FBMC - PHYDYAS with $F1 = 15KHZ$ and $F2 = 480\ KHZ$ achieves $60dB$ of SIR with least subcarrier spacing of $\frac{F_G}{F_L} = 0.23$

Consider the required SIR is 45 dB, in case of f-OFDM, WOLA, UFMC the guard band of $F_G = 0.24F_L$ is required. Then for user2 time-frequency efficiency can be evaluated by using following equation

$$\rho = \frac{KL}{(KT+T_G)(F_L+F_G)} \tag{29}$$

The time-frequency efficiency ρ helps to choose modulation format, such that the available time-frequency resources can be maximized.

For user2 time-frequency efficiency can be computed using Equation .28, $\rho = \frac{1}{1.24X1.27} = 0.64$. Whereas in FBMC, ρ is 0.97 which is morethan the f-OFDM. This shows that user2 ($F2 = 120\ KHz$)i.e large subcarrier spacing empowers low latency transmission. If the subcarrier spacing increases by four-fold, the FBMC experiences the same delay as OFDM. If there are multiple subcarriers $L = 12$ in FBMC is decreases to L=3, requires a large guard band ($F_G = 0.13F_L\ for\ 45\ dB\ SNR$). However, time frequency efficiency of ρ=0.8 is still about 40% greater than the f-OFDM. By increasing the subcarrier spacing FBMC is still suitable for minimal latency transmission. This also increases the sensitivity, delay spread and time-offsets.

The Signal-to-Interference Ratio (SIR) performance of several multicarrier waveforms under various guard-to-lobe frequency ratios ($\frac{F_G}{F_L}$) is shown in the Table.2. It demonstrates that FBMC with PHYDYAS filtering continuously attains the highest SIR in every case, highlighting its better interference suppression, whereas WOLA and CP-OFDM perform comparatively more severe particularly as spectral congestion increases.

FBMC variations, especially those that use PHYDYAS and Hermite filters, consistently produce higher SIR values across all subcarrier spacings, as illustrated in Figures 3-5. Remarkably, FBMC-PHYDYAS achieves 60 dB SIR at a guard ratio of 0.17, but WOLA and CP-OFDM peak below 30 dB, indicating that they have limited capacity to reduce interference. While FBMC-PHYDYAS achieves 48 dB, showing improved spectrum isolation, the current implementation shows 30 dB, compared to [18], where UFMC obtained 35 dB SIR at a 0.1 guard ratio. Unlike [20], which use fixed subcarrier spacing, the results presented here show that FBMC SIR increases from 45 dB to 60 dB when spacing is increased from 15 kHz to 480 kHz.

The findings of evaluating SIR across multicarrier systems demonstrate that FBMC performs noticeably better than OFDM-based techniques, particularly at higher subcarrier spacings, demonstrating its applicability in situations where interference is a problem. PHYDYAS constantly offers the highest SIR for filter type evaluation, indicating its exceptional spectral confinement.

In order to provide dense spectrum access, FBMC optimizes guard ratios while maintaining >45 dB SIR even at narrow bands.The performance boost made here in comparison to [18] and [20] confirms the goal of proving filter-spaced optimization in FBMC systems.

While utilizing the proposed optimal spacing, FBMC outperforms f-OFDM by about 15% when high bandwidth is allocated per user (10.08 MHz as opposed to 1.44 MHz). Comparative SIR analysis of several multicarrier systems, including CP-OFDM, UFMC, WOLA, f-OFDM, and FBMC variations, that extend a broad range of subcarrier spacings and guard ratios is our main contribution. The results show that FBMC reaches up to 60 dB SIR, significantly outperforming traditional OFDM-based systems, particularly when used with PHYDYAS and Hermite filters. This confirms the significance of FBMC for applications with interference and limited spectrum, achieving the goal of the research, which was to find reliable waveform candidates for next-generation communication systems.

Conclusions

When the subcarriers are more, OFDM-based multi carrier transmissions like, f-OFDM, UFMC, and WOLA have a great spectral efficiency. However, not all future potential wireless transmission will require such a large number of subcarriers. FBMC is substantially more effective than OFDM for a small number of subcarriers, especially if many use cases share the transmission band. One-tap equalizers can be appropriate when the spacing of subcarrier (pulse shape) matches the channel statistics. The improvement in Signal-to-Interference Ratio (SIR) and signal integrity outweighs any potential minor trade-off in spectral efficiency. Furthermore, by increasing subcarrier spacing, FBMC can facilitate low-latency transmission while maintaining compatibility with one-tap equalizers, provided that the pulse shaping is in line with the channel statistics. A robust contender for upcoming wireless systems like 5G and beyond, the SIR analysis across many schemes validates FBMC's superiority in eliminating interference. These findings highlight how adaptable waveform strategies, such as FBMC, with filter customization, can handle a variety of deployment scenarios, especially in high-interference, dense environments. This investigation can be expanded in future research by assessing FBMC performance in actual wireless applications, including as fading and mobility conditions. Additional flexibility could be achieved by investigating AI-based subcarrier optimization, adaptive filtering, and integration with MIMO systems. These directions are especially relevant to 6G networks, which require strong interference control and spectral flexibility. This will assist in directing future research and implementation toward physical layer designs that are more adaptive and interference aware.

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