Window-based alternative filters for f-OFDM in next generation wireless communication systems

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ABSTRACT

In this paper, the authors propose alternative filters to improve the spectral properties of the filtered orthogonal frequency division multiplexing (filtered-OFDM) candidate waveform for new wireless systems (fifth generation (5G) and next generation). The effectiveness of the proposed alternative filters is validated through extensive simulations and experiments in the 5G scenarios at waveform 2K. The results show that the alternative filters can improve the spectral containment capability of a filtered-OFDM signal by more than 100 dB when compared to an OFDM signal. The proposed filters meet the optimization requirements as well as the ongoing or planned standardization.

Keywords: Orthogonal frequency division multiplexing (OFDM); Filtered-OFDM; Fifth generation (5G) wireless system.

1. INTRODUCTION

Fifth-generation (5G) wireless technology is developing at an explosive rate and is one of the biggest areas of research within academia and industry. In this rapid development, signal processing techniques are of vital importance. Thanks to its low complexity and ability to achieve very high bandwidth efficiency as well as high data rate transmission over multipath fading channels [1–3], orthogonal frequency division multiplexing (OFDM) continues to be used for the next generation radio systems, such as the digital video broadcasting (DVB) system [4] and the wireless communication system 5G [5]. However, OFDM faces many challenges due to its inherent characteristics. For instance, strict time and frequency alignment are required to achieve orthogonality, resulting in heavy signaling and extra dedicated subcarriers (pilots) for synchronization. As a result, the spectrum performance of the system is degraded significantly. Another limitation of OFDM is that its out-of-band (OOB) emission is still not very good. To be more specific, a portion of the allocated bandwidth is reserved as a guard band to make room for the signals to meet the spectrum mask, which is a considerable waste of frequency.

Recent discussions on viable 5G technologies emphasize the need for waveforms that have better spectral containment per subcarrier than the well-known OFDM. A number of signal processing techniques proposed for 5G and the next generation wireless system, such as filtered-OFDM, filter bank multicarrier (FBMC), generalized frequency division multiplexing (GFDM), universal filtered multi-carrier (UFMC), and spectrally efficient frequency division multiplexing (SEFDM), are also being considered for international standards development and deployment [6-10]. These new waveforms are capable of overcoming the drawbacks of OFDM while retaining its advantages. First of all, the requirement for global synchronization is loosened, allowing for inter-subband asynchronous transmission. Secondly, if filters can reduce the OOB leakage, the guard band consumption will be likely to reduce to a bare minimum. Among all the above-mentioned waveform candidates, FBMC and filtered-OFDM have the lowest OOB leakage [6, 9]. Therefore, filtered-OFDM has been proposed for the 5G standard [5]. However, it should be noted that the remaining waveforms are also promising and being considered for future standards.

This paper reviews filtered OFDM, which is one of the best recent alternatives to OFDM and proposes alternative filters to improve its spectral properties. The simulations are implemented in a specific scenario, using a 5G waveform in mode 2K. Extensive experiments and simulations were performed to determine the most effective filter response. The simulation results illustrate the superior performance of the proposed alternative filters compared to existing methods.

2. REVIEW OF OFDM, FILTERED-OFDM, AND FBMC WAVEFORMS

2.1. OFDM basic

An OFDM signal is the sum of many independent signals modulated onto equal-bandwidth subcarriers. Consider an OFDM symbol as a vector $\mathbf{S} = \left[S(0), S(1), ..., S(N-1)\right]$. The complex baseband representation of an OFDM signal with N subcarriers is given by [1-3]:

$$s(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S(k) e^{j2\pi k \Delta f t}, \quad 0 \le t < NT \tag{1}$$

where $j = \sqrt{-1}$, Δf is the subcarrier spacing, and NT is the OFDM symbol duration. In OFDM, the subcarriers are chosen to be orthogonal (i.e., $\Delta f = 1/NT$).

Let $s(n)$ be the sampled version of $s(t)$. The OFDM signal samples are obtained by L times oversampling, where L is an integer greater than or equal to 1. These L-times oversampled time-domain samples are the inverse discrete Fourier transform (IDFT) of the data block with $L(N-1)$ zero-padding, which can be implemented by the inverse fast Fourier transform (IFFT). As a result, the oversampled IFFT output can be expressed as:

$$s(n) = \frac{1}{\sqrt{LN}} \sum_{k=0}^{LN-1} S(k) e^{j2\pi nk/LN} \tag{2}$$

As can be seen from the abovementioned calculations (1), OFDM is based on the use of rectangular pulses in the time domain, which leads to a slowly decaying behavior in the frequency domain. Therefore, OFDM is unsuitable in fragmented spectrum scenarios with strict OOB emission level constraints. To address this issue, null tones at the spectrum edges, or guard bands (GBs), are usually inserted. However, it causes a loss in spectral efficiency because some of the available subcarriers are not actually modulated. Furthermore, in the time domain, a guard interval (GI) or cyclic prefix (CP) is used to solve the delay spread of wireless channels. The main parameter is the GI length, Tg, which varies depending on the characteristics of the channel, but it should be greater than or equal to the maximum signal delay in the wireless channel. The GB and GI degrade the spectral performance of the system.

To compare different modulation schemes, their spectral efficiency must be estimated. If the useful data block duration is:

$$T_{fft} = \frac{1}{N\Delta f} \tag{3}$$

then after inserting GI, the transmitted signal block duration is:

$$T_s = T_{fft} + T_g \tag{4}$$

The efficiency of the frequency-time resource utilization of the OFDM signal can be calculated as follows:

$$\frac{1}{T_s N\Delta f} = \frac{T_{fft}}{T_s} = \frac{T_{fft}}{T_{fft} + T_g} = \frac{1}{1 + T_g / T_{fft}} = \frac{1}{1+\alpha} \tag{5}$$

2.2. Filtered-OFDM

Backward compatibility with conventional OFDM needs to be taken into account while selecting new modulation techniques for 5G and the next generation of communication standards. However, in order to respond to challenges, these techniques must also have the-following main features:

- Improved spectral characteristics: new modulation techniques must be able to mitigate OOB leakage among adjacent channels/users in order to fully exploit the fragmentation spectrum.
- High spectral efficiency: the spectral efficiency of the system must be significantly improved by reducing the guard band/time resources.
- Loose synchronization requirements: new modulation techniques must operate in asynchronous scenarios to simplify synchronization procedures.

One of the potential modulation techniques is filtered-OFDM [6, 12, 13]. Due to the fact that this scheme is based on OFDM and does not significantly complicate the system while having more robust filtering features than OFDM, filtered-OFDM was considered a candidate for usage in 5G [5]. If we consider the OFDM signal more broadly, then it can be described as:

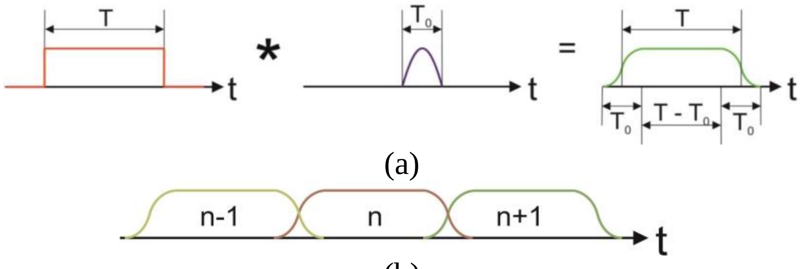
$$s(t) = \frac{1}{\sqrt{N}} \sum_m \sum_k S_m(k)\, p_t(t - mT)\, e^{j2\pi k\Delta f(t-mT)} \tag{6}$$

where *m* is the index of the symbol number; *k* is the index of the subcarriers; $p_t(t)$ is a prototype function used to perform signal pulse shaping.

The OFDM can be regarded as a specific case of filtered-OFDM if $p_t(t)$ is a rectangular function and the symbol length is $T = T_{fft} + T_g$ (4). To improve the spectral characteristics of the signal, the proposed prototype filter responses differ from the rectangular function and can create different transmitted signals. By carefully choosing the prototype functions $p_t(t)$, OOB leakage of the transmitted signal can be reduced even if the orthogonality is completely removed.

An OFDM symbol requires an undistorted transmitted signal part with duration T_u no less than the helpful signal part with duration T_{fft}, $T_u \geq T_{fft}$. Since OFDM requests a guard interval, this GI can be used for subsequent distortions. The window function

$p_t(t)$ can be built based on a rectangular window inside which the signal will be maintained. This window function is then convoluted with a filter of length T_0 smaller than GI. As illustrated in Fig. 1a, the resulting window function has smooth edges, an undistorted transmitted signal part duration $T_u = T - T_0$. As can be seen, the increase in the prototype function length correlates with the rise in the transmitted signal length. However, according to (6), signal overlap does not depend on the filter response length. An illustration of the signal overlap is shown in Fig. 1b.



(a)

(b)

Figure 1. *The filter response design in filtered-OFDM (a), and signal overlap between symbols (b).*

The selection of the filter response length and the window function for smoothing GI influence the suppression of OOB emission in the OFDM signal spectrum. The quality of anti-aliasing will improve as the filter response length is increased. However, this will distort the guard interval, which will negatively affect the demodulation properties, namely synchronization. As a consequence, there exists a theoretical efficiency limit for the filter response length in this approach. However, there is no such limit to the choice of the prototype function.

To evaluate the effectiveness of the consumption of time-frequency resources, the values of the parameters remain the same as in OFDM. Accordingly, the efficiency of the frequency-time resource utilization is $1/TN\Delta f < 1$. This is because the filtered-OFDM scheme is based on OFDM and a guard interval.

2.3. FBMC

In FBMC, an array of filters is applied to synthesize multicarrier signals at the transmitter and analyse received signals at the receiver. The transmitted signal is created by synthesizing the output signals of these transmitter filters as follows:

$$s_{FBMC}(n) = \sum_{i=1}^{KN-1} h(i)\, s(n-i),\ i = 0,1,2,\dots,KN-1 \tag{7}$$

where $s(n)$ is OFDM signal and $h(n)$ is the impulse response of the filter that is applied to generate the FBMC signal. The following formula gives $h(n)$:

$$h(n) = 1 + 2\sum_{k=1}^{K-1} H_k \cos\left(2\pi \frac{kn}{KN}\right) \tag{8}$$

wherein K denotes overlapping factor, N is the size of OFDM symbol, and H_k is the frequency domain prototype filter coefficients that are given in Tab. 1 [11].

Table 1. *The frequency domain prototype filter coefficients.*

K	H_0	H_1	H_2	H_3
2	1	$\sqrt{2}/2$	-	-
3	1	0,911438	0,411438	-
4	1	0,971960	$\sqrt{2}/2$	0,235147

3. PROPOSED ALTERNATIVE FILTERS FOR f-OFDM

In principle, a prototype filter must be designed with a sidelobe as small as possible, and the filter coefficients can change freely. In this work, the designed filter structure is identical to the conventional f-OFDM filter structure in [7] but the window function is altered to improve the spectral characteristics of the filtered OFDM waveform.

Because of their smooth implementation and the ability to significantly suppress the sidelobe compared to a rectangular window, a group of classic Hanning window functions can be considered to apply for f-OFDM. The Hanning window functions can be described as follows:

$$\mathrm{w}_{Hann}(n) = \cos^{\alpha}(\pi n) \tag{9}$$

Blackman (10) and Blackman-Harris (11) windows are also introduced for generating filtered-OFDM signals. These windows are defined as:

$$w_{Blackman}(n) = a_0 - a_1 \cos\left(\frac{2\pi n}{N}\right) + a_2 \cos\left(\frac{4\pi n}{N}\right) \tag{10}$$

where, $a_0 = \frac{1-\alpha}{2}$, $a_1 = \frac{1}{2}$, $a_2 = \frac{\alpha}{2}$, N is filter length, and $n = 0,1,2,...,N$.

The unqualified term Blackman window refers to $\alpha = 0.16$ $\left(a_0 = 0.42, a_1 = 0.5, a_2 = 0.08\right)$, which closely approximates the exact Blackman with $a_0 = 7938/18608 \approx 0.42659$, $a_1 = 9240/18608 \approx 0.49656$, and $a_2 = 1430/18608 \approx 0.076849$. These exact values place zeros at the third and fourth sidelobes, but result in a discontinuity at the edges and a 6 dB/oct fall-off. The truncated coefficients do not null the sidelobes as well, but have an improved 18 dB/oct fall-off [14, 15].

$$w_{Blackman-Harris}(n) = a_0 - a_1 \cos\left(\frac{2\pi n}{N}\right) + a_2 \cos\left(\frac{4\pi n}{N}\right) - a_3 \cos\left(\frac{6\pi n}{N}\right) \tag{11}$$

where $a_0 = 0.35875, a_1 = 0.48829, a_2 = 0.14128, a_3 = 0.01168$.

Blackman–Harris window is a straightforward generalization of the Hamming family produced by adding more shifted sinc functions, meant to minimize side-lobe levels [16].

It is further considered by the Gaussian window. This function is described as follows:

$$w_{Gaussian}(n) = \exp\left(-\frac{1}{2}\left(\alpha\frac{n-N/2}{N/2}\right)^2\right), \quad 0 \le n \le N; \alpha \ge 2 \tag{12}$$

4. SIMULATION RESULTS AND ANALYSIS

This section compares the spectrum properties of OFDM, filtered OFDM, and FBMC signals to determine the optimal filter parameters for each of the systems. In simulations, the 5G waveform parameters [5] are used for them, including carrier mode $2K\ (N = 2048)$ and guard interval $T_g = 144$, whereas the alternative filters are desired at carrier mode $2K$ with an overlapping factor of $K = 4$.

To evaluate the efficiency of the existing and the proposed algorithms, the parameter R, which is the average in-band-to-OOB power ratio, must be entered:

$$R = 10\lg\frac{P_1}{P_2} \tag{13}$$

where P_1 is the average in-band power, P_2 is the average OOB power.

Fig. 2 illustrates the spectrum of an OFDM signal without filtering and the areas within which the average powers P_1 and P_2 are calculated. As can be seen, the parameter R for OFDM is 39.5 dB.

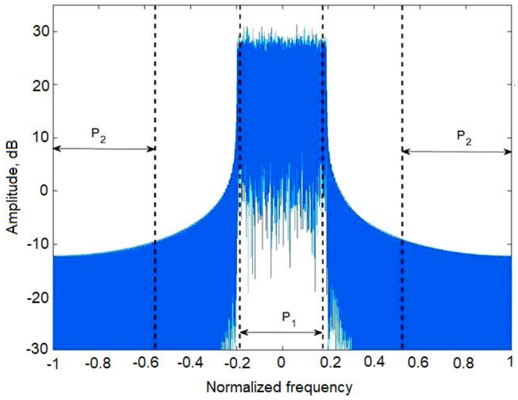


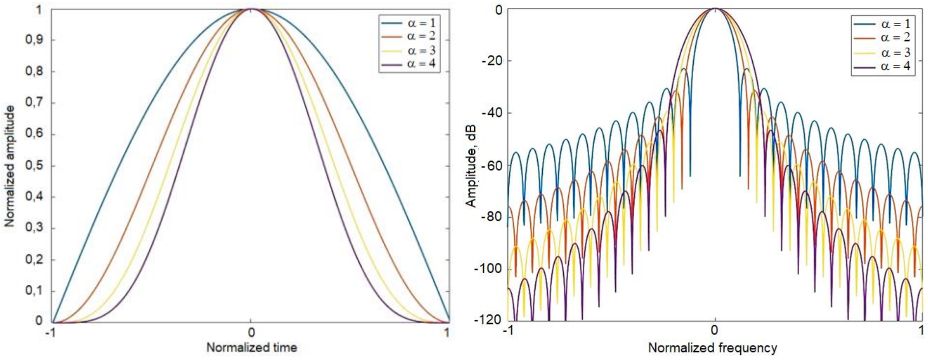
Figure 2. *The spectrum of an OFDM signal without filtering.*

Fig. 3 shows the impulse response of the Hanning windows (Fig. 3a, on the left) and their Fourier transforms (Fig. 3a, on the right) at different values of $\alpha = \{1,\ 2,\ 3,\ 4\}$. The curve describing the dependence of R on the overlap length T_0 is constructed to evaluate the efficiency of the Hanning windows with different values of α (Fig. 3b). We may see from Fig. 4 that:

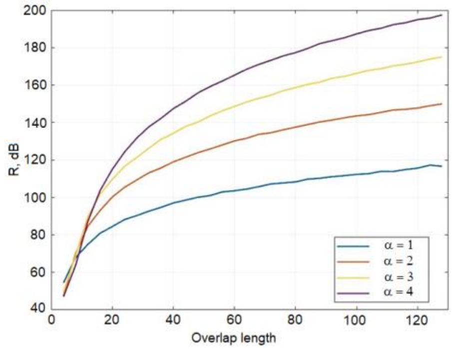
- There is a slight difference between the Hanning window functions for small smoothing lengths (up to 10 time samples), but an inverse dependence on the degree of the cosine (value of α) can be clearly seen;
- The higher the smoothing lengths (T_0) and degree of the cosine (α), the greater the value of R, i.e., the stronger the suppression of OOB emissions.

When $T_0 = 32$ (22.22% of the guard interval $T_g = 144$) and $\alpha = \{1,\ 2,\ 3,\ 4\}$, the values of R are 92 dB, 113 dB, 126 dB, and 137 dB, respectively. As a result, the application of Hanning windows at any smoothing length always results in a much lower OOB emission level compared to conventional OFDM. The Hanning window with

$\alpha = 4$ will be utilized in the following comparisons because it produces the best results in the experiments.



(*a*) *The impulse response and Fourier transform of the Hanning windows*

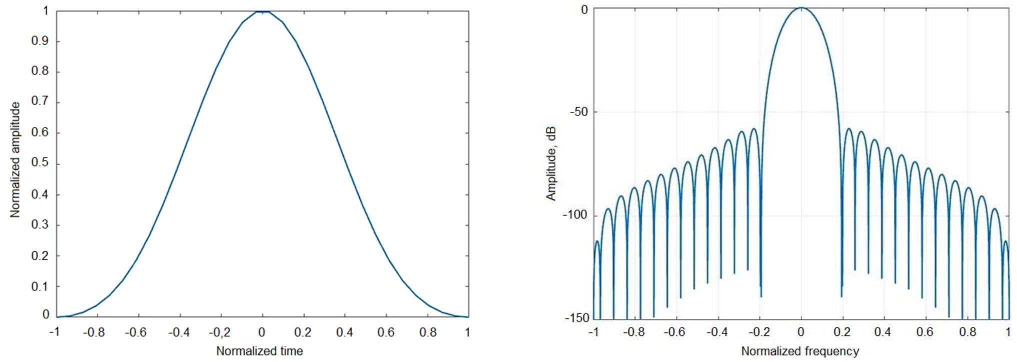


(b). The dependence of R on the overlap length T_0

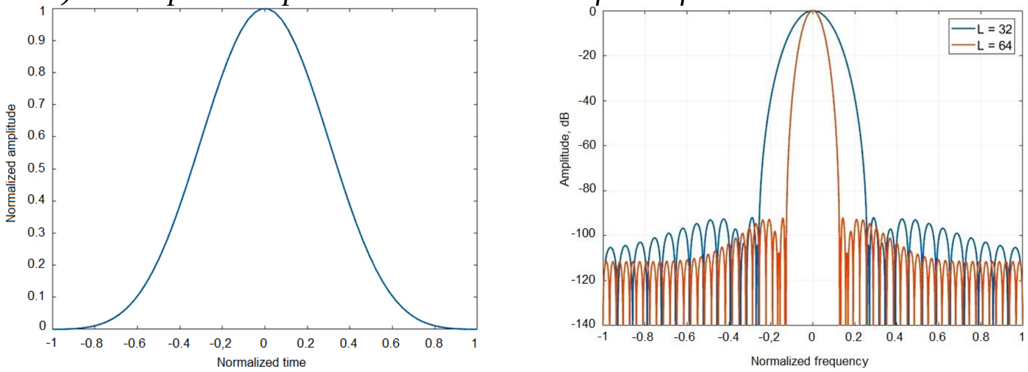
Figure 3. *The simulation results with Hanning window.*

Fig. 4 shows the impulse responses of the Blackman, Blackman - Harris, and Gaussian windows (on the left) and their Fourier transform (on the right). Fig. 5 illustrates the curves for these windows to indicate the dependence of R on the overlap length T_0. As demonstrated from Fig. 5 that changing the window functions leads to a high suppression of OOB components. The efficiency of the OOB leakage suppression achieved by utilizing the Blackman-Harris window function is higher than that of the others in the range of $T_0 = 16 \div 32$ samples. However, as the overlap length increases, this window's OOB leakage suppression level grows more slowly and achieves 160 dB at $T_0 = 120$. It's because the suppression level of out-of-band components changes slightly as the overlap length increases, but its main peak width is narrow (see Fig. 4b). This means that the average OOB power remains almost unchanged.

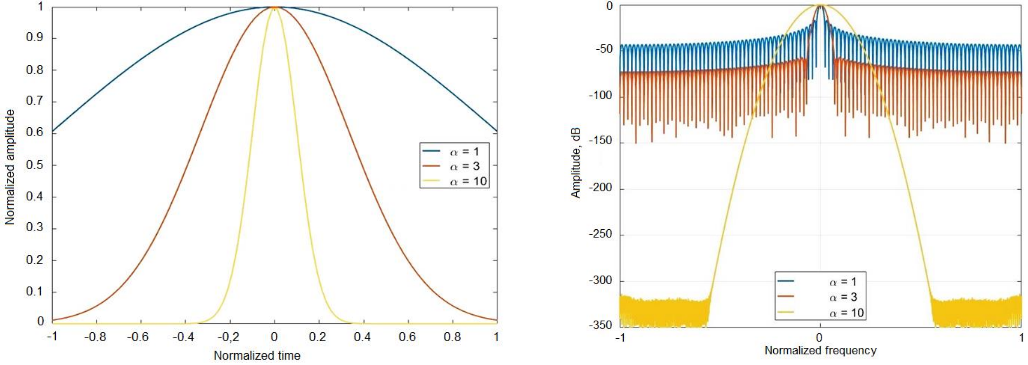
As illustrated in Fig. 4c for the Gaussian window, increasing the value of α causes an increase in OOB leakage suppression while expanding the main lobe. Furthermore, like the Blackman-Harris window, the curve $R(T_0)$ for the Gaussian window approaches a plateau region. The overlap length T_0 required to achieve the plateau depends on the value of α. A higher value of α results in a greater OOB leakage suppression level at the plateau (see right-handed Fig. 5), and a longer overlap length T_0 is required to reach the plateau. However, it causes a rise in signal distortion.



a) The impulse response and Fourier transform of the Blackman window.



b) The impulse response and Fourier transform of the Blackman-Harris window



c) The impulse response and Fourier transform of the Gaussian window

Figure 4. *The spectrum of an OFDM signal without filtering.*

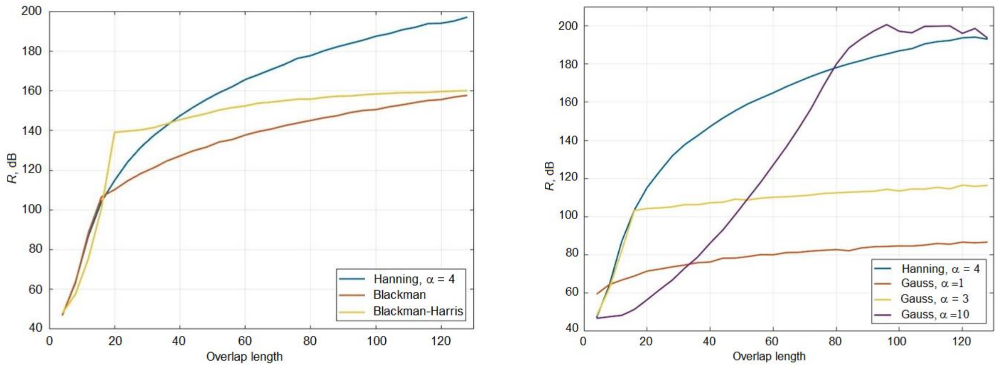


Figure 5. *Comparing the spectral containment efficiency of the windows.*

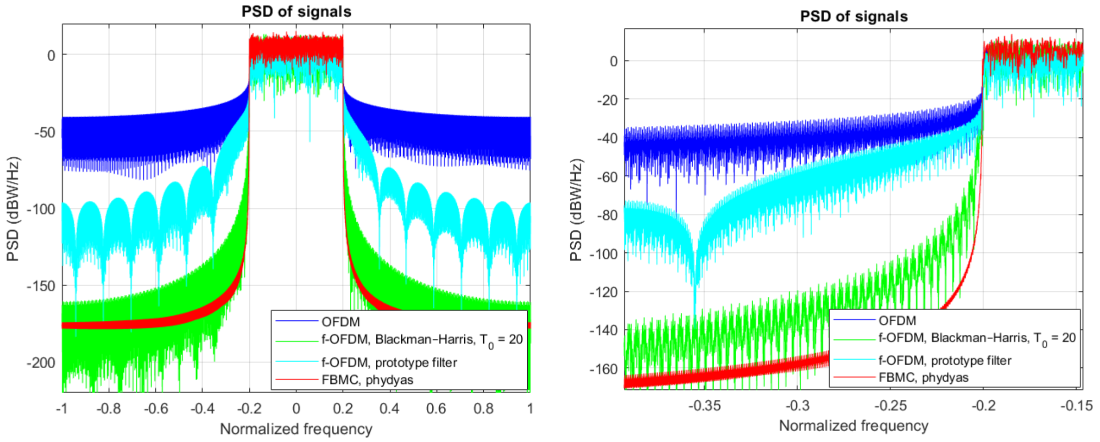


Figure 6. *Comparing the power spectral density (PSD) of f-OFDM with OFDM and FBMC.*

The last experiments were performed to fully assess the effect of the *R* parameter on OOB efficiency and compare the spectral efficiency of f-OFDM using alternative filters with that of FBMC, conventional f-OFDM that uses prototype filters, and OFDM. In this examination, the above-mentioned investigated filters with optimal parameters are selected. Specifically, the Backman-Harris filter with smoothing lengths $T_0 = 20$ is applied for f-OFDM, while FBMC uses the Phydyas filter. As shown in Fig. 6, the OOB radiation level of f-OFDM, which applies the Blackman-Harris filter with $T_0 = 20$ (known as proposed f-OFDM), is significantly lower than that of conventional f-OFDM and OFDM. Due to a slightly higher OOB emission level of the proposed f-OFDM, its effect on the adjacent channels is greater than that of the FBMC. However, this level of influence has been significantly reduced compared to conventional f-OFDM. Specifically, there is a good improvement in the characteristic of the spectrum around the bandwidth edges of f-OFDM when using the Blackman-Harris. As can be seen in Fig. 6 on the right, the PSD roll-off slope of the f-OFDM signal with the proposed filter is close to the FBMC signal. As a result, the GB may be lowered, increasing bandwidth efficiency. In addition, the low computational complexity is an advantage of the proposed f-OFDM over FBMC. This is possible because the use of an oversampling factor K = 4 in FBMC to achieve the above spectral efficiency results in the IFFT size increasing by 4 times, while the IFFT size in the proposed f-OFDM remains constant.

5. CONCLUSIONS

The paper has proposed alternative filters for increasing the spectral efficiency of filtered-OFDM signal. The performance of the proposed filter is demonstrated through Matlab simulations in the 5G scenarios. A comparative analysis was performed between OFDM, filtered-OFDM and FBMC systems. The simulation results show that the Blackman-Harris filter with a small smooth length, $T_0 = 20$, has a strong OOB suppression capability, so the generated signal has less impact on the adjacent channels and less distortion. In addition, the PSD roll-off slope of the f-OFDM signal generated by this filter is close to that of the FBMC signal, so a smaller GB is required. As a result, bandwidth efficiency is improved.

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TÓM TẮT

Các bộ lọc dựa trên cửa sổ cho f-OFDM trong các hệ thống thông tin vô tuyến thế hệ tiếp theo

Trong bài báo này, các tác giả đề xuất các bộ lọc thay thế để cải thiện các thuộc tính phổ của dạng sóng ứng viên ghép kênh phân chia theo tần số trực giao được lọc (f-OFDM) cho các hệ thống không dây mới (thế hệ thứ năm (5G) và thế hệ tiếp theo. Hiệu quả của các bộ lọc thay thế đề xuất được xác thực thông qua các mô phỏng và thử nghiệm trong các kịch bản tham chiếu 5G ở dạng sóng 2K. Kết quả cho thấy, khi so sánh với tín hiệu OFDM, các bộ lọc thay thế có thể cải thiện khả năng duy trì phổ của tín hiệu f-OFDM hơn 100 dB. Các bộ lọc thay thế đề xuất đáp ứng các yêu cầu tối ưu hóa cũng như các hoạt động tiêu chuẩn hóa đang diễn ra hoặc theo kế hoạch.

Từ khoá: Ghép kênh theo tần số trực giao (OFDM); OFDM được lọc (f-OFDM); Hệ thống vô tuyến thế hệ thứ 5 (5G).