Comparing f-OFDM and OFDM Performance for MIMO Systems Considering a 5G Scenario

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***Abstract*—The advances mobile communications has seen in recent years has rendered the radio spectrum a limited and, hence, an expensive resource. Therefore, technologies that support unlicensed access to spectrum are needed. Therefore, the adoption of novel modulation schemes becomes of utmost importance to obtain better spectral-localization and reduce the OOBE (*Out of Band Emission*) inherent to OFDM (*Orthogonal Frequency Division Multiplexing*) and, consequently, mitigating the interference between secondary (*unlicensed*) and primary users. In this scenario, we access the gain in the bit error probability using f-OFDM in MIMO systems, both used in the 5G RANGE project.**

***Index Terms*—5G RANGE, OFDM, f-OFDM, OOBE, Spectral-localization, MIMO.**

I. Introduction

In recent years, the growing demand for higher data rates has triggered an interest in new technologies that might be used to meet these new requirements [1]. In the current scenario, the expectation for 5G and everything it promises to offer is great. The future generation of mobile networks will present extremely challenging issues for telecommunications professionals. The new services are defined by the 3GPP (*3rd Generation Partnership Project*) [2], as follows:

- **Ultra Reliable Low Latency Communications (URLLC)**: low latency communications and high reliability,
- **Enhanced Mobile Broadband (eMBB)**: communications with higher data rate and spectral efficiency.
- **massive Machine Type Communications (mMTC)**: massive communications between machines, with low complexity and power consumption.

Besides these already proposed applications with their economic and social potentials, there are important services that are not being discussed by telecommunications organizations. With this perspective in mind, it was proposed by Brazilian and European institutions, a project with great challenges oriented to the 5G technology, which seeks to serve the needs of areas with low population density and geographical barriers. The purpose of the 5G RANGE [3] is to implement mechanisms for the new network to provide flexible solutions that can offer connectivity in an economically viable way to rural and urban areas. One of the factors that prevented previous network generations from covering these regions was the high price of the spectrum with the use of licensed bands, making it impossible to invest in sparsely inhabited regions. To minimize this problem, 5G RANGE proposes the unlicensed allocation of TVWS (TV-White Spaces) in VHF (*Very High Frequency*) and UHF (*High Frequency*), and as a secondary user, significantly reducing network costs.

In this secondary user scenario, it is of utmost importance to employ a physical layer waveform displaying low OOBE, providing spectrum agility and low interference for primary users. This requirement justifies the use of f-OFDM waveform, which has its operation based on OFDM [4] signal filtering, reducing its OOBE.

The objective of this work is to demonstrate the results obtained through simulations comparing OFDM and f-OFDM techniques in MIMO systems. In OFDM systems, when signals are transmitted at adjacent frequencies (or channels), it is possible to observe that signals leak to adjacent channels. Therefore, employing f-OFDM, it is expected that the interference generated between the signals will be smaller, decreasing the bit error rate. Also, we evaluated the performance of various MIMO detectors such as Maximum Ratio Combining (MRC), Zero Forcing (ZF), Minimum Mean Squared Error (MMSE), Maximum Likelihood (ML) and Sphere Decoding (SD). Particular attention is paid to this latter decoder as it has performance similar to ML but with reduced complexity [5].

This paper is divided as follows: the section II presents the system model, the results and discussion are presented in section III, and finally, the section IV presents the conclusions.

II. System Model

In this section, we present a description of the proposed study model, employing MIMO [6] for transmission and reception in two scenarios, in the first one, each transmitted signal goes through OFDM modulation and in the second scenario, f-OFDM modulation is employed. f-OFDM is one of the candidate methods for 5G waveforms and optimizes the operation of OFDM by reducing the OOBE. The model is based on the transmission three sets of four signals at three adjacent frequencies ($i.e.$, f_{c1}, f_{c2}, f_{c3}), as showed in Fig. 1, in both scenarios, so that it is possible to evaluate the effect of filtering on the OFDM signals. We consider $K = 4$ single antenna devices simultaneously transmitting at each one of the

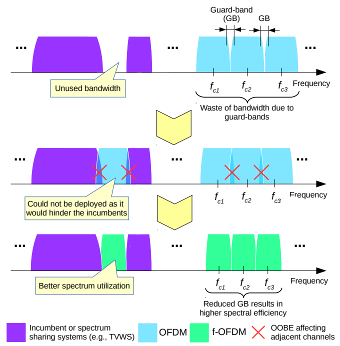


Figure 1. Signals at adjacent frequencies.

three available frequencies and a BS (*base station*) equipped with M antennas receiving and demodulating these signals.

Fig. 2 shows the uplink of a four-device/three-channel hypothetical MIMO system model, where each set of four devices, K, operates at frequencies f_{c1}, f_{c2} and f_{c3}, respectively. Also, each device is equipped with one antenna, thus forming a MIMO MAC channel (*Multiple Access Channel*). In this work, each OFDM symbol is created by applying a 128-point IFFT to the input signal, however, only 72 subcarriers are used for data transmission while the remaining ones are left for guard band. The subcarriers are spaced 15 kHz apart, resulting in 72×15 KHz $= 1.08$ MHz of useful bandwidth. This signal is equivalent to a 1.4 MHz LTE standard signal, where 1.08 MHz is the useful band, and the rest is the guard band, which is used to reduce interference between adjacent channels. However, in our proposed study model, the distance in frequency between the end of a signal and the beginning of another is of only one subcarier, $i.e.$, 15 kHz.

MIMO is a technology that has been used by the previous mobile communications networks [7, 8], and will be widely applicable to 5G [2] and beyond networks. The received signal from K single-antenna devices at a BS also equipped with M antennas can be modeled according to Eq. (1),

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n}, \tag{1}$$

where $\mathbf{s}$ is the $K \times 1$ transmitted signal vector, $\mathbf{y}$ is the $M \times 1$ received signal vector, $\mathbf{H}$ is the $M \times K$ channel matrix and $\mathbf{n}$ is the $M \times 1$ Gaussian noise vector. Since we employ a MIMO system to transmit multiple signals over the same time-frequency resource, the estimated signal can be determined using one of the techniques used in this work, that is, MRC, ZF, MMSE, ML, and SD. In this paper, we consider full channel knowledge.

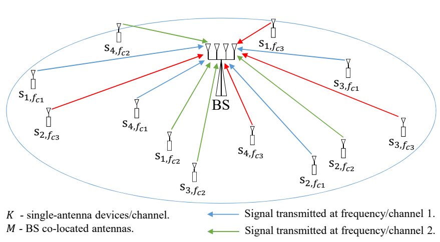


Figure 2. System model.

III. Results and Discussion

In this section, we present and assess the results regarding the two model scenarios using MIMO systems. We evaluate the performance gain obtained with the use of f-OFDM over OFDM, using experimental results. We employ the system model depicted in Fig. 2 and focus on the detection performance of the signals transmitted at the central frequency.

In Fig. 3 the comparison between the power spectral density (PSD) of OFDM and f-OFDM signals is presented. As can be noted, the addition of the FIR filter to the OFDM transmission chain drastically reduces OOBE. This reduction ranges from -40 dBW/Hz with OFDM to -100 dBW/Hz, -110 dBW/Hz and -120 dBW/Hz at a frequency of $0.4 \times fs$ (where fs is the sampling rate) with FIR filters of orders 32, 64 and 128, respectively.

Fig. 4 shows the base-band impulse response of the designed filter with bandwidth equal to 72×15 KHz $+ \ 2 \times \mathrm{N}_e$. It can be noticed that the main energy of the filters is confined within the sinc's main lobe, which in this case, spans 2.084 [μs]. Therefore, the filter's energy stays confined within the CP length (for normal CP it is approximately 4.7 [μs]), and consequently, ISI stays within tolerable levels.

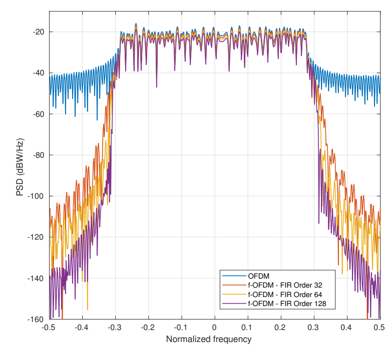


Figure 3. OFDM and f-OFDM PSD for filter orders 32, 64 and 128.

In Fig. 5 we present the frequency responses of the designed filters for f-OFDM with NPRB $= 6$, $\mathrm{N}_e = 3$, and filter order 32, 64 and 128 respectively. The figure shows the 3 dB cutoff frequency (red-dashed lines) of the filters, which, as designed, happens at half of the useful bandwidth plus the excess bandwidth, N_e, $i.e.$, 1.08 MHz$/2 + 3 \times 15$ KHz = 585 KHz. As expected, the 128-th order filter presents a steeper transition region, which results in less interference to

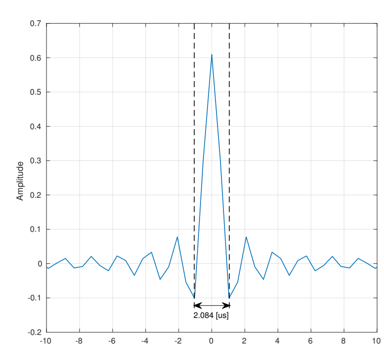
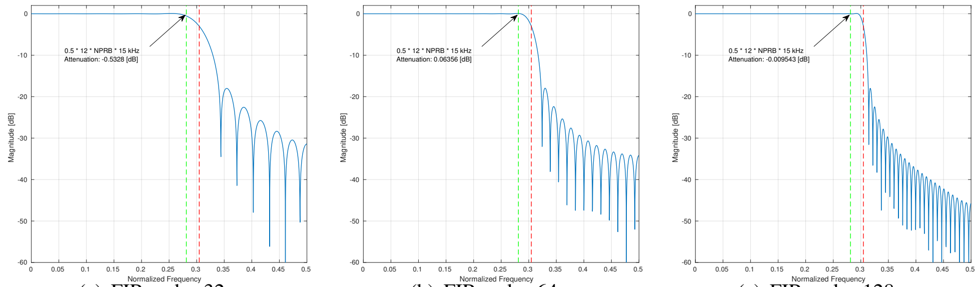


Figure 4. Impulse response of the designed filter for f-OFDM with bandwidth equal to 72×15 KHz $+ \ 2 \times \mathrm{N}_e$.



(a) FIR order 32. (b) FIR order 64. (c) FIR order 128.

Figure 5. Frequency responses of the designed filters for f-OFDM with NPRB $= 6$, N$_e = 3$, and filter orders 32 (a), 64 (b), 128 (c).

adjacent channels and a better frequency-localization when compared with OFDM. The figure also shows the frequency (green-dashed lines) of the subcarrier at the edge of the OFDM symbol. As can be seen, as the filter order increases, the subcarriers at the edges of the symbol are less affected by attenuation/overshoot at the edges.

In Fig. 6 we present the BER evaluation when QPSK modulation is used with 10^7 Monte Carlo iterations. The BER measurements we present are an average over all the subcarriers carrying data. As can be seen, the BER is lower when using f-OFDM modulation for all the considered filter orders. For the sake of performance comparison, we add to the figure the Matched Filter Bound (MFB) as a benchmark for the BER comparisons. The MFB is also called in the literature as the perfect interference-cancellation bound. As it is suggested by its name, the MFB performs as the kth device of a matched-filter receiver in the absence of other sources of interference such as devices at adjacent channels and multi-user interference, $i.e.$, cross-talking interference caused by devices using the time-frequency resources. As noticed, the BER of f-OFDM modulation improves as the filter order increases. Additionally, we also see that f-OFDM with SD and ML detection approaches the MFB faster as the filter order increases.

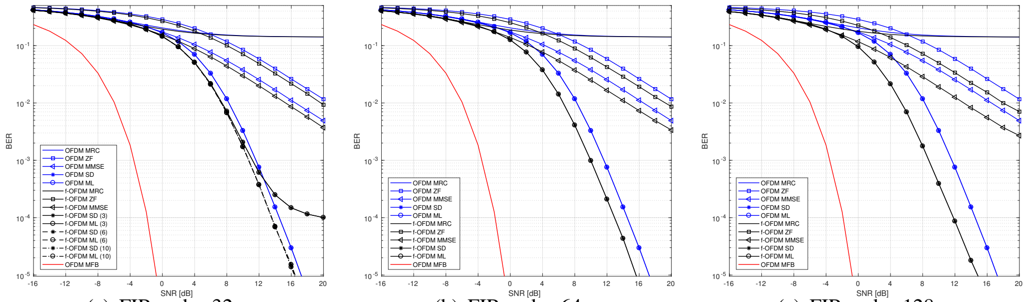
As expected, MMSE detection has the best performance and MRC detection has the worst one among the studied detectors. Considering a BER of 10^{-2} and taking the MMSE detector's performance into account we see that there is a gain of ≈ 1 [dB], ≈ 2 [dB], and > 3.5 [dB] for filter orders 32, 64 and 128 respectively. Additionally, it is important to emphasize the use of SD detection, which has smaller computational complexity when compared to the ML detection and still has performance similar to that detector.

It is also important to notice that for a filter order of 32 (see Fig. 6 (a)) and N$_e = 3$ the BER for SD and ML detectors reaches a BER floor of approximately 10^{-4} for SNR greater than 12 [dB]. From that point onward the performance of f-OFDM is worse than that of OFDM with SD and ML detection. This is due to the fact that the subcarriers at the edges of the OFDM symbols are heavily affected by the filter's poor performance at its edges ($i.e.$, attenuation and overshoot) becomes noticeable as can be seen in Fig. 5 (a). The attenuation and overshoot at the edges of the filter response are the limiting factors for BER at high SNR values. In order to validate this assumption, we also show in Fig. 6 (a) BER results for excess bandwidths, N$_e$, of 3 and 10 excess subcarriers. That increases the flat region of the pass-band, making the filter flatter at the edges, and consequently, the BER for f-OFDM with SD and ML detectors do not present a floor value anymore. This behavior is also shown with higher-order filters ($e.g.$, 64 and 128), where we do not verify the floor effect, once they exhibit a longer flat region (as is seen in Fig. 5 (b) and (c)).

Other interesting results are depicted in Fig. 7. In this figure, we see the benefits of having a BS equipped with a larger number of antennas. As can be seen, as the number of antennas increases the BER performance of the detectors asymptotically approaches that of the OFDM MFB. As can also be noticed, the performance of the sub-optimal detectors, ZF and MMSE, asymptotically approaches the performance of the almost-optimal and optimal detectors, SD and ML. This is due to the fact that as the number of antennas increases, the interference and noise tend to vanish as the devices' channels become asymptotically orthogonal due to the law of large numbers [9]. These results clearly prove that the interference caused by users transmitting at closely separated adjacent channels can be mitigated by having a BS equipped with a large number of antennas.

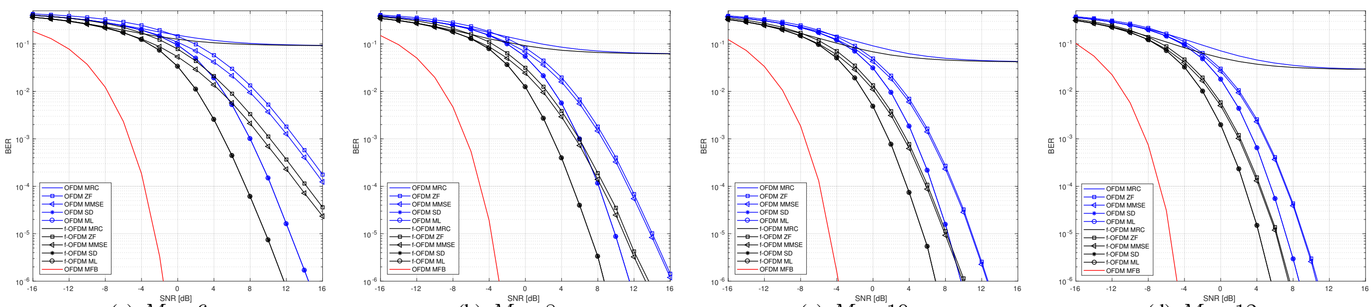
It is known that the OFDM modulation exhibit a high PAPR (Peak-to-Average Power Ratio), which is a limiting factor in some cases. This effect poses a challenge for RF power amplifier design, because as the OFDM signal varies greatly, the amplifier operating point must be reduced so that high signal values do not enter the nonlinear region of amplifier, as this distortion causes intermodulation between the subcarriers and creates OOBE, which is an effect we want to avoid.

In Fig. 8 we assess the PAPR presented by a single carrier, OFDM and f-OFDM modulation schemes. In the figure, we measure the CCDF (Complementary Cumulative Distribution Function) for each one of them compared modulations. We observe that the probability of the power of the OFDM and f-OFDM modulated signals being more than 3 [dB] above its average power level is higher than for a QAM modulated signal. For example, the power level above the average power level is of 2.46 [dB], 3.62 [dB], 4.11 [dB], 4.49 [dB] and 5.02 [dB] with a percentage of 10% for QAM, OFDM, f-OFDM 32, f-OFDM 64 and f-OFDM 128 respectively. We conclude that, although reducing the OOBE, the f-OFDM modulation presents as a drawback, a PAPR that is higher than that presented by the OFDM modulation and that gets worse as the filter order increases.



(a) FIR order 32. (b) FIR order 64. (c) FIR order 128.

Figure 6. BER performance for MIMO OFDM versus MIMO f-OFDM detection on uplink direction with $K = 4$, $M = 4$, NPRB $= 6$, $\mathrm{N}_e = 3$ and filter orders 32 (a), 64 (b), 128 (c).



(a) $M = 6$. (b) $M = 8$. (c) $M = 10$. (d) $M = 12$.

Figure 7. BER performance for MIMO OFDM versus MIMO f-OFDM detection on uplink direction with $K = 4$, NPRB $= 6$, filter order 128, $\mathrm{N}_e = 3$, and number of antennas, M, 6 (a), 8 (b), 10 (c), 12 (d).

IV. Conclusions

In this paper, we assessed the influence of the interference among adjacent signals in a MIMO system when OFDM and f-OFDM modulations are employed. The MIMO system performance was analyzed by means of the BER calculation, using MRC, ZF, MMSE, SD and SD detection methods. We demonstrate the importance of filtering the OFDM modulate signal as a way to mitigate interference at adjacent channels. Our analysis concludes that f-OFDM equipped systems can perform better than OFDM when power amplification is not an issue. Given that condition, we conclude that f-OFDM is an excellent candidate for future generations of wireless networks. Therefore, f-OFDM systems allow closer frequency coexistence of devices, which increases the spectral efficiency, as the distance among adjacent channels can be decreased.

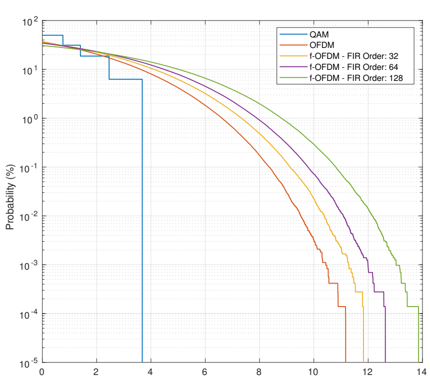


Figure 8. CCDF comparison of single-carrier and OFDM/f-OFDM modulation schemes.

Acknowledgment

This work was partially funded by (i) the Center for Research and Development in Telecommunications (CPQD), through participation in the project 5G-RANGE (Technical Cooperation Agreement for Research and Development between RNP and CPqD - H2020-EUB-2017) and also by (ii) the European Union's Horizon 2020 research and innovation programme under grant agreement No. 732174 (ORCA project).

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