



HAL
open science

Novel transmission technique based on intentional overlapping to improve spectral efficiency of multicarrier systems

Fatima Hamdar, Jérémy Nadal, Charbel Abdel Nour, Amer Baghdadi

► To cite this version:

Fatima Hamdar, Jérémy Nadal, Charbel Abdel Nour, Amer Baghdadi. Novel transmission technique based on intentional overlapping to improve spectral efficiency of multicarrier systems. PIMRC 2023: IEEE 32nd Annual International Symposium on Personal, Indoor and Mobile Radio Communications, Sep 2023, Toronto, Canada. 10.1109/PIMRC56721.2023.10293842 . hal-04168067

HAL Id: hal-04168067

<https://hal.science/hal-04168067>

Submitted on 21 Jul 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Novel transmission technique based on intentional overlapping to improve spectral efficiency of multicarrier systems

Fatima Hamdar¹, Jeremy Nadal¹, Charbel Abdel Nour¹, and Amer Baghdadi¹

¹IMT Atlantique, Lab-STICC, UMR CNRS 6285, F-29238 Brest, France

Abstract—A crucial element of cellular communication networks is the achievable spectral efficiency (SE). Indeed, motivated by the continuous growth in mobile data traffic in wireless networks, improving SE has represented one of the key goals of the 3rd Generation Partner Project (3GPP) along several generations of communication standards. In this paper, we propose a novel transmission scheme based on intentionally overlapping the subcarriers of adjacent users considering two state-of-the-art waveforms: the orthogonal frequency division multiplexing (OFDM) and the filter bank multi-carrier with offset quadrature amplitude modulation (FBMC/OQAM). We investigate the achievable spectral efficiency improvement of the proposed transmission scheme in the presence and absence of timing offset impairments under the tapped delay line B (TDL-B) multipath 3GPP model of the 5G QuaDRiGa channel. According to the test results, the proposed transmission technique achieves up to 20% SE improvement for FBMC/OQAM when associated to the overlap-save FBMC receiver and 12% for OFDM.

Beyond 5G, filtered multi-carrier waveforms, FBMC/OQAM, intentional overlapping, OFDM, overlap-Save FBMC receiver.

I. INTRODUCTION

The fifth generation (5G) of mobile communications has received a lot of interest from the academic and professional fields. Among all the crucial requirements, such as high peak throughput and ultra-low latency, the spectral efficiency (SE) enhancement is also highlighted [1], [2]. The radio spectrum resource is of fundamental importance for wireless communications, especially since it is becoming scarce. In fact, future wireless networks are expected to face worsening congestion levels than nowadays [3]. Therefore, SE enhancement becomes crucial for the development of beyond 5G wireless communication systems.

The orthogonality of signals is emphasized by the Nyquist pulse-shaping criterion to prevent inter-symbol interference (ISI). However, this comes at a sacrifice in SE. Hence, increasing the constellation order is one method to enhance the SE when the orthogonality condition is to be respected. Unfortunately, high order constellations are more susceptible to nonlinear effects. Loosening the orthogonality condition is a different technique to increase the SE of low-order modulations. For instance, the well-known faster-than-Nyquist (FTN) signaling approach [4], [5] reduces the spacing between two adjacent pulses in the time domain considerably below the Nyquist rate. Therefore, controlled ISI is introduced. Despite the fact that ISI-free performance can be achieved with FTN signaling, Nyquist's first criterion has been widely applied in

traditional communication systems motivated by the limitations of hardware implementations caused by the complexity of the ISI cancellation algorithms. Spectrum sharing (SS) is another method for SE enhancement. It is a way to maximize spectrum utilization by allowing multiple users with varied priorities to share the same frequency band without interfering with one another. However, as [6] noted, there are some challenges with the network design of SS in terms of spectrum sensing, decision-making, and admission control.

In addition to these approaches, SE enhancement based on overlapping techniques has been studied in the literature. A systematic partially overlapping model is described in [7], which demonstrates how careful utilization of overlapped channels can considerably enhance spectrum usage. The authors in [8] proposed a multi-carrier transmission scheme called high compaction multi-carrier modulation (HC-MCM) to improve the SE of the orthogonal frequency division multiplexing (OFDM) waveform. The HC-MCM can easily attain a high transmission rate by arbitrarily overlapping the spectra of its subcarriers with a technique that involves truncating the transmitting signal with a rectangular window in the time domain. However, similarly to OFDM, the proposed multicarrier transmission scheme still suffers from a high out-of-band-power leakage (OOBPL), hence requiring guard bands that waste spectrum resources. Moreover, it reveals to be vulnerable to timing offset (TO) impairments which is expected to hinder its ability of managing/cancelling the overlapping-induced interference. Furthermore, the work in [8] limited the study to an additive white Gaussian noise channel, neglecting the effect of multipath. The authors in [9] incorporated partial time and frequency overlapping between adjacent symbols considering the filtered multi-tone (FMT) modulation. However, they simply considered an exponentially decaying channel in their simulations. Therefore, the results may differ over more realistic channels. Moreover, the FMT modulation is less bandwidth efficient than other filtered multicarrier waveforms due to the roll-off factor of the pulse-shaping filter. For all these reasons, considering other filtered multicarrier waveforms to address these drawbacks reveals to be interesting in order to achieve the highest SE gain.

Filter bank multi-carrier waveform using offset quadrature amplitude modulation (FBMC/OQAM) was investigated as a 5G alternative for OFDM motivated by its advantages in terms of robustness against imperfect synchronizations and lower OOBPL. The latter aspect improves frequency localization, hence reducing the impact on neighboring bands. This reduces,

or even eliminates, the need for guard bands leading to a SE improvement. Moreover, FBMC is naturally more robust to TO impairments than OFDM, which maintains the SE improvement in the presence of TO. In fact, the efficiency of all non-orthogonal previously mentioned approaches for SE improvement resides in their ability to manage the induced interference. Therefore, by harnessing the inherent potentials of the FBMC/OQAM waveform in terms of robustness to impairments, it can be possible to address the overlapping-induced interference.

Therefore, in this paper, we propose a novel transmission technique where intentional overlapping is introduced among the subcarriers of adjacent users. Based on FBMC/OQAM, the proposed scheme efficiently manages overlapping-induced interference and significantly improves the SE for single-input-single-output (SISO) transmissions. The specific contributions presented in this paper can be summarized as follows:

- 1) Proposal of an efficient flexible overlapping transmission technique achieving new tradeoff levels between error rates and SE.
- 2) Evaluation of the performance of the proposed technique for the FBMC/OQAM waveform augmented with the overlap-save (OS)-based FBMC receiver. The evaluation is conducted using bit error rate (BER) simulations over the tapped delay line B (TDL-B) 5G Qudriga multipath channel. The results are compared to that of a typical OFDM receiver.
- 3) Design space exploration of the achievable SE improvement considering OFDM and the FBMC/OQAM waveforms in the presence and absence of TO impairments.

The rest of the paper is organized as follows. Section II describes the FBMC/OQAM transceiver considered for our study. The proposed overlapping transmission technique is detailed in Section III. Section IV describes the simulation setup, along with performance comparisons of the proposal when associated to FBMC/OQAM and OFDM. Then, the SE improvement attained by the proposed transmission technique is evaluated in the presence and absence of TO impairments. Section V concludes the paper.

II. SYSTEM MODEL

This section describes the FBMC/OQAM transceiver considered in our study.

A. FBMC transmitter

The *polyphase* network (PPN)-based [10] modulator is one of the main implementations for FBMC modulation. It consists of one size- M IFFT, followed by a PPN for the filtering stage. To reduce the computational complexity of the PPN processing, a short prototype filter (PF) g of length $L = M$ can be used. The orthogonality in the real field is preserved using the OQAM modulation scheme. Consequently, the generated signal from the previous iteration is added to the PPN output signal after being delayed by $M/2$ samples.

Therefore, to express the above procedure mathematically, the transmit signal can be written as

$$s(k) = \sum_{m=0}^{M-1} \sum_{n=-\infty}^{\infty} a_n(m)g_{m,n}(k) \quad (1)$$

where $g_{m,n}(k) = (-1)^{nm}g(k-n\frac{M}{2})e^{j\pi(m+n)/2}e^{j2\pi mk/M}$, M is the total number of subcarriers, $a_n(m)$ are the user's pulse-amplitude modulated (PAM) symbols within FBMC symbol n , subcarrier index m .

B. Overlap-Save FBMC receiver

The FBMC-OS receiver was proposed in [11]. With N_{UF} being the up-sampling factor used for the OS algorithm and M the total number of subcarriers, the receiver processing starts by applying an FFT of size $N = N_{UF}M$ on the received signal R_n . Similarly to OFDM, equalization is performed immediately after the FFT via a zero forcing (ZF) equalizer as follows

$$X_n(m) = C_n(m) \times R_n(m) \quad (2)$$

where the ZF equalization matrix at frequency bin m defined as the conjugate of the channel frequency response $C_n(m) = H_n^*(m)$, and $X_n(m)$ is the user's equalized signal. Then, the frequency-shifted responses of the PF G_ℓ are applied to $X_n(m)$ through N_{UF} stages of circular convolution. Therefore, the output of the ℓ^{th} filtering stage vector is

$$Y_n(m, \ell) = \sum_{p=-\Delta}^{\Delta} G_\ell(p)X_n(\ell + (m-p)N_{UF}) \quad (3)$$

where $\Delta = (N_G - 1)/2$ and N_G denotes the number of non-truncated filter coefficients.

The vector outputs of the filtering stage are added up to get the analysis filter bank output $Y_n(m)$. Finally, the transmitted data symbols $\hat{a}_n(m)$ of the corresponding user are recovered after extracting the real part of the linear phase rotated filtering stage outputs as follows

$$\hat{a}_n(m) = \text{Re} \left(Y_n(m) \phi_n^*(m) \right). \quad (4)$$

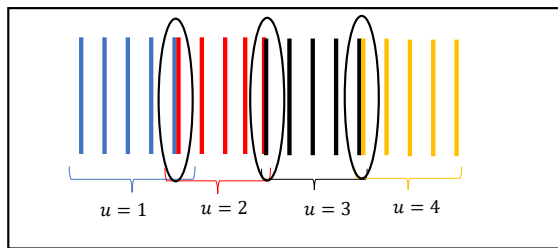
III. PROPOSED OVERLAPPING TRANSMISSION TECHNIQUE

A. Description of the proposed overlapping schemes

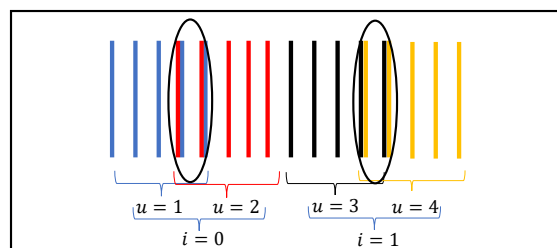
We consider a scenario where U users transmit data on different adjacent frequency bands (or sub-bands). Some of these sub-bands can overlap, resulting in two possible types of overlap: two-sided (2S) or one-sided (1S) overlap as shown in Figures 1a and 1b respectively. Therefore, if OL denotes the number of overlapped subcarriers per user, and SB the number of subcarriers allocated for each user, then the SE gain G_{SE} thanks to the overlap is

$$G_{SEOL} = \frac{OL}{SB}, \quad OL \in [0, \dots, SB] \quad (5)$$

It is crucial to select the appropriate scheme that results in a lower level of interference in order to improve system performance. The overlap between adjacent data symbols located at frequency bin p and time q can be used to calculate



(a) Two-sided (2S) overlapping



(b) One-sided (1S) overlapping

Fig. 1: Illustration of the proposed overlapping transmission schemes with $OL = 2$.

the induced interference $J_n(m)$ for the data symbol at symbol n and frequency bin m . In fact, by taking the weighted sum of the neighboring overlapped data symbols, denoted as $d_{n+q}(m+p)$ with the weights given by the ambiguity function of the PF, denoted as $A_g(\tau, \mu)$, we can compute

$$J_n(m) = \sum_{(p,q) \in \Omega^*} d_{n+q}(m+p) A_g\left(-\frac{qM}{2}, \frac{p}{M}\right) \quad (6)$$

along with

$$A_g(\tau, \mu) = \int_{-\infty}^{+\infty} g_t(t + \tau/2) g_r^*(t - \tau/2) e^{i2\pi\mu t} dt \quad (7)$$

where g_t and g_r are the transmit and receive PFs respectively, $\Omega = \llbracket -\infty, +\infty \rrbracket \llbracket -\frac{M}{2}, \frac{M}{2} \rrbracket$, and $\Omega^* = \Omega \setminus (0, 0)$.

Note that,

$$d_n(m) = \begin{cases} 1, & m \in \Omega_c \\ 0, & \text{otherwise} \end{cases}$$

where Ω_c is Ω_1 for the 1S scheme (Figure 1b) and Ω_2 for the 2S scheme (Figure 1a), with

$$\begin{aligned} \Omega_1 &= \llbracket 0, \dots, OL - 1 \rrbracket \\ \Omega_2 &= \llbracket 0, \dots, \frac{OL}{2} - 1 \rrbracket \cup \llbracket M - \frac{OL}{2}, \dots, M - 1 \rrbracket \end{aligned}$$

Therefore, the interference power σ^2 induced from overlapping by OL subcarriers can be computed as follows

$$\begin{aligned} \sigma^2 &= E[J_n(m)^2] \\ &= \sum_{(p,q) \in \Omega^*} A_g\left(-\frac{qM}{2}, \frac{p}{M}\right)^2 \end{aligned} \quad (8)$$

where $m - p \in \Omega_c$

Hence, using (8) and by employing the near perfect reconstruction 1 (NPR1) short PF [12], we compare in Figure 2 the interference power versus OL of the two proposed overlapping transmission schemes with $CR = 1$. Since the NPR1 PF is highly localized in time, the interference is limited to only adjacent FBMC symbols. Therefore, $\Omega = \llbracket -1, 1 \rrbracket \llbracket -\frac{M}{2}, \frac{M}{2} \rrbracket$. Both schemes display an increase in interference level with OL , while the 2S overlapping suffers from a higher level of interference than the 1S. Consequently, we chose the 1S scheme for the rest of the study. In this case, the set of overlapped users

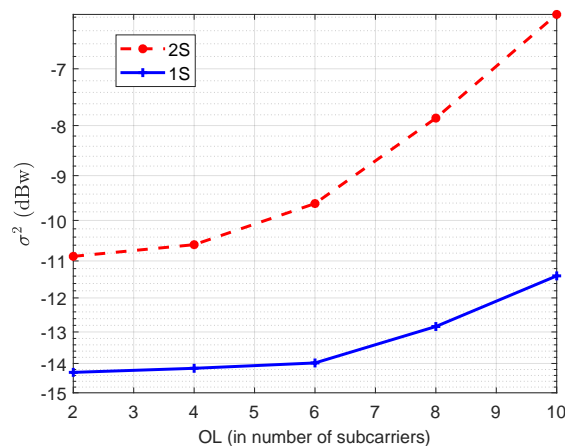


Fig. 2: Interference power comparison of the proposed one-sided and double-sided transmission schemes with $CR = 1$.

is indexed by i . Therefore, the FBMC/OQAM transmit signal $s(k)$ in (1) will be modified as follows

$$s(k) = \sum_{u=1}^U \sum_{n=-\infty}^{\infty} \sum_{m \in \mathcal{F}_u} a_n(m - f_u) g_{m,n}(k) \quad (9)$$

along with

$$\begin{aligned} \mathcal{F}_u &= \{f_u, \dots, f_u + SB - 1\} \\ f_{u+1} - f_u &= \begin{cases} 1 + SB + OL, & \text{if } i_{u+1} - i_u = 0 \\ SB, & \text{otherwise} \end{cases} \end{aligned}$$

where f_u is the u^{th} user starting subcarrier index, and i_u is the set index of the u^{th} user.

Similarly, the OFDM transmit signal $s(k)$ considering the proposed overlapping transmission scheme can be expressed mathematically as shown below

$$s(k) = \sum_{u=1}^U \sum_{n=-\infty}^{\infty} \sum_{m \in \mathcal{F}_u} a_n(m - f_u) e^{j2\pi \frac{(k - L_{CP})m}{M}} \quad (10)$$

where $a_n(m)$ are the complex user's transmitted symbols on the m^{th} subcarrier within the n^{th} OFDM symbol, and L_{CP} is the cyclic prefix length.

B. Procedure for SE enhancement

OFDM is vulnerable to adjacent channel interference (ACI) due to its low-frequency localization, necessitating the introduction of guard bands. The added guard bands reduce the data rate and, therefore, the SE. Thanks to the introduced filtering stage, FBMC/OQAM is more robust against ACI. Therefore, overlapping-induced interference management can be more efficient with the FBMC/OQAM waveform by exploiting its inherent advantage. The introduction of channel coding can help combat interference. Therefore, if CR_{OL} is the coding rate relevant to OL , and K the modulation order, the tuple (CR^*, K^*, OL^*) should be chosen such that the ratio of the energy per bit to the spectral noise density $\frac{Eb}{N_0}$ is minimized for a target SE α as

$$(CR_{OL}^*, K^*, OL^*) = \underset{SE=\alpha}{\operatorname{argmin}} \left(\frac{Eb}{N_0}(CR_{OL}, K, OL) \right). \quad (11)$$

Next, the CR_{OL}^* of the selected combination is optimized to maximize the SE for a target BER = β at $\frac{Eb}{N_0} = \gamma$. Target β and γ values are issued from the non-overlapping case ($OL = 0$). This translates mathematically as follows

$$CR'_{OL} = \underset{BER=\beta, \frac{Eb}{N_0}=\gamma}{\operatorname{argmax}} (SE(CR_0, K, 0)). \quad (12)$$

Eventually, the SE gain corresponding to the selected combination can be computed as follows

$$G_{SE_{OL}} = \frac{CR'_{OL}}{CR_{OL}^*}. \quad (13)$$

IV. APPLICATION EXAMPLE

We first describe our simulation setup. Then, the performance of the FBMC-OS receiver using the NPR1 short PF is compared to OFDM considering the proposed overlapping transmission scheme. In our simulations, the channel state information is assumed to be perfectly estimated at the receiver side. Furthermore, the number of non-truncated filter coefficients is set to $N_G = 7$ for a SIR of 55 dB [12]. The total number of users is $U = 4$ where the transmit powers of all transmissions are equal and normalized to 0 dBW. For the FBMC-OS receiver, N_{UF} is set to 4 leading to the FBMC-OS₄ receiver notation. This choice represents a good compromise between system performance and complexity.

At the receiver, one reference set of overlapped users was processed to simplify the performance analysis and to reduce the simulation time. In Figures 1a and 1b, the set centered on user $u = 2$ or $u = 3$ can be considered as reference.

A. Simulation setup

The TDL-B multipath 3rd generation partner project (3GPP) channel model is used for our simulations considering a delay spread τ of $1\mu s$. Chosen parameters follow the 5G standard [1]. The 5G new radio low-density parity check code (LDPC) is used in our simulations [13] with base graph 1. A short-random interleaver is considered rather than a long one since the interference pattern is well-defined, allowing for lower latency. Simulation parameters are summarized in Table I.

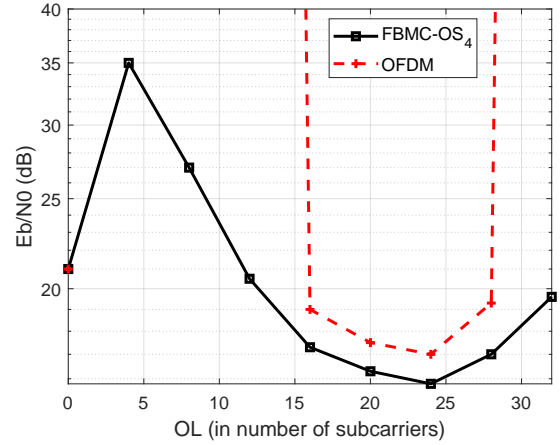


Fig. 3: Eb/N_0 vs OL of the considered receivers over the TDL-B 5G QuaDRiGa channel for a target BER of 10^{-4} .

Parameters	Value
Carrier frequency	3.5 GHz
Cyclic prefix	36
Channel model	TDL-B
Channel type	NLOS
Total number of subcarriers	512 subcarriers
Sub-band size per user	128 subcarriers
Number of UE	4
BS height	25 m
Interleaver type	Short-random
Modulation schemes	16QAM, 64QAM

TABLE I: Simulation Parameters

B. Selection of the best tuple

We consider now (11) for selecting the best tuple of (CR^*, K^*, OL^*) leading to the highest SE gain. We plot in Figure 3 the required $\frac{Eb}{N_0}$ versus OL for different tuples achieving the same SE with the FBMC-OS₄ and OFDM receivers and a target BER of 10^{-4} .

We start first by analyzing the results for $K = 16$. Regarding the FBMC-OS₄ receiver, $\frac{Eb}{N_0}$ initially increases with OL . After $OL = 4$, it decreases until reaching a minimum value of 15.8 dB at $OL = 24$ and $CR = 1/2$. The performance starts to degrade after $OL = 24$, showing that the maximum value of OL for exhibiting the best performance is 24 subcarriers. Similar interpretation can be made when considering the OFDM receiver, where $\frac{Eb}{N_0}$ starts increasing with OL until $OL = 12$, and then reaches a minimum value of 17 dB at $OL = 24$ and $CR = 1/2$. Note that FBMC can attain lower values of $\frac{Eb}{N_0}$ than OFDM for the same value of OL thanks to its inherent capabilities to combat interference. For $K = 4$, the target SE is not achievable by any tuple, since the CR cannot exceed 1. On the other hand, the target BER is not achievable by any tuple when $K = 64$, and therefore its corresponding curve is not shown in the figure. To summarize, the tuple $(CR^*, K^*, OL^*) = (1/2, 16, 24)$ is selected for the rest of the work.

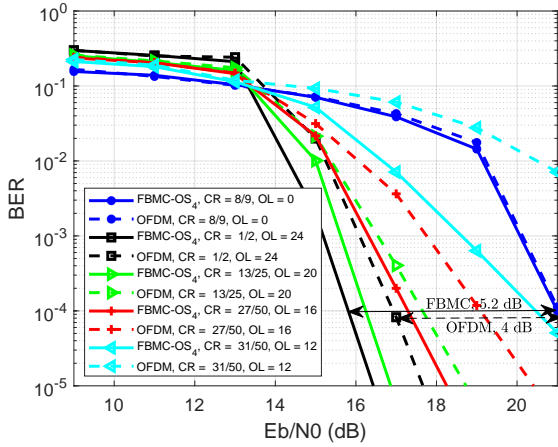


Fig. 4: BER performance comparison of the OS_4 -FBMC receiver over the TDL-B 5G QuaDRiGa channel with different tuples achieving the same SE.

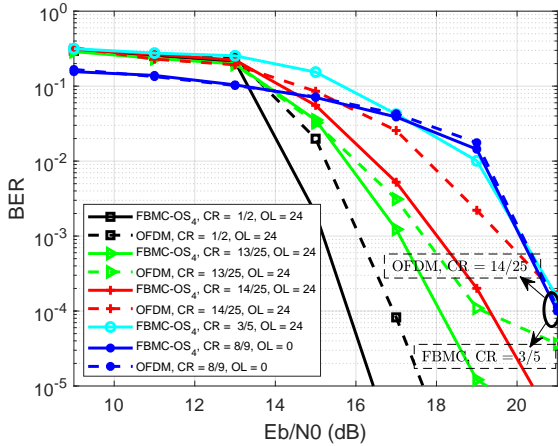


Fig. 5: SE improvement capability for the proposed transmission technique for the OFDM and FBMC- OS_4 receiver over the TDL-B 5G QuaDRiGa channel, with $OL = 24$.

C. Simulation results over the 5G multipath channel

In order to provide a more detailed understanding of the efficiency of the proposed approach, we also compare in Figure 4 the BER performance as a function of the E_b/N_0 of both the OFDM and FBMC- OS_4 waveforms for the considered scenario. Several combinations of CR_{OL} and OL (in number of subcarriers) are considered targeting the same SE with $K^* = 16$.

When the subcarriers do not overlap (i.e., $OL = 0$) and a CR of $8/9$ is used, both waveforms exhibit the worst BER performance. Increasing the amount of overlap between subcarriers results in a higher degree of interference, making it necessary to reduce the CR while maintaining the same SE. This, in turn, leads to a significant improvement in BER performance, as illustrated in the same figure for various combinations of OL values, specifically 12, 16, 20, and 24. In particular, overlapping by 24 subcarriers yields the best

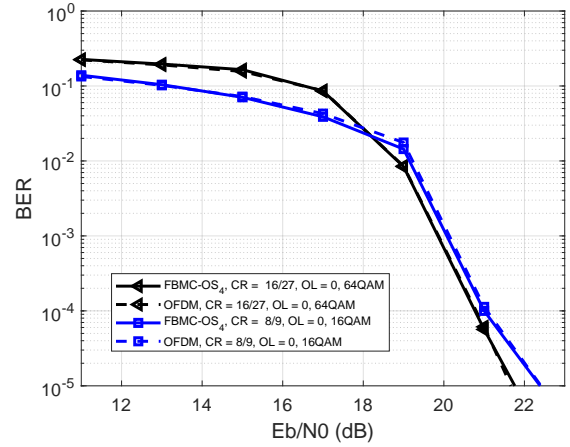


Fig. 6: BER performance comparison of the OFDM and FBMC- OS_4 receiver over the TDL-B 5G QuaDRiGa fading channel, with 16QAM and 64QAM modulation schemes, and same SE.

performance, providing a gain of approximately 5.2 and 4 dB in E_b/N_0 for FBMC and OFDM, respectively. This finding confirms the conclusions drawn in Section IV-B from Figure 3.

D. Spectral efficiency gain

We use (12) to evaluate the SE gain of the best overlapping case of $OL = 24$ relative to the non-overlapping scenario. Figure 5 depicts the BER performance for $OL = 24$ with increasing CR_{24} values. We determine the SE gain once the BER performance of both scenarios is nearly identical for a target $\frac{E_b}{N_0}$ ($\gamma = 21$ dB). As shown in Figure 5, the curve corresponding to the non-overlapping scenario intersects with the one corresponding to the overlapping scenario at $CR_{24} = 3/5$ for FBMC/OQAM and $14/25$ for OFDM, resulting in a 20% and 12% SE gain for FBMC/OQAM and OFDM, respectively. Therefore, FBMC/OQAM augmented with the FBMC-OS receiver provides superior performance and a higher SE gain compared to OFDM.

An alternative and simple method to improve the SE could be increasing the modulation order. Therefore, we compare in Figure 6 the BER performance with equal SEs of 64QAM with non-overlapping subcarriers (i.e., $OL = 0$) and $CR = 16/27$ to that of 16QAM with $CR = 8/9$. As depicted in the figure, 64QAM performs similarly to 16QAM for a target BER of 10^{-4} , confirming the efficiency of our proposed transmission scheme to improve the SE.

E. Effect of timing offsets

TO impairments occur when the transmitter and receiver windows are not aligned in time. It is always the case in practice due to the channel induced propagation delay. Therefore, it is important to investigate the robustness in terms of BER performance of the proposed transmission technique and the two considered waveforms in the presence of TO impairments. Corresponding results are plotted in Figure 7.

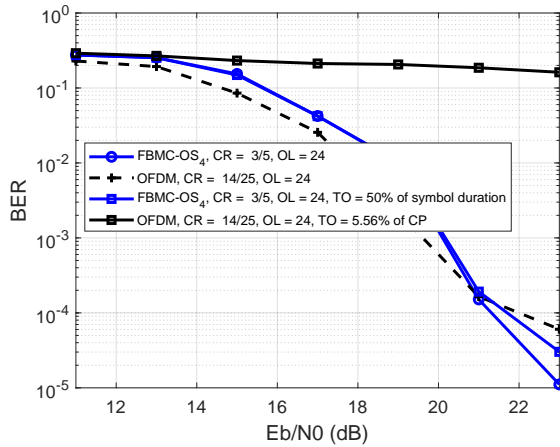


Fig. 7: BER performance comparison of the FBMC-OS₄ and OFDM receivers over the TDL-B 5G QuaDRiGa fading channel in the presence of TOs, with $OL = 24$.

Without overlapping, OFDM exhibits a high vulnerability to TO impairments since it cannot support any TO value larger than half of its cyclic prefix duration. This vulnerability is worsened by overlapping. Indeed, considering the case that corresponds to the highest SE gain (i.e., $OL = 24$ with $CR = 14/25$) for OFDM, a TO that corresponds only to 5.56% of the CP duration was enough to severely degrade performance, leading to an irreducible error floor as depicted in Figure 7. On the contrary, FBMC augmented by the OS receiver can support asynchronous communications as demonstrated in [11]. Thus, applying a much larger TO value that corresponds to 50% of the symbol duration shows the same BER performance down to the target BER of 10^{-4} with a slight performance degradation for lower error rates ($Eb/N0 > 21$ dB). This slight performance degradation is brought on by the introduced change in the interference pattern due to TO impairments. This can be, at least partly, compensated for by a suitable design of the interleaver located between the waveform and the outer channel code.

V. CONCLUSION

This article proposes a novel transmission scheme designed to improve spectral efficiency. It is based on intentionally overlapping the subcarriers of adjacent users considering the OFDM and FBMC/OQAM waveforms. The corresponding results reveal that the FBMC transceiver outperforms OFDM over the TDL-B 5G Quadriga channel while confirming the targeted SE improvement by the proposal. In particular, with the OS₄ receiver, the FBMC transceiver offers up to 40% higher SE gain compared to OFDM. Additionally, an appealing benefit of the FBMC-OS₄ receiver resides in its robustness against TO when compared to OFDM. Indeed, with a TO reaching 50% of the symbol duration, it outperformed the OFDM receiver suffering only from a TO of 5.56%. Consequently, augmented by the OS-based receiver, the FBMC/OQAM waveform proves to be a promising challenger for OFDM in future communication systems.

ACKNOWLEDGEMENT

This work was carried out in the context of Beyond5G, a project funded by the French government as part of the economic recovery plan, namely “France Relance”, and the investments for the future program.

REFERENCES

- [1] 3GPP TR 138 901, v15.0.0, “5G; Study on channel model for frequencies from 0.5 to 100 GHz”, 2018.
- [2] Banelli, P., Buzzi, S., Colavolpe, G., Modenini, A., Rusek, F. *et al.*, “Modulation Formats and Waveforms for 5G Networks: Who Will Be the Heir of OFDM?: An overview of alternative modulation schemes for improved spectral efficiency,” *IEEE Signal Processing Magazine*, vol. 31, no. 6, pp. 80–93, 2014.
- [3] Andrews, J. G., Buzzi, S., Choi, W., Hanly, S. V., Lozano, A. *et al.*, “What Will 5G Be?” *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 6, pp. 1065–1082, 2014.
- [4] Fan, J., Guo, S., Zhou, X., Ren, Y., Li, G. Y. *et al.*, “Faster-Than-Nyquist Signaling: An Overview,” *IEEE Access*, vol. 5, pp. 1925–1940, 2017.
- [5] Rusek, F. and Anderson, J., “The two dimensional Mazo limit,” in *Proceedings. International Symposium on Information Theory, ISIT*, 2005, pp. 970–974.
- [6] Akhtar, A. M., Wang, X., and Hanzo, L., “Synergistic spectrum sharing in 5G HetNets: A harmonized SDN-enabled approach,” *IEEE Communications Magazine*, vol. 54, no. 1, pp. 40–47, 2016.
- [7] Mishra, A., Shrivastava, V., Banerjee, S., and Arbaugh, W., “Partially overlapped channels not considered harmful,” in *Proceedings of the joint international conference on Measurement and modeling of computer systems*, 2006, pp. 63–74.
- [8] Hamamura, M. and Tachikawa, S., “Bandwidth efficiency improvement for multi-carrier systems,” in *IEEE 15th International Symposium on Personal, Indoor and Mobile Radio Communications (IEEE Cat. No.04TH8754)*, vol. 1, 2004, pp. 48–52 Vol.1.
- [9] Esad Ankarali, z., Şahin, A., and Şahin, A., “Intentional-overlapping for multicarrier schemes based on user-specific filters,” *Analog Integr Circ Sig Process*, vol. 78, pp. 683–690, 2013.
- [10] Hirosaki, B., “An Orthogonally Multiplexed QAM System Using the Discrete Fourier Transform,” *IEEE Trans. on Commun.*, vol. 29, no. 7, pp. 982–989, 1981.
- [11] Nadal, J., Leduc-Primeau, F., Nour, C. A., and Baghdadi, A., “Overlap-Save FBMC Receivers,” *IEEE Transactions on Wireless Communications*, vol. 19, no. 8, pp. 5307–5320, 2020.
- [12] Nadal, J., Nour, C. A., and Baghdadi, A., “Design and Evaluation of a Novel Short Prototype Filter for FBMC/OQAM Modulation,” *IEEE Access*, vol. 6, pp. 19610–19625, 2018.
- [13] 3GPP TS 38.212 V17.3.0; Technical Specification Group Radio Access Network; NR; Multiplexing and channel coding”, Release 17 2022.