New Multi-Carrier Candidate Waveform For the 5G Physical Layer of Wireless Mobile Networks

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***Abstract*—In this paper, a new multi-carrier candidate waveform for the future generation of mobile (5G) is introduced, explored and evaluated. The newly developed design of the Orthogonal Generalized Frequency division multiplexing (OGFDM) can improve the performance in terms of the channel capacity and Bit Error Rate (BER) for the wireless transmission of the multi-carrier system. In addition, compared to the most candidate waveform, Generalized Frequency Division Multiplexing (GFDM), the innovative multi-carrier OGFDM can double, boost and even maximize the capacity of wireless channel at the acceptable level of the BER. This is essentially achieved due to major adaptations have been made on the Filtration level, Oversampling level and Modulation level of the currently recommended GFDM. Thus, depending on the Digital Hilbert Filter (DHF), the presented solution can attain the orthogonality between the un-orthogonal filtered subcarriers of the multi-carrier GFDM technique. Moreover, by utilizing an adjustable oversampling factor, the examined system can stay reliable even in the worst conditions of the wireless channel. Furthermore, employing the adaptive bit loading instead of the fixed modulation format, the announced waveform can reach the maximum rate of transmission with the venial limit of error. The main parameters of each promoted level are precisely specified in accordance with the optimum system performance. Besides, the different levels of the multi-carrier OGFDM are presented in the physical layer (PHY) of a wireless electrical back-to-back transceiver system. A MATLAB simulation was introduced to evaluate the system performance (BER & channel capacity) in presence of the Additive White Gaussian Noise (AWGN).**

Keywords*—*Orthogonal Generalized Frequency Division Multiplexing (OGFDM); Generalized Frequency Division Multiplexing (GFDM); Multi-carrier system; Digital Hilbert Filter (DHF); Oversampling factor; Adaptive modulation

I. Introduction

The fifth generation (5G) of mobile networks tends to satisfy the exceptional and accelerated growth of modern transmission applications [1]. Thus, the key predicted scenarios for upcoming wireless networks of mobile like the Bit-pipe Communication [2], Machine Type Communication [3], Tactile Internet [4] and Wireless Regional Area Network [5] are presently investigated by the wireless research community.

Unfortunately, due to some technical issues like the out of band emission, wasted Bandwidth (BW) of the cyclic prefix and sensitivity to the frequency offset, the currently employed Orthogonal Frequency Division Multiplexing (OFDM) cannot be able to achieve the requirements of the future mobile market [6].

As a direct result, modern studies have shown new candidate waveforms rapidly evolving from the traditional OFDM [7] to several filtered waveforms. For instance, the Filter Bank Multi-Carrier (FBMC) [8], the Universal Filter Multi-Carrier (UFMC) [9], the Filtered OFDM (F-OFDM) [10], and the Generalized Frequency Division Multiplexing (GFDM) [11]. As such, the new generation of mobile can be considered as a "*filtration era*".

To explain more, waveform developers have tended to apply the digital filtration on different levels of allocation. Hence, the filtration can be utilized either for each orthogonal subcarrier as in the FBMC [12], or for each fixed group of orthogonal subcarriers like in the UFMC [13], or for each flexible group of orthogonal subcarriers as in the F-OFDM [14]. Moreover, due to confliction between the orthogonal subcarriers and digital filters, the filtration is applied for each un-orthogonal subcarrier like in the GFDM which is considered as the most candidate waveform for the future generation of mobile [15].

Very recently, a single carrier candidate waveform termed as Orthogonal Generalized Frequency Division Multiplexing (OGFDM) is proposed [16]. The lately introduced waveform, which is essentially based on the Physical layer (PHY) of the GFDM, has achieved the orthogonality between the un-orthogonally filtered subcarriers of a single frequency centre (fc) of the GFDM. Hence, achieving the orthogonality in the filtration stage instead of the subcarriers stage. Thus, the digital orthogonal Hilbert filters have emerged as an effective solution for the affected BW efficiency of the GFDM.

The key concept behind them is the change in phase between the applied filters which makes them able to work concurrently [17]. Consequently, this kind of orthogonality enables to create a new wireless mobile infrastructure can allow the frequencies of subcarriers to be filtered in a dual way. As such, in terms of the single carrier transmission, the utilized OGFDM can double the capacity of transmission in compare to the GFDM [16].

To further broaden the range of functionalities and their related applications, it is greatly beneficial if the single frequency carrier of the OGFDM is extra extended to the multiple frequency carriers of the OGFDM. Thus, a further BW efficiency can be achieved herein with this proposed expansion.

This, however, result in raising the level of induced interference among the increasing number of filtered subcarriers. Hence, the transmitted signal, that gradually suffers from power loss, tests different cases of attenuation depending on the conditions of transmission [18]. Thus, the possibility of the interference that occurs between the rolled-off filters increases as the level of the filter expansion enlarges due to the decreased average of the transmission power [19].

Consequently, the trade-off relation between the overall channel capacity and the roll-off factor of the filter is investigated herein to identify the optimal guidelines of the system design under various wireless channel status.

The adaptive modulation format is broadly utilized with the introduced multi-carrier OGFDM system to access the highest level of the BW efficiency. Thus, the same frequency subcarriers can possibly be reused in a better way depending on transmission conditions [20].

In this paper, the new design of the OGFDM is basically achieved in the PHY of the wireless transmission system. In addition, the performance in terms of the channel capacity and the Bit Error Rate (BER) is deliberated in an electrical back-to-back system.

The rest of the paper is structured as follows: Section II discusses the main concepts of the proposed system physically and mathematically. Section III evaluates the system performance utilizing a MATLAB simulation. Section IV summarizes the outlines of the paper.

II. Multi-carrier OGFDM System Model

After the successful trial of employing the orthogonal digital Hilbert filters for the single carrier of the GFDM [16], in this paper, the supportive Hilbert filters are essentially utilized for the multi-carrier level of the most candidate waveform (GFDM). Thus, introducing an advanced design of the OGFDM to achieve extensively the orthogonality for the GFDM from the multi-carrier perspective.

Comparing to the GFDM, the improved scheme can enhance the performance of the multi-carrier wireless transmission in terms of the channel capacity and BER yet keeping the computational complexity at a similar level to the GFDM.

As is seen in Fig. 1, on the transmitter side of the multi-carrier OGFDM, particularly, at the Modulation level where all management operations of the bits loading are achieved, the most common modulation formats are adaptively applied for the frequency subcarriers.

In addition, assorted constellation table is introduced depending on the variant size of the bit token (N) that is previously assigned for each generated complex number.

As a result, with enhanced channel state, an extra number of bits can be gained from this hybrid shape of modulation increasing the BW efficiency.

In the frequency domain, the power consumption of the frequency subcarriers is variant depending on the types of applied modulation. This, however, can be solved by adopting the normalization process which is basically employed for setting the average power of the Gray map to one.

Moving on the Oversampling level where the sampling operation of the employed subcarriers are manipulated, the normalized subcarriers are appropriately up-sampled by a factor of K, where K indicates the number of the applied subcarriers at the multi-carrier system.

It's worth noting that, occasionally, the up-sampling operation can be raised by a dual value of K to treat some undesirable situations that essentially affect the capacity of the channel.

Afterwards, the process is moved to the Filtration level where the up-sampled subcarriers are filtered by the shaping filters of the Hilbert pair. Thus, each two adjacent frequencies of subcarriers are orthogonally filtered and assigned for the same fc.

Comparing to the GFDM, every fc, can simultaneously accommodate a filtered couple of the subcarriers. As such, the promoted system can improve the BW efficiency due to the extra (doubled) number of the filtered subcarriers with the same BW.

The convoluted subcarriers are then combined digitally utilizing a proper electrical adder. In addition, the integrated sequence of data is passed through the digital-to-analog converter (DAC) producing an analog signal ready for transmission through a suitable antenna.

As is shown in Fig. 2, on the receiver side of the multi-carrier OGFDM where reverse operations are applied to retrieve the original data, the received signal is initially digitized using the analog-to-digital converter (ADC).

After that, at the Filtration level, the corresponding matching filters are utilized to de-multiplex the stream of data on each used fc. Subsequently, the convoluted subcarriers are

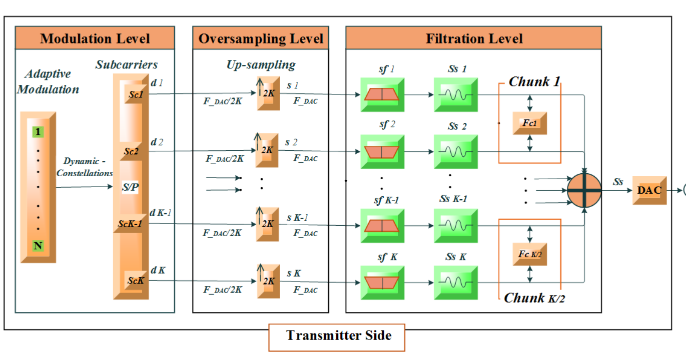

Fig. 1. Wireless transmission system of the multi-carrier OGFDM.

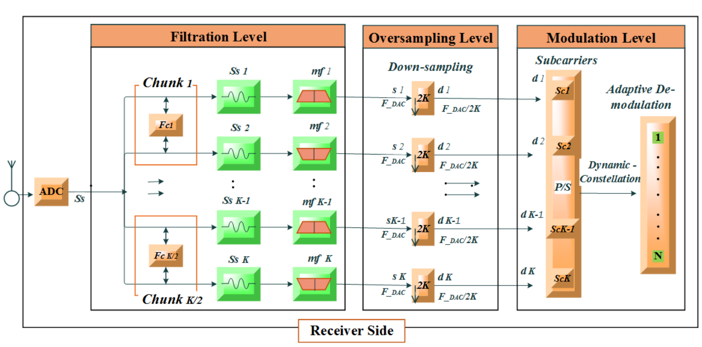

Fig. 2. Wireless reception system of the multi-carrier OGFDM.

processed at the Oversampling layer by down-sampling each employed subcarrier.

Eventually, at the Modulation level, after performing the de-normalization process, diffident shapes of modulation appear for the employed subcarriers. Thus, the adaptive demodulation system is utilized to convert dynamically the complex numbers into binary digits.

Mathematically speaking, the main components of the proposed multi-carrier system are expressed as follows:

On the transmitter side, where the Hilbert filters are utilized for the multi-carrier, the impulse responses of each h^{th} pair of shaping filters are represented as follows [16]:

$$\begin{aligned} sf_h^A(t) = g(t)\cos(2\pi fc_h t) \\ sf_h^B(t) = g(t)\sin(2\pi fc_h t) \end{aligned} \quad (1)$$

where fc_h signifies the frequency centre of the h^{th} Hilbert pair and, the superscripts A and B denote both the in-phase and quadrature phase of the orthogonal filter respectively.

In addition, the $g(t)$ indicates the baseband pulse which is demonstrated as follows [16]:

$$g(t) = \frac{\sin[\pi(1-\alpha)\gamma] + 4\alpha\gamma\cos[\pi(1+\alpha)\gamma]}{\pi\gamma[1-(4\alpha\gamma)^2]} \quad (2)$$

where $\gamma = t/\Delta t$, α indicates the BW excess of the filter and Δt refers to the sampling interval before the oversampling process.

At the receiver side, where the Hilbert filters are inversely employed for the multi-carrier, the impulse responses of each corresponding pair of the matching filters are expressed as follows [16]:

$$\begin{aligned} mf_h^A(t) = sf_h^A(-t) \\ mf_h^B(t) = sf_h^B(-t) \end{aligned} \quad (3)$$

To extract the intended signal, the convolution operation is performed between the shaping and matching filters as follows [16]:

$$sf_i^C(t) \otimes mf_j^D(t) = \left\{ \begin{array}{ll} \delta(t-t_0) & \text{if C = D and i = j} \\ 0 & \text{if C} \neq \text{D or i} \neq \text{j} \end{array} \right\} \quad (4)$$

where t_0 represents the potential delay time, the subscripts i and j state to the position of the fc, and the superscripts C and D refers either in-phase or quadrature-phase stage.

Presuming that the frequency sampling of both the ADC & DAC is identical, the fc allocation of each Hilbert pair in the multi-carrier system is specified as follows:

$$fc_h = (2h-1)(BW/K) \quad (5)$$

where, h represents the order of Hilbert pair and $BW = F_{(DAC/ADC)})/2$.

Due to the optimal selection of every utilized fc, the frequency responses of Hilbert filters are orthogonally accommodated and sequentially distributed in the spectral region of the available BW.

It's worth pointing that, the main problem that could be faced with the multi-carrier system is the intra-channel interference which essentially can degrade the system performance.

As a result, the relation between the frequency sampling of the employed subcarrier (Sub_S) and the roll-off (α) factor of the applied filter is significantly considered herein. The impact of these two key factors on allocated BW of the filter (F_{BW}) is expressed as follows [21]:

$$F_{BW} = Sub_S * (1+\alpha). \quad (6)$$

where 1 >= α >= 0.

To explain more about this, it is seen from Fig. 3 that with the typical oversampling ($OV = K$), the interference between filtered subcarriers is decided depending on the value of the roll-off. Thus, for the ideal case system (α =0), the allocated BW of each utilized filter is equal to the offered sampling rate of each employed subcarrier, hence, no interference occurs among adjacent filters.

On the other hand, for the worst situation (α =1), the occupied size of each applied filter is doubled resulting in increasing the interference dramatically. This, as a result, comes up with escalating the level of the BER, hence, decrease the capacity of the channel at the acceptable level of error.

To address this issue, as is clear from Fig. 4, the oversampling operation is reconfigured by doubling the number of generated copies for each employed subcarrier yet keeping the same allocation of fc.

It worth noting that, the free band spaces which are mainly created after doubling the OV can be considered as perfect

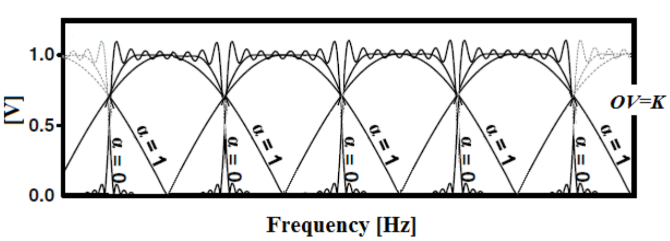

Fig. 3. Typical case (OV=K).

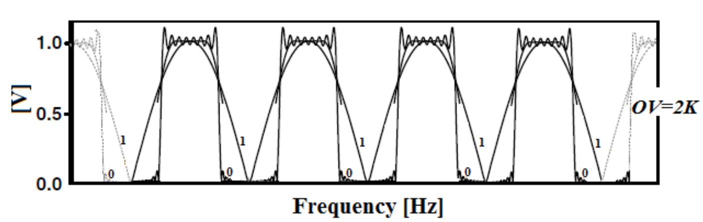

Fig. 4. Dual case (OV=2K).

guard areas for adjacent filters. Hence, free interference filters can be applied for the worst conditions.

However, according to Shannon's theorem [22], the channel capacity is reduced due to the BW reduction in comparison to the optimal α case of the typical oversampling. as follows:

$$Cap_{(Dual)} = (BW/2) * log_2(1 + SNR) \tag{7}$$

III. Experimental work

To demonstrate experimentally the performance characteristics in terms of the channel capacity and BER, a numerical simulation is extensively undertaken for the proposed multi-carrier OGFDM in the PHY of an electrical back-to-back wireless transmission system.

Unless explicitly stated, sixteen filtered subcarriers of frequencies ($K = 16$) are considered. Accordingly, the typical factor of oversampling ($OV = 16$) is applied. In addition, the α factor is initially fixed at its optimal value (α = 0.1). Besides, the most common modulation formats starting from the BPSK to the 256 QAM are employed adaptively.

As is seen from Fig. 5 and Fig. 6, the new system is essentially promoted from the single carrier to multi-carrier concept. Thus, an extra BW efficiency is achieved by developing the OGFDM spectrum from one fc to an arranged set of fcs.

Since the advanced Hilbert filters are orthogonally utilized with the multi-carrier OGFDM system, it is clear from Fig. 7 that a doubled channel capacity is obtained with the OGFDM in compare to the non-orthogonal GFDM. Thus, a stable 2 dB gain is reached between the channel capacity of the presented OGFDM and the GFDM with different modulation formats.

In addition, despite the dual amounts of transmission with the OGFDM, the level of calculated BER for the OGFDM under the AWGN is still quite identical for the GFDM, $BER = 10^{-3}$.

It's worth noting that, the main parameters of the applied filters are optimally controlled to ensure the best capacity of the channel at the acceptable level of the BER. Hence, factors like the taps number and α access can highly impact the overall system performance.

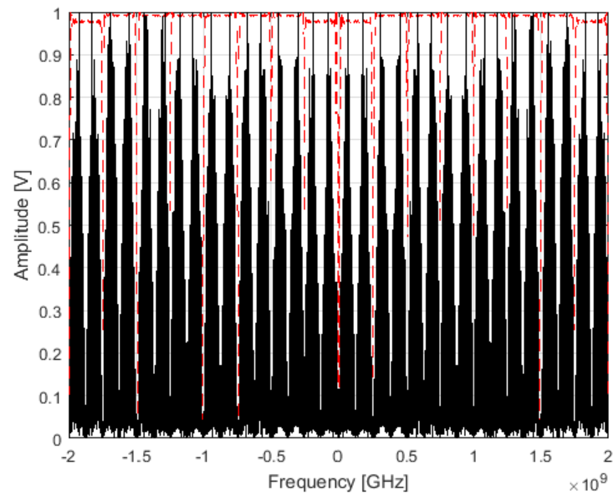

Fig. 6. The transmission spectrum of the multi-carrier OGFDM.

On the other hand, moving from the single carrier to the multi-carrier scheme comes up with introducing the induced interference between the adjacent filters of the applied subcarriers.

As is seen in Fig. 8, whenever the α parameter of the typical oversampling is expanded, the average rate of error is increased due to enlarged interference between adjacent filters of the same SNR. Hence, the BER of the same type of filters (In-phase / Out-phase) is extremely growing for raised grades of the α.

Consequently, with the poor conditions of the transmission ($1 >= \alpha >= 0.5$), the capacity of the wireless channel is collapsed significantly. Thus, the impact of the α factor shows a big variation for the acceptable limits of BER at the same

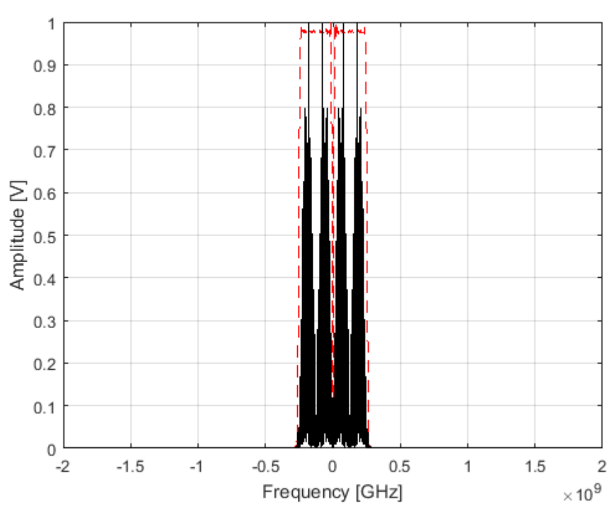

Fig. 5. The transmission spectrum of the single carrier OGFDM.

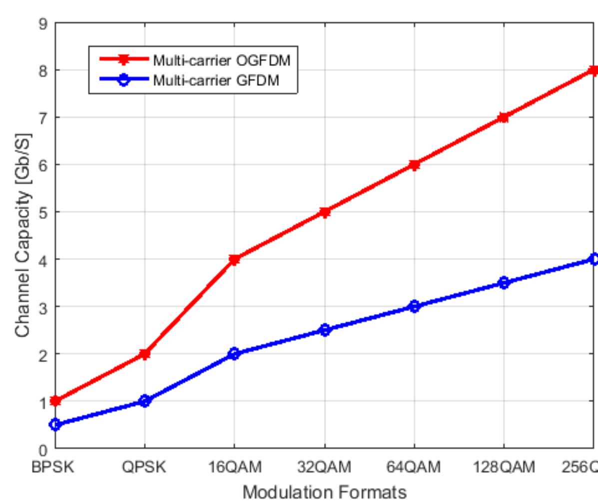

Fig. 7. Channel capacity of the multi-carrier OGFDM vs GFDM.

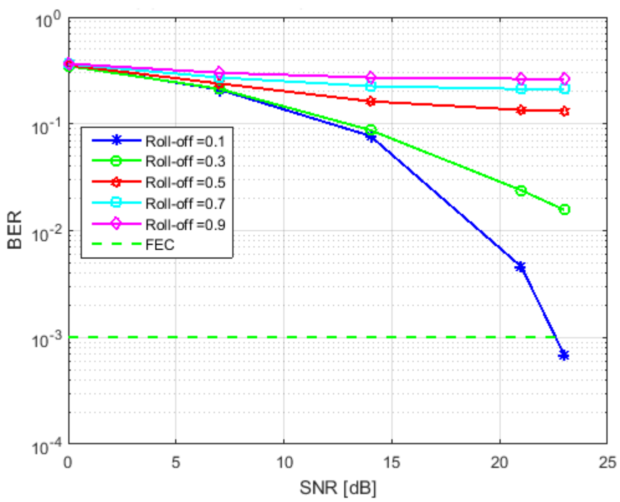

Fig. 8. The BER of variant roll-off factor with typical oversampling.

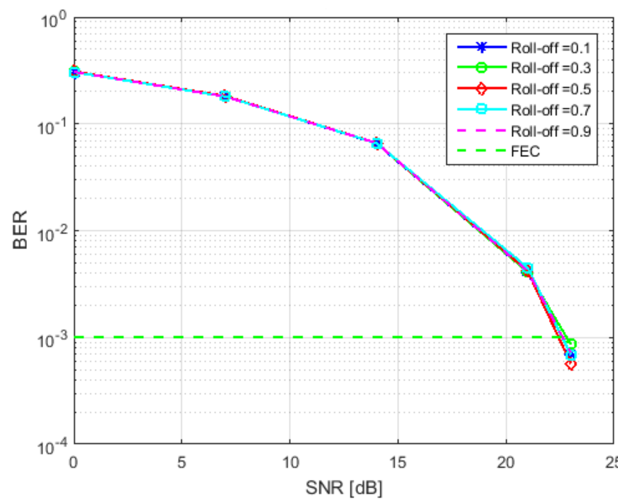

Fig. 9. The BER of variant roll-off factor with dual oversampling.

level of the SNR.

As a result, the maximum channel capacity of a received signal can be achieved only with the optimum value of the α (α =0.1), where the minimum degree of interference is gained.

To address this issue, a new oversampling manipulation is performed herein to remove the impact of the enlarged α factor among the adjacent filters. Hence, to avoid any probable intra-channel interference, a productive cooperation is achieved between the filtration and oversampling levels.

As is shown in Fig. 9, where the dual oversampling ($OV = 2K$) is utilized, the α influence at each similar level of the SNR is quite identical since the interference is avoided among the neighboring filters. Hence, the bad behaviour of the α is accommodated depending the new offered band intervals. Thus, regardless the value of α factor, a higher channel capacity is secured at accepted limits of errors.

Regarding the BW efficiency, it is clear from Fig. 10 that the calculated BW efficiency for the typical oversampling is taken firstly for the optimal value of α (α=0.1), where the maximum BW efficiency is achieved for the acceptable level of the SNR (SNR = 23 dB).

On the other hand, a sharp reduction of BW efficiency is recorded for the α equals to 0.5. Hence, using the typical case of oversampling, the system shows a severe fluctuation in the BW efficiency for different levels of the α.

For this reason, the dual oversampling is employed to demonstrate a steady level of the BW efficiency for both good (α =0.1) and bad (α=0.5) access of the α.

Moreover, since the obtained BW efficiency is decided by the two important factors (BW and SNR), around 10% extra improvement is achieved because of the improved level of the SNR. Hence, despite the halved spaces of the available BW due to the doubled oversampling with all α cases (good & bad), the BW efficiency is reduced by about 40% instead of 50% due to the avoided interference among the adjacent filters.

This, however, yet much better than the achieved BW efficiency of the typical oversampling with bad α values (α $>=$ 0.5), where the efficiency of the BW is decreased by about 85% due to the difficulty in dealing with the exaggerated interference among adjacent filters. That's mean, with the dual case, the achieved BW efficiency is about 60% against only 15% with the typical case. Hence, utilizing the dual oversampling, four times enhancement can be gained at the bad situations (α $>=$ 0.5).

Consequently, the dual case is more suitable for bad transmission circumstances than the typical one and vice-versa. Accordingly, neither dual oversampling nor typical one alone can come up with the optimal solution. Thus, a combination of both can be considered as an optimal processing to avoid any probable intra-channel interference for the future candidate waveform.

Regarding the adaptive modulation, it is clear from Fig. 11 that, the channel capacity of transmission is extra enhanced

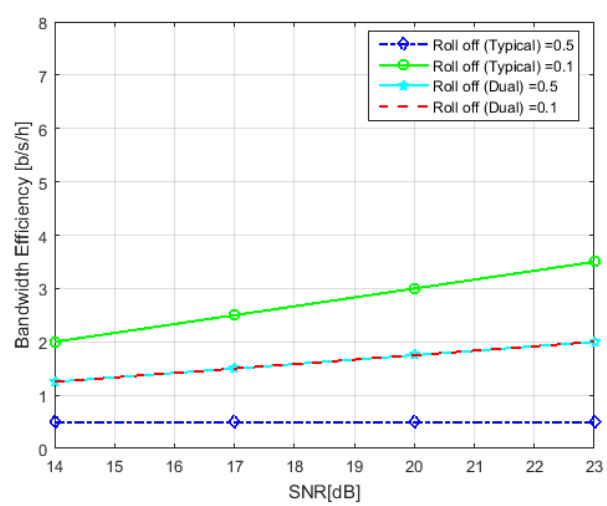

Fig. 10. BW efficiency of the multi-carrier OGFDM with typical and dual oversampling.

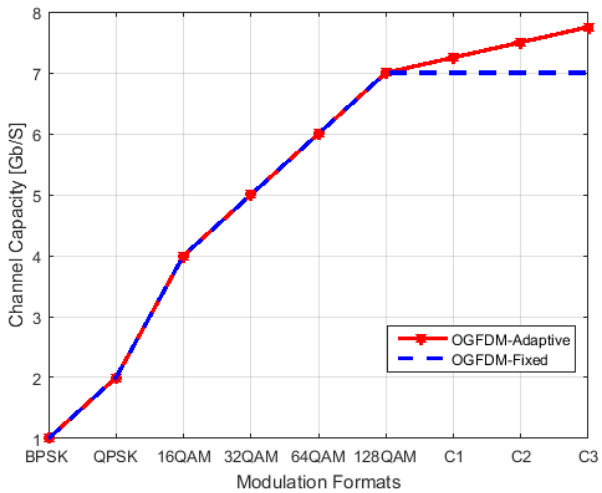

Fig. 11. Higher channel capacities (C1, C2, C3) of the multi-carrier OGFDM with the adaptive modulation than the fixed one.

in accordance with the improved channel condition. Hence, in contrast to the fixed modulation, the capacity of the channel can be maximized up to around 14% of its original obtained value. Thus, the raised level of the SNR gives a higher priority for improving the channel capacity of the adaptive OGFDM than the BER of the fixed system. As such, for any two adjacent shapes of the fixed modulation like the 128 and 256 QAM, a set of adaptive channel capacities, for example, (C1, C2, C3) can be achieved yet keeping the BER at the stable case (10^{-3}).

The key idea beyond this flexible modulation is the ability to bend to the real fading circumstances in comparison to the fixed scheme which is basically intended for the worst conditions. Thus, apart from the worst channel condition, the capacity performance of the adaptive system outweighs the capacity of the fixed system.

Ultimately, the main conditions of this investigated system are stated in Table I.

TABLE I. SYSTEM PARAMETERS OF MULTI-CARRIER OGFDM

Parameter	Value
No. of frequency centres	8
$F_{DAC/ADC}$	4 GHz
SNR	23 dB
α	0 - 1
System mode	Multi-carrier
Number of subcarriers	16
Filter-Length	32
Spectral efficiency BW	1Hz
Oversampling	Typical & Dual
Modulation Format	Fixed & Adaptive
OGFDM symbols	2000
Filter type	Hilbert filter

IV. CONCLUSION

In this paper, a new design of the OGFDM with the multi-carrier system has been proposed, explored and evaluated, for the first time. The introduced system with 16 subcarriers can extra provide a higher channel capacity, more data reliability, and better resource shareability than the single carrier OGFDM. The key principle beyond this developed multi-carrier scheme is utilizing the Hilbert filters for orthogonally multiplexing / de-multiplexing a group of frequency subcarriers. The overall performance (channel capacity, BER) of the multi-carrier system is investigated at the PHY of an electrical back-to-back transmission system. Functionally speaking, the introduced system is essentially divided into three main levels, the Filtration, Oversampling, and Modulation. Regarding the Filtration level, the findings show that utilizing the orthogonal filters, the channel capacity of the multi-carrier OGFDM is doubled achieving a 2 dB gain relative to the GFDM. In addition, the best channel capacity of the received signal is reached with the optimum value of α (α = 0.1) and SNR equals to 23 dB. On the other hand, with the poor conditions of the transmission ($\alpha >= 0.5$), the capacity of the wireless channel is severely collapsed at the typical oversampling mode (OV = 16). Regarding the Oversampling level, by adopting a doubled value of oversampling (OV = 32), the bad reaction of the increased α factor is accommodated perfectly. Hence, the overall channel capacity is improved regardless of the enlarged values of α ($0.5 <= \alpha <= 1$). However, comparing to the typical case, the capacity of the channel is reduced with the good values of α due to the narrowed BW at the dual oversampling mode. As a result, neither the typical nor the dual mode alone can be able to achieve the optimal channel capacity. Consequently, a combination of both can be applied for optimum system performance. Regarding the Modulation level, by employing the adaptive modulation, better channel capacities are achieved than the fixed modulation format. Thus, maximize the performance capacity of the wireless channel to about 14% without a fully move to a higher scheme of the fixed modulation. As such, an extra enhancement in the BW efficiency is gained yet keeping the BER at the acceptable level (10^{-3}). Such an experimental demonstration offers a good opportunity to validate the theoretical part of the multi-carrier OGFDM model.

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