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Development of a GFDM waveform with radio defined with software

Desarrollo de una forma de onda GFDM con radio definida por software

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ABSTRACT

In this paper the performance of a Generalized Frequency Division Multiplexing waveform is evaluated when compared to an Orthogonal Frequency Division Multiplexing signal. For the development of the previous waveforms, the GNU radio software and the Software Defined Radio (SDR) equipment USRP N210 are used. Through a spectrum analyzer the power of both waveforms are measured and the Out-of-Band Radiation is analyzed. Then, the results obtained are compared and the advantages and disadvantages of the implementation of GFDM as a waveform within the fifth generation systems are exposed.

RESUMEN:

En este documento se evalúa el desempeño de una forma de onda GFDM (Generalized Frequency Division Multiplexing) que es comparada con una señal OFDM (Orthogonal Frequency Division Multiplexing). Para el desarrollo de las anteriores formas de onda se utilizan el software GNU radio y los equipos de Radio Definida por Software (SDR) USRP N210. Mediante un analizador de espectros se mide la potencia de ambas formas de onda y se analiza la Radiación Fuera de Banda (OOB). Luego, se comparan los resultados obtenidos y se exponen las ventajas e inconvenientes de la implementación de GFDM como forma de onda dentro de los sistemas de quinta generación.

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1. Introduction

Currently the communications systems are in an evolution stage towards the fifth generation networks (5G) [1]; this is because of the quantity of users and mobile devices are in constant growth. Besides some of the new applications and services raised by IoT (*Internet of Things*) [2-3] demand that the communications are transformed at URLLC (*Ultra-Reliable Low-Latency Communications*) systems [4-5], providing shorter time responses that the offered by 4G networks nowadays [6]. It's for this reason that it is make fundamental to choose a waveform that offer high performance in terms of spectral efficiency (SE), latency, transmission rate and energy consumption in order to achieve the implementation of next generation systems, [7].

OFDM is the waveform employed for the 4G today because it provides transmission rates that cover adequately the requirements raised by the services rendered in this generation [8], without use an excessive computational complexity [7]. Likewise, it has been widely used in digital television and different technologies like WIMAX, WIFI, and LTE among other [9-12]. However, OFDM has many problems that do not allow it to be a waveform candidate for the 5G systems, [8]. One of them is that it owns a high PAPR (*Peak to Average Power Ratio*) that results in inefficient power use, as well as out of band emissions that do not allow to achieve an optimum spectrum use.

For the above, to use in a better way the radioelectric spectrum one of the proposals it's to implement GFDM on the 5G networks [13] which differs from OFDM because it doesn't consist in an orthogonal carriers system but it is based in a block multi-carrier scheme [14] that allows to transmit several symbols for each sub-carrier achieving thus increase the transmission rate.

Equally, OFDM allow to improve the spectral efficiency, reduce the PAPR, decrease the OoB radiation and belittle BER (*Bit Error Rate*) [15], since it utilized a RRC (*Root Raised Cosine*) or RC (*Raised Cosine*) filter in each sub-carrier [14]. Also GFDM gathers characteristics that would allow it to be compatible with technologies of spectrum dynamic access as cognitive radio [16].

In consequence, the implementation of these communication systems require to use specialized and expensive equipment. However, thanks to SDR is possible made and test the different wave types and technologies using the same hardware, and it has become in an excellent alternative due to its versatility [17-18]. Which has allowed it to perform tests in FM, DVB-T, WLAN, GSM, and LTE, among others [19-22].

As indicated above, the applications that have been made using software-defined radio equipment consist of the implementation of proposals for the next generation of digital terrestrial television systems ISDB-TB using the FBMC modulation (*Filter Bank Multi-Carrier*) [23]; In addition, some models have been designed to improve existing modulation schemes, such as the validation of 16-CQAM (Cantor Quadrature Amplitude Modulation) with SDR [24]; it has also been possible to implement spectrum access efficiently using cognitive radio networks [25-26]; and even tests have been made with arrangements of intelligent antennas to direct the radiation pattern towards a specific point or a signal of interest (SOI), [27].

The structure of this article is as follows: First, it is explained the GFDM including OoB radiation meaning and they are exposed some proposals to solve the OoB emissions problem; later the materials are described, elements and equipment employed to generate the waveforms as well as the instrumentation that it has been taken in measuring of the data that was analyzed; Then, it is described the process to test GFDM an OFDM systems; After, it is explained and discussed the results obtained; and finally the conclusions are exposed.

2. Out of Band radiation and GFDM

A large number of multi-carrier schemes have been proposed to replace OFDM, which is the waveform used by various communication systems today. [28-29], because this is affected by phenomena such as the high ratio of PAPR [30] that introduces very high power hops with respect to the average power value that the system can deliver, causing degradation in the performance of the transmitter when the signal passes through a non-linear power amplifier [31]. Although in the domain of the OFDM frequency it shows a uniform spectrum of power, observing its waveform in the time domain gives an unstable signal [32].

Although PAPR is a major problem in OFDM, Out-of-Band emissions become the most marked problem presented in this modulation scheme, and this reason turns out to be one of the greatest challenges in the implementation of the new generation systems.

[4] Frequency Modulation. [5] Digital Video Broadcasting – Terrestrial. [6] Wireless Local Area Network. [7] Global System for Mobile communications.
[8] Long Term Evolution.

2.1. *Out of Band Emissions (OOBE)*

The phenomenon of Out-of-Band radiation is generated within systems that employ OFDM [33], because components such as power amplifiers distort the signal causing unwanted radiation that results in the creation of side lobes at the ends of the assigned band.

Therefore, to mitigate this phenomenon, various techniques have been used that aim to reduce interference on adjacent bands, [34]. One of them is the use of guard spaces on both sides of the transmission channel in order to attenuate the radiation on neighboring channels. Although this methodology greatly reduces OOBE in the adjacent bands, it reduces the spectral efficiency considerably since in these guard bands no information is sent and for this reason this spectrum is wasted. In the case of LTE systems, it is estimated that the value of the guard interval is 10% of the bandwidth assigned to the transmission channel [35-36].

On the other side, the carrier cancellation technique allows to reduce the side lobes product of unwanted emissions in the adjacent bands by using a specific number of carriers to transmit, and assign the unused ones to the end of the transmission channel and in this way reduce radiation in adjacent bands [34]. This type of methods has been modeled for WiMAX technology and MIMO-OFDM systems (*Multiple Input – Multiple Output*) [37], but its implementation decreases the SE.

Likewise, another of the proposed schemes to solve the problem of OOB radiation is to apply a spectral conformation filter in the time domain. One of the advantages of this technique is that the spectral efficiency may increase depending on its implementation, but it results in an increase in the PAPR [34] which is another of the great disadvantages of OFDM and has been explained previously.

On the one hand, the use of analog filtering, in combination with digital pre-distortion in the frequency domain, reduces OoB radiation within Multi-User MIMO systems (MU-MIMO) but degrades the signal to interference, noise and distortion (SINDR), which results in a considerable deterioration in the BER, [38].

2.2 *Model of a GFDM system*

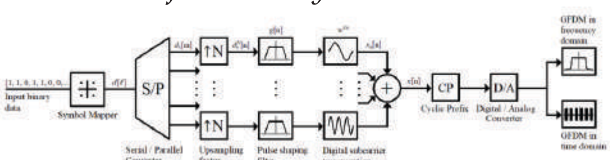

Figure 1. Model of a GFDM system. Source: own, based in [41].

On the other hand, GFDM is based on the modulation of independent blocks, where each block contains a number of subcarriers and sub-symbols. To achieve the transmission of information using this type of systems, the process described in Figure 1 is performed.

Initially, information data are available in binary form; these are modulated in QAM (*Quadrature Amplitude Modulation*) to obtain the symbols that can be mapped in a constellation diagram. The resulting symbols are expressed in a complex way; in Figure 1, the symbol flow is denoted by $d[\ell]$, where $\ell = 0, 1, 2, 3 \ldots K-1$. Where $d[\ell] \in \mathbb{C}$ and K is the number of subcarriers that transmit information (active sub-carriers). The resulting flow of symbols passes through a Series - Parallel converter. As a result of this process we have a matrix, expressed in (1).

$$d_k[m] = \begin{bmatrix} d_0[0] & \cdots & d_0[M-1] \\ \vdots & \ddots & \vdots \\ d_{K-1}[0] & \cdots & d_{K-1}[K-1] \end{bmatrix} \tag{1}$$

Here, M is the number of sub-symbols and K is the number of sub-carriers. After, the symbols of each sub-carrier enter to an up-sampling process [39], to get the sequence that show the equation (2).

$$d_k^N[n] = \sum_{m=0}^{M-1} d_k[m]\delta[n-mN] \tag{2}$$

In (2) it can be seen that the Dirac delta function is applied to the symbols of each subcarrier ($\delta[\ \ ]$) [40], responsible for raising the sampling rate N times, obtaining in this way a plot of length MN in the *k-th* sub-carrier, [41]. Subsequently a pulse shaping filter is used for each of the sequences obtained after increasing the sampling; the objective of these filters is to minimize Out-of-Band emissions in the resulting waveform at the output of the GFDM system [42]; the pulse shaping filter is a sequence of size n just like the frame that contains the data information, [43]. To apply the filter to each of the data sequences, circular convolution is used, as illustrated in (3).

$$(d_k^N \circledast g)[n] \tag{3}$$

The data obtained in this stage is made a frequency shift by applying a digital subcarrier converter, denoted in figure 1 as $w^{kn} = e^{j\frac{2\pi}{N}kn}$ so that each GFDM subcarrier signal is spaced in the frequency domain; the equation (4) describes each of these subcarriers:

$$x_k[n] = (d_k^N \circledast g)[n] * w^{kn} \quad (4)$$

In order to obtain the GFDM waveform to be transmitted, all the signals generated from the digital subcarrier converters are added, as shown in (5).

$$x[n] = \sum_{k=0}^{K-1} x_k[n] \quad (5)$$

After obtaining the GFDM waveform, a cyclic prefix (CP) is added for each modulated block - instead of in each symbol as in OFDM - with the objective of minimizing inter-symbol interferences (ISI) and making the system, [44]. Finally, the modulated signal is passed through a Digital-Analog converter in order to be transmitted through the physical layer of the system used.

3. Materials and methods

To implement the systems and perform the measurements to be evaluated, laboratory equipment is required both to generate the waveforms that are being studied and the instrumentation that helps to capture the data that will be analyzed. Next, the methodology and resources used in the present investigation are mentioned.

As a matter of fact, the structure of the elements that are used to generate the OFDM and GFDM waveforms in order to perform the pertinent measurements to be evaluated are shown in Figure 2.

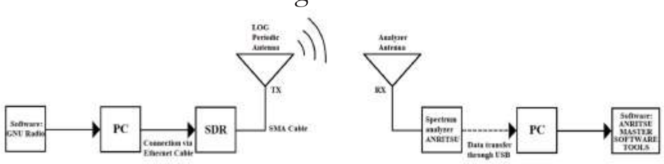

Figure 2. Block structure for measurements of the OFDM and GFDM waveforms. Source: own.

In Figure 2, it can be seen that the parameters to adjust to be able to model the signals to be transmitted originate from the programming made in "GNU Radio" - whose program description is found in Table 1; To be able to perform the proper programming using GFDM, external libraries must be used that are downloaded independently [45]. GNU Radio uses the resources of a computer to establish a connection with Software-Defined Radio equipment through the Ethernet ports (the Gigabit-Ethernet standard is more specifically used because the radio equipment handles this standard); through the radio device the transmission of the signal generated using a Periodic Log antenna is made.

However, the waveform transmitted by the SDR equipment is received by the spectrum analyzer which, during a time interval, will record the received power values in a previously adjusted frequency range, allowing to observe in detail both the waveform that is commissioned of transmitting the data as the Out-of-Band radiation that is generated in terms of the type of modulation used. This data is stored and transported to a computer through a USB memory to be analyzed in detail in the "Anritsu Master Software Tools" program, described in Table 1.

3.1. *Software Defined Radio (SDR)*

The operation of these equipment consists of carrying out the signal processing through a computer program to then make use of the hardware present in these devices, in this way it allows generating the waveforms that it is desired to transmit and in addition it can be capable of demodulating the information received [17]. A specific example of Software-Defined Radio is the USRP (Universal Software Radio Peripheral) designed by the company Ettus Research, the USRP N210 devices are the ones used in the present work to adequately generate the OFDM and GFDM waveforms.

3.2. *Elements used*

The elements used are shown in Table 1, it illustrates the OFDM and GFDM systems studied and implemented in this work, in order to be developed in an appropriate manner.

Figure 3, illustrates the arrangement of the equipment that was used to generate the OFDM and GFDM signals using all the elements described in Table 1, in addition to taking into account the structure described in the blocks of Figure 2.

ELEMENT	DESCRIPTION
Antenas LP410:	Log Periodic antenna that operate in a frequency range of 400 MHz to 1 GHz and gain of 5 - 6 dBi, [46].
USRP N210:	This equipment allows to process signals with frequency ranging from DC to 6 GHz, has expansion ports for additional cards and ports to synchronize with multiple USRPs, [46].
Cable SMA-SMA [47]:	It allows to connect the Periodic Log antenna with the USRP equipment, it has minimum losses up to a frequency of 6 GHz, [46].
Anritsu MS2721B:	Spectrum analyzer that operates up to a frequency of 7.1 GHz, ideal for spectrum analysis of wireless digital signals such as mobile networks and digital video signal testing, [48].
Anritsu Master Software Tools:	Program that allows to see in detail the data caught in the Anritsu spectrum analyzer, it can also illustrate measurements in the frequency domain and see the spectrogram taken in a range of frequencies during a certain interval of time, [48].

Table . Materials and tools utilized. Source: own.

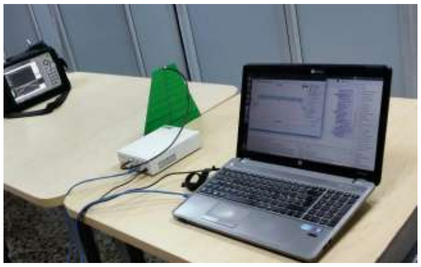

Figure 3. Arrangement of laboratory equipment to perform the measurements of the evaluated waveforms. Source: own.

To perform the behavior analysis in each of the waveforms to be studied (GFDM and OFDM), the initial parameters are adjusted according to Table 2.

PARAMETER	GFDM	OFDM
FFT length	128	128
Active Sub-Carriers (#)	110	110
Number of Sub-Symbols (#)	9	1
Cyclic Prefix length (CP)	64	32
Cyclic Suffix length (CS)	16	N/A
Frequency (MHz)	670	670
Total Band (MHz)	654.655 - 675.378	654.655 - 675.378
Band Width (MHz)	10.723	10.723
Antenna Gain (dBi)	5	5

Table 2. Initial Parameters. Source: own.

4. Results

In this chapter, it is analyzed the data that was obtained from the measurements made to each of the waveforms taking into account that OFDM and GFDM must be comparable according to the initial parameters seen in the Table 2.

In addition, Figure 4 shows the result of the measurement taken, corresponding to the spectral representation of an OFDM signal; the data taken includes a range of frequencies ranging from 653.5 MHz to 686.5 MHz, you can see the power levels in both the frequency domain and a spectrogram.

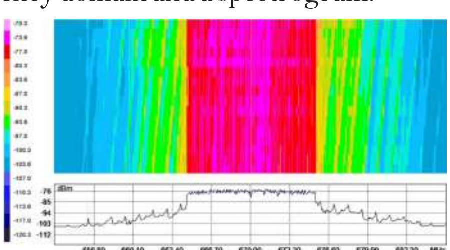

Figure 4. OFDM Spectrogram. Source: own.

At the same way, the representation for GFDM is illustrated in Figure 5.

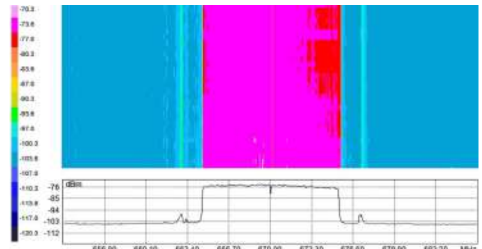

Figure 5. GFDM spectrogram. Source: own.

In systems that transmit multiple carriers the OOBE starts at the ends of the necessary band (B_N) and it extends up to 250% of the bandwidth necessary to carry out the transmission in both limits of B_N, as shown in Figure 6. The radiations that are found after 250% of B_N they are known as spurious emissions, [50].

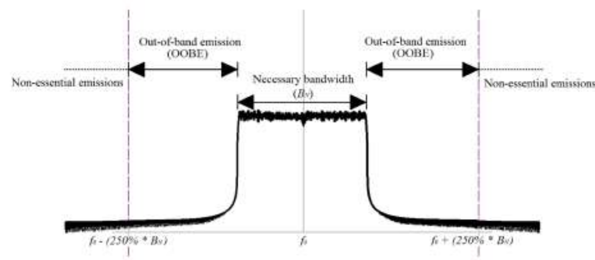

Figure 6. Out-of-Band radiation domain of 250% (2.5 times the necessary bandwidth) and non-essential emissions (general meaning). Source: own.

However, according to [51] a transmission in which the central frequency $(F_0)$is in the frequency range of 30 MHZ $<F_0<$1 GHz and in which the $B_N$is greater than 10 MHz, OOBE is extend until 1,5 B_N+ 10 MHz, as indicated in Figure 7.

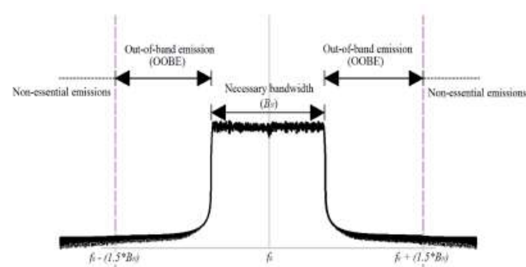

Figure 7. Out-of-Band radiation domain and non-essential emissions with "30 MHZ $<f_{0<}$1 GHz" y "B_N>10MHz". Source: own.

Once the power values are obtained, they are converted to units of power spectral density (PSD) using (6), in order to perform the respective analysis.

$$PSD_{(dBm/Hz)} = P_{dBm} - 10\log(BW_{Hz}) \qquad (6)$$

Then, a comparison between GFDM and OFDM is made in terms of the power spectral density as shown in Figure 8.

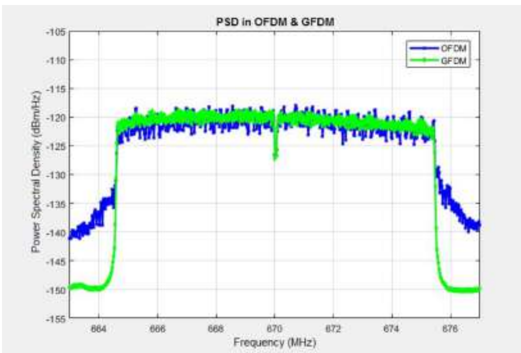

Figure 8. Comparison of the Power Spectral Density between a GFDM and OFDM signal. Source: own**.**

Figure 8, shows that the GFDM signal concentrates almost all of the power within the necessary bandwidth for transmission. In contrast, lateral lobes are generated in OFDM at both ends of the bandwidth necessary for transmission.

4.1 Case 1

To compare the results obtained, the first case compares the Out-of-Band radiation between GFDM and OFDM, assuming that a guard band of 10% is used, as stipulated in [35] and taking into account that the bandwidth allocated for the transmission is 10,723 MHz, the Figure 9 shows the results of the comparison.

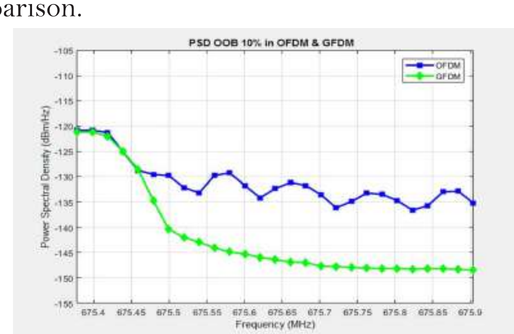

Figure 9. PSD comparison for 10% of the Out-of-Band domain between GFDM and OFDM.Source: own.

Table 3, shows the results obtained for power and spectral power density for OFDM and GFDM.

PARAMETER	GFDM	OFDM
Edge Sub-Carrier power (dBm)	-76,4093332	-76,0746085
OOB power 10% (dBm)	-103,66703	-90,4387824
PSD OOB 10% (dBm/Hz)	-121,180546	-120,845821
PSD edge Sub-Carrier (dBm/Hz)	-148,438243	-135,209995

Table 3. Power and PSD results in 10% of the Out-of-Band domain. Source: own.

When performing the analysis of the results shown in Table 3, it is possible to say that GFDM presents a reduction of 27.25 dBm/Hz with respect to the PSD in the last Sub-Carrier, while in OFDM there is a reduction of only 14.36 dBm/Hz.

4.2 Case 2

In the second case, both waveforms are compared to determine the bandwidth of the OOB emission, taking in consideration that a noise floor is -104 dBm.

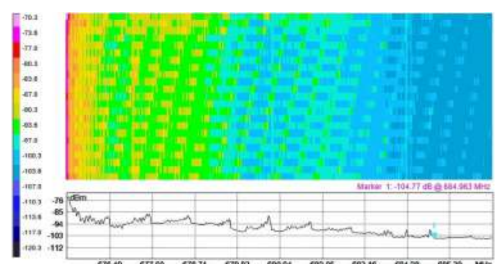

Figure 10. Out-of-Band spectrum in OFDM. Source: own.

Figure 10, shows the extent to which the out of band domain of an OFDM signal arrives, evidencing that it reaches a frequency of 684.963 MHz. Taking into account that the extreme frequency of the assigned band is 675.378 MHz, it can be deduced that the OOBE in OFDM occupies a bandwidth of 9.58 MHz, the Figure 11 shows the GFDM OOB.

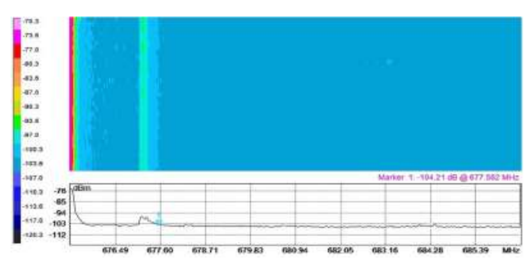

Figure 11. Out-of-Band spectrum in GFDM. Source: own.

According to Figure 11, it can be said that the Out-of-Band domain of a GFDM signal has a value of 2.18 MHz, which indicates a reduction of about a quarter of the bandwidth domain with respect to the OFDM signal.

4.3 Case 3

The amount of power spectral density that concentrates GFDM with respect to OFDM is analyzed. Another point is that Figure 12 presents the percentage of PSD that manages to concentrate GFDM and OFDM within the necessary bandwidth.

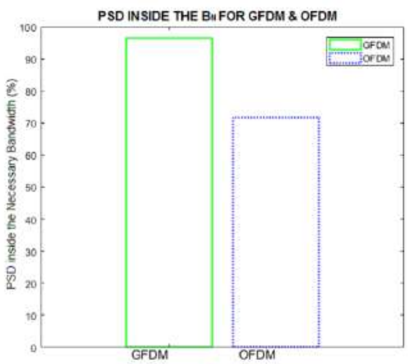

Figure 12. Concentrated PSD percentage within the bandwidth required for a GFDM and OFDM signal. Source: own.

As it can be seen in Figure 12, GFDM manages to concentrate 96.46% of its PSD within the width of

5. Conclusions

Based on the results obtained, it is possible to say that GFDM can perfectly become the waveform used by 5G systems, because it is capable of concentrating 24.72% more of the PSD within the bandwidth of the frequency necessary to transmit the information in relation to OFDM. In addition, it manages to reduce emissions in the Out-of-Band domain with respect to OFDM by 77.24%. For this reason, in the future the use of guard bands in wireless communication systems can be considerably reduced, thus increasing the spectral efficiency.

Thanks to the GFDM waveform allows the reduction of Out-of-Band radiation, it is possible to transmit more information through a channel adding more subcarriers, therefore GFDM would also allow a reassignment of frequencies where the bands used commercially are closer one of the another minimizing interference problem.

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