SC-FDMA Waveform Enabling Frequency Holes in a Shared Spectrum Context

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***Abstract*—Single-Carrier Frequency Division Multiple Access (SC-FDMA) is a well suited waveform for satellite link thanks to its low Peak-to-Average Power Ratio (PAPR) level, compared to Orthogonal Frequency Division Multiple Access (OFDMA). Moreover, it allows a frequency access which is very attractive given the growing interest in integrated satellite-terrestrial system and dynamic use of the spectrum. The purpose of this article is to prove that doing frequency holes to enable the dynamic use of the spectrum don't degrade so much waveform envelope fluctuations while enabling efficient transmission.**

***Keywords*— shared spectrum; integrated satellite terrestrial system; OFDM; SC-FDMA; (EW)-SC-FDMA; satellite payload impairments; carrier to intermodulation ratio.**

I. INTRODUCTION

For spectral resource optimization in a dynamic spectral resource sharing context, a waveform which seems to be promising for the satellite is the Single-Carrier Frequency Division Multiple Access (SC-FDMA). Its interest has already been demonstrated in the Digital Video Broadcasting (DVB) - Next Generation broadcasting system to Handheld (NGH) [1] standardization process in an S-band mobile system. This waveform is also recommended in an International Telecommunication Union (ITU) working group [5] for satellite International Mobile Telecommunications-Advanced (IMT-advanced) systems. More recently, interest of this waveform raised in European Telecommunications Standards Institute - Satellite Communication and Navigation (ETSI-SCN) and DVB - Second Generation Satellite Extensions (S2x) standardization process applicable to higher frequency bands (Ku, Ka).

Besides, the 5G Infrastructure Public-Private Partnership (5G PPP) consortium [6] targets for new systems a dynamic sharing of existing frequency bands (Cognitive Radio) and the emergence of integrated satellite terrestrial systems. Integration of satellite will allow delivering 5G services in areas of low population density and to ensure communications everywhere in case of a disaster.

Multi-carrier waveform is not the historical waveform used on satellites. But, as European Union is promoting through incoming 5G the integration of satellite and terrestrial components [6], paradigm is currently being modified. Indeed, to make easier spectrum scalability, satellite should be able to choose sub-bands it uses depending on existing terrestrial systems. Moreover, in the case of integrated systems specifically, to encourage mass market terminal deployment, terminal should be able to receive the satellite signal or terrestrial one with the same chipset. This emphasizes the need for satellite to use a multi-carrier granular access, as it is already the case in terrestrial systems. If Orthogonal Frequency Division Multiple Access (OFDMA) first appears as obvious solution, it should be mentioned that this waveform has a high crest factor, which does not allow optimizing the efficiency of satellite amplifiers. An intermediate solution is the use of SC-FDMA, keeping the granular access in frequency, but severely limiting the envelope fluctuations, it becomes even more attractive to the satellite. This is why this waveform has been chosen here to address this problem.

One example of such integrated system (the spectrum of the terrestrial and satellite components is managed by the same company) is given hereafter. It provides a service to nomadic or mobile devices. To optimize the spectrum use according to the traffic, the scheduler decides if a part of the band is allocated to either satellite component or terrestrial one, as it is depicted in Figure 1.

In section II, description of the waveform enabling frequency holes is done. In section III, satellite payload impairments are discussed and then in section IV, methodology used to analyze results obtained is introduced. Finally, in section V, simulations results are presented, comparing OFDMA, SC-FDMA and Extended-and-Weighted SC-FDMA (EW-SC-FDMA) performances over non-linear channel, and considering frequency holes.

II. SC-FDMA WAVEFORM MODELIZATION WITH FREQUENCY HOLES

A. Basic SC-FDMA modeling

Because there have been several studies on SC-FDMA waveform [3][4], modeling will not be strictly detailed. However, differences with OFDMA transceiver architecture will be emphasized. General SC-FDMA transceiver is summarized in Figure 3, and is described hereafter.

Firstly, interleaved and coded bits b_n are mapped into symbols c_i, $i \in [0 \dots M-1]$. Spreading operation, specific to SC-FDMA transmission, is then done by applying an M–Discrete Fourier Transform (DFT) to the c_i symbols to get C_k symbols, $k \in [-\frac{M}{2} \dots \frac{M}{2}-1]$:

$$C_k = \frac{1}{\sqrt{M}} \sum_{i=0}^{i=M-1} c_i \, e^{-j\frac{2\pi ki}{M}}. \quad (1)$$

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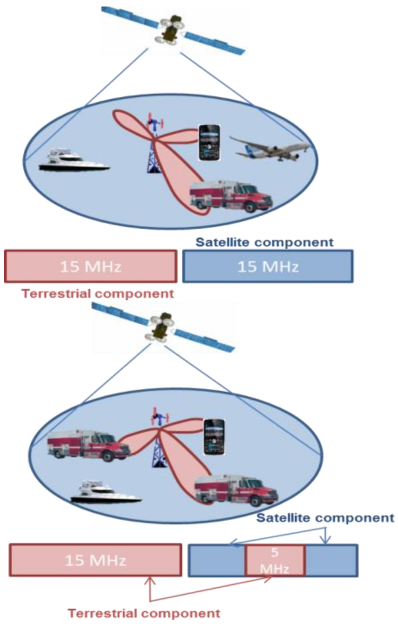

Figure 1. Example of integrated system managing efficiently its spectrum.

In case of Extended-and-Weighted SC-FDMA (EW-SC-FDMA), as it can be seen in Figure 2, some of the edge C_k symbols are duplicated and put at the opposite side edge in the guard band. Main sizing parameter here is α, called the roll off factor. Extension process outputs M', equals to (1+α)M, complex symbols $C_{k'}$. Weighting process is finally applied over these subcarriers in order to have a square root raised cosine shaping [3]. It multiplies term by term $H_{SRC}(k')$ with $C_{k'}$ to get $S_{k'}$. Note that $H_{SRC}(k')$, $k' \in \left[-\frac{M'}{2}; +\frac{M'}{2}-1\right]$, is the frequency response of the square root raised cosine filter, given by:

$$H_{SRC}(k') = \begin{cases} 1, & 0 \leq |k'| < \frac{(1-\alpha)}{2}M \\ \cos\left[\frac{\pi}{2\alpha M}\left(|k'| - \frac{(1-\alpha)}{2}M\right)\right], & \frac{(1-\alpha)}{2}M \leq |k'| < \frac{(1+\alpha)}{2}M \end{cases} \quad (2)$$

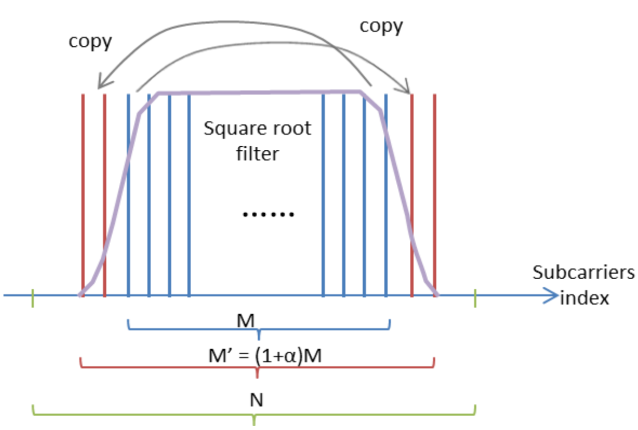

Figure 2. Extension and weighting process.

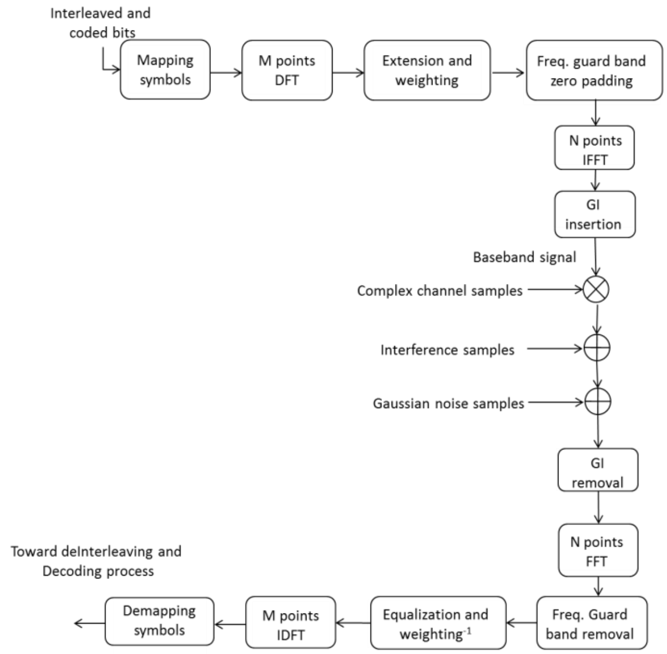

Figure 3. SC-FDMA transceiver architecture

It can be pointed out that when α equals to 0, process is strictly equivalent to SC-FDMA process. Next, unused subcarriers in the guard band are filled by zero, exactly N - (1+α)M, to get a vector owning N complex symbols, $S_{k''}$. Note that to be compliant with OFDMA process, N should be a power of 2, that is not the case for M. Lastly, OFDMA modulation process can be done by applying a N-Inverse Fast Fourier Transform (IFFT) and inserting guard interval, getting baseband signal s_n.

For receiver considerations, the equalization should use a Minimum Mean Square Error (MMSE) frequency domain algorithm [3][4], working subcarrier by subcarrier. Furthermore, a slightly difference which can be observed with SC-FDMA receiver compared to OFDMA one, is the way to compute the Log Likelihood Ratio (LLR) metrics at the demapping symbols step. Classic LLR formulation is reminded here:

$$LLR(b_i) = ln \frac{\sum_{x \in c_i^1} exp\left(-\frac{|I-\rho_I I_x|^2 + |Q-\rho_Q Q_x|^2}{2\sigma^2}\right)}{\sum_{x \in c_i^0} exp\left(-\frac{|I-\rho_I I_x|^2 + |Q-\rho_Q Q_x|^2}{2\sigma^2}\right)}, \quad (3)$$

where x is a symbol of the Quadrature amplitude modulation (QAM) constellation, c_i^j represents the symbols of the constellation carrying the bit b_i when b_i is equal to j, I and Q are the in phase and quadrature components of the received signal, $\rho_{I/Q}$ is the fading on the I or Q component, $2\sigma^2$ is the Additive White Gaussian Noise (AWGN) variance, I_x and Q_x denote the reference symbols of the QAM constellation. In SC-FDMA receiver, because of the despreading process, i.e., there is a M points Inverse-DFT between equalization and demapping process, it is assumed that $\rho_{I/Q}$ can be

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approximated to the mean square of the frequency channel response of the corresponding OFDMA symbol over the active subcarriers $H_c(k')$:

$$\rho_{I/Q} \approx \sqrt{\frac{\sum_{k'=-M'/2}^{k'=\frac{M'}{2}-1} |H_C(k').H_{SRC}(k')|^2}{M}}. \quad (4)$$

B. *Frequency holes insertion*

Frequency holes are inserted inside useful signal at the spreading process level. In fact, spreading applies a L<M DFT over the incoming c_i symbols before filling M-L other symbols with zero, as it is drawn in Figure 4.

Some vocabulary is necessary to define where frequency hole is located. β is defined as the relative bandwidth occupied by frequency holes over maximum achievable useful bandwidth:

$$\beta = \frac{M-L}{M}. \quad (5)$$

Δ is the relative shift of the frequency hole center relatively to the bandwidth center. To clarify these notations, an example is given in Figure 5.

C. *Interference model*

The interferer location is defined as it is done for the frequency holes, with β and Δ parameters. Generative model is quite simple: complex symbols are generated according to a normal law $\mathcal{N}(0;\beta)$, supposing power of the useful signal as unitary power when occupying all possible subcarriers. Interference symbols are applied to subcarriers as if it was an OFDMA signal. When frequency holes are defined, interference is added exactly at the hole location.

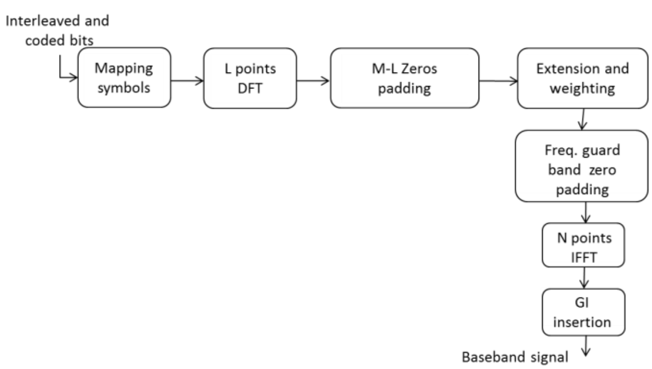

Figure 4. SC-FDMA transceiver architecture enabling frequency holes

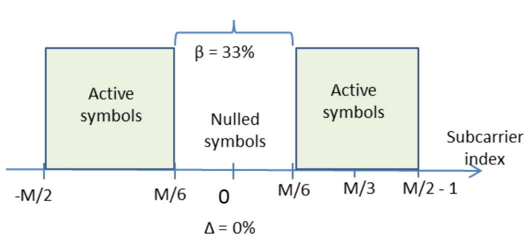

Figure 5. Position and size example of a frequency hole

III. SATELLITE PAYLOAD IMPAIRMENTS

In the literature, satellite payload impairments models usually include three main origins: nonlinear amplifier, selective input filters and phase noise [2]. For the current work, it is assumed that only non-linearity effects are considered. Phase noise is not considered because it is well known that effect is very weak over a Quadrature Phase Shift Keying (QPSK) modulation combined with current stability specifications over satellite local oscillators. Input filters distortion may have an effect over the performances, but as the three studied waveforms (OFDMA, SC-FDMA, EW-SC-FDMA) have a subcarrier equalization process, it can be predicted that the effect would be quite closed to each other, while not negligible. This is the reason why it was decided to focus on non-linearity effects only, knowing there are envelope fluctuations differences between waveforms. A typical un-linearized model is chosen, giving Output Back Off (OBO) [dB] as a function of Input Back Off (IBO) [dB], and giving phase slope Kp [degrees/dB] as a function of IBO:

$$\text{OBO} = \sqrt{U} - \sqrt{U + V.IBO^2}, \quad (6)$$

$$Kp = \begin{cases} 0 \; when \; IBO \in [-\infty; -15\,dB] \\ 0.2 \; when \; IBO \in]-15\,dB; -9\,dB], \\ 2 \; when \; IBO \in]-9\,dB; +5\,dB] \end{cases} \quad (7)$$

Where U=24.29 and V=1.28. Typical representation is given in Figure 6.

Nonlinear conversion is applied to complex baseband signal as a look-up table, before entering to propagation channel process, as it is shown in Figure 7.

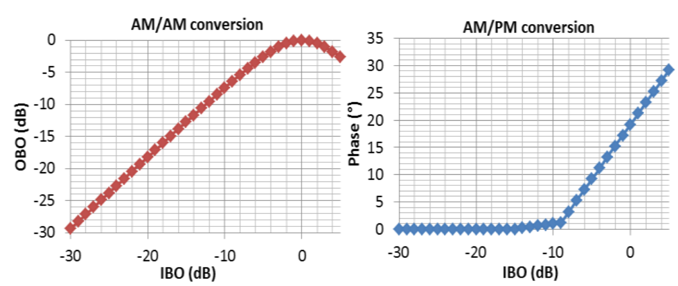

Figure 6. Non linearity conversion curve

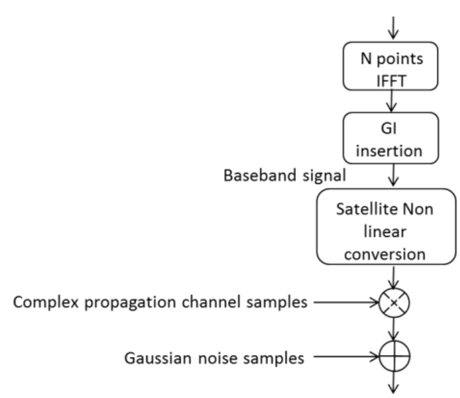

Figure 7. Insertion of non-linearity conversion in the transceiver

Note that the output of the satellite non-linear block delivers unitary power.

IV. COMPARATIVE METHOD ANALYSIS

We are about to compare different waveforms enabling creation of a frequency hole inside their spectrum. Here is proposed a method to compare waveforms, considering power loss, signal quality loss, and Carrier over Intermodulation ratio. Power loss is corresponding to OBO value, and signal quality loss equals to the performance gap considering non-linearity sub-block or not. Total loss metric is then defined as:

$$Total\ loss = signal\ quality\ loss + power\ loss$$

$$\begin{cases} power\ loss = |OBO| \\ signal\ quality\ loss = \frac{C'+I_m}{N}_{BER=10^{-5}} - \frac{C}{N}_{BER=10^{-5}}, \end{cases} \qquad (10)$$

Where $\frac{C}{N}_{BER=10^{-5}}$ is the required signal to noise ratio in dB with ideal amplifier response at bit error rate (BER) 10^{-5}, and $\frac{C'+I_m}{N}_{BER=10^{-5}}$ is the required amplified signal power (pure signal plus intermodulated part) to noise ratio in dB at bit error rate 10^{-5}. Both metrics are given at the receiver input location. Assuming that I_m has a Gaussian behavior, pure Signal over Intermodulation power ratio $\left(\frac{C'}{I_m}\right)$ can be derived (linear form):

$$\left(\frac{C'}{I_m}\right) = \frac{1+\left(\frac{C'+I_m}{N}\right)_{BER=10^{-5}}}{\left(\frac{C}{N}\right)^{-1}_{BER=10^{-5}} * \left(\frac{C'+I_m}{N}\right)^{-1}_{BER=10^{-5}} {}^{-1}}. \qquad (11)$$

Signal over Intermodulation power ratio is also an important criterion according to satellite operators, because it demonstrates the ability of the payload to work with any spectral efficiency. As a result, performances of the waveforms will be compared at equal $\left(\frac{C'}{I_m}\right)$ ratio. It shall be pointed out that for a same spectral efficiency, $\left(\frac{C'}{I_m}\right)$ is directly linked to signal quality loss considering (10) and (11). Thus, judicious representation may be, for each waveform, required |OBO| to get BER $= 10^{-5}$ vs $\left(\frac{C'}{I_m}\right)$ representation.

V. SIMULATIONS

A. Parameters and simulation chain

Simulations are performed by using a DVB-NGH like transceiver chain [1]. DVB-NGH specifications enable SC-FDMA utilization without extension and weighting functionality. Besides, frequency hole, interferences and on-board nonlinear amplifier had to be considered as it is depicted in Figure 8. A significant importance should be given to the way signal over noise ratios are computed when dealing with frequency holes. As power at output of the amplifier is unitary in simulations, it was chosen to get noise power considering the maximum achievable band for useful signal, independently from the frequency hole width. This choice may appear unsuitable for conventional multi-carrier receiver, which may be able to ignore the subcarriers carrying only noise. However, for results comparison, it enables to avoid any surboosting effect because of both frequency holes and unitary power: waveforms are compared at same E_S/N_0. Lastly, simulation parameters are summarized in Tab. I.

B. Enveloppe fluctuations

Because dealing with non-linearity effects, the study of envelope fluctuations for each waveform may help to understand further results. This is why complementary cumulated distribution function for instantaneous power is given for each studied waveform in Figure 9.

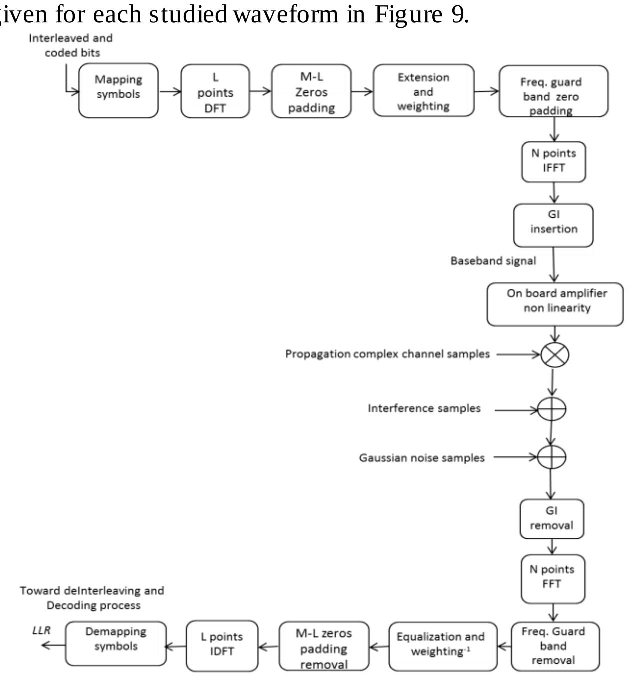

Figure 8. Simulation Chain, including SC-FDMA, frequency hole, interference and non linearity functionalities

TABLE I. MAIN PARAMETERS FOR PERFORMED SIMULATIONS

Parameter name	Value
Satellite signal Bandwidth	15 MHz
Sampling frequency	120/7 MHz
Modulation and coding	QPSK ½ (real coder efficiency 4/9) LDPC + BCH encoder 16200 bits codeword
Max active subcarriers (M)	426
OFDM FFT size (N)	512
OFDM Guard interval	1/16
Total OFDM symbol duration	31.73 µs
SC-FDMA	$\alpha = 0$ (SC-FDMA) or $\alpha = 5\%$ (EW-SC-FDMA)
Frequency hole insertion	$\Delta=0$, $\beta=33\%$ when activated
Interference insertion	$\Delta=0$, $\beta=33\%$ when activated
Satellite RF model	Typical Voltera model for un-linearized TWTA when activated
Propagation channel	Ideal (AWGN) in this study

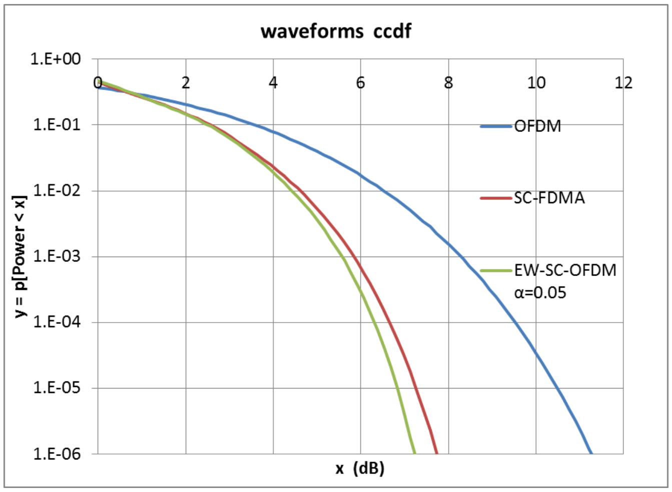

Figure 9. Comparison of waveforms power fluctuation

As it can be found in literature, SC-FDMA waveform performs better than OFDMA one. Using extension can help to better decrease fluctuations, but in this paper 5% roll off factor was chosen, that explains the small difference with SC-FDMA. However, one shall note that this comparison is considering waveforms without frequency holes insertion.

C. Results without frequency holes

As a reference, BER simulations have been performed according to the method described in chapter IV. For a wide range of C/I_m, it appears in Figure 10 that SC-FDMA like waveforms outperform OFDMA, gap increasing when C/I_m is growing. These results emphasize the fact that when no interferer is present, SC-FDMA is a good choice to be compatible from terrestrial multi-carrier legacy and to enjoy efficient use of the satellite payloads.

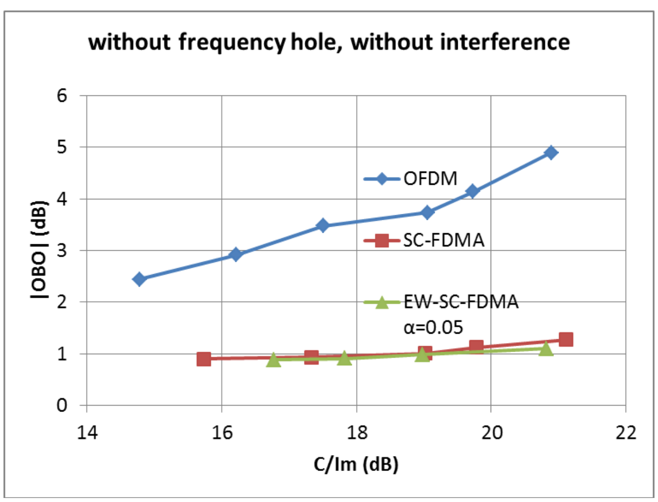

Figure 10. Comparison of waveforms when no frequency holes are inserted and without interference

D. Results with frequency holes

Here, frequency hole was inserted with Δ=0 and β=33% parameters. Especially for single carrier waveforms, inserting a such wide hole inside useful bandwidth may modify its fluctuations behavior. But, as it is depicted in Figure 11, single carrier waveforms performances are not so much degraded by the hole insertion, and remain quite competitive compared to OFDMA, despite the large width of the hole.

E. Results with interferences

Interferences are inserted with Δ=0 and β=33% parameter. I_0, the power spectrum density of interferer is the same as C_0, the power spectrum density of the signal. That leads to relatively weak level of interferers but with quite large bandwidth (1/3 of achievable useful bandwidth). With no real surprise, it is first checked that inserting hole in any of the three waveforms results in a negligible degradation (see it in Figures 12, 13, and 14), because only secondary lobes of active useful subcarriers capture interferences when frequency hole is inserted.

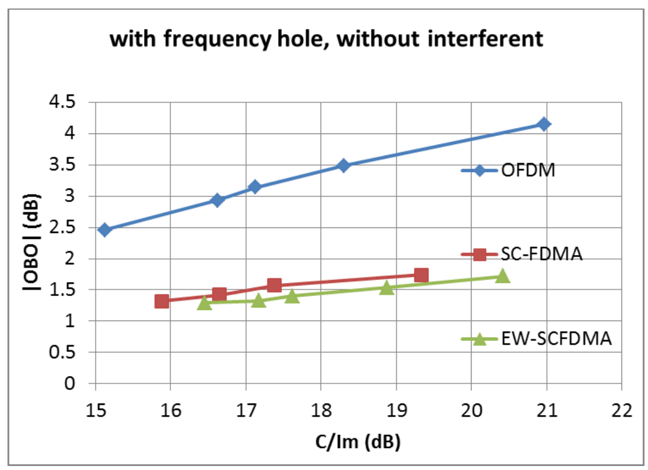

Figure 11. Comparison of waveforms when frequency holes are inserted and without interference

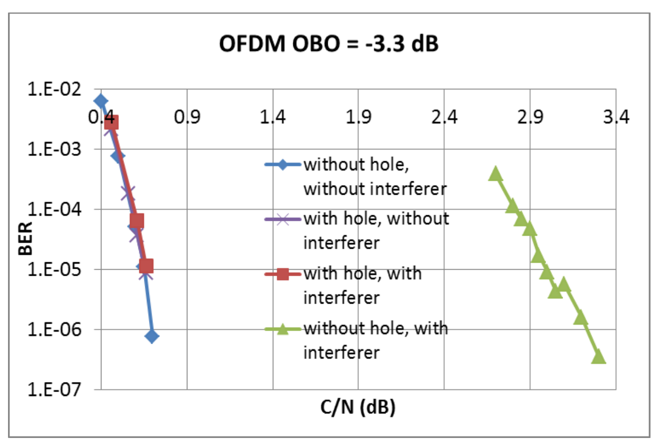

Figure 12. OFDM behaviour with weak interferent

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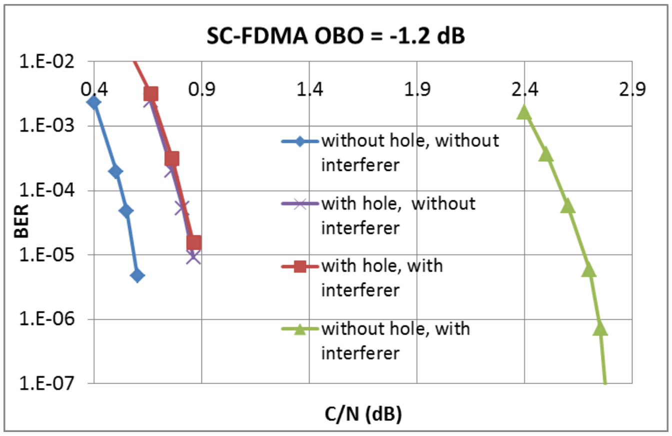

Figure 13. SC-FDMA behaviour with weak interferent

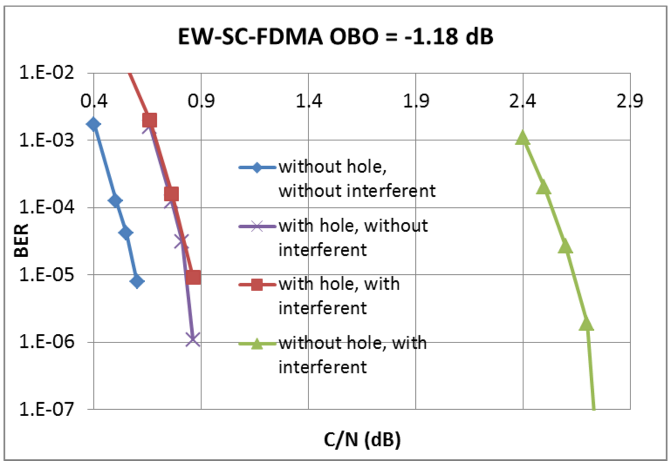

Figure 14. EW-SC-FDMA behaviour with weak interferent

Besides, no creating hole when interferer is present is showing quite degraded results, even if the interferer has a weak level. Reader shall point out that weak interferer was chosen to visualize the degradation on the same curve. But, from a system point of view, power spectrum density of a terrestrial interferer would be greater than satellite useful signal one, and would emphasize the need for such frequency hole in the waveform.

VI. CONCLUSION

At a time where, on one hand, historical satellite chipset manufacturers are working to enlarge their modulated carriers bandwidths to maximize the payload efficiency, and on the other hand there is a need to make easier spectrum scalability, a SC-FDMA based solution was introduced to address this issue. In this paper, it has been shown that SC-FDMA waveform fluctuations enable using payload in an efficient way, and that creating frequency hole do not degrade so much envelope fluctuations; SC-FDMA waveform remains in all cases relevant compared to OFDMA. Thus, using this waveform would take advantage of both frequency scalability and payload efficiency, while offering a solution at physical layer level for dynamic spectral resource sharing systems.

For further work, a study case with several powers and bandwidths for the interferer should be done to better demonstrate the need for inserting frequency hole. Moreover, total achievable bit rate should be considered: by using the spectrum compression effect when creating frequency hole, spectral efficiency could be improved and may balance the lack of spectrum.

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