Filtered Based UFMC Waveform Applied on Joint DVB-T2/NUC System

Anne-Carole Honfoga[1,2](✉), Michel Dossou[2], Péniel Dassi[2], and Véronique Moeyaert[1]

[1] Electromagnetism and Telecommunications Department, University of Mons, Mons, Belgium
{anne-carole.honfoga,veronique.moeyaert}@umons.ac.be
[2] LETIA (of Polytechnic School of Abomey-Calavi), University of Abomey-Calavi, Calavi, Benin
michel.dossou@epac.uac.bj, penieldassi@gmail.com
https://web.umons.ac.be/en/
https://www.uac.bj

Abstract. The Digital Video Broadcasting-Terrestrial, second generation (DVB-T2) system is now mature and being deployed worldwide in direct deployment or in replacement of Digital Video Broadcasting-Terrestrial, first generation (DVB-T). Nevertheless, attempts to improve its performance in terms of distance to Shannon limit, Bit Error Rate (BER), Signal to Noise Ratio (SNR) or coverage are still reported in the literature. On the one hand, the authors of this paper recently reported that Universal Filtered MultiCarrier (UFMC) is, among 5G waveforms, the best compromise in terms of improvement, spectrum efficiency and complexity for the replacement of Cyclic Prefix - Orthogonal Frequency Division Multiplexing (CP-OFDM) in DVB-T2 system. On the other hand, a gain in DVB-T2 performance in Additive White Gaussian Noise and Rayleigh environments was reported in the literature using optimized Non Uniform Constellations (2D-NUCs). This paper first focuses on the maximum obtainable performance improvement of DVB-T2 CP-OFDM with NUCs in Typical Urban 6 (TU6) environment. It concentrates afterwards on the ultimate gain achievable using joint UFMC and NUCs in DVB-T2. TU6 channel is defined in DVB-T2 standard as a generic channel used in simulation to emulate an urban propagation environment. In these conditions, a gain of 0.5 dB (for BER $= 3.10^{-3}$) is reported in TU6 using CP-OFDM NUC 32K 256-QAM and Code Rate (CR) $= 1/2$ and $3/5$ in place of sole CP-OFDM. Also, using both technologies in conjunction, namely UFMC NUC 32K 256-QAM CR $= 1/2$ and $3/5$, a gain of 1.2 dB (for BER $= 3.10^{-3}$) is achievable which provides a good SNR margin e.g. to increase the emitter's coverage.

Keywords: NUC · UFMC · Urban environment · DVB-T2

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1 Introduction

DVB-T2 is the european broadcasting standard second generation which has been adopted or deployed by many countries in Europe and Africa. Due to its high flexibility in the choice of parameters and its performance compared to DVB-T, DVB-T2 has been studied in the scientific literature over the last decade in order to improve its performance and allow the broadcasters to have technical information details for the system implementation.

In this research landscape, many studies have been focused on the field trials, signal robustness (SNR improvement), channel capacity and the spectral efficiency improvement. Indeed, a common method to approach the channel capacity established by Shannon is the application of Bit Interleaved Coding Modulation (BICM) chain when designing a system [1]. This chain consists in the serial concatenation of a Forward Error Correction (FEC) code, a bit interleaver and a constellation mapper. It has namely been adopted in european standards like DVB-T2 [2], Digital Video Broadcasting - Next Generation Handheld (DVBNGH) [3] and also in next-generation terrestrial broadcast american standard Advanced Television Systems Committee, third generation (ATSC 3.0) [4]. The BICM chain firstly designed is that used in DVB-T2 and includes uniform labelled Quadrature Amplitude Modulation (QAM) constellation mapping which induces a noticeable gap between the system capacity and the Shannon limit. Indeed, these constellations approach Shannon limit very closely for low SNR, but the gap becomes more apparent for higher SNR [1].

Despite the fact that both DVB-T2 and ATSC 3.0 standards employ BICM chain, their performance are different. While QAM is used in the BICM chain for DVB-T2, Non Uniform Constellations (NUCs) are used in this chain for ATSC 3.0 system which allows this system to be closer to the Shannon limit. Conventional QAM employed signal points on a regular orthogonal grid whereas NUCs loosened this restriction. The non-uniform concept was first introduced by Foschini [5] which noted the capacity shortfall of uniform QAM and minimized symbol error rates over an Additive White Gaussian Noise (AWGN) channel by providing different constellations which offer a capacity improvement. Indeed, constellation shaping techniques can be separated into two variants: probabilistic shaping and geometrical shaping techniques. While probabilistic shaping addresses the symbol probabilities by using a shaping encoder, the geometrical shaping called NUC, modifies the location of constellation symbols. Two kinds of approaches (1D-NUCs and 2D-NUCs) have been obtained. 1D-NUCs have non-uniform distance between constellation symbols but maintain the square shape which preserves demapping complexity whereas 2D-NUCs increase this complexity by relaxing the square shape constraint. However, 2D-NUCs present better performance than QAM and 1D-NUCs [6]. Several works tackled the demapping complexity reduction of 2D-NUCs [7,8].

On the one hand, BICM brings a capacity gain using the constellation shaping approach. On the other hand, DVB-T2 still uses OFDM which is not optimum in term of spectral efficiency. Indeed, due to the Cyclic Prefix (CP) added to OFDM symbols in order to deal with channel impairment, a spectral efficiency loss is obtained. To overcome this OFDM issue, filter based waveforms proposed for 5G became suitable for DVB-T2. Bank MultiCarrier (FBMC) and UFMC present a filtering characteristic which allows them to deal with channel impairments while avoiding the CP. Thanks to a better spectral behaviour of these waveforms, FBMC has been recently proposed as an alternative to OFDM in DVB-T2 [9]. Moreover, UFMC has been considered more suitable to OFDM in DVB-T2 transmission considering the compromise between respectively their spectral efficiency as it consists in redundant part of data, their SNR gain and their complexity [10]. In comparison with the classical OFDM, UFMC presents a SNR gain of 1.2 dB at a BER of 10^{-3}. On the other hand, the performance gain of 2D-NUCs have been previously highlighted with AWGN and Rayleigh channel models for DVB-T2 [11]. In order to evaluate the maximum reachable gain with constellation shaping technique and multicarrier modulation, the joint use of 2D-NUCs employed in terrestrial broadcasting system ATSC 3.0 and 5G waveform (UFMC) (called DVB-T2/UFMC/NUC) has been proposed for DVB-T2 transmission as the sole use of 2D-NUCs and UFMC respectively allow the increasing of DVB-T2 system performance. DVB-T2/UFMC/NUC has many advantages such as: the increase of the system spectral efficiency due to the CP cancellation and the few guard band of UFMC, the decrease of the bit error probability by reducing the number of constellation points which have the same I (In Phase) or Q (Quadrature) components, the use of Chebyshev filter instead of rectangular filter in OFDM. Also, the characteristic of UFMC waveform makes the system suitable for low capacity applications.

The rest of this paper is structured as follows. Section 2 presents related works about NUCs and UFMC. Section 3 briefly introduces the BICM capacity and the NUCs constellation concept. In Sect. 4, UFMC filtered based waveform is presented. Section 5 presents the lite version of DVB-T2 physical layer and parameters. In Sect. 6, simulation results and performance analysis are presented. Finally, the main findings of the work are summarised in Sect. 7.

2 Related Works

NUCs and 5G waveforms UFMC have been the object of many researches during the last years. NUCs have been proposed in many standards such as: DVB-NGH [3] and ATSC 3.0 [4]. Also, they have been proposed recently for DVB-T2 [11], broadcast/multicast services [12], broadcasting Ultra High Definition (UHD) TeleVision (TV) [13] and converged network of broadcast and broadband [14]. UFMC is a waveform which has been firstly proposed for Long Term Evolution (LTE) [15] and later for 5G system [16,17]. Its low complexity of implementation has been recently demonstrated [18]. In this section, these works are briefly presented.

2.1 NUCs Related Works

- 1D-NUCs have been proposed in DVB-NGH standard in 2012 for Handheld services. The performance obtained is better than DVB-T2 performance [3].

- 1D-NUCs and 2D-NUCs have been compared in DVB-T2 system in 2014 using AWGN and rayleigh channels and the results shown that 2D-NUCs present better performance than 1D-NUCs [11].
- 1D-NUCs and 2D-NUCs of high order constellations have been proposed for UHD TV broadcasting in 2014 to increase the capacity and the performance gain. The results shown that 4096-1D-NUC presents better performance than 4096-QAM and could be used for high data rate transmissions [13].
- An iterative algorithm has been proposed in 2016 to optimize the NUCs for multiple applications like multicast and broadcast services and maximize the gain obtained under different channels [12].
- 2D-NUCs and QAM have been compared in different channel scenarios including Doppler effect. The results show that NUCs can provide a performance gains and induce a high data rate in a converged network [14].

2.2 UFMC Related Works

- Filtered based waveform UFMC has been firstly proposed for LTE communications as an alternative to CP-OFDM [15] in oder to reduce InterCarrier Interference (ICI) and cancel the CP overhead. Due to filtering operation applied on a group of consecutive subcarriers (called sub-band), the out-of-band side lobe levels are reduced which minimizes the ICI.
- Afterwards, UFMC and FBMC have been proposed for 5G system where their performance were compared to CP-OFDM performance. The results shown that UFMC is suitable for 5G communications as it is designed for low latency systems [16,17].
- Furthermore, a low complexity of UFMC hardware implementation has been proposed in 2020. The results shown that UFMC complexity could be comparable to the complexity of OFDM [18].
- UFMC, FBMC and CP-OFDM have been compared in DVB-T2 in terms of spectral efficiency, Power Spectral Density (PSD), performance gain and complexity. The results shown that UFMC is suitable to DVB-T2 transmissions as it outperforms OFDM with a complexity comparable to that for OFDM [10].

3 BICM Capacity and NUC Constellation

The channel capacity is the maximum mutual information between the channel input and the channel output. This capacity has been defined by Shannon as the maximum possible throughput over any given channel [19].

3.1 BICM Capacity

The channel is described by its transition probabilities $p(r_k|s_k = x_l)$ where k denotes the discrete time index, s_k and r_k represent respectively the transmitted and received symbols at time k. The symbol constellation x_l is taken from an alphabet X. When an AWGN channel is used, $p(r_k|s_k = x_l)$ is a gaussian distributed probability density function, centered around the transmitted symbol with a zero mean noise and noise variance according to SNR.

Shannon proved that maximum Mutual Information (MI) can be achieved if the transmitted alphabet (set of constellation points) is Gaussian distributed [12,13]. Then, the theoretical limit expressed in the normalized capacity form is given by $C(bit/s/Hz) = log_2(1 + SNR)$ where SNR is the ratio between the average transmitted power P and the noise power N. However, this limit can never be achieved by any pratical system due to the alphabet X which contains a finite transmitted symbol number. The gaussian distribution is not possible to be achieved in reality. In many communications systems, most pratical finite symbol alphabet inputs are implemented such as QAM. The BICM capacity that characterizes these systems is given by [12]:

$$C = M - \sum_{m=1}^{M} E_{b,y}[log_2 \frac{\sum_{x_l \in X} p(y|x_l)}{\sum_{x_l \in X_b^m} p(y|x_l))}] \quad (1)$$

where M is the number of bits per symbol, y is the received signal, $p(y|x_l)$ is the transition probability density function (p.d.f) of transmitting x_l and receiving y. b can take 0 or 1 values. X_b^m is the subset of the alphabet X (all the possible values x_l ($l = 1, ..., N$) of constellations) for which bit label m is equal to b. $E_{b,y}$ denotes expectation with respect to b and y. If N denotes the number of constellation points, the alphabet of the transmitted symbols needs to be normalized following the power constraint:

$$P_{total} = \frac{1}{N} \sum_{l=1}^{N} |x_l|^2 = 1 \quad (2)$$

The main parameters affecting $p(y|x_l)$ are the SNR and the constellations points position in AWGN channel. The uniform design criteria is the straightforward way to design an alphabet X resulting in uniform constellations.

3.2 Non Uniform Constellations

Uniform constellations are characterized by uniform spacing between constellations points and square shape of the constellations. However, a noticeable gap between BICM capacities with QAM and the Shannon limit is reported [20]. Furthermore, this gap increases with the constellation order [12,13]. At an SNR of 16 dB, the difference with the Shannon limit observed for 256-QAM, 1D-256-NUCs and 2D-256-NUCs are respectively 0.4 dB, 0.15 dB and 0.1 dB [12,13]. In order to reduce the significant gap of uniform QAM constellations, optimal constellation which achieves the smallest gap has been researched. To optimize the uniform constellation, 1D-NUCs have been designed by relaxing the uniformity constraint while keeping the rectangular structure of the constellation. This method confirms the fact that 1D-NUCs can be viewed as a QAM constellation which can be separated into two Pulse Amplitude Modulation (PAM) constellations. Then two PAM demappers are sufficient to demap 1D-NUCs. 2D-NUCs have been designed by relaxing both uniformity and the square or rectangular shape constraints. The constellation values can take any shape inside one quadrant. The other three quadrants are derived from the first quadrant by symmetry. This allows 2D-NUCs to achieve a better performance than 1D-NUCs and the BICM chain capacity to be closer to the Shannon limit with a counterpart in term of increased complexity.

3.3 Relevance of 2D-Demapper for 2D-NUCs

In order to detect the symbol transmitted at the receiver, euclidean distance metric computation is used. The higher the euclidean distance number is, the higher the complexity is. Euclidean distance number computed for 1D-NUCs and 2D-NUCs are respectively $2^{\frac{M}{2}+1}$ and 2^{M} while one dimensional and two dimensional demappers are respectively used for them. Moreover, the number of parameters to be optimized (called Degrees of Freedom (DOF)) is different for both 1D-NUCs and 2D-NUCs. Equations (3) and (4) are presented in [1,11,12]. In Eq. (3), the term $sqrt(N)$ is due to the rectangular structure of the constellation: the optimal level on the real and imaginary axes are equal. The factor $\frac{1}{2}$ is due to the fact that the optimization is carried out on the positive levels only (the negative levels are identical). In Eq. 4, the factor $\frac{1}{4}$ shows that the four quadrants are symmetric and the factor 2 is due to the fact that the real and imaginary parts of each constellation point are optimized separately. The term -1 in both Eqs. 3 and 4 is due to the power normalization constraint.

$$DOF_{1D-NUCs} = \frac{sqrt(N)}{2} - 1 \tag{3}$$

$$DOF_{2D-NUCs} = 2\frac{N}{4} - 1 \tag{4}$$

Using these equations, we can observe that the higher the constellation size is, the higher the DOF is. In particular, the DOF of 2D-NUCs increases faster with N than in the case of 1D-NUCs. This induces the fast increasing of 2D-NUCs demapper complexity. By this way, one can justify the choice of 2D-NUCs only for constellations of size 16, 64 and 256-QAM and 1D-NUCs for constellations of size 1024 and 4096 in ATSC 3.0. In the following sections, our study is focused on the gain which could be obtained with the use of 2D-NUCs proposed for ATSC 3.0 in DVB-T2. Filter based waveform UFMC will also be applied to 2D-NUCs in DVB-T2 in order to maximize the performance gain. The constellation and capacity optimization algorithm are beyond the scope of this paper. The following section presents the filtered based UFMC waveform.

4 Comparison of CP-OFDM and UFMC

In this section, the main waveforms are briefly introduced and are compared.

4.1 CP-OFDM

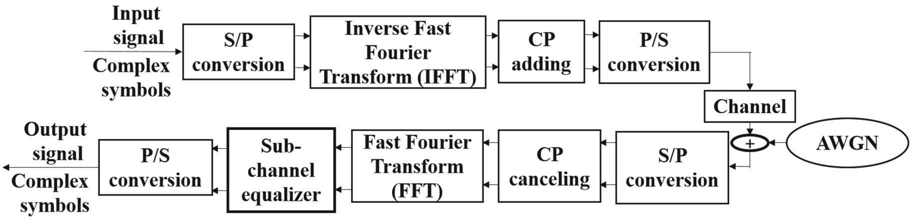

Fig. 1. CP-OFDM block diagram

In CP-OFDM, a set of complex symbols is mapped onto a set of orthogonal carriers (Fig. 1). The symbol mapping method used in DVB-T2 is QAM. Due to the sole use of Inverse Fast Fourier Transform (IFFT) (resp. FFT) process, the complexity of CP-OFDM is very low. The principle of OFDM is to divide the total bandwidth into M subcarriers, so that channel equalization can be reduced as a one tap coefficient per subcarrier. Finally, a CP is added at the beginning of each symbol. It guarantees circularity of the OFDM symbol if the channel delay spread is lower than the CP length [21]. However, CP-OFDM induces high OOB leakage, which requires the need for large guard band and degrades overall spectral efficiency due to the guard band and the CP overhead.

4.2 Filtered Based Waveform: UFMC

OFDM is a multicarrier modulation used in broadband multicarrier communications. However, it presents the shortcoming such as the constraint of Cyclic Prefix (CP) to deal with channel impairment and the high Out Of Band (OOB) emission. UFMC is a waveform for which CP is avoided and induces low OOB emission. The filtering in UFMC is based on a group of subcarriers (sub-band) instead of filtering each subcarrier (FBMC) or filtering together all subcarriers (filtered-OFDM). Dolph-Chebyshev filter for which the Side Lobe Level (SLL) and the filter length can be managed as parameters, has been adopted in order to increase system performance [10,12]. UFMC uses a shorter filter length and in its design, the filter length must be equal to the CP length in order to deal with frequency selective channels. The main parameters of UFMC are L the filter length, SLL, B the sub-band number and B_w the sub-band bandwidth. B_w represents the number of subcarriers used for each sub-band.

Figure 2 presents a UFMC transceiver. Contrary to other waveforms, UFMC uses only the transmit filters. Filters are not applied at the receiver. Indeed,

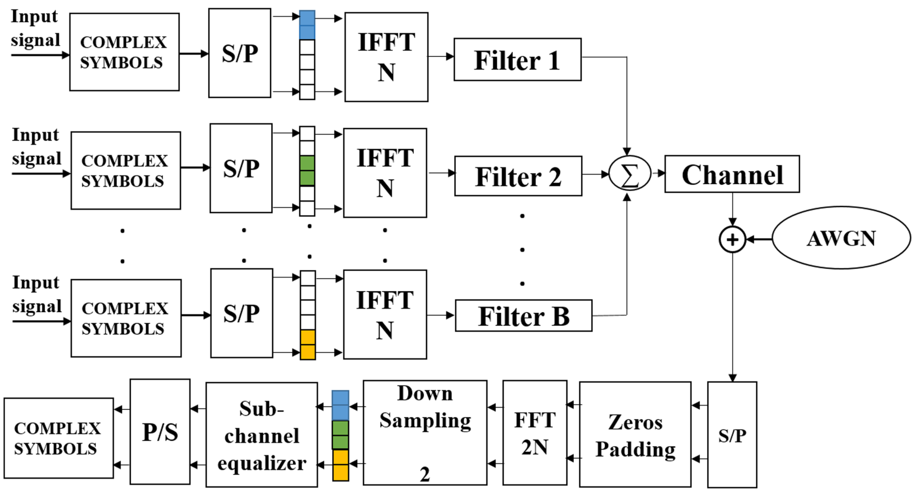

Fig. 2. UFMC block diagram

UFMC employs two NFFT points in the receiver allowing the data symbol recovering without the need of CP. However, the 2 NFFT points cause noise increase problem to the UFMC reception and thus degrade the UFMC performance compared to OFDM when only AWGN is used as channel. Indeed, while the contribution of gaussian noise on the CP is canceled in OFDM at the receiver, in UFMC this contribution is maintained on the filter length used in UFMC. As the 2 NFFT points used in demodulation includes the filter length contribution, this effect is highlighted on UFMC performance when gaussian noise is used. Otherwise, UFMC performance is better than that for OFDM in the presence of frequency selective channels. Furthermore, both OFDM and UFMC use a one tap Zero Forcing equalizer. Deep comparison between OFDM and UFMC in terms of transmitter, receiver and their PSD is presented in [10]. UFMC could substitute CP-OFDM with a high spectral efficiency (128% improvement) due to the CP cancellation and its little guard band (2816 instead of 5503 in OFDM).

5 DVB-T2 Physical Layer

In this section, the DVB-T2 system is briefly presented as well as the modeled channel and simulation parameters.

5.1 Lite Version Including NUCs and UFMC

DVB-T2 is the second generation terrestrial broadcasting system published by European Telecommunications Standards Institute (ETSI) in 2009. It offers a choice of flexibility to broadcasters. Compared to DVB-T, it introduces many innovative features allowing to reach a throughput of 50.32 Mbit/s [22]. The main two parts of this system are the BICM block and the multicarrier modulation block. In the specific way, the first block includes a FEC code Bose-Chaudhuri-Hocquenghem (BCH) and Low Density Parity Check (LDPC), a bit interleaving and a QAM mapping. The second block includes Orthogonal Frequency Division Multiplexing (OFDM)-CP. Indeed, the adoption of a powerful FEC schemes in substitution to combination of a convolutional code with an outer Reed Solomon code results in a larger FEC gain obtained at the price of increased complexity induced by these coders. As known, LDPC is based on a high density parity check matrix with short or long FEC frames and the decoding step is processed using a Belief Propagation (BP) algorithm. Despite the gain provided by FEC scheme, QAM constellations optimization has been studied in the literature. As known, 1D-NUCs with 64 and 256 constellations points have been proposed for DVB-NGH [3] and both 1D and 2D-NUCs have been proposed in ATSC 3.0 in order to increase the BICM capacity. Due to the performance gain obtained with 2D-NUCs in [4,11] and UFMC in [10], we propose in this paper to substitute QAM constellations by 2D-NUCs constellations (like in ATSC 3.0) in DVB-T2, also replacing the OFDM waveform by UFMC. Furthermore, long FEC frame is used at the LDPC coder. Figure 3 presents the implemented system used for simulation.

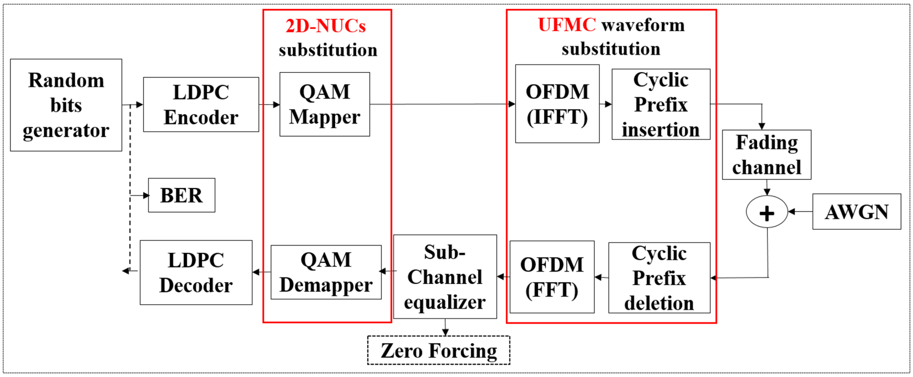

Fig. 3. DVB-T2 model implemented

Due to the fact that LDPC and QAM mapper are in the BICM main blocks which take out the BICM performance, we focus our simulation only on these blocks. As the interleaving block is useful in the presence of impulsive noise, this block is not used in the simulation.

5.2 Channel Used and Parameters

In this subsection, the DVB-T2 system parameters are presented in Table 1.

Table 1. DVB-T2 systems parameters

NFFT	1K, 2K, 4K, ((8, 16, **32**)K and ext)
Modulation	4, **16**, **64**, **256**-QAM
FEC frame	**long (64800 bits)**, short (16200 bits)
CR LDPC	**1/2**, **3/5**, **2/3**, 3/4, 4/5, 5/6
Bandwidth	1.7, 5, 6, 7, **8**, 10 MHz
CP	**1/128**, 1/32, 1/16, 19/256, 1/8, 19/128, 1/4

Table 2. TU6 channel [22]

PDP description	Path 1	2	3	4	5	6
Delays (ns)	0	200	500	1600	2300	5000
Power (dB)	−3	0	−2	−6	−8	−10

Parameters in red color represent those used in simulation. NFFT is the number of subcarriers used with OFDM. The term *ext* means extended. As 4-QAM constellation has not been optimized for NUCs, the other constellations sizes are used for NUCs simulation. Due to the fact that simulation results given in [11] shown that 2D-NUCs outperform QAM in DVB-T2 system and the gain is highligthed for lower code rates such as 1/2, 3/5 and 2/3, our simulation will be focused on them. UFMC parameters used for simulations are: $L = 32768/128 = 256$, $B = 128$, $B_w = 234$ and $SLL = 60\,\text{dB}$. Indeed, the maximum gains of NUCs are obtained for CR with high FEC. This means that the number of redundancy bit is high [11] and justifies the choice of these CR. The FFT mode 32K has been chosen as this mode is mainly used by broadcasters for rooftop antenna reception [23]. The constellation size of 256 is used for TU6 channel due to the density of constellation points which performance is normally bad in the worse reception condition. Moreover, the choice of the parameters more suitable for UFMC depends on the CP of the system and the density of the sub-bands. CP=1/128 (low CP of DVB-T2 standard) has been chosen in order to fulfill the UFMC requirements in term of filter length used. Also, it is proven that UFMC performance are better when the number of sub-band increases [10] and the number of bit per symbols increases [24]. The channel bandwidth of 8MHz has been chosen as it is the bandwidth used for network deployment by broadcasters in many European and African countries. In order to evaluate performance in DVB-T2 environment, TU6 channel which models urban environment is used. The Power Delay Profile (PDP) of this channel is presented in Table 2. Method used to implement TU6 channel is based on Tapped Delay Line (TDL) model described in [22]. The Root Mean Square (RMS) delays spread of TU6 is about $1.0616.10^{-7}$ s.

5.3 Non Uniform Constellations Shapes

In this subsection, NUCs used in simulation are presented for each code rate. Figure 4, Fig. 5 and Fig. 6 present 2D-64-NUCs and 2D-256-NUCs respectively for code rate 1/2, 3/5, 2/3.

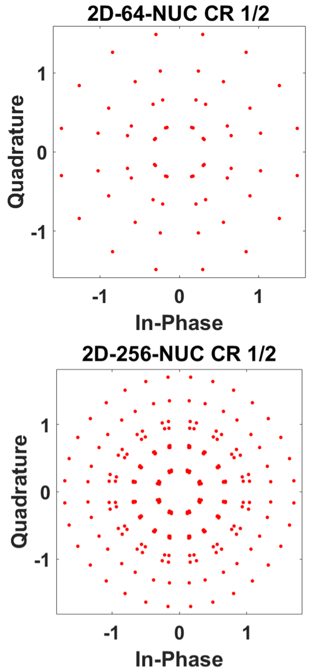

Fig. 4. 2D-64-NUC and 2D-256-NUC constellations for CR 1/2 [4]

As noticeable, these constellations are optimised for each code rate. This means that in comparison with QAM constellations which are designed to work with any code rate, these constellations are designed and optimized for a specific SNR value. This value depends on the FEC frame length, the code rate and the channel distribution. Note that these constellations are already proposed for DVB-T2 system [11].

6 Simulation Results

In order to evaluate the combination of NUCs and UFMC performance in DVB-T2 system, our simulator has been validated (6.A) using AWGN and parameters previously presented. The simulation tool is Matrix Laboratory (MATLAB) version 2016. Simulations have been performed using the Monte-Carlo method. The reception process takes place for each iteration of SNR and the BER is computed

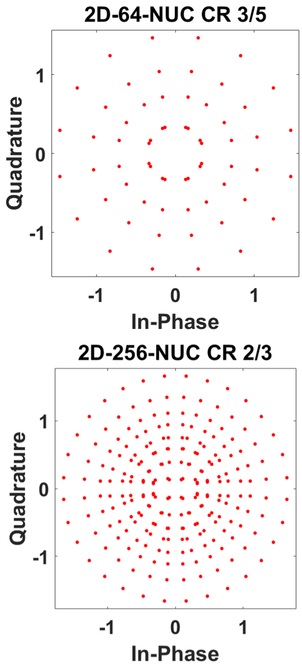

Fig. 5. 2D-64-NUC and 2D-256-NUC constellations for CR 3/5 [4]

between the bits randomly generated and the bits after LDPC decoder. The system has been simulated (6.B) in presence of frequency selective TU6 channel using high order constellations due to the fact that the gain in NUCs and UFMC is maximum with these constellations. Using this channel, 100 different channel realizations have been generated and the performance results presented in this paper are the mean of the computed BER for each realization.

6.1 System and Performance Validation Using AWGN

In order to validate the simulator, OFDM/QAM and OFDM/NUCs simulation results are presented. Results have been compared to simulation results about DVB-T2/OFDM given at 10^{-4} in the implementation guideline of DVB-T2 [22].

Figure 7 presents the simulation results for constellation sizes 16, 64 and 256 and code rates 1/2, 3/5 and 5/6. At a BER of 10^{-4}, the simulation results for DVB-T2/OFDM/QAM and those presented in [22] are comparable. However, when compared to DVB-T2/OFDM/2D-NUCs, there is a noticeable gain for combination of constellations and code rates. The more the constellation size increases, the more the 2D-NUCs gain increases. This confirms the good behaviour of our simulator and the literature trends. Furthermore UFMC/QAM and UFMC/NUCs simulation results are presented on Fig. 9 in order to confirm the fact that NUCs can be used with UFMC waveform.

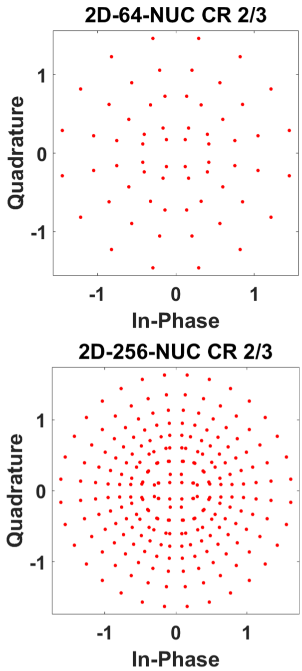

Fig. 6. 2D-64-NUC and 2D-256-NUC constellations for CR 2/3 [4]

Table 3 presents (based on Fig. 3 and Fig. 4) the gains obtained respectively for OFDM and UFMC when NUCs are used. By analysing these gains, we can conclude that the behaviour of NUCs in DVB-T2/OFDM and DVB-T2/UFMC is equivalent at a BER of 10^{-4}: to respectively 1.2 dB and 1.3 dB for $N = 256$ and $CR = 1/2$. Moreover the maximum gain is obtained for constellation $N = 256$ and $CR = 1/2, 3/5, 2/3$. However, UFMC presents a loss when compared to OFDM in presence of gaussian noise. The noise increasing problem in UFMC reception is due to the fact that $2{*}NFFT$ points are used to achieve efficient demodulation without CP. If UFMC filter impulse response length is L, $(NFFT + L)$ time domain noise samples contribute to the frequency domain noise. As results, the noise power is larger than that for OFDM like presented in [25]. The following part of this section presents simulation results using frequency selective channel which highlights both NUCs and UFMC performance (Fig. 8).

6.2 Simulation Results Using TU6

In order to present UFMC/NUCs performance in DVB-T2 environment, TU6 channel is exploited. Simulation results are obtained using the average of 100 independent channel realisations of a statistical fading generators.

Simulation results are presented on Fig. 9 and Fig. 10 respectively for CR 1/2 and 3/5 and a constellation of size 256. At a BER of 10^{-2}, UFMC/NUCs

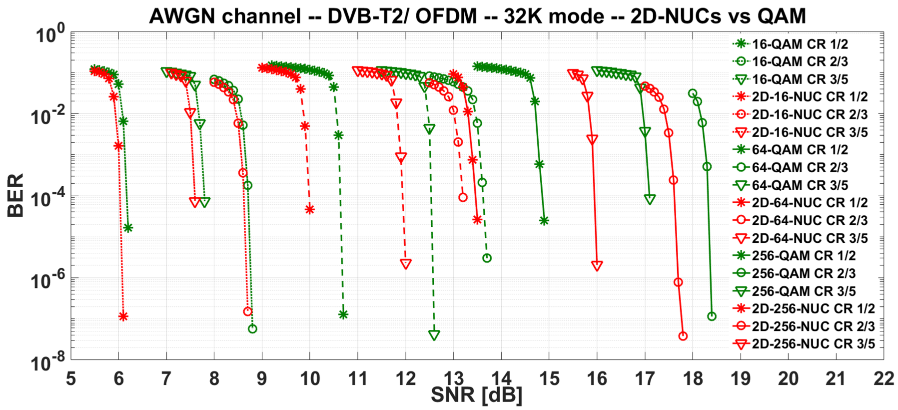

Fig. 7. 2D-NUCs and QAM comparison in DVB-T2/OFDM system

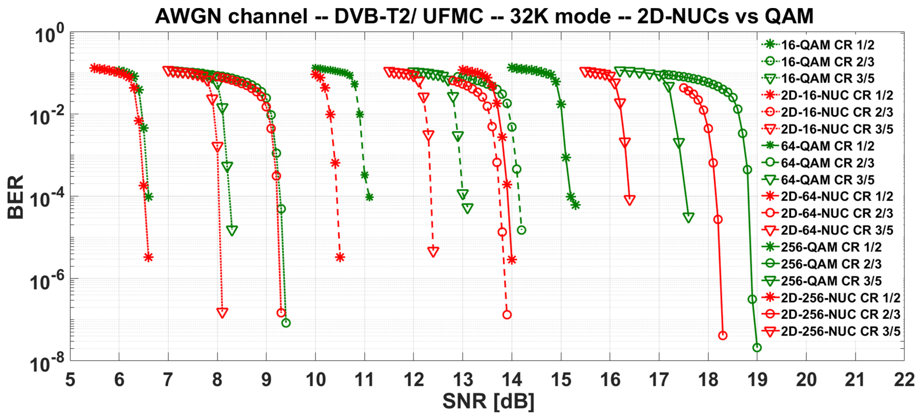

Fig. 8. 2D-NUCs and QAM comparison in DVB-T2/UFMC system

Table 3. Performance gain of NUCs compared with QAM for DVB-T2/OFDM and DVB-T2/UFMC with AWGN (BER = 10^{-4})

Waveforms		OFDM			UFMC		
Mod		QAM	NUC	NUC	QAM	NUC	NUC
CR	N	SNR[dB]		Gain[dB]	SNR[dB]		Gain[dB]
1/2	16	6.2	6	**0.2**	6.6	6.5	**0.1**
1/2	64	10.5	10	**0.5**	11.1	10.4	**0.7**
1/2	256	14.7	13.4	**1.3**	15.2	13.9	**1.3**
3/5	16	7.7	7.5	**0.2**	8.2	8	**0.2**
3/5	64	12.5	11.9	**0.6**	13	12.3	**0.7**
3/5	256	17	16	**1.0**	17.5	16.4	**1.1**
2/3	16	8.7	8.6	**0.1**	9.3	9.2	**0.1**
2/3	64	13.6	13.2	**0.4**	14.2	13.7	**0.5**
2/3	256	18.3	17.6	**0.7**	18.8	18.2	**0.6**

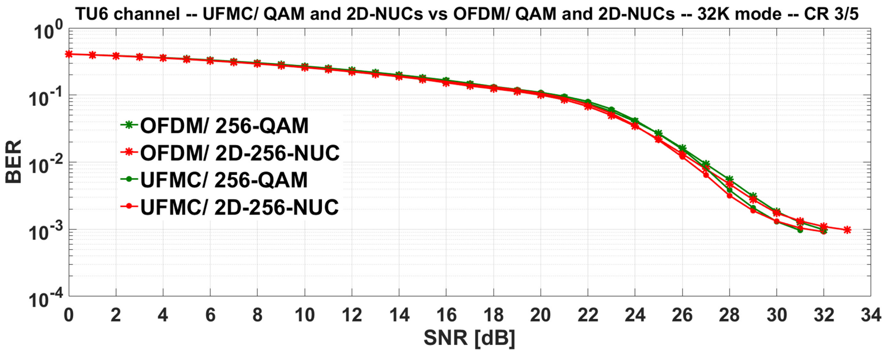

Fig. 9. 2D-NUCs and QAM comparison in DVB-T2/OFDM and DVB-T2/UFMC systems using TU6 channel, constellation size 256 and CR 3/5

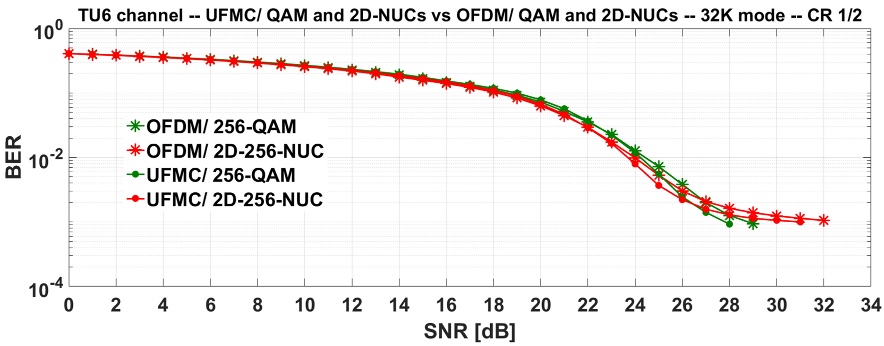

Fig. 10. 2D-NUCs and QAM comparison in DVB-T2/OFDM and DVB-T2/UFMC systems using TU6 channel, constellation size 256 and CR 1/2

Table 4. Performance gain of NUCs compared with QAM for DVB-T2/OFDM and DVB-T2/UFMC using TU6 channel

Waveforms	OFDM			UFMC		
Mod	QAM	NUC	NUC	QAM	NUC	NUC
BER	SNR[dB]		Gain[dB]	SNR[dB]		Gain[dB]
Constellation size 256, CR 1/2						
10^{-2}	24.5	24	**0.5**	24.3	23.6	**0.7**
3.10^{-3}	26.5	26	**0.5**	25.8	25.3	**0.5**
2.10^{-3}	27	27	**0.0**	26.4	26.4	**0.0**
10^{-3}	29	32	**−3.0**	27.8	30.5	**−2.7**
Constellation size 256, CR 3/5						
10^{-2}	27	26.6	**0.4**	26.8	26.3	**0.5**
3.10^{-3}	29.2	29	**0.2**	28.4	28	**0.4**
2.10^{-3}	29.8	29.6	**0.2**	29	28.8	**0.2**
10^{-3}	32	32.2	**−0.2**	30.8	31	**−0.2**

Table 5. Performance gain of UFMC/NUCs compared with OFDM/QAM in DVB-T2 system using TU6 channel

UFMC/QAM	CR	BER	10^{-2}	3.10^{-3}	2.10^{-3}	10^{-3}
vs	1/2	Gain [dB]	0.2	0.7	0.6	1.2
OFDM/QAM	3/5	Gain [dB]	0.2	0.8	0.8	1.2
UFMC/NUCs	CR	BER	10^{-2}	3.10^{-3}	2.10^{-3}	10^{-3}
vs	1/2	Gain [dB]	**0.9**	**1.2**	**0.6**	**−1.5**
OFDM/QAM	3/5	Gain [dB]	**0.7**	**1.2**	**1**	**1**

outperforms UFMC/QAM by 0.7 dB and 0.5 dB and OFDM/QAM by 0.9 dB and 0.7 dB respectively for CR 1/2 and 3/5. At a BER of 3.10^{-3}, UFMC/NUCs outperforms OFDM/QAM by 1.2 dB for CR 1/2 and 3/5 .

Table 4 presents the gain obtained with NUCs using OFDM and UFMC. As presented on the Figs. 9 and 10 and in this table, NUCs outerform QAM for low SNR values. For high SNR values, NUCs present a loss when compared to QAM. The performance gain obtained with the joint usage of UFMC and NUCs are presented on Table 5.

6.3 Analysis

Based on the results presented above, NUCs constellations shaping technique can be jointly used with UFMC in DVB-T2. It presents better performance in AWGN and in TU6 respectively for low SNR values less than 20 dB and 26 dB. For high SNR value, 2D-NUCs performance become worse for both DVB-T2/OFDM/NUCs and DVB-T2/UFMC/NUCs. These results can be explained by three reasons. Firstly, as the aim of this work is to present NUCs in worse reception condition, one hundred independent channel realizations are used for TU6 channel. Due to the averaging of these channel realizations used in simulation, the worse possible realizations of this channel are represented. Secondly, LDPC codes are designed to work in a waterfall region specific for low SNR values. The waterfall region is the SNR region where the BER decreases quickly. This region is followed by the error floor region which starts at a point after which the BER curve does not fall as quickly and a performance flattens [26]. Lastly, NUCs have been designed for specific SNR values. This explains the good behaviour for NUCs in AWGN channel and in low SNR region for TU6 channel. The saturation effect noticed for all the BER curves is due to the first two regions. However, NUCs and UFMC can be jointly used in DVB-T2 and could allow this system to increase its spectral efficiency [10], its performance gain and to be closer to the Shannon limit.

DVB-T2 is already deployed, is ongoing or planned deployments in more than 100 countries corresponding to a real-life implementation in those countries, as shown on the ITU interactive map [27]. The improvements proposed in this work can be considered as principles proposals which can be followed for the next standard revision.

7 Conclusion

In this paper, the impact of BICM/2D-NUCs in DVB-T2/OFDM and DVB-T2/UFMC has been evaluated using constellation shaping proposed for ATSC 3.0. Gaussian noise only and TU6 channel are used to highlight respectively NUCs performance and UFMC/NUCs performance. We evaluated SNR gain of NUCs compared with both DVB-T2/OFDM and DVB-T2/UFMC. Simulation results shown that with 2D-NUCs, 1.3 dB SNR gains can be achieved in DVB-T2 using gaussian noise with both OFDM and UFMC. Furthermore, OFDM has been substituted by UFMC and the gain achieved when compared to OFDM/QAM is about 1.2 dB at a BER of 3.10^{-3} in TU6 channel. These results allow to give some trends about application of 5G waveform UFMC and NUCs jointly in DVB-T2 system. However, the use of this constellation shaping requires the 2D demapper which increases complexity with the constellation order due to the In-phase (I) and Quadrature (Q) component independently optimized.

Nevertheless, many complexity reduction algorithms such as sub-region demapping, sphere demapping proposed in literature can be implemented in the receiver in order to exploit these performance gains. These algorithms are based either on the reduction of the number of Euclidean distance to compute or the number of operators of high complexity of realization used in the reduction.

Future works could be done by exploring topics such as:

- The use of other performance evaluation tools like Modulation Error Ratio (MER) and Error Vector Magnitude (EVM).
- The joint use of NUCs and rotated constellation in order to better improve DVB-T2 BICM capacity.
- The impact of Carrier Frequency Offset (CFO) on UFMC/NUC in DVB-T2.
- The implementation of low complexity demapping algorithm when NUCs and Signal Space Diversity (SSD) technique are used together.
- The complexity evaluation of UFMC/NUC and OFDM/QAM in DVB-T2.

Acronyms list

ATSC 3.0 Advanced Television Systems Committee, third generation. 2
AWGN Additive White Gaussian Noise. 2, 4, 8
BCH Bose-Chaudhuri-Hocquenghem. 9
BER Bit Error Rate. 1
BICM Bit Interleaved Coding Modulation. 2
BP Belief Propagation. 9
CFO Carrier Frequency Offset. 17
CP Cyclic Prefix. 2, 3
CP-OFDM Cyclic Prefix - Orthogonal Frequency Division Multiplexing. 1

CR Code Rate. 1, 10
DVB-NGH Digital Video Broadcasting - Next Generation Handheld. 2, 9
DVB-T Digital Video Broadcasting-Terrestrial, first generation. 1, 2, 8
DVB-T2 Digital Video Broadcasting-Terrestrial, second generation. 1, 2, 10
ETSI European Telecommunications Standards Institute. 8
EVM Error Vector Magnitude. 17
FBMC Filter Bank MultiCarrier. 3
FEC Forward Error Correction. 2, 9, 10
ICI InterCarrier Interference. 4
IFFT Inverse Fast Fourier Transform. 7
LDPC Low Density Parity Check. 9–11
LTE Long Term Evolution. 3
MER Modulation Error Ratio. 17
MI Mutual Information. 5
NUCs Non Uniform Constellations. 2
OFDM Orthogonal Frequency Division Multiplexing. 9, 18
OOB Out Of Band. 7
PAM Pulse Amplitude Modulation. 6
PDP Power Delay Profile. 10
PSD Power Spectral Density. 4, 8
QAM Quadrature Amplitude Modulation. 2, 4, 5
RMS Root Mean Square. 10
SLL Side Lobe Level. 7
SNR Signal to Noise Ratio. 1–3, 5
SSD Signal Space Diversity. 17
TDL Tapped Delay Line. 10
TU6 Typical Urban 6. 1, 10
TV TeleVision. 3
UFMC Universal Filtered MultiCarrier. 1, 3
UHD Ultra High Definition. 3

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