Pilot configuration optimization for ATSC 3.0

Eduardo Garro, Jordi Joan Gimenez, Sung Ik Park,
and David Gomez-Barquero

***Abstract*—The next-generation U.S. Digital Terrestrial Television (DTT) standard ATSC 3.0 allows a higher flexibility compared to the previous state-of-the-art DTT standard, DVB-T2 (Digital Video Broadcasting - Terrestrial 2nd Generation). This higher flexibility allows broadcasters to select the configuration that better suits their needs, looking for a performance and/or capacity increase of the services (either a single type of service or more).**

In the particular case of pilot patterns, whereas DVB-T2 provides 8 different patterns with a unique pilot amplitude, ATSC 3.0 expands up to 16, with 5 different amplitudes for each one. The impact of the pilot pattern and amplitude for ATSC 3.0 has not been evaluated yet. Thus, this paper is focused on the pilot configuration optimization for time and power multiplexing mode, TDM and LDM respectively, of ATSC 3.0. The selection of the optimum pilot configuration is not straightforward. On the one hand, the pilots must be sufficiently dense to follow channel fluctuations. On the other hand, as long as pilot density is increased, more data overhead is introduced. Moreover, this selection is particularly essential in LDM mode, because the LDM implementation in ATSC 3.0 requires that both layers must share all the waveform parameters, including pilot pattern configuration. In addition, there is an error proportional to the channel estimate of the top layer that affects to the lower layer.

***Index Terms*—ATSC 3.0, terrestrial broadcasting, channel estimation, pilot pattern, Layered Division Multiplexing (LDM).**

I. Introduction

THE Advanced Television System Committee (ATSC) has released the next-generation U.S. Digital Terrestrial Television (DTT) standard, known as ATSC 3.0 [1]. It outperforms current terrestrial broadcasting state-of-the-art standard, DVB-T2 (Digital Video Broadcasting - Terrestrial 2nd Generation) [2] increasing the flexibility to broadcasters. It provides a higher spectral efficiency and extends into a wider operating range in terms of Signal-to-Noise Ratio (SNR) [1].

The selection of the transmission configuration that guarantees the maximum capacity (data-rate) for the desired coverage (robustness) is the main planning goal of a broadcaster. The direct approach is to select the appropriate Modulation and Coding rate (ModCod) that satisfies these constraints [3]. For such case, ATSC 3.0 provides a larger granularity in SNR ratio, and improves the performance by using new Low-Density Parity Check (LDPC) codes [4] and Non-Uniform Constellations (NUC) [5]. In particular, there are 2 LDPC code lengths (16200 and 64800 bits) in both DTT standards, but whereas DVB-T2 allows 6 code rates and 4 modulation orders, in ATSC 3.0 there are 12 code rates (from 2/15 to 13/15) and 6 modulation orders (from QPSK to 4096QAM). Hence, while DVB-T2 offers a performance ranging from 1 to 22 dB SNR under AWGN channel conditions, ATSC 3.0 provides a performance ranging from -6.2 dB to 32 dB.

Regarding multiplexing modes, whereas DVB-T2 offers Time Division Multiplexing (TDM) to carry services aimed at different reception conditions, ATSC 3.0 supports three options, time, frequency and a new power multiplexing mode, known as Layered Division Multiplexing (LDM) [6]. In LDM, the transmitted signal consists of two independent signals, namely layers, superimposed together by assigning different power to each one, according to the Injection Level (Δ). Thus, whereas TDM mode reduces the capacity of the multiplexed services (Phyisical Layer Pipes, PLP) maintaining the same SNR threshold, LDM maintains the same capacity, but in return it modifies the SNR threshold.

ATSC 3.0 has also increased the flexibility of the waveform generation parameters, i.e. time interleaving, Scattered Pilot Pattern (SP), Fast-Fourier Transform (FFT) and Guard Interval (GI). Time interleaving length has been increased by using a sheer convolutional TI (CTI). In addition, ATSC 3.0 provides up to 16 different SP, with up to 5 different amplitudes for each one, known as pilot boostings. It has also increased the FFT/GI combinations. There are 12 GI lengths (from 27 to 700 μs) and 3 FFT sizes (8K, 16K and 32K).

Different studies have shown the impact of the TI, FFT, and GI in ATSC 3.0 [7], [8], but the impact of SP has not been evaluated yet. Hence, the proposed paper is focused on the pilot configuration optimization for TDM and LDM modes of ATSC 3.0. It could be assumed that the SP must be sufficiently dense to follow channel fluctuations. Nevertheless, at the same time, as long as pilot density is increased, more data overhead is introduced. In addition, the possibility of using 5 pilot boostings for each SP makes the selection even more tricky. In another vein, it should be noted that the LDM implementation in ATSC 3.0 requires that both layers must share all the waveform parameters [9], including SP, in order to limit receiver's complexity. Thus, a trade-off between the optimum configuration for the mobile layer (higher robustness by a denser SP), and for the fixed layer (higher capacity by a sparser SP) arises.

The paper is structured as follows: Section II overviews the ATSC 3.0 transmitter and receiver waveform parameters. The impact in performance due to the channel estimation at receiver is presented in Section III. Section IV describes the methodology and the simulation setup followed for perfor-

This work was partially supported by the Institute for Information & communications Technology (IITP) grant funded by the Korea government (MSIP) (R0101-15-294, Development of Service and Transmission Technology for Convergent Realistic Broadcast), and by the Ministerio de Educación y Ciencia, Spain (TEC2014-56483-R), co-funded by European FEDER funds.

E. Garro, J.J. Gimenez and D. Gomez-Barquero are with the Universitat Politecnica de Valencia, Valencia, 46022, Spain (e-mail: {edgarcre,jorgigan,dagobar}@iteam.upv.es).

S.I. Park is with the Broadcasting System Department, ETRI, Daejeon, Korea (e-mail: psi76@etri.re.kr).

mance evaluation. The results assessed by physical layer simulations are presented in Section V. Finally, the conclusions are summarized in Section VI.

II. ATSC 3.0 Waveform Overview

Fig. 1 presents the ATSC 3.0 transmitter block diagram. The input stream passes through a BICM chain. Next, the waveform processing is performed. The selection of the configuration for every waveform parameter leads to different capacity - robustness trade-offs. A brief explanation of each one is presented next.

- *Time Interleaver (TI)*: increases the robustness of the system against impulsive noise and time selective fading thanks to the time diversity introduced. However, it increases the demodulation latency and limits the maximum data rate of the service [10], [11].
- *Frequency Interleaver (FI)*: Increases frequency diversity. It is performed throughout the complete channel bandwidth on a per OFDM symbol basis to separate burst errors in the frequency domain [12].
- *Scattered Pilot Pattern (SP)*: Pilots are carriers that do not contain net information but whose value is known by the receiver in order to get a proper channel estimation at pilot positions. Next, the channel estimates at data cells are obtained by interpolation. SP must be sufficiently dense to follow channel fluctuations in both frequency (D_x) and time (D_y) [13]. More details are given in Section III.
- *Inverse Fast Fourier Transform (IFFT)*: OFDM systems, as ATSC 3.0, are very sensitive to inter-carrier interference (ICI), which depends on the FFT size. The smaller the FFT size, the more ICI that the system can withstand. ATSC 3.0 has adopted three different FFT sizes (8, 16, and 32k).
- *Guard Interval (GI)*: GI must be, at least, equal to the length of the multipath channel in order to limit intersymbol interference (ISI). Thus, it is also important in Single Frequency Network (SFN) topologies. As long as GI is increased, the longer the SFN distances allowed. However, it also increases the overhead. ATSC 3.0 has adopted twelve GI lengths. Table I presents the duration of guard intervals allowed for each FFT size, with their corresponding overheads.

Fig. 1 also illustrates the processing when LDM mode is used. If this multiplexing mode is enabled, grey blocks in the figure are also needed. In such case, there are two input streams. The robust one, passes through a Core Layer BICM (CL BICM). The second input stream, providing a high data rate service and known as Enhanced Layer (EL), passes through a second and independent EL BICM chain. Both layers are then added by assigning a Δ dB power reduction to the EL with respect to the CL. Last, waveform processing is performed. As it can be seen, the waveform processing is common for both LDM layers and, hence, channel estimation is performed only once at receivers. As each layer is intended for different reception conditions, the common waveform parameters restriction leads LDM to additional commitments regarding capacity - robustness trade-offs.

Table I
ATSC 3.0 GI duration and overheads (6 MHz bandwidth)

GI Pattern	Samples	Duration (μs)	8k FFT Ov.(%)	16k FFT Ov.(%)	32k FFT Ov.(%)
GI1_192	192	27.8	2.3	1.2	0.6
GI2_384	384	55.5	4.7	2.3	1.2
GI3_512	512	74.1	6.3	3.1	1.6
GI4_768	768	111.1	9.4	4.7	2.3
GI5_1024	1024	148.1	12.5	6.3	3.1
GI6_1536	1536	222.2	18.8	9.4	4.7
GI7_2048	2048	296.3	25	12.5	6.3
GI8_2432	2432	351.9	-	14.8	7.4
GI9_3072	3072	444.4	-	18.8	9.4
GI10_3648	3648	527.8	-	22.3	11.1
GI11_4096	4096	592.6	-	25	12.5
GI12_4864	4864	703.7	-	-	14.8

III. Channel Estimation in ATSC 3.0

Since the radio channel is frequency selective and time-varying in wireless communication systems, a dynamic estimation of the channel is needed. Channel estimation is performed by inserting scattered pilot subcarriers into the OFDM symbols. The pilot-based channel estimation consists of different algorithms to estimate the channel at the scattered pilots that varies among receivers. An interpolation of the channel across data cells is next needed. This interpolation could be frequency-only or a 2-dimensional time/frequency interpolation, which depends on the SP assumed. Therefore, there are two terms that affect the good or bad estimation of the channel frequency response (CFR): scattered pilot configuration used by the broadcaster, and the channel estimator employed by receivers.

A. Scattered Pilot Configuration assumed at Transmitters

The scattered pilot configuration is divided into two parameters: scattered pilot (SP) pattern that defines the amount and location of the scattered pilots inside the ATSC 3.0 frames, and the pilot boosting that defines their amplitude with respect to data carriers. There are some considerations for each parameter.

1) Scattered Pilot Pattern: As the CFR varies with both time and frequency, the SP is characterized by two terms, the frequency separation of pilots, D_x, and the length of the SP in OFDM symbols, D_y. Fig. 2 illustrates the pilot distribution over 8 OFDM symbols, assuming an SP with $D_x = 3$ and $D_y = 2$. The 16 different SP patterns of ATSC 3.0 are extracted from 8 D_x values (3, 4, 6, 8, 12, 16, 24, and 32) and from 2 D_y values (2, 4). It could be assumed that the densest SP provides the most accurate channel estimation. Nevertheless, at the same time it introduces the highest data rate overhead. Table II presents the SP with their corresponding overhead in ATSC 3.0.

The values of D_x and D_y must be selected according to the CFR characteristics. Their implications are presented next.

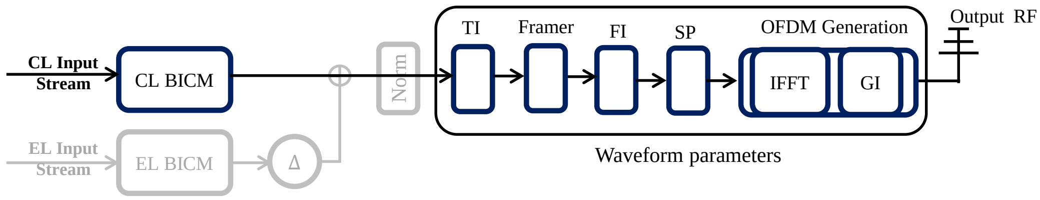


Figure 1. ATSC 3.0 transmitter block diagram. Grey blocks are only enabled when LDM mode is used. Each LDM layer passes through an independent BICM process. They are then aggregated before, so that they share the same TI length, SP, FFT size and GI length. At the receiver, only one channel estimation for both layers is performed.

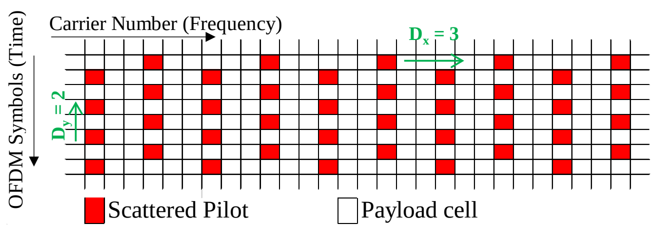


Figure 2. Scattered Pilot Pattern SP3_2 ($D_x = 3$, $D_y = 2$).

Table II
ATSC 3.0 Scattered Pilot Patterns (SP)

SP	D_x	D_y	Ov. (%)	SP	D_x	D_y	Ov. (%)
SP3_2	3	2	16.7	SP8_4	8	4	3.1
SP4_2	4	2	12.5	SP16_2	16	2	3.1
SP3_4	3	4	8.3	SP12_4	12	4	2.1
SP6_2	6	2	8.3	SP24_2	24	2	2.1
SP4_4	4	4	6.3	SP16_4	16	4	1.6
SP8_2	8	2	6.3	SP32_2	32	2	1.6
SP6_4	6	4	4.2	SP24_4	24	4	1.0
SP12_2	12	2	4.2	SP32_4	32	4	0.8

Table III
Scattered Pilot pattern to be used for each allowed FFT and GI combination

GI	8k FFT	16k FFT	32k FFT
GI1_192	SP32_2, SP32_4, SP16_2, SP16_4	SP32_2, SP32_4	SP32_2
GI2_384	SP16_2, SP16_4, SP8_2, SP8_4	SP32_2, SP32_4, SP16_2, SP16_4	SP32_2
GI3_512	SP12_2, SP12_4, SP6_2, SP6_4	SP24_2, SP24_4, SP12_2, SP12_4	SP24_2
GI4_768	SP8_2, SP8_4, SP4_2, SP4_4	SP16_2, SP16_4, SP8_2, SP8_4	SP32_2, SP16_2
GI5_1024	SP6_2, SP6_4, SP3_2, SP3_4	SP12_2, SP12_4, SP6_2, SP6_4	SP24_2, SP12_2
GI6_1536	SP4_2, SP4_4	SP8_2, SP8_4, SP4_2, SP4_4	SP16_2, SP8_2
GI7_2048	SP3_2, SP3_4	SP6_2, SP6_4, SP3_2, SP3_4	SP12_2, SP6_2
GI8_2432	-	SP6_2, SP6_4, SP3_2, SP3_4	SP12_2, SP6_2
GI9_3072	-	SP4_2, SP4_4	SP8_2, SP3_2
GI10_3648	-	SP4_2, SP4_4	SP8_2, SP3_2
GI11_4096	-	SP3_2, SP3_4	SP6_2, SP3_2
GI12_4864	-	-	SP6_2, SP3_2

a) Separation between pilot carriers (D_x): The last path that can contribute constructively and so does can be correctly equalized by a receiver depends on the delay spread, i.e. on the coherence bandwidth. According to the Nyquist sampling theorem, this limit when both time and frequency interpolation are implemented [13] is estimated as:

$$T_n = \frac{T_U}{D_x} \tag{1}$$

where T_n represents the Nyquist limit and T_U is the useful symbol duration.

For ATSC 3.0 it has been assumed that receivers are only able to correctly equalized those signals with echoes up to 75% or 89% of Nyquist limit. That is, only those GIs which length is shorter than 75% or 89% of T_n are allowed. This ratio is also known as Guard Utilization Ratio (GUR). It can be seen that as it is increased with the useful symbol duration and reduced with the SP, the Nyquist limit restricts the GIs allowed for each SP.

b) Length of pattern in symbols (D_y): If the transmitted signal is expected to be received in mobility conditions, it should be considered that the channel will vary across OFDM symbols. Thus, the pilots need to be inserted at some ratio (D_y) that is function of coherence time, which is related with the Doppler shift limit. As symbols occur at the rate $f_S = 1/(T_U + T_G)$ Hz, the Doppler shift limit for frequency channel variation, f_D, that can be measured is:

$$f_D = \frac{\pm 1}{2D_y \cdot (T_U + T_G)} Hz \tag{2}$$

where T_G is the GI length in time.

From the expression it can be observed that the smaller the D_y, the GI, and the FFT size, the higher the Doppler shift limit. Hence, in order to support high speeds even with 32k FFT size, $D_y = 4$ was discarded for this FFT size.

As summary, taking the Nyquist (D_x) and Doppler (D_y) limits into account, the different FFT/GI-SP combinations allowed in ATSC 3.0 are presented in Table III.

2) Pilot Boosting: The other pilot parameter that affects the performance is the pilot boosting. In order to provide a reasonable trim, the equalized data Signal-to-Noise Ratio metric (SNR_{Eq}) was considered as a good metric for obtaining the best overall performance taking into account the different

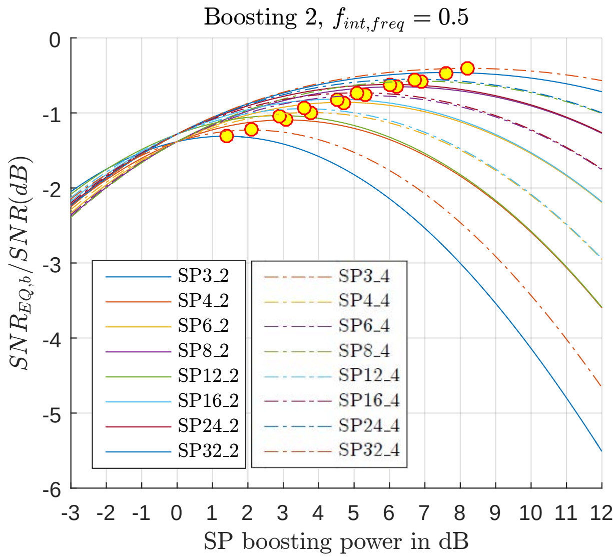


Figure 3. Equalized SNR performance and optimum boosting value for all SP patterns assuming a $f_{int,freq} = 0,5$

Table IV
ATSC 3.0 SCATTERED PILOT BOOSTING (dB)

	Boosting b (dB)				
SP	**0**	**1**	**2**	**3**	**4**
SP3_2	0	0	1.40	2.20	2.90
SP3_2	0	1.40	2.90	3.80	4.40
SP4_2	0	0.60	2.10	3.00	3.60
SP4_4	0	2.10	3.60	4.40	5.10
SP6_2	0	1.60	3.10	4.00	4.60
SP6_4	0	3.00	4.50	5.40	6.00
SP8_2	0	2.20	3.80	4.60	5.30
SP8_4	0	3.60	5.10	6.00	6.60
SP12_2	0	3.20	4.70	5.60	6.20
SP12_4	0	4.50	6.00	6.90	7.50
SP16_2	0	3.80	5.30	6.20	6.80
SP16_4	0	5.20	6.70	7.60	8.20
SP24_2	0	4.70	6.20	7.10	7.70
SP24_4	0	6.10	7.60	8.50	9.10
SP32_2	0	5.40	6.90	7.70	8.40
SP32_4	0	6.70	8.20	9.10	9.70

receiver equipments. It is estimated as:

$$SNR_{EQ,b} = \frac{\sigma_s^2 \times k}{\sigma_N^2 + \sigma_N^2 \times f_{int}/b} = SNR \times \frac{k}{1 + f_{int}/b} \quad (3)$$

where σ_s^2 is the data variance, σ_N^2 is the noise variance, b is the SP boosting factor, k is the power normalization ($k = D_x{\cdot}D_y/(D_x{\cdot}D_y{-}1){+}b$), and $f_{int} = f_{int,time} \times f_{int,freq}$ is the noise reduction factor by interpolation. As f_{int} varies depending on receiver manufacturers, the five different boosting values of ATSC 3.0 (from 0 to 4) are extracted from $f_{int,freq} = \{0, 0.25, 0.5, 0.75, 1\}$ values. Fig. 3 presents the process of how to select the optimum boosting value for each SP with $f_{int,freq} = 0.5$. The pilot boosting for the SP patterns of ATSC 3.0 are listed in Table IV.

Table V
ATSC 3.0 DATA POWER REDUCTION (dB)

	Δ_{BP} (dB)				
SP	**0**	**1**	**2**	**3**	**4**
SP3_2	0	0	0.26	0.46	0.65
SP3_2	0	0.13	0.34	0.49	0.60
SP4_2	0	0.08	0.32	0.51	0.65
SP4_4	0	0.17	0.34	0.46	0.58
SP6_2	0	0.16	0.37	0.51	0.64
SP6_4	0	0.18	0.32	0.43	0.52
SP8_2	0	0.18	0.37	0.49	0.61
SP8_4	0	0.17	0.30	0.40	0.47
SP12_2	0	0.20	0.34	0.46	0.54
SP12_4	0	0.17	0.27	0.35	0.41
SP16_2	0	0.19	0.32	0.41	0.49
SP16_4	0	0.16	0.25	0.32	0.37
SP24_2	0	0.18	0.28	0.36	0.43
SP24_4	0	0.14	0.22	0.28	0.32
SP32_2	0	0.17	0.26	0.33	0.39
SP32_4	0	0.13	0.19	0.24	0.28

On the other hand, although higher pilot boosting improves channel estimation accuracy, it also decreases the power of the data carriers, and so does the overall SNR of the system. This data cell power reduction is approximated as an SNR reduction and can be estimated as:

$$\Delta_{BP}\,(\text{dB}) = 10 \cdot \log_{10} \frac{N_{data} + N_{SP} \cdot A_{SP}^2}{N_{data} + N_{SP}} \quad (4)$$

where N_{data} refers to number of data cells per OFDM symbol, N_{SP} refers to number of scattered pilots per OFDM symbol, and A_{SP} refers to pilot boosting relative to data cells. The corresponding data cell power reduction for each pilot boosting and SP of ATSC 3.0 is listed in Table V[1].

B. Channel Estimator implemented at Receivers

There are different techniques to estimate the CFR. The use of one or another estimator by the receiver has a significant impact on the expected performance.

Channel estimation in OFDM is a two dimensional (2-D) problem that varies with time and frequency. 2-D methods could be applied to estimate the channel from pilots. However, due to the computational complexity of 2-D estimators, it is commonly simplified by a cascade of two 1-D problems. In such case, complexity reductions can be achieved with reasonable performance loss [14].

Assuming a two 1-D estimator, the first step is to estimate the channel at pilot positions. The simplest technique is the Least Square (LS) estimation, which does not exploit the correlation of the channel across frequency and time [15]. Considering the system model:

$$Y[n,k] = X[n,k]H[n,k] + N[n,k] \quad (5)$$

[1]Continual and edge pilots have not been considered in Equation (4) and Table V

where $X[n,k]$ is the data, $H[n,k]$ is the CFR, and $N[n,k]$ is the AWGN noise at k-th subcarrier of the n-th OFDM symbol. The LS estimation of $H[n,k]$ is:

$$\widehat{H}[n,k] = \frac{Y[n,k]}{X[n,k]} = H[n,k] + \frac{N[n,k]}{X[n,k]} \tag{6}$$

Other estimation techniques such as Maximum Likelihood (ML) or Linear Minimum Mean Square Error (LMMSE) provide more accurate estimates. Nevertheless, their complexity is significantly increased as they require knowledge of channel statistics.

The second step in the CFR estimation is the interpolation across the scattered pilot carriers in order to obtain $\widehat{H}$ on data carriers. In this step, the linear interpolation at data positions has the lowest complexity. Nevertheless, it provides the poorest performance for channels with high frequency-selectivity, i.e., channels with large delay spread [16]. More accurate estimates can be obtained by applying different smoothing filters, such as Wiener filtering [17].

Thus, as it has been shown there are different aspects regarding the channel estimation applied at reception that affects to the performance. It can be seen that there will be an error introduced by the non-ideal estimation. MSE is usually considered as a performance measure of channel estimates, and it is defined as $MSE = E\|H[n,k] - \widehat{H}[n,k]\|^2$. This error will depend on the noise power, pilot boosting and interpolation error. When LDM is used, a fine channel estimation is even more crucial because of an additional error, which is described in next section.

C. Channel Estimation in LDM

As it has been explained, LDM mode requires of the CL signal cancellation in order to obtain the EL. If the CL signal has not been properly obtained, a cancellation error appears. This error is known as Cross-Layer Interference (CLI). The CLI also depends on an accurate channel estimation, so that the need of a precise CFR estimation in LDM is even higher than for non-LDM systems. The estimation of the CLI is presented next.

Assuming a transmitted LDM signal as:

$$X_{LDM}[n,k] = X_{CL}[n,k] + X_{EL}[n,k] \tag{7}$$

where $X_{CL}[n,k]$ and $X_{EL}[n,k]$ denote the CL and EL transmitted data at k-th subcarrier of n-th OFDM symbol, respectively. As the power level of the sum of both layers must be normalized, the power level of each layer is defined by the injection level (Δ), according to:

$$P_{CL} = \frac{10^{\frac{\Delta}{10}}}{1+10^{\frac{\Delta}{10}}} \tag{8}$$

$$P_{EL} = \frac{1}{1+10^{\frac{\Delta}{10}}} \tag{9}$$

The LDM received signal is:

$$\begin{aligned} Y_{LDM}[n,k] &= Y_{CL}[n,k] + Y_{EL}[n,k] = \\ &(X_{CL}[n,k] + X_{EL}[n,k])H[n,k] + N[n,k] \end{aligned} \tag{10}$$

For the CL demodulation, the EL is treated as an additional interference of power P_{EL}. To decode the EL, the receiver has to cancel the CL first. From Equation (10) the EL can be estimated as:

$$\widehat{Y}_{EL}[n,k] = Y_{LDM}[n,k] - \widehat{X}_{CL}[n,k]\widehat{H} \tag{11}$$

where $\widehat{X}_{CL}$ represents the remodulated CL signal. As the EL is intended to provide high capacity services at high SNR, it can be assumed that the CL decoding is error free, that is $\widehat{X}_{CL}[n,k] = X_{CL}[n,k]$. Thus, the EL can be obtained as:

$$\begin{aligned} Y_{EL}[n,k] &= X_{CL}[n,k](H[n,k] - \widehat{H}[n,k]) + \\ &X_{EL}[n,k]H[n,k] + N[n,k] = \\ &CLI[n,k] + X_{EL}[n,k]H[n,k] + N[n,k] \end{aligned} \tag{12}$$

Assuming CLI as a AWGN noise, the CLI power can be estimated as:

$$P_{CLI} = MSE \cdot P_{X_{CL_{Rx}}} = MSE \cdot 10^{\Delta/10} \tag{13}$$

It should be observed, that CLI power is proportional to the channel estimation error (MSE) and the CL power. Although it was shown in different literature references [6] that this additional interference is almost negligible in comparison with the LL noise threshold, it has to be taken into account in channel estimation studies.

IV. Methodology and Simulation Setup

The performance of all the different studies is evaluated by means of physical layer simulations with a validated ATSC 3.0 software simulator. Despite the proposed paper is focused on the optimization of the SP for TDM and LDM modes of ATSC 3.0, the impact of other waveform parameters such as FFT size and TI length is provided first.

The different studies are structured as follows.

A. FFT size and TI length impact for TDM systems. As these parameters mainly relate to time-varying channels, the results are only obtained for mobile reception. The configurations adopted are:

- *Channel model:* TU-6 for Doppler shifts 11, 17, 22, 33, 44, 55, 83, and 111 Hz.
- *Pilot configuration:* SP3_2 with pilot boosting 2.
- *FFT and GI:* The 3 FFT sizes (8k, 16k, and 32k). The GIs are extracted from Table III and assuming SP3_2. To sum up, GI3_512 for 8k, GI5_1024 for 16k, and GI7_2048 for 32k.
- *TI lengths:* CTI of 512, 724, and 1024 convolutional rows. They approximately represent 50, 100, and 200 ms, respectively.

B. SP density and pilot boosting impact for TDM mode. The configurations assumed are:

- *Mobile channel model:* TU-6 for Doppler shifts 33 Hz and 55 Hz.
- *Fixed channel models:* Rice (DVB-F1) for a common fixed reception, and 0 dB echo (50% GI) as a way of characterizing an SFN.
- *TI length:* CTI of 724 rows, equivalent to 100 ms.

Table VI
SIMULATION CONFIGURATIONS FOR SP AND PILOT BOOSTING

SP	FFT 8k	FFT 16k	FFT 32k
SP3_2	GI7	GI11	GI9
SP4_2	GI6	GI10	-
SP6_2	GI5	GI8	GI7
SP8_2	GI4	GI6	GI6
SP12_2	GI3	GI5	GI5
SP16_2	GI2	GI4	GI4
SP24_2	-	GI3	GI3
SP32_2	GI1	GI2	GI2

- *Pilot configuration:* SP3_2, SP4_2, SP6_2, SP8_2, SP12_2, SP16_2, SP24_2, SP32_2 with all the pilot boostings. It can be noted that only SP with $D_y = 2$ are considered, as they are the only ones allowed for 32k FFT size.
- *FFT and GI:* 8k, 16k, and 32k for mobile reception. As the FFT size does not impact on performance for fixed reception, only 16k size has been assumed for this scenario, as it allows the use of every SP. The GIs used (extracted from Table III) are summarized in Table VI.

C. SP density and pilot boosting impact for LDM mode.

- An LDM injection level $\Delta = 4$ dB is assumed. This value distributes the total transmission power as $P_{CL} = 71.5\%$ and $P_{EL} = 28.5\%$.
- The rest of parameters are configured equally as for TDM.

Other parameters common in all the studies are:

- 6 MHz bandwidth (BW) signal.
- Mobile transmission mode: QPSK 4/15 (data rate of 3.1 Mbps)
- Fixed transmission mode: 64NUC 10/15 (data rate of 23.8 Mbps)
- All simulations are conducted under realistic channel estimation. An LS estimator for the scattered pilot carriers with a two 1-D interpolator is assumed. The interpolation is constituted by a linear time interpolator for obtaining the CFR at data carriers between OFDM symbols and a Wiener frequency interpolator for obtaining the CFR at data carriers of the same OFDM symbol.
- The results are obtained for a Bit Error Rate (BER) of 10^{-4}.

V. SIMULATION RESULTS

A. FFT size and TI depth impact in TDM systems

Fig. 4 presents the SNR threshold in dB at different speeds for 8k, 16k, and 32k FFT sizes and 50, 100, and 200 ms TI lengths. The figure shows that for pedestrian and very high speeds the system performance decreases. In the case of pedestrian reception the performance loss comes from the lack of time diversity, due to the large coherence time. For high speeds, the higher the FFT size the lower the Doppler limit, i.e. lower speeds are allowed. In particular, the Doppler limits for 8k, 16k and 32k, from (2), are 187 Hz, 92 Hz, and 50 Hz, respectively. For a carrier frequency $f_c = 600$ MHz these limits correspond to 335, 165, and 90 km/h approximately, which approximates to the limits in the figure.

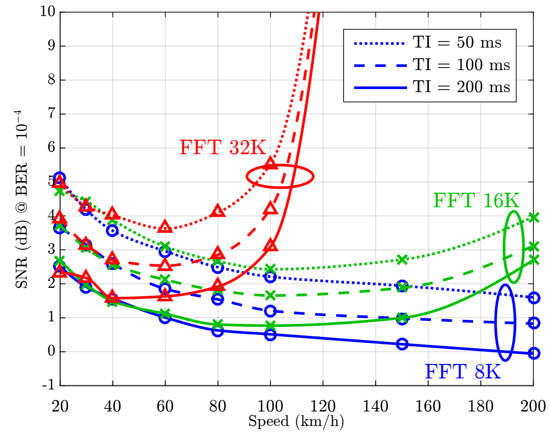


Figure 4. SNR threshold in dB for different FFT sizes and TI lengths at different speeds ($f_c = 600$ MHz). SP3_2 with pilot boosting 2 was assumed.

The same figure also shows that the gain introduced by the TI at pedestrian and vehicular speeds is around 1 dB for all the FFT sizes. However, when the receiver speed is increased to the ICI-limited zone, the benefits for using longer TI are minor.

As a conclusion, if the maximum planned speed is below the Doppler limit, that is, below the ICI-limited zone, the highest TI length is recommended. In the case of ATSC 3.0, the highest TI length is 1024 convolutional rows, which represents approximately 200 ms.

B. SP and Pilot Boosting impact for TDM systems

This section studies the impact of SP density and boosting on TDM systems for fixed and mobile reception.

1) Fixed roof-top scenario in TDM systems: Fig. 5 presents the SNR threshold obtained for the different SPs and pilot boostings for 16k FFT size.

Pilot density: It can be seen that the impact of the SP density is not significant. This behaviour occurs because the sparsest pattern already provides the minimum required frequency separation. Table VII shows that the Nyquist limit of each SP is always longer than the Rice or 0 dB echo channel delay spreads. Hence, the fact of using denser patterns hardly improves the performance. Moreover, it can lead to an slightly worse performance for pilot boostings higher than 0.

Pilot Boosting: It can be seen that as long as pilot boosting is increased, the overall performance decreases. This is because pilot boosting 0 already provides an accurate estimation, so that there is no need to use higher boostings. In such cases the SNR threshold is increased (see Table V) more than the reduction of the channel estimation error. This conclusion can also be assumed for denser SPs with the same pilot boosting. The sparsest one is enough, so that using a denser SP will reduce the SNR more than the channel estimation error.

Table VII
DELAY SPREADS FOR RICE AND 0 dB ECHO CHANNELS. FFT 16K

Channel	GI	Delay Spread	SP	Nyquist limit
Rice	*All*	5.42 μs	*Any*	$\geq$ 74 μs
0 dB echo (50% GI)	GI11	296.3 μs	SP3_2	790 μs
	GI10	263.9 μs	SP4_2	592 μs
	GI8	175.9 μs	SP6_2	395 μs
	GI6	111.1 μs	SP8_2	296 μs
	GI5	74.1 μs	SP12_2	197 μs
	GI4	55.5 μs	SP16_2	148 μs
	GI3	37.1 μs	SP24_2	98 μs
	GI2	27.8 μs	SP32_2	74 μs

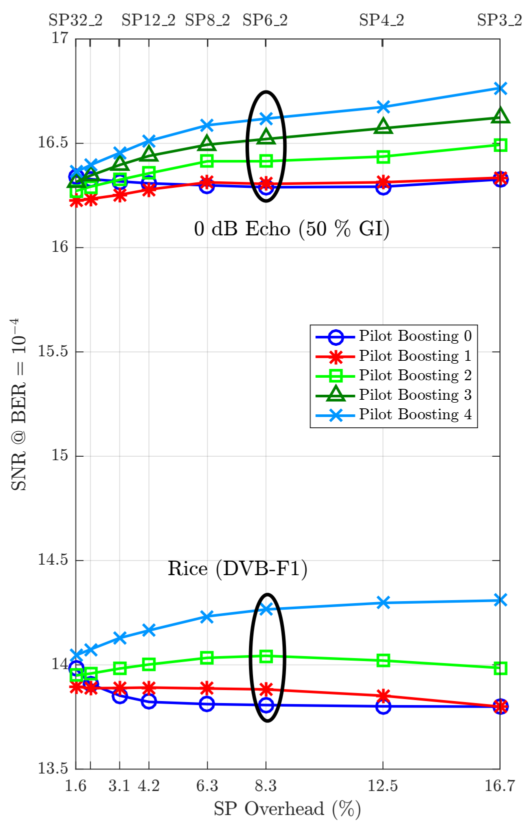


Figure 5. SP pattern and boosting impact on SNR performance for fixed reception (TDM).

In summary, it can be concluded that for TDM systems in fixed reception, an sparse SP with the minimum pilot boosting is good enough for obtaining an accurate channel estimation and a good performance.

2) Mobile scenario in TDM systems: In the case of mobile reception conditions, the results were obtained for Doppler shifts equal to 33 and 55 Hz (60 km/h and 100 km/h, respectively for $f_c = 600$ MHz). Fig. 6 illustrates the SNR threshold obtained for all the SP configurations for 33 Hz Doppler shift. As similar curves were obtained for the 55 Hz, they are not represented in the paper.

Pilot density: The fact of using denser SPs can provide meaningful gains with pilot boosting 0 (performance gains from SP32_2 to SP3_2 are 1.2 dB FFT 8k, 0.6 dB for FFT 16k, and 0.3 dB for FFT 32k). For the rest of the boostings the performance gains by increasing SP density are no longer noticeable (0.6 dB FFT 8k, 0.2 dB for FFT 16k, and -0.2 dB for FFT 32k from SP32_2 to SP3_2 approximately). Since the TU-6 channel delay spread is equal to 5 μs, which is again shorter than the Nyquist limit allowed by each FFT/SP, it can be considered that the selection of D_x is not critical as it occurred for fixed reception. On the other hand, it can be observed that the performance for FFT 32k in comparison with the other two FFT sizes is decreased. This performance loss is because 33 Hz is close to the Doppler limit of FFT 32k. Since this limit depends on D_y, and ATSC 3.0 should be able to demodulate in mobile reception conditions, the use of higher D_y values were not allowed for FFT 32k.

Pilot boosting: In this scenario, the best overall performance is achieved with pilot boosting 1. When pilot boosting is higher than 1, the same trend as in fixed reception can be observed, increasing pilot boosting decrease overall performance. Again, the same reason given for fixed reception is applied. The reduction on the channel estimation error by using higher pilot boosting is smaller than the associated SNR threshold increase it requires. Nevertheless, in this scenario, there is an slight performance gain from pilot boosting 0 to pilot boosting 1 that decreases with the SP density and is independent of the FFT size. Specifically, the performance gains for using boosting 1 instead of boosting 0 are 0.5 dB for all the FFT sizes when SP32_2 is used, 0.3 dB when SP16_2 is used, and 0 dB when SP3_2 is used.

In summary, the use of the pilot boosting not higher than 1 is recommended for mobile reception, provided a dense enough SP is used. As an specific recommendation, SP12_2 with boosting 1 could be considered the optimum SP because it offers almost the same performance as denser patterns but much less capacity overhead.

C. SP and Pilot Boosting impact for LDM systems

The same studies run for TDM systems were done for LDM with an injection level of $\Delta = 4$ dB. Same conclusions about channel estimation for the CL are expected, because in LDM the SPs are not affected by the EL. However, it should be studied the impact of CLI on the EL performance.

1) Fixed roof-top and mobile scenarios in a LDM system: Fig. 7 shows the CL SNR threshold for a Doppler shift of 33 Hz (60 km/h at $f_c = 600$ MHz). As expected, the results for mobile reception are almost the same to the ones obtained for TDM systems. Nonetheless, there are some considerations to highlight.

Pilot density: The performance gains by using denser SPs can be obtained for pilot boosting 0, as in TDM, but these gains are bigger (from SP32_2 to SP3_2 the SNR threshold is reduced 1.8 dB for FFT 8k, 1.1 dB for FFT 16k, and 1 dB for FFT 32k). For the rest of the boostings, the performance is practically the same for every SP, as in TDM systems.

Pilot boosting: Again, for not very dense SPs, pilot boosting 0 is not recommended. Moreover, with this multiplexing

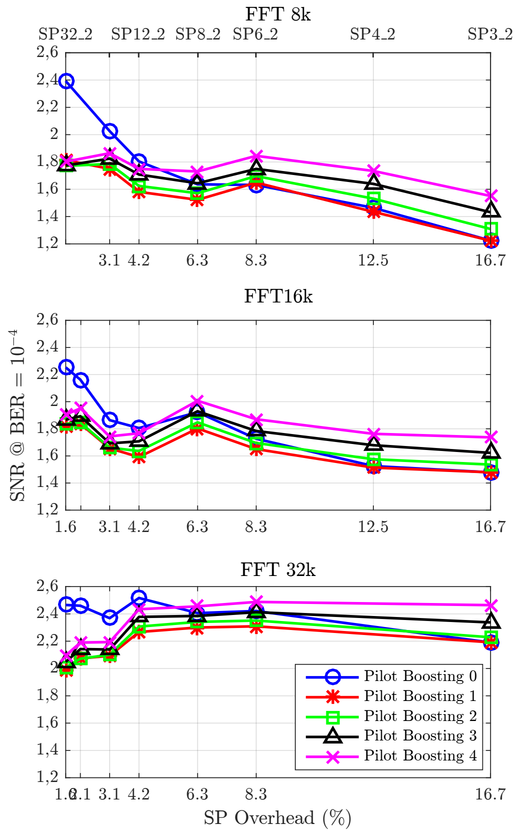


Figure 6. SP pattern and boosting impact on SNR performance for mobile reception at 60 km/h in TDM systems (f_c = 600 MHz).

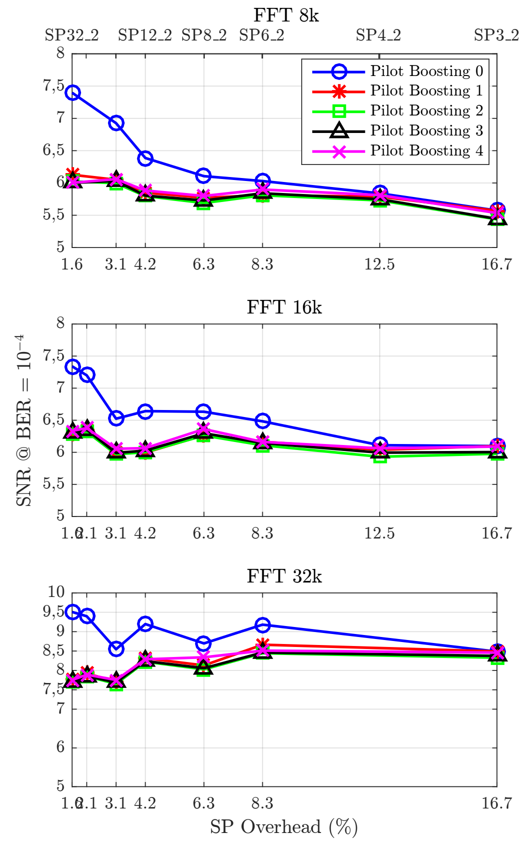


Figure 7. SP pattern and boosting impact on SNR performance for mobile reception at 60 km/h (CL LDM, $\Delta = 4$ dB).

mode, the performance gains from pilot boosting 0 to pilot boosting 1 are increased (the SNR threshold is reduced about 1.5 dB with SP32_2 for every FFT size). Another conclusion that can be extracted is that the performance of using pilot boosting higher than 1 is not decreased. In this case, the better estimation accuracy obtained by higher boostings compensates not only Δ_{BP}, but the LDM layers normalization power.

Regarding the EL performance, it can be observed that despite the CLI introduced, the results are very similar to TDM. Apart from the 5.5 dB SNR threshold increase inherent to LDM with $\Delta = 4$ dB[2]. Other considerations that can be highlihted:

Pilot density: As it has been said for the CL, the only difference with respect to TDM systems is that using denser SPs with pilot boosting 0 improves the performance in a greater proportion, because of the performance loss of the sparsest SPs.

Pilot boosting: As long as pilot boosting is increased, the overall performance decreases. This is because pilot boosting 0 already estimates the CFR accurately.

Although the CLI can be considered almost negligible, it has been mentioned that the main differences in channel estimation of LDM with respect to TDM systems are for the sparsest patterns with boosting 0. The reason comes from this additional CLI associated with LDM. In (13) it was shown that the CLI depends on two factors, the quality of the channel estimator, i.e. the MSE, and the LDM injection level, Δ. Fig. 9 shows the MSE for SP4_2, SP12_2, and SP32_2 (top figure) and the EL SNR threshold for different Δ (bottom). It can be observed at the top part of the figure that the highest MSE, and so does, the highest CLI, is introduced by SP32_2 with pilot boosting 0. In addition, when Δ is increased, more power is assigned to the CL, so that a higher CLI power is produced. It can be observed at the bottom part of the figure that as long as Δ is increased the performance gaps between SPs is increased as well. Taking into account all these considerations, in order to reduce CLI as much as possible, it is recommended not to use an sparse SP with pilot boosting 0, especially when Δ is higher than 3 dB.

VI. Conclusions

This paper evaluates the performance of the different pilot configurations allowed in ATSC 3.0 by physical layer simulations under realistic channel estimations. In contrast with DVB-T2, ATSC 3.0 offers up to 16 different scattered pilot patterns (SP), where each one could use up to 5 different pilot boostings. Thus, the selection of the optimum pilot configuration is not as obvious. The studies were done with

[2]The Enhanced Layer SNR threshold is approximately $\Delta + 10\log(1 + 10^{-\Delta/10})$ dB higher than the SNR without LDM

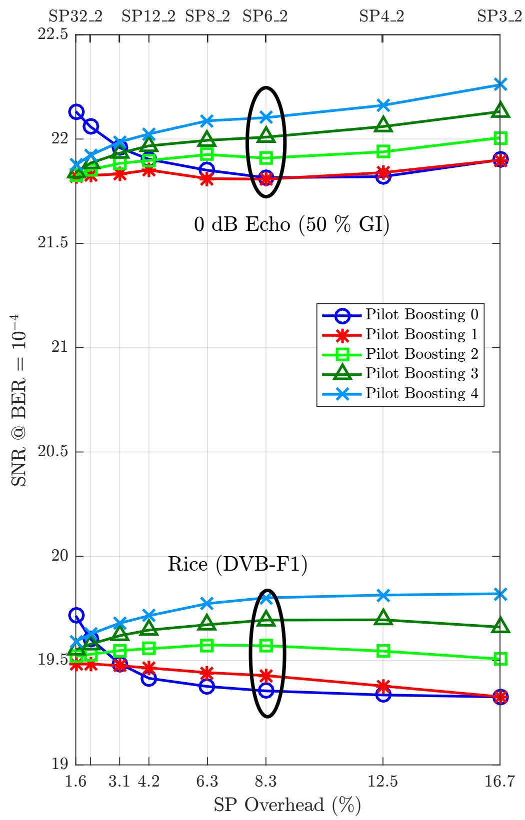


Figure 8. SP pattern and boosting impact on SNR performance for fixed reception (EL LDM, $\Delta = 4$ dB).

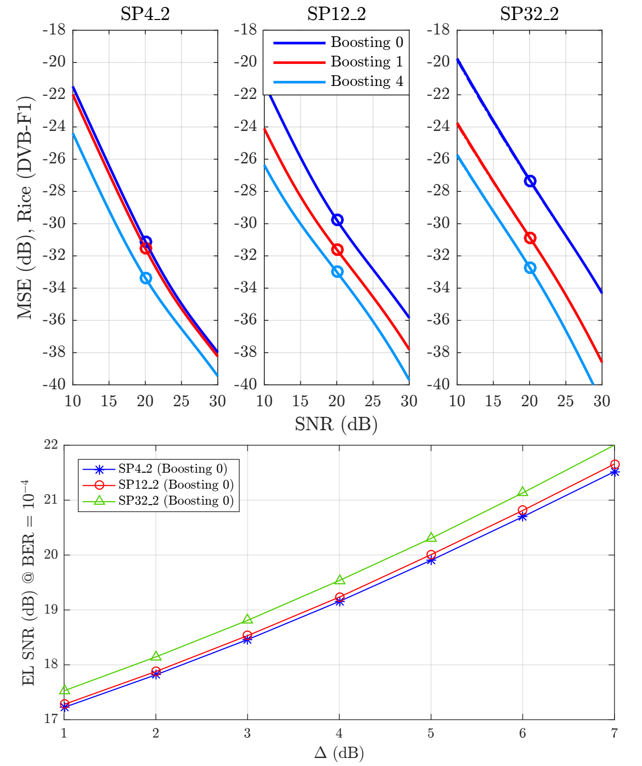


Figure 9. CLI depends on the MSE of Channel Estimation (top) and on the Δ (bottom). Rice fading channel. SP4_2, SP12_2, and SP32_2

different fading channels, Rice and 0 dB echo (50% GI) for fixed reception and TU-6 for mobile reception. The studies have been conducted for Time (TDM) and Layered Division Multiplexing (LDM) modes of ATSC 3.0.

From the simulation results obtained for TDM systems, it can be observed that for fixed reception conditions, the use of dense SP is not needed, as all of them accomplish with the Nyquist limit. Regarding pilot boosting, an accurate channel estimation can be obtained by using higher values. However, the use of high pilot boostings decreases overall performance. From the simulation results, it is observed that despite the greater accuracy, it is recommended the use of the minimum pilot boosting. Regarding mobile reception, the same conclusion applies for pilot boosting, but a denser SP than for fixed reception is needed. As an specific recommendation, SP12_2 with boosting 1 is proposed as the optimum pilot configuration. The overhead of this SP is only 4.2%, and it allows the use of SFN networks of distance between transmitters up to 45 km and 105 km for 16k FFT size and 32k FFT size, respectively.

On the other hand, LDM introduces a new challenge for broadcasters since its ATSC 3.0 implementation requires that both layers have to share all the waveform parameters, including the SP. Thus, a trade-off for the optimum SP configuration between robustness of the mobile layer and capacity of the fixed layer arises. Taking into account all these considerations, in order to reduce the inter-layer interference because of non-ideal channel estimation, it is recommended not to use an sparse SP with pilot boosting 0 for high injection levels.

References

[1] L. Fay, L. Michael, D. Gomez-Barquero, N. Ammar, and M. W. Caldwell, "An Overview of the ATSC 3.0 Physical Layer Specification," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 159 – 171, March 2016.

[2] I. Eizmendi *et al.*, "DVB-T2: The Second Generation of Terrestrial Digital Video Broadcasting System," *IEEE Trans. Broadcast.*, vol. 60, no. 2, pp. 258–271, June 2014.

[3] L. Michael and D. Gomez-Barquero, "Bit-Interleaved Coding and Modulation (BICM) for ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 181 – 188, March 2016.

[4] K. J. Kim *et al.*, "Low-Density Parity-Check Codes for ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 189 – 196, March 2016.

[5] N. S. Loghin *et al.*, "Non-uniform constellations for atsc 3.0," *IEEE Trans. on Broadcast.*, vol. 62, no. 1, pp. 197–203, March 2016.

[6] L. Zhang *et al.*, "Layered Division Multiplexing: Theory and Practice," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 216 – 232, March 2016.

[7] J. Montalban, M. Velez, I. Angulo, P. Angueira, and Y. Wu, "Large size FFTs over time-varying channels," *Electronics Letters*, vol. 50, no. 15, pp. 1102–1103, 2014.

[8] C. Regueiro *et al.*, "LDM Core Services: Indoor and Mobile Performance in ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 244 – 252, March 2016.

[9] S. I. Park *et al.*, "Low Complexity Layered Division Multiplexing System for ATSC 3.0," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 233 – 243, March 2016.

[10] P. Klenner *et al.*, "Physical Layer Time Interleaver for the ATSC 3.0 System," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 253 – 262, March 2016.

[11] P. F. Gomez, D. Gomez-Barquero, D. Gozalvez, A. Añorga, and M. Breiling, "Time Interleaving in DVB-NGH," in *Next Generation Mobile Broadcasting*, D. Gomez-Barquero, Ed. Boca Raton, FL, USA: CRC Press, 2013, pp. 355–388.

[12] M. Earnshaw, K. Shelby, H. Lee, Y. Oh, and M. Simon, "Physical layer framing for atsc 3.0," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 263–270, 2016.

[13] "Frequency and Network Planning Aspects of DVB-T2," European Broadcasting Union, Tech. Rep. 3348, Nov 2013.

[14] J. Montalban *et al.*, "Cloud Transmission: System Performance and Application Scenarios," *IEEE Trans. Broadcast.*, vol. 60, no. 2, pp. 170–184, June 2014.

[15] M. K. Ozdemir and H. Arslan, "Channel Estimation For Wireless OFDM Systems," *IEEE Communications Surveys Tutorials*, vol. 9, no. 2, pp. 18–48, 2007.

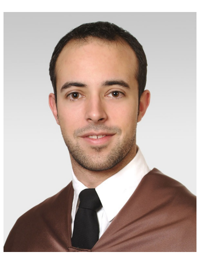
[16] S. Coleri, M. Ergen, A. Puri, and A. Bahai, "Channel estimation techniques based on pilot arrangement in ofdm systems," *IEEE Trans. Broadcast.*, vol. 48, no. 3, pp. 223–229, 2002.

[17] P. Hoeher, S. Kaiser, and P. Robertson, "Two-dimensional pilot-symbol-aided channel estimation by wiener filtering," in *1997 IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. 3, 1997, pp. 1845–1848 vol.3.

Eduardo Garro is a R&D at Mobile Communications Group (MCG) of the Institute of Telecommunications and Multimedia Applications (iTEAM) at Universitat Politècnica de València (UPV). He received a M.Sc. degree in Telecommunications engineering and a second M.Sc. degree in Communications and Development of Mobile Services from UPV, Spain in 2013 and 2014 respectively.

In 2012, he joined the iTEAM, working with Agencia Nacional del Espectro (ANE), the spectrum regulator of Colombia on the coexistence between DTT and 4G (LTE) technologies. He has also participated on the planning and optimization of DVB-T2 networks in Colombia.

He is currently pursuing his Ph.D. degree in terrestrial broadcasting. His research activities are focused on Layered Division Multiplexing (LDM) systems for broadcasting networks. He is a current member of the ATSC forum and has been actively participating during the ATSC 3.0 standardization process.



Jordi Joan Gimenez received a M.Sc. degree in Telecomunications engineering from the Universitat Politcnica de Valncia in 2010, a M. Sc. degree in Technologies, Systems and Communication Networks in 2011, and a Ph. D. in Telecommunication from UPV in 2015. During his doctoral studies, he was a Guest researcher at the Royal Institute of Technology (Stockholm, Sweden), and at Teracom AB (Stockholm, Sweden), the Swedish Digital Terrestrial TV operator. He has been a Post-Doctoral Guest Researcher at the Insitüt für Rundfunktechnik (Munich, Germany) in 2015.

Dr. Gimenez is a researcher at iTEAM-UPV, within the research group working on terrestrial broadcasting and the optimization of next-generation broadcast systems. He has participated in the standardization process of the next-generation handheld standard DVB-NGH, as well as in the DVB technical group working on the assessment of transmission technologies for the next generation terrestrial broadcasting (DVB TM-T MIMO Study Mission). Part of the results of his research has also been presented in the ATSC 3.0 standardization process, within the Waveform Ad-Hoc group.

His main research interests include the network planning of next-generation terrestrial broadcast networks, the characterization and modelling of propagation in the broadcast frequency bands, as well as the implementation of multiple RF channel aggregation technologies for an improved spectrum usage.

Sung Ik Park received the BSEE from Hanyang University, Seoul, Korea, in 2000 and MSEE from POSTECH, Pohang, Korea, in 2002, and Ph.D. degree from Chungnam National University, Daejeon, Korea, in 2011 respectively.

Since 2002, he has been with the Broadcasting System Research Group, Electronics and Telecommunication Research Institute (ETRI), where he is a senior member of research staff. His research interests are in the area of error correction codes and digital communications, in particular, signal processing for digital television. In addition, he received a Scott Helt memorial award of IEEE transaction on broadcasting in 2009, outstanding paper award of 2012 IEEE international conference on consumer electronics (ICCE), and best paper award of 2012, 2014, 2015 IEEE international symposium on broadband multimedia systems and broadcasting (BMSB) respectively.

He currently serves as an Associate Editor of the IEEE TRANSACTIONS ON BROADCASTING and distinguished lecturer of IEEE BROADCASTING TECHNOLOGY SOCIETY.

David Gomez-Barquero received the double M.Sc. degrees in telecommunications engineering from the Universitat Politecnica de Valencia (UPV), Spain, and the University of Gävle, Sweden, in 2004, the Ph.D. degree in telecommunications from the UPV in 2009; and he carried out a 2-year post-doc at the Fraunhofer Heinrich Hertz Institute, Germany.

He is a Senior Researcher (Ramon & Cajal Fellow) with the Institute of Telecommunications and Multimedia Applications, UPV, where he leads a research group working on next generation broadcasting technologies. Previously, he hold visiting research appointments at Ericsson Eurolab, Germany, the Royal Institute of Technology, Sweden, the University of Turku, Finland, the Technical University of Braunschweig, Germany, the Sergio Arboleda University of Bogota, Colombia, and the New Jersey Institute of Technology, USA.

Dr. Gomez-Barquero has been since 2008 actively participating in the digital television standardization, including DVB-T2, T2-Lite, DVB-NGH, and ATSC 3.0, acting as Vice-Chairman of the Modulation and Coding Ad-Hoc Group. He is the Editor of the book entitled *Next Generation Mobile Broadcasting* (CRC Press, 2013), and Associate Editor of the IEEE TRANSACTIONS ON BROADCASTING.