Layered Division Multiplexing with Multi Radio-Frequency Channel Technologies

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***Abstract*—The Advanced Television System Committee (ATSC) is to release the next-generation U.S. Digital Terrestrial Television (DTT) standard, known as ATSC 3.0. Layered Division Multiplexing (LDM) is one of the new physical layer technologies included in the standard, which enables the efficient provision of mobile and fixed services by superposing two independent signals with different power levels. ATSC 3.0 has also adopted a novel transmission technique known as Channel Bonding (CB), which splits the data of a service into two sub-streams that are modulated and transmitted over two radio-frequency (RF) channels.**

This paper investigates the potential use cases, implementation aspects and performance advantages, for combining LDM with channel bonding and also with the multi-RF channel technology Time Frequency Slicing (TFS), introduced in DVB-T2 (as an informative annex) and DVB-NGH, which allows distributing the data of a service across two or more RF channels by means of time slicing and frequency hopping.

***Index Terms*—Layered Division Multiplexing (LDM), Time Frequency Slicing (TFS), Channel Bonding (CB), ATSC 3.0, terrestrial broadcasting.**

I. Introduction

THE Advanced Television System Committee 3rd generation (ATSC 3.0) digital terrestrial television (DTT) standard [1], [2] introduces new transmission techniques with respect to the current state-of-the-art DTT technology, Digital Video Broadcasting - Terrestrial Second Generation (DVB-T2) [3], to increase system performance and spectrum flexibility. The efficient simultaneous provision of mobile and fixed services to users, as well as an increased throughput to deliver high quality services such as Ultra High Definition Television (UHDTV) are primary targets of the new system.

Power-based Layered Division Multiplexing (LDM) [4] is one of such novel technologies. In LDM, the transmitted signal consists of two independent signals (layers) superimposed together by assigning different power to each layer. With this, a robust layer carries service to mobile receivers while a high capacity layer is intended to transmit services to fixed users. LDM can outperform traditional solutions for the delivery of fixed and mobile services based on Time Division Multiplexing (TDM) [5], [6], such as the use of physical layer pipes (PLPs) or future extension frames (FEFs) in the T2-Lite profile in DVB-T2 [7], or Frequency Division Multiplexing (FDM), as implemented in Integrated Services Digital Broadcasting - Terrestrial (ISDB-T) [8]. With LDM, each layer uses the full radio-frequency (RF) bandwidth and transmission time, leading to a higher spectral efficiency. This additional gain can be translated into an increased robustness (or coverage gain) for the same service data rate, or a capacity gain [9]. The implementation of this technique requires increased complexity. LDM mobile receivers can be really simple since they only demodulate the robust layer. Receivers decoding the high capacity layer require the previous cancellation and removal of the robust layer. Furthermore, the implementation of LDM in ATSC 3.0 has been limited so that many components are shared between the two layers [10]. On the other hand, the optimum transmission parameters cannot be independently selected per layer, what drives to a trade-off between robustness and capacity.

Additional spectral efficiency increase by multi-RF channel technologies was also discussed during ATSC 3.0 standardization process. In particular, two multi-RF channel variants were evaluated: Channel Bonding (CB), which basically consists of splitting service data across two RF channels [11], [12], and Time Frequency Slicing (TFS) [13], that transmits data in a slot-by-slot manner by frequency hopping across an RF-Mux of two or more RF channels (in practice, up to 6) [13]. The main advantages of these two techniques are, basically, capacity and coverage gains. CB enables services that exceed the data rate offered by a single RF channel. Moreover, it can also provide advantages in combination with scalable high-efficient video coding (SHVC), as well as LDM does [14]. Both TFS and CB also lead to an almost ideal StatMux (Statistical Multiplexing) since it is performed with a large number of services. Improved RF performance can be exploited by means of an increased frequency diversity potentially over hundreds of MHz by using inter-RF frequency interleaving. This can be translated into a coverage gain for the reception of all services within a RF-Mux, since the reception of a service does not only depend on the quality conditions of a single RF channel. A uniform distribution of the encoded data across two RF channels might allow the recovery of data even when one of the RF channels is corrupted as long as a proper code rate is selected. By similar mechanisms, an increased robustness against interferences is also feasible, which may allow for reducing frequency reuse factor and thus increasing network spectral efficiency [15]. Regarding implementation, CB requires of two tuners at the receiver, each one fixed on a RF channel while the reception with TFS can be performed, under certain circumstances, using a single tuner.

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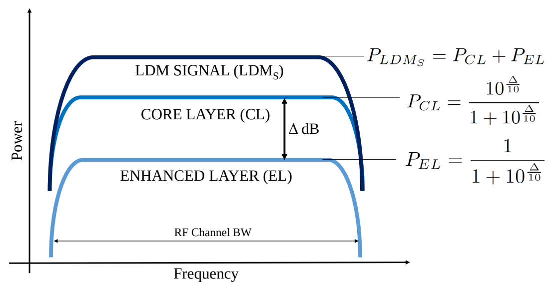

Fig. 1. LDM Concept. Core layer (CL) and enhanced layer (EL) sharing the same RF channel by different power assignment. EL is inserted Δ dB below CL level.

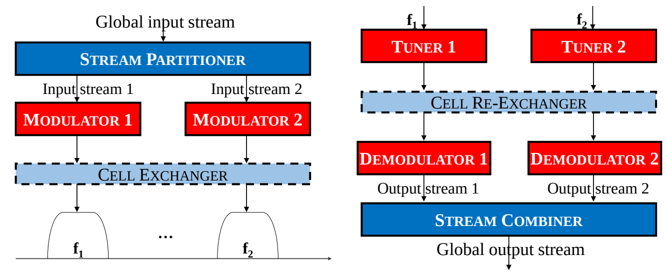

Fig. 2. Channel bonding transmitter (left) and receiver (right) block diagrams. The cell exchanger and re-exchanger are by-passed with Plain CB and active with SNR averaging CB.

LDM and multi-RF channel technologies have never been implemented in a terrestrial broadcasting standard and their joint performance is not known. This paper presents the potential use cases of combining LDM and CB or TFS. It evaluates the performance of the joint implementation by means of physical layer simulations and analyses the main implementation aspects at both transmitter and receiver sides.

The paper structure is as follows: Section II details the main characteristics of LDM, CB and TFS. Section III evaluates the possible use cases of a joint implementation of LDM with CB and TFS. The main transmitter and receiver implementation aspects are analysed in Section IV. Section V describes the methodology and the simulation setup followed for performance evaluation. The simulation results of LDM with multi-RF channels are presented in Section VI. Finally, conclusions are summarized in Section VII.

II. Overview of Technologies

A. Layered Division Multiplexing (LDM)

The concept of LDM, formerly known as Cloud Transmission (Cloud Txn) [16], involves the superposition of multiple signals, with different transmit power levels, forming a multi-layer signal. ATSC 3.0 defines LDM with only two layers. The top layer, known as Core Layer (CL), is the most robust one as it can be configured even with a negative Signal-to-Noise Ratio (SNR) threshold [17]. The lower layer, Enhanced Layer (EL), is set with a high capacity (less robust) mode so that it can be used to provide high data rate services to fixed roof-top receivers. The so-called injection level, Δ, is the parameter that defines the ratio between the power assigned to the upper and lower layer. As long as Δ is increased, more power is assigned to the CL and less to the EL, and viceversa. This is directly related with the SNR of both layers. At the receiver side, the EL is demodulated once the CL has been demodulated, cancelled and removed from the received signal.

As it can be seen in Fig. 1, each layer passes through an independent Bit-Interleaved Coded Modulation (BICM) module, so they can be configured with different modulation and coding rate (MODCOD) parameters. However, several restrictions have been imposed in ATSC 3.0 to limit the receiver complexity. The layers are combined together before the time interleaver, so they share the same Time Interleaver (TI), as well as the same Orthogonal Frequency Division Multiplexing (OFDM) waveform parameters: Fast Fourier Transform (FFT), Guard Interval (GI), and Pilot Pattern (PP) scheme. As a result, there is a trade-off when configuring the common transmission parameters for the two layers between the optimum Core Layer (CL) and Enhanced Layer (EL) parameters:

- A low carrier spacing, a low-dense PP, and a low TI depth should be chosen to reduce the overheads due to GI and PP and the demodulation latency for fixed service (EL) receivers.
- A high carrier spacing, dense PP, and a larger TI depth are recommended to deal with fading effects and to avoid Inter-Carrier Interference (ICI) caused by Doppler shift for the mobile service (CL).

Considering these common parameters, when the waveform is configured to favour fixed reception, the CL has a penalty in mobility performance. The lack of an optimum transmission configuration for the CL can be partly compensated by a very robust MODCOD, even with negative SNR threshold. In ATSC 3.0, code rates 2/15, 3/15, and 4/15 provide a negative SNR threshold (-5.7 dB, -3.7 dB, and -2.2 dB respectively) for Rayleigh channel using QPSK modulation [18].

B. Channel Bonding (CB)

CB enables the bundling of two standard-bandwidth RF channels. Basically, the process splits the data of a high-capacity stream into two sub-streams that are modulated and transmitted each one in a different RF channel. At the receiver, a simultaneous demodulation of the RF channels takes place by means of two independent tuners. The demodulated streams are combined back to create the original single data stream. The RF channels do not necessarily need to be adjacent to each other, thus allowing the reception of channels in different bands e.g. Very High Frequency (VHF) and Ultra High Frequency (UHF).

ATSC 3.0 defines two operation modes for CB. Fig. 2 illustrates the transmitter and receiver block diagrams for both CB modes. The basic mode is known as *Plain CB*, which enables doubling the transmission of services that exceed single RF channel throughput. The second operation mode, known as *SNR averaging*, exploits inter-RF frequency interleaving across the two RF channels, improving transmission robustness [12]. An additional block, the *cell exchanger*, is employed to ensure an even distribution of data across two RF channels. Cell exchanger distributes the odd and even cells of each Forward Error Correction (FEC) codeword in each RF

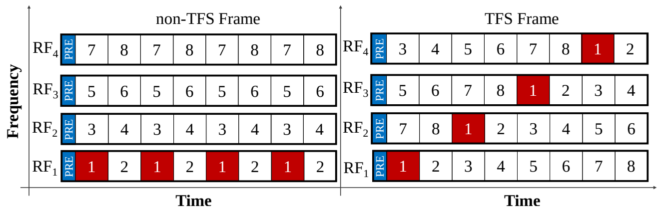

Fig. 3. Non-TFS (left) and TFS (right) transmission with 4 RF channels and 8 services.

TABLE I
POTENTIAL GAINS OF LDM AND MULTI-RF USE CASES

Gain	LDM + CB (both layers)	LDM + CB (EL only)	LDM + TFS
Increased Data-rate	✓	✓	
StatMux Gain	✓	✓	✓
Increased RF Performance	✓		✓

channel respectively. The reverse operation takes places at the receiver to recover data.

C. Time Frequency Slicing (TFS)

TFS was already introduced as not-normative annex in DVB-T2 and was fully adopted in the Digital Video Broadcasting - Next Generation Handheld (DVB-NGH) specification. TFS distributes the data of each service across two or more RF channels by means of time slicing and frequency hopping. Fig. 3 illustrates the transmission of services over 4 RF channels in a traditional way and with TFS. FEC codewords of a service are time interleaved, divided into slots and sequentially transmitted over multiple RF channels. Service data recovery is performed by means of frequency hopping over the different channels within the RF-Mux.

Ideally, in order to exploit the extended frequency diversity, each FEC codeword should be evenly split and sent across the RF-Mux. This distribution is achieved by the TI and a proper framing, so each data-slot containing time-interleaved data of the desired service suffers different SNR conditions according to the RF channels whereby it is received. At the receiver, TFS can be performed with a single tuner provided there is a gap time for tuning between slot boundaries and the tuner is fast enough for seamless reception. The inclusion of these time gaps introduces overheads which can limit the peak data rate of the services.

III. USE CASES FOR LDM AND MULTI-RF CHANNEL

This section describes the potential use cases for a joint multi-RF and LDM implementation. Table I collects the most relevant use cases and the related advantages that can be exploited.

The most complete combination is the transmission of both LDM layers with CB using the SNR averaging mode with two RF channels in the same frequency band. This mainly allows doubling the service data rate of each layer, an enhanced StatMux as well as improving transmission robustness by inter-RF frequency interleaving. The same transmission mode for both LDM signals is compulsory in this use case, to ensure an appropriate cell exchanging procedure.

The selected CB use cases implement the same transmission mode for both LDM signals or just the EL signal and consider the allocation of the RF channels in the same frequency band in order not to excessively increase receiver complexity. Note that the integration of two different types of antenna on mobile receivers is especially tricky in the case of VHF antennas.

With LDM, CB can also be implemented just in the EL. Implementing CB for the CL would increase mobile receiver complexity since two tuners will be required. When CB is implemented in the EL, Plain CB is the only mode allowed, since SNR averaging would exchange the cells of two independent CL streams, what is not desired. If CB is implemented on both layers, the CL sub-streams are no longer independent and form part of a stream that is partitioned. In such case, mobile receivers should implement two tuners.

With TFS, LDM must be performed in both layers what enables inter-RF frequency interleaving as well as StatMux gains.

The most important gains that can be obtained with these combinations are explained below.

A. Increased Peak Service Data-rate

This advantage can only be obtained when CB is employed since it allows the simultaneous reception of data from two different RF channels. This implementation would allow the transmission of services that exceed the data rate of a single RF channel.

In a classical single RF channel LDM transmission considering a commonly used MODCOD combination QPSK 4/15 for the CL and 64QAM 10/15 for the EL, the capacities of each layer would be 2.5 Mbps and 20 Mbps respectively. If either Plain CB or SNR Averaging are performed over the two LDM layers, their data rates can be doubled (5 Mbps for CL, and 40 Mbps por EL).

According to [19], and considering that about half data rate is required with High Efficiency Video Coding (HEVC) compared to H.264 [20], HD720p and HD1080p services would require around 2.5 Mbps and 5 Mbps respectively. In such case, the CL with CB could transmit a HD1080p service instead of a HD720p service.

B. StatMux Gain

Both LDM layers could exploit StatMux gain when using CB and TFS. Table II depicts an illustrative example of the feasible gains for different video services considering the StatMux gain values[1] for HD services in H.264. The same StatMux gain values are assumed for HEVC coding. The capacities of the CL and EL are, again, 2.5 Mbps (QPSK 4/15) and 20 Mbps (64QAM 10/15). The data rate of the HD services were already introduced in the previous subsection.

[1]According to [21], the StatMux gain for HD H.264 is around 15% for 3-4 programmes, 30% for 9-12 programmes, and 32% for 18-24 programmes

TABLE II
STATMUX GAIN IN NUMBER OF SERVICES FOR LDM AND MULTI-RF

Layer	Type of service	2 RF	4 RF	6 RF
CL	HD720p @ 2.5 Mbps	0	0	1
EL	HD1080p @ 5 Mbps	2	4	7
EL	4K UHD @ 15 Mbps	0	1	2

A 4K UHDTV service using HEVC is considered to require 15 Mbps. It can be seen that the most important gains are achieved with HD1080p service in the EL. The StatMux gain increases with the number of RF channels, with significant gains for 6 RF channels. Thus, the most important gains are expected with TFS, thanks to the aggregation of more than 2 RF channels.

C. Increased RF Performance

CB and TFS could offer an increased RF performance by extending the frequency interleaving across multiple RF channels, so that an increased frequency diversity is achieved. CB can offer this increased RF performance by employing SNR averaging mode between the two RF channels. Furthermore, the use of TFS could provide a higher frequency diversity by the availability of using more than 2 RF channels.

As it was described in Section II-A, the two layers share the same TI, FFT, GI, and PP in order to limit receiver complexity. As a result, there is a trade-off in the selection of these parameters for optimum mobile or fixed reception. For mobile reception, it is desirable that the interleaving duration is longer than the channel coherence time, which is inversely proportional to the Doppler spread [22]. In the case of pedestrian reception when deep fading occurs, the coherence time would be large, and, thus, the required time interleaving duration should be high. However, this is not always possible due to the limited amount of memory at the receiver for time de-interleaving (TDI) as well as due to the increase latency required, which would affect the performance because of higher zapping times.

For fixed reception, the most important degradation comes from the existing imbalances between RF channels [23]. Inter-RF frequency interleaving averages these SNR imbalances thus harmonizing the coverage of the RF channels whereby the services are transmitted.

IV. IMPLEMENTATION ASPECTS OF LDM WITH MULTI-RF CHANNEL TECHNOLOGIES

A. LDM with TFS

The implementation of TFS for both layers is the unique possible solution given that the LDM layers are combined before the TI and TFS framer [24]. The joint LDM and TFS transmitter and receiver block diagrams are illustrated in Fig. 4. The two LDM layer streams (CL Input Stream and EL Input Stream) pass through different BICM modules (CL BICM and EL BICM). They are then aggregated by injecting the EL Δ dB below CL. The distribution of the two layers aggregated, namely the LDM signal, across the N RF channels is handled by the TI and the TFS framer. At the receiver, the tuner hops among the N RF channels in the RF-Mux. The received signal is then demodulated in order to first get the CL stream. The remodulation and cancellation of the CL is also performed if it is desired to receive the EL stream.

TFS requires of an even distribution of data across the RF channels, what is achieved by means of time interleaving and a proper framing. With LDM in ATSC 3.0, the TI is configured according to the size and the number of cells of the CL FEC codewords regardless of the EL FEC codewords. Thus, if CL and EL number of cells are different it may happen that they are not equally and evenly spread across the RF-Mux, compromising the expected performance of the EL. The correct TFS operation on the EL also depends on the time interleaver scheme employed. The TI schemes that can be selected in ATSC 3.0 are:

- A sheer convolutional interleaver (CI) when there is a single service per frame (S-PLP) [25].
- A hybrid TI constituted by a joint cell and a twisted block interleaver (BI) for intra-frame TI, when there are multiple services per frame (M-PLP) [25].

Fig. 5 presents the TI output for the CL and EL cells of a frame that are transmitted in RF1 channel when the RF-Mux is composed of 4 RF channels. It is assumed that the EL constellation order is 3 times that of the CL. Each CL FEC codeword involves 12 cells, so there will be 4 cells per EL FEC codeword. Thus, there are 3 times more EL FEC codewords per frame than CL FEC codewords. In this example, there are 8 CL FEC codewords and 24 EL FEC codewords. This illustrative example can be considered as a simplified version of the LDM MODCOD distribution of CL QPSK 4/15 - EL 64QAM 10/15 with a FEC codeword length of 64800 bits. The cells are column-wise written in the TI matrix. The cells are read-out in a different way according to each TI. Additionally, the DVB-NGH BI is also shown for comparison, since it is used for TFS operation in DVB-NGH [26].

The sequences to the RF1 channel show that the TI that reaches the best even distribution of cells is the hybrid cell and twisted block interleaver, where almost one cell of each EL FEC codeword is transmitted.

At the receiver side, the critical point with TFS is tuning operation. TFS reception is possible with a proper scheduling at the transmitter which allocates time gaps between consecutive data slots to enable tuning operation. These time gaps create overheads that restrict peak service data rate. These time margins must include tuning operations (AGC (Automatic Gain Control) + PLL (Phase Locked Loop)) and channel estimation in the time domain (time interpolation among pilot carriers at the start and end of each slot). The necessary time margin for frequency hopping time (t_{hop}) is calculated by equation (1), where t_{tuning} depends on the signal bandwidth, FFT, and GI. t_{ChE} depends on the number of symbols required for time interpolation in a scattered PP (D_Y-1) [13].

$$t_{hop} = 2t_{ChE} + t_{tuning} \tag{1}$$

On the other hand, peak service data rate is also limited by the available TDI memory at the receiver.

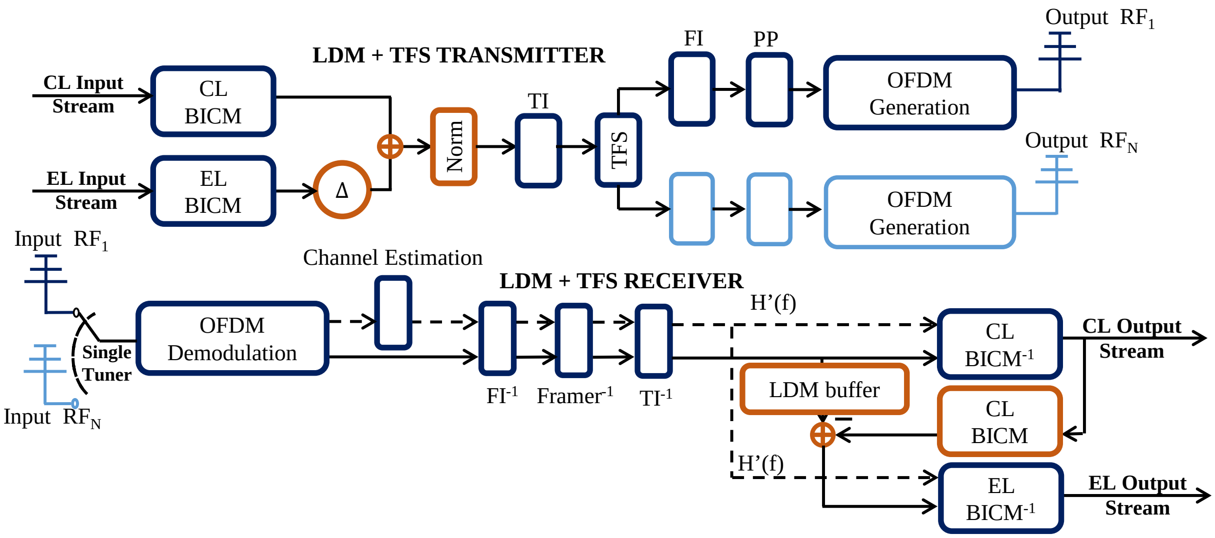

Fig. 4. LDM + TFS transmitter and receiver block diagrams. At the transmission, CL and EL Input streams pass through independent BICM modules. Then, they are aggregated by injecting the EL dB below CL. Next, TI and TFS Framer are executed over the LDM signal in order to transmit it across the N different RF channels of the RF-Mux. At the receiver, the tuner hops among the RF channel frequencies, demodulating first the CL stream, and if it is desired the EL stream by the LDM cancellation process.

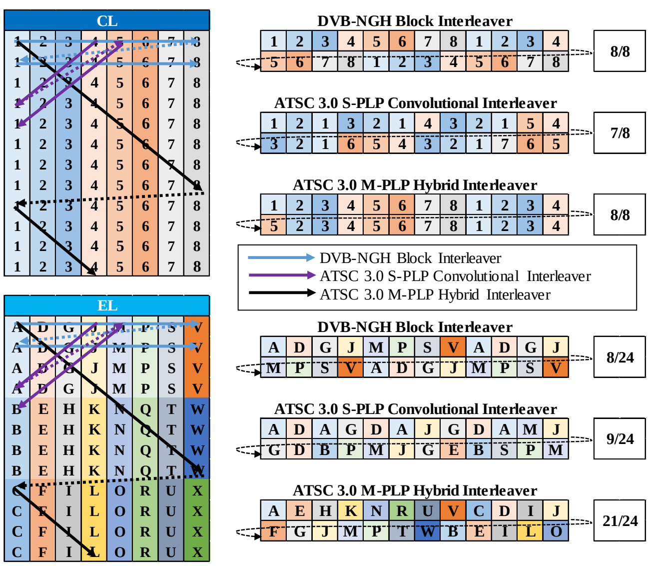

Fig. 5. Left part of the figure, CL and EL frame matrices composed by 8 FEC codewords of 12 cells (in numbers) and 24 FEC codewords of 4 cells (in letters) respectively. Right part, CL and EL cell output sequences to RF1 of a RF-Mux of 4 RF channels with the different TI read-out wise schemes. Cells of the 8/8 CL FEC codewords, and 21/24 EL FEC codewords are transmitted with ATSC 3.0 Hybrid TI

TABLE III
CL Peak service data rate overheads. 6 MHz FFT 16k GI 1/16.

RF-Mux	D_Y	Overhead	Mbps
QPSK 4/15 (2.5 Mbps)			
4	4	51%	1.23
4	2	37%	1.57
2	4	37%	1.57
2	2	26%	1.85

TABLE IV
EL Peak service data rate overheads. 6 MHz FFT 16k GI 1/16.

RF-Mux	D_Y	Overhead	Mbps
64QAM 10/15 (20 Mbps)			
4	4	51%	9.56
4	2	37%	12.30
2	4	37%	12.30
2	2	26%	14.54

Tables III and IV provide the data rate overhead for CL and EL considering ATSC 3.0 parameters 6 MHz FFT 16k and GI 1/16. One symbol is considered to be required for tuning, and the values for D_Y are 2 or 4. RF-Muxes of 2 and 4 RF channels are considered. The overhead has been calculated with respect to the single data rate of 2.5 Mbps and 20 Mbps for the CL and EL respectively. A maximum 250 ms frame duration and 2^{19} cells of TDI memory limitation are assumed. The results show that either increasing the number of RF channels in the RF-Mux or decreasing the pilot pattern density in the time domain (higher D_Y) makes peak service data rate significantly increase.

B. LDM with Channel Bonding

Fig. 6 shows the joint LDM and CB transmitter and receiver chains for both LDM layers. It can be observed that the transmitter is composed by one stream partitioner per layer, forming two streams per LDM layer, which are next modulated and combined (CL stream 1 with EL stream 1; CL stream 2 with EL stream 2). In the figure it can be observed that the layers of the LDM signals share the same TI, PP, and FFT, and are transmitted on both RF channel. The two transmitted LDM signals are received by two independent tuners. The received

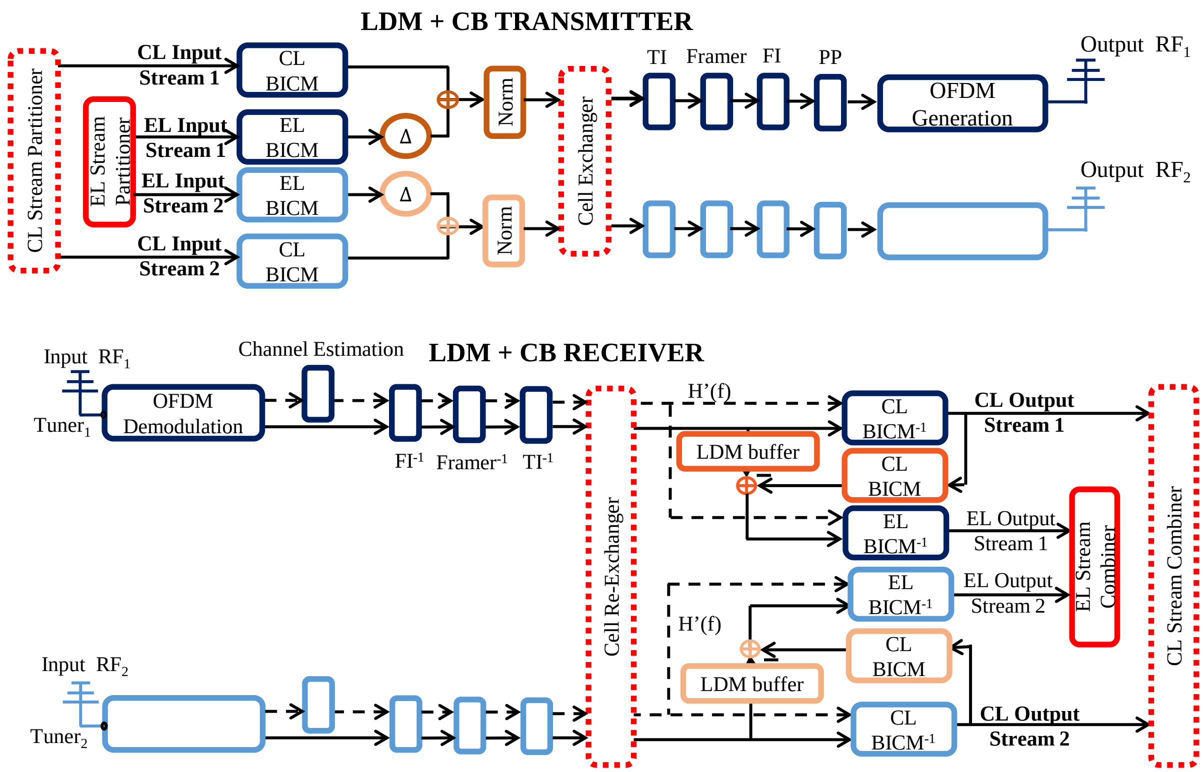

Fig. 6. LDM + CB transmitter and receiver block diagrams. Each LDM layer stream is partitioned into 2 sub-streams, one for each RF channel. Two tuners are needed at the receiver. If CL does not perform CB, CL streams are independent and cell exchanger, cell re-exchanger, CL partitioner, and CL combiner are disabled.

LDM signals are then demodulated in order to get the CL streams, which are next combined in the CL stream combiner. At the same time, the remodulation and cancellation of the CL streams are carried out in order to obtain the two EL streams. Last, the two EL streams are combined in the EL stream combiner. Notice that the cell exchanger and re-exchanger are only allowed when CB is performed to both LDM layers. If there were two independent CL streams, and Plain CB was only performed to the EL, blocks marked with dots would not be implemented (i.e. the CL stream partitioner, CL stream combiner, the cell exchanger, and cell re-exchanger).

The inter-RF frequency interleaving in CB is achieved by means of the cell exchanger. In contrast to TFS, the cell exchanger assigns one half of the cells on RF1 channel and the other half on RF2 channel, independently of the size of the FEC codewords.

V. Methodology and Simulation Setup

The performance of LDM and multi-RF is evaluated by means of physical layer simulations for mobile and fixed reception with a software simulator validated during the ATSC 3.0 standardization process. The performance of the multi-RF transmission is compared with the transmission over the RF channel with the worst SNR condition, i.e. the one that would be limiting the reception of the complete set of services in a classical transmission. Cells of a service are spread in a frame which length is set by the time interleaving duration.

For fixed reception, the effect of transmitting slots of data across different RF channels is emulated taking into account the SNR imbalances between RF channels according to the statistical model presented in [23]. This model accounts for the signal strength variations between UHF channels derived from the transmitter antenna systems and propagation. Notice that only the average values of the imbalances between pairs of frequencies are taken into account for these simulations. According to the model, the worst RF channel coincides with the one with highest frequency.

For mobile reception, the degradation caused by Doppler shift is taken into account. For this purpose, each RF channel is modelled by a different TU-6 channel with a given number of time realizations. Each TU-6 channel is characterized with the Doppler shift given by

$$f_d\,(\mathrm{Hz}) = v\,(\mathrm{m/s}) \cdot \frac{f_c\,(\mathrm{Hz})}{c\,(\mathrm{m/s})} \tag{2}$$

where f_d is the Doppler shift, v is the receiver speed, f_c is the carrier frequency of the RF channel, and c is speed of light. It can be observed that f_d varies according to the carrier frequency of the RF channel assumed. A correlation factor (ρ) is defined in order to represent the potential time correlation for different signals being broadcast from the same station. According to [27], the correlation is approximately stated between 0.4 and 0.8 in urban environments. The process is made by correlating the phase of the TU-6 channel time realizations tap-by-tap. To emulate the multi-RF transmission,

TABLE V
RF CHANNEL IMBALANCES (dB) RESPECT TO THE LOWEST FREQUENCY

RF1 503MHz	RF2 533MHz	RF3 563MHz	RF4 593MHz	RF5 623MHz	RF6 653MHz
0	-1.1	-2.15	-3.15	-4.09	-4.99

each FEC codeword is split into N_{RF} data slots which are sequentially filtered by the corresponding TU-6 channel realization of the assigned RF channel (with 4 RF channels, the transmission sequence would be $f_1, f_2, f_3, f_4, f_1, ...$).

The transmission and channel parameters assumed for the simulations are the following:

- Ideal channel estimation is considered.
- 6 MHz channel bandwidth is used.
- 16k FFT, 1/16 GI fraction are the waveform parameters shared by both layers.
- 50, 100, and 200 ms TI duration are considered.
- The channel model for mobile reception is TU-6 channel.
- The speeds evaluated on the mobile performance are 3, 10, 20, 30, 70, 100, and 160km/h.
- The correlation factor between RF channels considered on the first study are $\rho = 0, 0.3, 0.5, 0.7, 0.9, 1$. For the rest of the studies, a correlation factor of $\rho = 0.7$ is assumed.
- The channel model for fixed reception adopted is Rician (DVB-F1) channel.
- The transmission mode for the mobile service adopted is QPSK 4/15, (2,5 Mbps).
- The transmission mode for the fixed service assumed is 64NUQAM 10/15 (19,5 Mbps).
- An injection level of 4 dB is considered, which distributes the total transmission power according to 70% for the CL, and 30% for the EL, approximately.

An intermediate frequency spacing of 30 MHz has been considered. The main results are based on a RF-Mux of 2 RF channels centered at 503 and 533 MHz carrier frequencies. In addition, in order to evaluate the effect of using more than two RF channels, RF-Muxes of 4 and 6 RF channels are also implemented. The additional RF frequencies are centered at 563, 593, 623, and 653 MHz. The imbalances between RF channels and the different Doppler shifts for all the speeds under evaluation are presented in Table V and Table VI respectively.

TABLE VI
DOPPLER SHIFT f_d (HZ) PER RF CHANNEL

Speed	RF1	RF2	RF3	RF4	RF5	RF6
3 km/h	1.40	1.48	1.56	1.65	1.73	1.81
10 km/h	4.66	4.93	5.21	5.50	5.77	6.05
20 km/h	9.31	9.87	10.43	10.98	11.54	12.10
30 km/h	13.97	14.81	15.64	16.47	17.31	18.14
70 km/h	32.60	34.55	36.49	38.44	40.38	42.32
100 km/h	46.57	49.35	52.13	54.91	57.69	60.46
160 km/h	74.52	78.96	83.41	87.85	92.30	96.74

TABLE VII
EL WITH TFS PERFORMANCE LOSSES (dB) FOR THE DIFFERENT TI SCHEMES WITH RESPECT TO IDEAL TI

RF-Mux	Hybrid TI	CI	DVB-NGH BI
2 RF channels	0	0.18	0.51
4 RF channels	0	1.08	1.24
6 RF channels	0	1.36	1.86

VI. LDM + MULTI-RF CHANNEL PERFORMANCE EVALUATION

This section presents the results of the performance evaluation of the proposed LDM and TFS/CB use cases with inter-RF frequency interleaving.

A first study assesses the EL performance for the different TI schemes. Next, the results are mainly focused on the performance of the CL in mobile reception, for different time interleaving durations, correlation factors ρ, receiver speeds, and number of RF channels. All the results are obtained for a Bit Error Rate (BER) of 10^{-4}, since there are no important differences for lower values.

A. LDM EL + multi-RF performance for fixed reception. Influence of the TI scheme.

Different TI schemes available in ATSC 3.0 (hybrid TI and CI) as well as the block-type TI of DVB-NGH are used to evaluate the even distribution of cells for the EL of the LDM+TFS system. For reference, performance is also compared to the ideal distribution of cells as well as the performance of the worst RF channel in each RF-Mux. RF-Muxes of 2, 4, and 6 RF channels are considered. The time interleaving duration is set to 100 ms. The SNR of the RF channels under evaluation is set according to the methodology explained in the previous section.

Fig. 7 illustrates the performance of the evaluated cases. The result confirms that the ATSC 3.0 hybrid TI provides the best performance since it fits the ideal TI scheme case. Regarding the other TI schemes, it can be observed that DVB-NGH provides the worst performance with respect to the ideal whereas the CI is in-between. Table VII summarizes the performance loss of the three TI schemes under evaluation with respect to the ideal performance.

It can be concluded that the ATSC 3.0 hybrid TI scheme is the optimum for LDM and multi-RF operation. This scheme is assumed for the rest of the simulations in this paper. Assuming this TI, the potential gain of inter-RF frequency interleaving for fixed reception comes from the SNR averaging between the different SNR of the RF channels involved in transmission.

B. LDM CL + multi-RF performance for mobile reception

Performance in mobile reception for the CL is evaluated next. Fig. 8 depicts the multi-RF gain that can be achieved in pedestrian reception ($v = 3\ km/h$) assuming just different correlation factors between the two RF channels centered at 503 and 533 MHz. No SNR imbalances are considered in this result in order to know the impact of the time-correlation

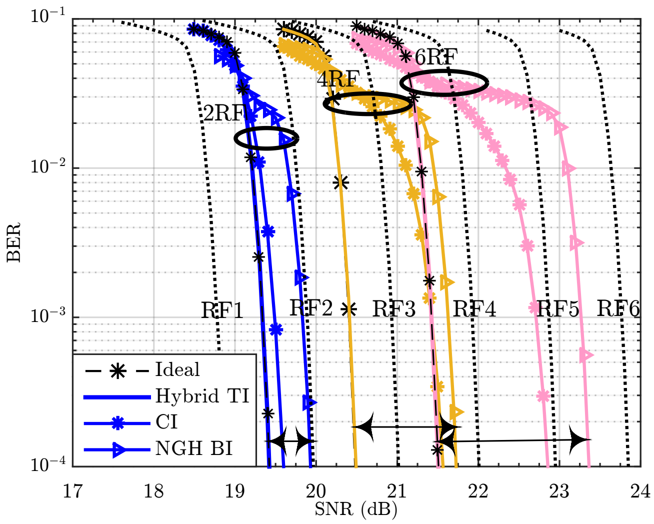

Fig. 7. Performance of the EL for different TI schemes for RF-Muxes of 2, 4, and 6 RF channels. 2RF-Mux constituted by RF1 and RF2 (1.1 dB SNR imbalance between best and worst RF channel). 4RF-Mux constituted by RF1, RF2, RF3, and RF4 (3.15 dB SNR imbalance between best and worst RF channel). 6RF-Mux constituted by RF1, RF2, RF3, RF4, RF5, and RF6 (5 dB SNR imbalance between best and worst RF channel).

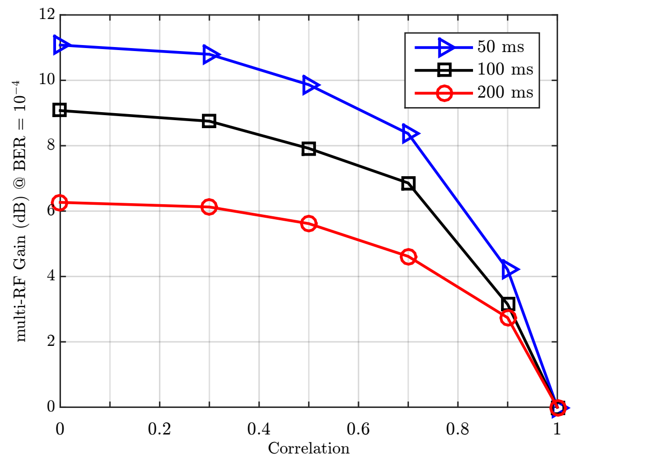

Fig. 8. 2-RF gain at BER = 10^{-4} for different correlation factor between channel realizations. 50, 100, and 200 ms interleaving durations.

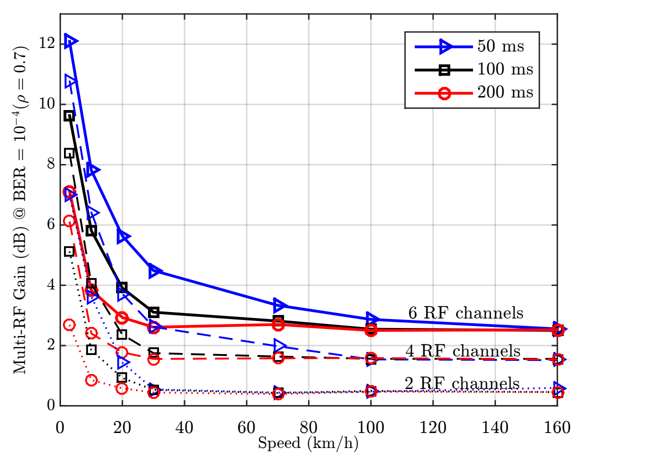

Fig. 9. Multi-RF gain at BER = 10^{-4} for different speeds. 50, 100, and 200 ms interleaving durations. Correlation factor of $\rho = 0.7$.

between the channels. It can be observed that the higher the correlation between the channel realizations, the lower the multi-RF gain obtained. For totally uncorrelated channels ($\rho = 0$), the multi-RF gains obtained are in the range 3.5-8.7, depending on the time interleaver duration. On the other hand, if the channels are totally correlated ($\rho = 1$), no multi-RF gain is achieved for the time interleaving durations assumed.

One important aspect to note is that a higher multi-RF gain is reached with a low time interleaving durations, since higher time interleaving durations do not provide better performance for RF-Mux transmission in contrast with single RF transmission. For large interleaving durations the additional gain by inter-RF frequency interleaving is limited. However, there is a significant improvement for lower interleaving durations.

Assuming $\rho = 0.7$, the multi-RF gains for pedestrian reception are 6.5, 4.6, and 2.1 dB for 50, 100, and 200 ms respectively.

Fig 9 illustrates the multi-RF gains for the CL for different speeds and considering RF channel multiplexes of 2, 4, and 6 RF channels. In this case, the SNR imbalances between RF channels (see Table V) are considered.

For a 2RF-Mux, an imbalance of 1.1 dB between the two RF channels is assumed. As it was stated above, the lower the time interleaving duration, the higher the achieved gains by inter-RF frequency interleaving. Furthermore, it can be observed that the highest gains are achieved at low speeds. In fact, for speeds higher than 30 km/h, the gains due to the uncorrelated channel realizations are negligible, regardless the time interleaver duration. The 0.5 dB ground gain of the RF-Mux corresponds to the imbalance between the best and the worst RF channel, and it is independent of the receiver speed.

For a 4RF-Mux, the worst RF channel would have an imbalance of 3.15 dB with respect to the best RF channel, and for a 6RF-Mux this imbalance ascends to about 5 dB. The reason is based on the higher frequency separation between the worst and the best RF channel in the RF-Mux. For low-speed reception the RF-Mux gains rise up to 12 dB if a 6RF-Mux and a time interleaving duration of 50 ms is used. In addition, as long as the number of RF channels are increased the gains derived from the uncorrelated channel realizations are extended up to 100 km/h for this interleaver duration.

As a summary, Table VIII presents the gains for a classical scenario, where a time interleaving duration of 100 ms is commonly used, with the three RF-Mux compositions for pedestrian reception. It can be seen that the increased gains of 6 RF channels in comparison with 4 (1.3 dB) are less significant than those from the step of 2 to 4 RF channels (3.2 dB).

VII. Conclusions

This paper investigates the Layered Division Multiplexing (LDM) combination with multiple radiofrequency (multi-RF) channel technologies. Channel Bonding (CB), which only uses

TABLE VIII
MULTI-RF GAINS FOR TI = 100 MS @ 3KM/H

	2RF	4RF	6RF
$f_{separation}$	30 MHz	90 MHz	150 MHz
RF Channel Imbalances	0.5 dB	1.5 dB	2.5 dB
RF Channel Incorrelation	4.6 dB	6.8 dB	7.1 dB
Total Gain ($G_{Imb} + G_{f_d}$)	5.1 dB	8.3 dB	9.6 dB

2 RF channels and Time-Frequency Slicing (TFS), that enables the use of up to 6 RF channels, were considered.

There are three main advantages that CB and/or TFS could offer to LDM: increased peak service data-rate (only with CB), enhanced Statistical Multiplexing (StatMux) thanks to a pool with a large number of services (with CB and TFS) and/or an increased RF performance due to a higher frequency diversity by means of an inter-RF frequency interleaving (with CB with SNR averaging and TFS).

The joint LDM and CB leads to two possible use cases. One option is that the two LDM layers perform the SNR averaging CB mode. The other is Plain CB for the EL, which allows a simpler mobile receiver implementation. Regarding joint LDM and TFS, there is only one possible use case. TFS must be applied to both layers since its combination takes place before the TFS scheduling is carried out.

Regarding implementation, the combination of LDM with TFS does not always guarantee the desired frequency diversity for both layers since it depends on the Time Interleaver (TI) scheme employed which is configured according to the CL transmission mode. It is concluded that the hybrid TI (constituted by a cell interleaving and a twisted block interleaving) provides the best even distribution of data. In addition, TFS produces an overhead in the peak service data-rate that should be taken into account. It was observed that the overhead increases with the number of RF channels (in the worst case, with 4 RF channels the overhead could increase up to 51%).

According to the performance in mobile and fixed reception, it was shown that high gains are obtained with time-uncorrelated channels for pedestrian reception. The gains range from 2.1 to 6.5 dB for time interleaving durations from 200 to 50 ms respectively, with a typical factor of $\rho = 0.7$.

Important gains can be exploited from the SNR imbalances between the studied RF channels. These gains increases with the frequency separation between RF channels but the gain increase from 4 to 6 RF channels is lower (8.3 dB to 9.6 dB) than that from 2 to 4 RF channels (5.1 dB to 8.3 dB).

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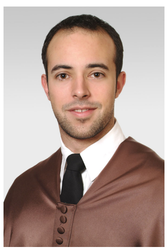

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