

Implementation of a 3-layer LDM Broadcast System Backward-compatible with ISDB-T_B

Ricardo Seriacopi RABACA, Fadi JERJI, Cristiano AKAMINE

Electrical Engineering and Computing Program, Mackenzie Presbyterian University, São Paulo, Brazil

ricardo_sr2@hotmail.com, fadi.jerji@gmail.com, cristiano.akamine@mackenzie.br

Submitted December 22, 2020 / Accepted April 8, 2021

Abstract. *This paper presents an implementation of a 3-layer transmitter and receiver using Layer Division Multiplexing (LDM), in Software Defined Radio (SDR). The main idea of this work is to show another point of view of the traditional LDM technique that uses two layers. This proposal uses an attenuated intermediate layer, called Middle Layer (ML), between the highest power layer, called Upper Layer (UL), and the most attenuated layer, called Lower Layer (LL). The UL is fully compatible with the Integrated Services Digital Broadcasting Terrestrial - Version B (ISDB-T_B). The ML, with greater robustness, and LL, with higher capacity, use powerful channel coders, a custom frame size and an adapted bit interleaver. With the use of this modified LDM, it is possible to develop a system with different robustness levels between layers and with lower layers that complement each other, to achieve bit rates that allow for the deployment of High Definition Television (HDTV), in the UL, and Ultra High Definition Television (UHDTV), in the ML and LL. In addition, a system was also implemented with three layers, but with the ML with higher capacity and the LL with greater robustness. The performance of the 3-layer system was compared with the 2-layer LDM technique and there was an improvement in the system modularity, without a decrease in the bit rate.*

Keywords

ISDB-T_B, LDM, Low-Density Parity-Check (LDPC), SDR

1. Introduction

Television (TV) is and will remain a major mean of communication with the duty to inform, educate, entertain and interact with people around the world [1].

Since there is a progressive need for higher data rates, an increasing amount of bandwidth will be needed for telecommunication systems. Therefore, it is necessary to develop systems that regard the efficient use of spectrum, as this is an expensive and limited natural resource. As the wire-

less communication networks, such as the Wireless Fidelity (Wi-Fi) and mobile communication networks, are occupying a large part of this spectrum, traditional services, such as the digital television (DTV) is restricted to a smaller portion of it. In the case of DTV, there is a need for video transmission with higher image definition, availability of interactivity, among others, which will imply the need for more efficient systems. Thus, future communication systems will have to take advantage of the available bandwidth and adopt the use of more robust models to achieve higher transmission rates [2], [3].

To perform the transition from analog to digital TV correctly, several countries distributed set-top-boxes (STBs), televisions with built-in digital converters or financial aid, with the objective of preparing the population for the implementation of the new digital TV. Therefore, it is important to develop a backward-compatible system, that does not allow these already distributed equipment to become obsolete.

Layered Division Multiplexing (LDM) is an effective approach for increasing data rates for different services in wireless channels. This technique is a physical-layer non-orthogonal-multiplexing technology to efficiently deliver multiple services with different robustness and throughputs in one channel [4]. Therefore, the LDM technique allows for the transmission of data divided into layers using different power levels, at the same time and frequency.

Using this technology, it is possible to maintain the compatibility of the already installed receivers and increase the spectral efficiency by using, for example, new coding, interleaving and modulation techniques, in the attenuated layer. Thus, the Integrated Services Digital Broadcasting Terrestrial - Version B (ISDB-T_B) STB receives the combined signal, with all the layers, and demodulates the UL, considering the additional layers signals as noise. In the case of equipment prepared for the LDM technique, it is possible to perform the cancellation stages of the reception process and demodulate and recover the data from each layer.

The first studies about this technology were presented in [2] where the Cloud Transmission (Cloud Txn) concept was proposed. The main idea of this work was to introduce a new transmission system for terrestrial broadcasting, that would allow for a more efficient use of the spectrum.

A few years after this first approach, a system was developed by [5], that used the concept of Cloud Txn. It was a multi-layer transmission system, which allowed for the delivery of multiple layers over the same broadcast channel, where each layer was associated with its own injection power level and lower-layer signals were recovered using signal cancellation techniques. Due to its significant performance advantages and the proposed simple implementation, a 2-layer LDM was accepted as a Physical Layer (PHY) baseline technology for the modern Advanced Television Systems Committee (ATSC) 3.0 [6].

The spectrum efficiency of the Cloud Txn/LDM broadcast system depends to a great extent on the degree of robustness against co-channel interference and noise. To increase the resilience of the system against electromagnetic noise and allow for the Signal-to-Noise Ratio (SNR), in dB, to be a negative value with a Quasi Error Free (QEF) performance, the Low-Density Parity-Check (LDPC) codes are a good solution, due to their Shannon-limit-approaching performance over Additive White Gaussian Noise (AWGN) channels, an asymptotically better performance than other codes [5].

In 1962, Robert Gallager introduced the concept of capacity-approaching codes over a symmetric memoryless channel [7]. LDPC codes have been adopted in many wireless broadcasting standards, such as, the Digital Terrestrial Multimedia Broadcast (DTMB), the Digital Video Broadcasting (DVB) and the ATSC 3.0 [8–12]. These codes were chosen for the mentioned systems, due to its performance advantage and low encoding and decoding complexity. There are some efficient decoding algorithms of LDPC codes such as the sum-product algorithm (SPA) which is known as the best performing, without short cycles [13], and the most complex decoding algorithm and the min-sum algorithm (MSA) which is a simplified method that can greatly reduce decoding complexity compared to SPA [14], but it may introduce substantial performance degradation in terms of bit error rate (BER) or frame error rate (FER) [15].

Another advantage of LDM is that it can co-exist with all the other emerging PHY technologies, such as the multiple antenna technologies, Non-Uniform constellations (NUCs), Bit-Interleaved-Coded-Modulation (BICM), Peak-to-Average-Power-Ratio (PAPR) reduction technologies, etc [4].

The purpose of this work is to develop a transmitter-receiver couple, using Software Defined Radio (SDR), that is a new perspective of the modified version of ISDB-T_B LDM created by [16] which uses a 3-layer LDM system with ISDB-T_B BICM in the Upper Layer (UL) [17], [18] and a BICM stage with modified LDPC encoders/decoders, bit interleavers/deinterleavers, costumed frame size and soft-decision demodulators in the Middle Layer (ML) and the Lower Layer (LL). This model allows for the transmission of a modified DTV standard, using the ML and LL, as well as the ISDB-T_B transmission, in the UL, producing a backward-

compatible system, that can be used in a transition process between DTV generations.

The main contributions of this paper are:

1. A new approach toward the LDM technique is explained and implemented in SDR, using a ML between the UL and LL;
2. A custom frame (19968 bits) LDPC encoder and decoder were developed, to maintain the synchronism between layers;
3. The mathematical representation, the theoretical explanation of the degradation of each layer and a comparison between the expected calculated results and the measured values are shown;
4. A comparison between the traditional 2-layer LDM and the proposed 3-layer LDM is realized, using similar configurations;
5. An investigation concerning the behavior of the proposed LDM is presented using several injection level (Δ) values, robustness levels and different LDPC decoding algorithms.

The remainder of this paper is organized as follows. Section 2 presents related work. In Sec. 3, the most relevant information about the ISDB-T/T_B 3-layer LDM broadcast system are presented. In Sec. 4, the mathematical approach is presented. Section 5 presents the details of the proposed transmitter and receiver implementation. In Sec. 6, the results and a discussion about each tested configuration are shown. And finally, Section 7, contains the conclusion of this paper.

2. Related Work

As mentioned in the previous section, the early studies concerning the layer division multiplexing technique were published using the Cloud Txn concept. In articles such as [2, 5, 19], the early analyzes and theoretical approaches were introduced and some system performance, capacity and application scenarios were shown.

Still on the perspective of the Cloud Txn concept, a first proposal was presented by [20] which used ISDB-T_B in the UL. Later studies were published using LDM nomination and some new characteristics such as the introduction of LDPC codes in the LL [21], an implementation using diversity at reception in order to improve robustness [22], [23], an ISDB-T_B LDM system with the BICM stage of ATSC 3.0 in the LL and diversity at reception [24] and a real-time ISDB-T_B LDM receiver using SDR [16].

Important concepts in the LDM context were also investigated, such as, the error propagation in the cancellation stage [25], more effective channel estimators [26–30], more efficient video encoding techniques [31–33], the comparison between LDM and the traditional time-division multiplexing (TDM) or frequency-division multiplexing (FDM) [34], the use of NUCs to improve LDM performance [35], the application of the technique in satellite broadcast system [36], performance analysis using optimized demappers [37] and the use of Multiple-Input Multiple-Output (MIMO) schemes [38].

The modern ATSC 3.0 recommends the use of the LDM modulation technique. Therefore, several articles were published with studies concerning the capacity of LDM in ATSC 3.0 [39], memory use aspects for the LDM technique in the system [40], MIMO schemes utilization [41], field tests [42], studies about efficient schemes for decoding and LDPC application [43–45], performance analysis for mobile services [46], among others.

2-layer LDM can be considered a recent method. Therefore, a system which uses an additional layer has not been extensively investigated. There is a study that analyze the capacity of the 3-layer LDM in order to confirm that it has an advantage when compared to a TDM/FDM system [47]. There is also a proposal for 3-layer LDM focused on mobile broadcasting services [48]. It uses a 3-layer LDM based on amplitude shift keying (ASK) to reduce hardware complexities and power consumption of the receiver. Because the third layer of the ASK modulation can be retrieved directly from the received signal without the demodulation and reconstruction stages of UL signal. Therefore, it can be retrieved without increasing the complexity and power consumption of the receiver.

Considering the approaches described in this section, it is proven that the proposal of this work contains innovative factors. Since the main objective of the system is to guarantee the backward compatibility with the broadcasting system currently in operation in many countries (ISDB-T_B) in the UL, as well as having an aggregated bit rate of the ML and the LL, which allows Ultra High Definition Television (UHDTV) resolutions, such as 4K.

3. 3-layer LDM Broadcast System

In this work, the main idea is to transmit and receive three signals divided into layers using different power levels, at the same time and frequency. Its working is similar to the traditional 2-layer LDM broadcast system proposed by [16], with the addition of a third layer (ML) in the system, in order to verify bit rate and robustness improvements.

In addition, a comparison between the 2-layer and the 3-layer techniques is made to investigate the improvements of having a more modular system. Thus, the proposed system would make it possible to receive the content of the ML and would allow the received signal from the more attenuated layer (LL) to provide complementary information, achieving better image quality.

3.1 Transmitter

At the transmission stage, all the steps of the ISDB-T_B are used in the UL, preserving that this layer is compatible with the standards [17], [18].

The BICM structure of the ML and LL is done using tailored irregular LDPC codes, with a frame size of 19968 bits, in order to guarantee synchronism between the three layers. Furthermore, a bit interleaver that is modified to match the LDPC frame size is used.

Figure 1 [16] shows the 3-layer LDM transmitter used in this work. Some of digital signal processing stages were used in [16], such as the ISDB-T_B BICM, the time and frequency interleaving, the framing, the Orthogonal Frequency Division Multiplexing (OFDM) modulation and the Guard Interval (GI) insertion. At the input of each BICM stage, a respective Transport Stream (TS) file is inserted.

In the transmitter shown in Fig. 1, there are three separated BICM stages, because each layer must be encoded and mapped separately. In order to combine the ML and the LL, a first attenuation stage is applied, using the Δ_1 value (in dB), in other words, a multiplication factor (α_1) is calculated, in order to attenuate the LL signal. After that, the first stage of LDM technique is performed, combining the ML with the attenuated LL. Then, a first power normalization stage is done, using the normalization factor β_1 to normalize the combined (ML and LL) signal to 1 Watt (W).

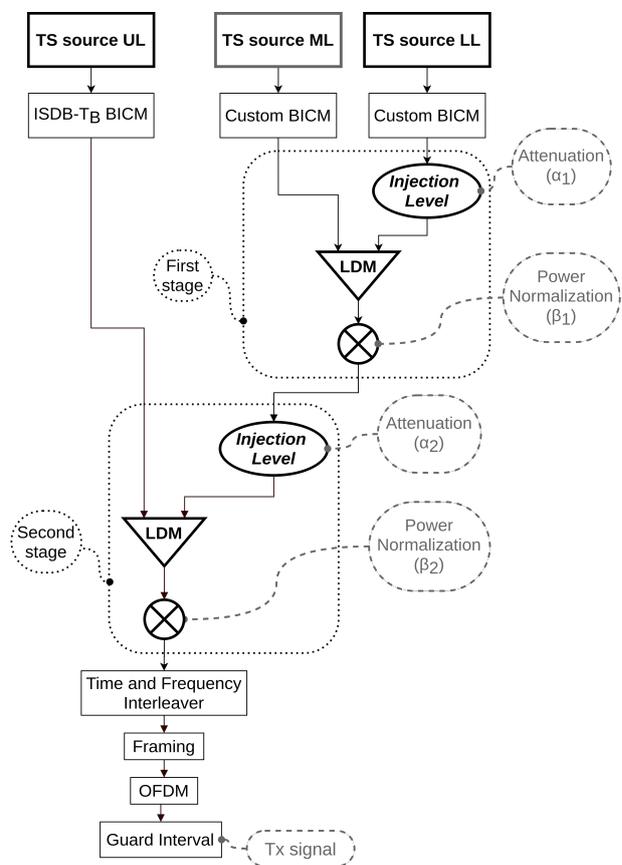


Fig. 1. 3-layer LDM Transmitter [16].

The second stage of layer combination is similar to the first LDM multiplexing, but, at this point, the recently generated (ML and LL) signal is attenuated, using an α_2 factor and is summed with the UL signal. After that, another power normalization process is done, using the power normalization value β_2 to normalize the 3-layer LDM signal to 1 W. The $\alpha_1, \beta_1, \alpha_2$ and β_2 equations are shown in Sec. 4.

To complete the transmission stage, the time and frequency interleaving are applied, the framing process is done, the OFDM modulation is realized and the GI is inserted [16]. Finally, the 3-layer LDM signal is transmitted.

3.2 Receiver

The proposed receiver is shown in Fig. 2 [16], [49] and uses a synchronization stage, where the time, sampling, frequency and frame are synchronized. After that, the steps of OFDM demodulation, channel estimation and equalization are realized and, finally, the frequency and time de-interleaving are performed. The digital signal processing stages of the frequency and time de-interleaving, were the same used in [16]. The OFDM synchronization and channel estimation stages were proposed by [49].

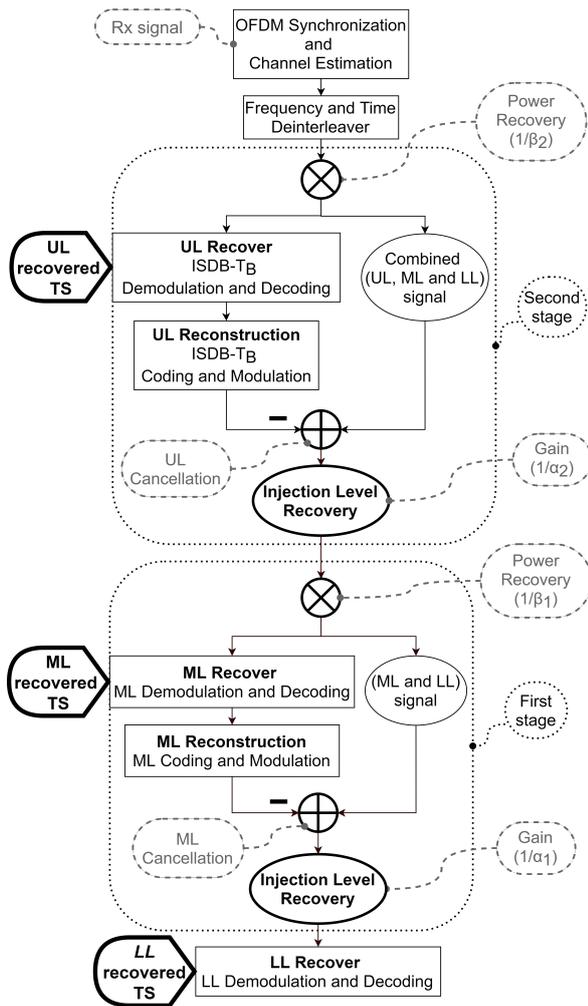


Fig. 2. 3-layer LDM Receiver [16], [49].

A first power recovery stage is required, in order to compensate the second power normalization stage realized at the transmitter. Thus, an inverted normalization factor is applied ($1/\beta_2$). After that, the UL can be de-mapped and decoded and its data can be recovered.

After the UL recovery step, it is necessary to reconstruct it again by applying the encoding and mapping processes, in order to subtract it from the combined (UL, ML and LL) signal. To perform this cancellation, a buffer is required.

A first gain stage is applied ($1/\alpha_2$), to revert the effect of the second attenuation stage (α_2). Thus, the combined (ML and LL) signal attenuation that was realized at the transmission is reversed.

A second power recovery stage is required ($1/\beta_1$), in order to compensate the first power normalization stage that was performed at the transmitter to normalize the combined (ML and LL) signal. After that, the ML can be de-mapped and decoded and its data can be recovered.

The same process that was done to reconstruct UL, is also done with ML. Thus, the signal of ML is encoded and mapped again, in order to be subtracted from the combined (ML and LL) signal. After this last cancellation, only the LL signal remains and the last gain stage ($1/\alpha_1$) is done. To finish the reception process, the LL signal can be de-mapped and decoded and its data can be recovered.

4. Mathematical Representation

In this section, the mathematical representation of the LDM technique is explained. Thus, the equations about the attenuation and normalization factors are exposed, as well as the calculations of the expected values of SNR for each layer are shown.

4.1 Injection Power Level

The values used as attenuation and normalization factors, commented at the previously explanation about the transmitter and receiver, can be calculated where is only necessary to know the Δ value (in dB), which will be used in the LDM.

The calculation of the attenuation factor (α) value is given by

$$\alpha = \frac{1}{10^{\frac{\Delta}{20}}}. \tag{1}$$

The other value used in the process is the normalization factor (β), which is necessary to normalize the combined signal to 1 W. The β value is obtained by

$$\beta = \frac{10^{\frac{\Delta}{20}}}{10^{\frac{D}{20}}} \tag{2}$$

where D is calculated using (3).

$$D = \left[10 \times \log_{10} \left(1 + \frac{1}{10^{\frac{\Delta}{10}}} \right) \right] + \Delta \quad (3)$$

These equations are used in 2-layer LDM. In this work, these factors are calculated twice, since two different Δ values are used, the first for the combination of ML with LL and the second for the combination of UL with (ML+LL). Therefore, two attenuation factors and two normalization factors are used. The first set of factors (α_1 and β_1) is applied when the first stage of LDM, with Δ_1 , is realized and the second set of factors (α_2 and β_2) is used on the second stage of LDM, with Δ_2 .

4.2 Layers Degradation

To analyze the effect of LDM on the SNR threshold, first, is necessary to know the SNR threshold value for each configuration used in each layer separately, without the use of the multiplexing technique.

Using the measured SNR values and the Δ values that will be used in each multiplexing stage, it is possible to calculate the new SNR thresholds for each layer and expected levels of robustness for the proposed system.

Equation (4) demonstrates the calculation of the required value of SNR (in dB) in the UL for a system using 2-layer LDM with the presence of LL [5], [16]

$$SNR_{UL} = SNR_{UL0} - k \quad (4)$$

where SNR_{UL0} represents the value of the SNR required by the system with the absence of LL and without the use of LDM and k represents the degradation of UL, which is calculated using (5) [5], [16]

$$k = 10 \times \log_{10} \left(1 - 10^{\frac{SNR_{UL0} - \Delta}{10}} \right). \quad (5)$$

Equation (6) can be used to calculate the value of the theoretical necessary SNR to allow for the recovery of the LL [5], [16]

$$SNR_{LL} = SNR_{LL0} + \Delta + C \quad (6)$$

where C represents the power correction for the used value of Δ and is calculated using (7)

$$C = 10 \times \log_{10} \left(P_0 + \frac{1}{10^{\frac{\Delta}{10}}} \right) \quad (7)$$

where P_0 is the normalized power of 1 W of UL and LL before the LDM.

Using (4) and (6) it is possible to calculate the theoretical degradation of both layers and find the approximated values of the minimum SNR for UL and LL in a 2-layer LDM.

The 2-layer LDM equations were modified to fit the proposed system which uses an additional layer.

In this new model, the UL suffers interference from ML and LL. Therefore, the adapted calculation for the UL SNR is shown in (8).

$$SNR_{UL} = SNR_{UL0} - k_1 - k_2 \quad (8)$$

where SNR_{UL0} represents the value of the required SNR without the use of LDM and k_1 and k_2 represents the degradation of UL because the presence of ML and LL, respectively, which are calculated using (9) and (10), respectively:

$$k_1 = 10 \times \log_{10} \left(1 - 10^{\frac{SNR_{UL0} - \Delta_2}{10}} \right), \quad (9)$$

$$k_2 = 10 \times \log_{10} \left(1 - 10^{\frac{SNR_{UL0} - (\Delta_2 + \Delta_1)}{10}} \right). \quad (10)$$

The ML suffers interference from LL and UL. Thus, the SNR_{ML} calculation is shown in (11)

$$SNR_{ML} = SNR_{ML0} + \Delta_2 + C_1 - k_3 \quad (11)$$

where SNR_{ML0} represents the value of the SNR required by the ML, without the use of LDM. C_1 represents the power correction, for the used value of Δ_1 and is calculated using (12). k_3 represents the degradation of ML, caused by LL presence and is calculated using (13)

$$C_1 = 10 \times \log_{10} \left(P_0 + \frac{1}{10^{\frac{\Delta_1}{10}}} \right), \quad (12)$$

$$k_3 = 10 \times \log_{10} \left(1 - 10^{\frac{SNR_{ML0} - \Delta_1}{10}} \right). \quad (13)$$

Equation (14) shows how is calculated SNR_{LL}

$$SNR_{LL} = SNR_{LL0} + \Delta_2 + \Delta_1 + C_2 + C_1 \quad (14)$$

where SNR_{LL0} represents the SNR value required by the LL, without LDM and C_2 represents the power correction, for the used value of Δ_2 and is calculated using (15)

$$C_2 = 10 \times \log_{10} \left(P_0 + \frac{1}{10^{\frac{\Delta_2}{10}}} \right). \quad (15)$$

Using (8), (11) and (14) it is possible to find the approximated values of minimum SNR for UL, ML and LL in the proposed 3-layer LDM.

4.3 Bit Rate Equations

The UL useful bit rate value can be calculated using (16) [24], where N_S is the number of segments and can take the value (1 to 13), N_{DC} is the number of data carriers for each mode (96 for Mode 1, 192 for Mode 2 and 384 for Mode 3), N_{BS} is the number of bits per symbol, R_{CC} is the rate of Convolutional Code (CC) and can take one of the values 1/2, 2/3, 3/4, 5/6, and 7/8, R_{RS} is the rate of Reed-Solomon (RS) code of the value 188/204, T_u is the symbol duration time, and GI is the guard interval used in the system and it can take one of the values 1/4, 1/8, 1/16 and 1/32.

$$Rb_{UL} = \frac{N_S \times N_{DC} \times N_{BS} \times R_{CC} \times R_{RS}}{T_u \times (GI + 1)} \quad (16)$$

where T_u is calculated using (17) [24], B_w is the bandwidth (6, 7 or 8 MHz) and R_{NC} is the constant value of 1.125.

$$T_u = \frac{(N_S + 1) \times N_{DC} \times R_{NC}}{B_w} \quad (17)$$

The bit rate available in the ML and LL, Rb_{ML} and Rb_{LL} , respectively, can be calculate using (18) and (19) [24], where N_S , N_{DC} , N_S , T_u and GI are the same as the values used in the UL, N_{BSML} and N_{BSLL} are the number of bits per symbol of each layer and R_{LDPCML} and R_{LDPCLL} are the respective code rates (CRs) of LDPC custom frame for ML and LL.

$$Rb_{ML} = \frac{N_S \times N_{DC} \times N_{BSML} \times R_{LDPCML}}{T_u \times (GI + 1)} \quad (18)$$

$$Rb_{LL} = \frac{N_S \times N_{DC} \times N_{BSLL} \times R_{LDPCLL}}{T_u \times (GI + 1)} \quad (19)$$

5. Implementation

In this section, details concerning the implementation of the proposed system are presented.

The UL data, used in the transmission, was encoded with CC and RS codes with $CR = 2/3$ as defined in the ISDB-T_B BICM. The encoded data was modulated in 16-Quadrature Amplitude Modulation (QAM), in order to guarantee a High Definition Television (HDTV) quality on UL. The ISDB-T_B modulation parameters used in all of the tests were Mode 3 (8k Inverse Fast-Fourier-Transform (IFFT) size), $GI = 1/16$, IFFT sampling frequency (F_S) = 8.12698 MHz, $N_S = 13$, $B_w = 6$ MHz and Time Interleaver (TI) = 0.

The ML and LL BICM were implemented using QAM constellations, a LDPC code of the frame size of 19968 bits and the CRs of 2/15, 5/15, 10/15 and 13/15 were employed along with a bit interleaver of the same size [16]. As the Mode 3 of ISDB-T_B uses 4992 carriers, the LDPC code frame size, used in the ML and LL, was designed for 19968 (4×4992) bits, in order to maintain the synchronism between all the system layers.

Figure 3 shows the constellation of an example of transmission configuration where ML is modulated with Quadrature Phase Shift Keying (QPSK), LL with 16-QAM and $\Delta_2 = 14$ dB and $\Delta_1 = 8$ dB. In this case, the UL that is modulated using 16-QAM is delimited by the black dotted line, the ML is delimited by the gray dashed line and the LL is delimited by the black continuous line. Thus, each UL symbol is composed of a QPSK, which is composed of four 16-QAM constellations.

Figure 4 shows the constellation of an example of transmission configuration where ML is modulated with 16-QAM, LL with QPSK and $\Delta_2 = 14$ dB and $\Delta_1 = 18$ dB. The UL that is modulated using 16-QAM is delimited by the black dotted line, the ML is delimited by the gray dashed line and the LL is delimited by the black continuous line. Thus, each UL symbol is composed of a 16-QAM, which is composed of sixteen QPSK constellations.

The implementation of the reception stage was done using soft-decision demodulators, for the ML and the LL, that uses Log-Likelihood Ratio (LLR) and MSA, in the first testing configuration, and SPA, in the second testing configuration, LDPC decoders. Using these techniques, it was possible to transmit and receive the combined signal of the 3-layer LDM broadcast system in SDR.

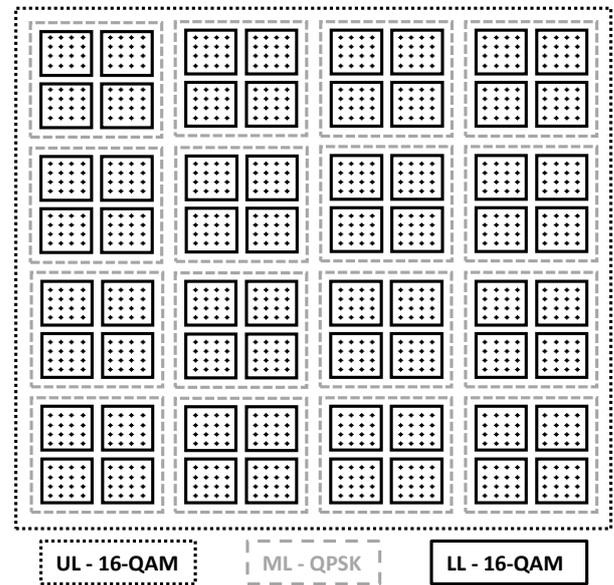


Fig. 3. 3-layer LDM constellation example.

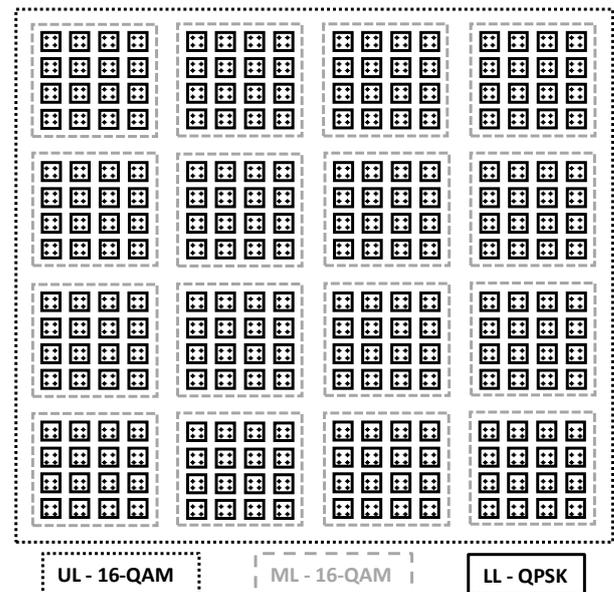


Fig. 4. Inverted 3-layer LDM constellation example.

6. Results

In this section, the obtained results of the performance tests using several configurations are presented.

To realize the simulations and perform the digital signal processing, a computer with an I7 6700@3.4 GHz processor, 16GB RAM, GeForce GTX 1060 6GB/PCIe/SSE2 Graphics Card, Ubuntu 18.04 64 bits and the software GNU Radio Companion (GRC) 3.7.13.4 was used.

An extensive computer simulation was performed in order to find the minimum SNR for ML and LL. Aiming to find the UL operating thresholds, tests were performed using the transmitter of the proposed system. The Radio Frequency (RF) signal was transmitted using an Universal Software Radio Peripheral (USRP) B210, which performs the conversion of the digital signal to RF. The UL thresholds were checked using commercial receivers, such as those distributed to participants of government social programs in the Analogue switch-off (ASO) process in Brazil [24].

Figure 5 shows the test setup used for the UL SNR measurements [24]. The UL SNR test was performed according to [50]. The USRP B210 generated the LDM signal and the band power in the Vector Signal Analyzer (VSA) input was adjusted to -40 dBm considering the useful bandwidth of 5.57 MHz. The power adjustment was made using the Attenuator 1 connected to the B210's RF output while the Attenuator 2 was configured with its maximum attenuation value of 139 dB. After this adjustment, the Attenuator 1 was set to 139 dB to measure only the noise band power. Thus, Attenuator 2 was adjusted to keep the noise band power level at -40 dBm in the VSA, considering the bandwidth of 5.57 MHz. It is worth mentioning that the inserted signal in the receiver's input connector suffers an attenuation of 6 dB due to the matching pad placed at the splitter's output.

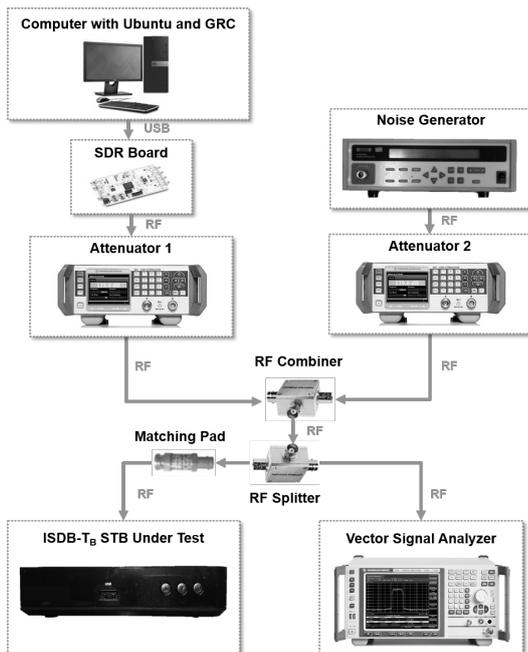


Fig. 5. ISDB-T_B UL SNR measurements test setup [24].

The SNR is calculated using the values of Attenuators 1 and 2. Setting Attenuator 1 to the reference value and adjusting the Attenuator 2 to reach the receiver's threshold value of a BER of 3×10^{-6} after applying RS or the Threshold of Visibility (TOV). For the threshold, the Attenuator 2 value was noted and the SNR was calculated. This process was repeated for all the configurations tested in this work.

The ISDB-T_B STB receives the combined signal, with all the layers, and demodulates the UL, considering the additional layers signals as noise.

During the ML and LL simulations, an AWGN noise was injected in order to measure the SNR value that corresponds to the BER threshold value of 3×10^{-6} after applying the LDPC decoder. These thresholds are used considering a reception with less than one uncorrected error event per hour. These values guarantee the QEF after the decoder [51]. The binary data source Pseudo-Random Binary Sequence 23 (PRBS 23) was used in these tests. The maximum number of iterations for the MSA and SPA LDPC decoders was set to 50.

6.1 SNR Thresholds without LDM

To analyze the effect of LDM on the SNR threshold, first, a series of test was performed to measure the SNR TOV value for each configuration used in each layer separately without the use of the LDM technique. The ISDB-T_B configuration (RS+CC) results are presented in Tab. 1. The LDPC configuration results are presented in Tab. 2.

ISDB-T _B (RS+CC)	Minimum SNR [dB]	Bit Rate [Mbps]
QPSK CR = 2/3	4.1	5.73
16-QAM CR = 2/3	9.9	11.45
64-QAM CR = 3/4	16.7	19.33

Tab. 1. ISDB-T_B SNR TOV values without LDM.

LDPC Custom Frame	Minimum SNR [dB]		Bit Rate (Mbps)
	MSA	SPA	
QPSK CR = 2/15	-1.2	-3.4	1.24
QPSK CR = 5/15	1.9	0.4	3.11
QPSK CR = 10/15	3.7	3.1	6.22
16-QAM CR = 5/15	7.4	5.4	6.22
16-QAM CR = 10/15	9.7	9.0	12.43
16-QAM CR = 13/15	12.7	12.2	16.16
64-QAM CR = 5/15	11.9	9.7	9.32
64-QAM CR = 10/15	14.9	13.9	18.64
64-QAM CR = 13/15	18.4	17.9	24.24

Tab. 2. LDPC configuration SNR thresholds without LDM.

6.2 2-layer LDM System SNR Thresholds

After the individual SNR thresholds verification, for each configuration, a 2-layer system was structured in order to verify the robustness that the chosen decoding algorithm arouse to the LL.

Some tests were done using the proposed UL with a 16-QAM constellation and $CR = 2/3$. A variety of Δ values have been tested using commercial STBs to define the minimum value for correct operation, mainly for UL, since it needs to continue to be decoded by already installed ISDB-T_B receivers. Figure 6 shows the 2-layer LDM results using Δ values of 11, 12, 13 and 14 dB. For values below 11 dB, the interference in the UL, caused by the LL presence, has already affected the robustness of the system, to the point of making the recovery of information unfeasible.

As the measured SNR value for ISDB-T_B, without LDM technique application, and with the configuration using 16-QAM and $CR = 2/3$, was approximately 10 dB, the minimum Δ value must be above this value. Using (5), it can be noted that, for Δ values equal to or below the SNR_{UL0} value, it becomes impossible to perform the degradation calculation.

Analyzing the results shown in Fig. 6, it is possible to compare the measured results and the expected values for each layer, using (4) and (6). In the LDM configuration number 2, with $\Delta = 13$ dB and LDPC SPA, the values $SNR_{UL} = 13.1$ dB and $SNR_{LL} = 27.3$ dB were measured. Using (4) and (6), the expected values $SNR_{UL} = 12.8$ dB and $SNR_{LL} = 27.1$ dB were calculated. Therefore, it is possible to make a prediction of the expected SNR values for both layers of the LDM even before taking measurements.

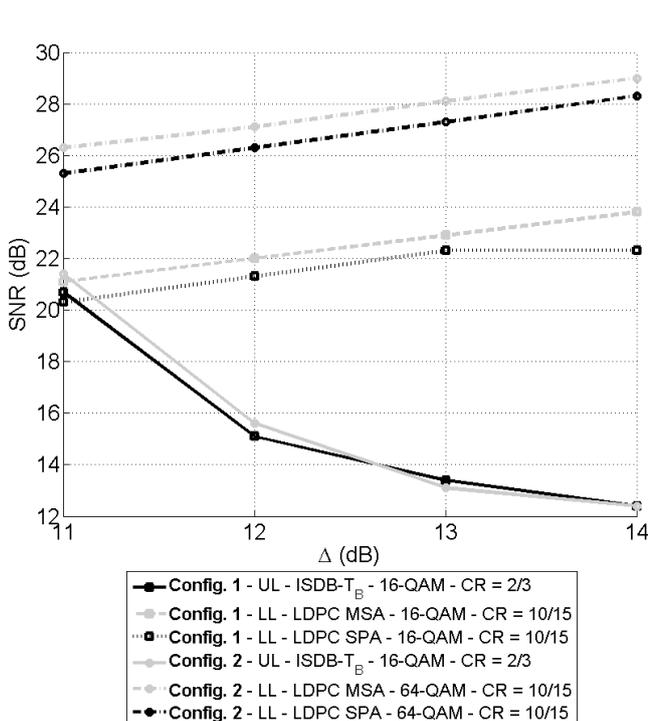


Fig. 6. 2-layer LDM - SNR vs. Δ results.

6.3 3-layer LDM System SNR Thresholds

At the beginning of the 3-layer LDM development, the same reasoning used in the 2-layer system was followed, that is, the choice of the each layer configuration followed the hierarchical logical of having the upper layers with higher robustness and the lower layer with a higher bit rate. Therefore, the first deployed configuration uses a 16-QAM in the UL, a QPSK in the ML and another 16-QAM in the LL. This configuration is similar to a 2-layer system that uses a 16-QAM in the UL and a 64-QAM in the LL.

As with 2-layer LDM testing, a variety of Δ_2 values have been tested to define the minimum value for the correct operation of the UL and several Δ_1 values were checked, in order to guarantee a proper operation of the ML. These variations and its respective results are shown in Figs. 7 and 8.

Figure 8 shows the 3-layer LDM results using $\Delta_2 = 12$ dB.

Using the results shown in Figs. 7 and 8, it is possible to compare the measured results and the expected values for each of the layers, using (8), (11) and (14). In the LDM configuration number 6, with $\Delta_2 = 12$ dB, $\Delta_1 = 7$ dB and LDPC SPA, the values $SNR_{UL} = 15.2$ dB, $SNR_{ML} = 18.7$ dB and $SNR_{LL} = 29.0$ dB were measured. The expected values of $SNR_{UL} = 14.6$ dB, $SNR_{ML} = 18.2$ dB and $SNR_{LL} = 29.0$ dB were calculated.

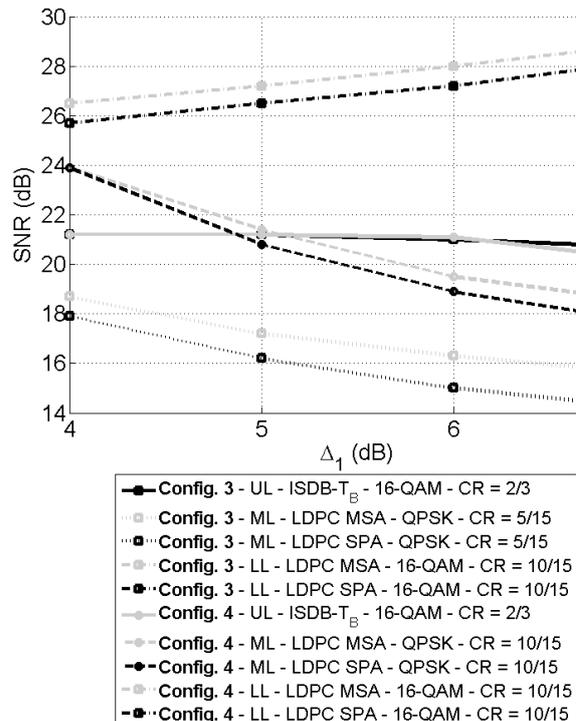


Fig. 7. 3-layer LDM with $\Delta_2 = 11$ dB - SNR vs. Δ_1 results.

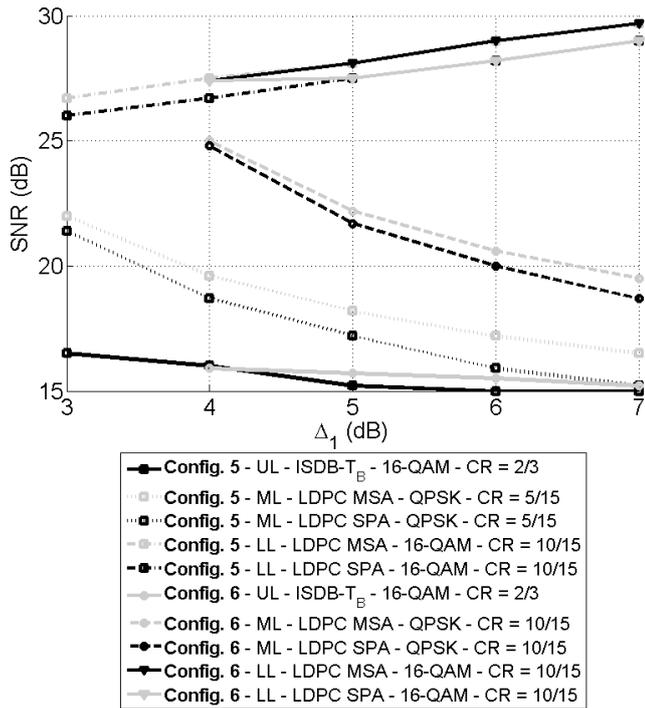


Fig. 8. 3-layer LDM with $\Delta_2 = 12$ dB - SNR vs. Δ_1 results.

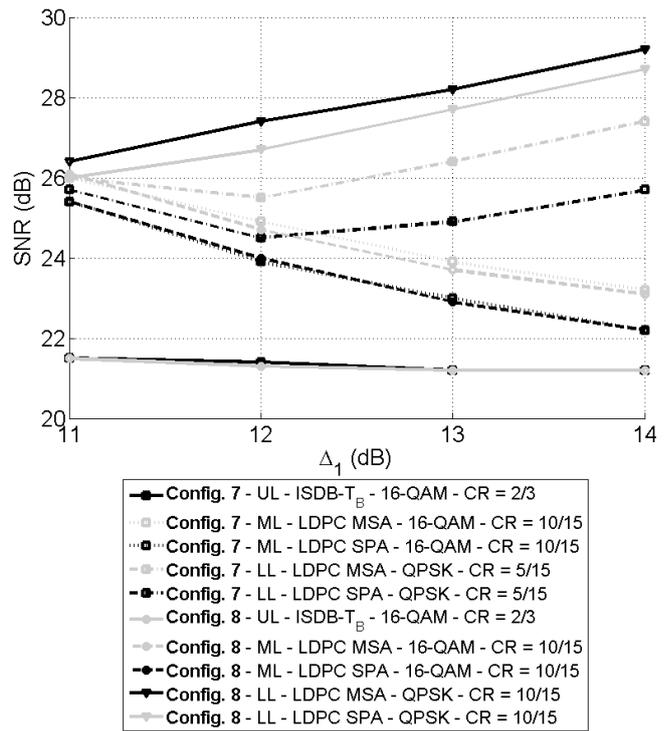


Fig. 9. Inverted 3-layer LDM with $\Delta_2 = 11$ dB - SNR vs. Δ_1 results.

6.4 Inverted 3-layer LDM System SNR Thresholds

To investigate a new way of performing the multiplexing process and a possible performance gain, a configuration with inverted robustness between ML and LL was deployed. The implementation has a 16-QAM in the UL, another 16-QAM in the ML and a QPSK in the LL, placing the most robust modulation in the most attenuated layer of the system.

Using a configuration with higher capacity (bit rate) in the ML and a greater robustness configuration in the LL, it becomes possible to allocate a smaller portion of the transmission rate in the most attenuated layer of the system. Thus, the layer that needs a higher SNR value to be received, has its importance reduced, considering its influence on the total bit rate of the 3-layer LDM.

The inverted 3-layer LDM configuration results are presented in Figs. 9 and 10. Figure 10 shows the 3-layer LDM results using $\Delta_2 = 12$ dB.

It is also possible to make a comparison of the measured results and the expected values for each layer of this new approach, using the same equations as the initial implementation of the 3-layer system. For the LDM configuration number 9, with $\Delta_2 = 12$ dB, $\Delta_1 = 13$ dB and LDPC SPA, the values $SNR_{UL} = 15.4$ dB, $SNR_{ML} = 23.9$ dB and $SNR_{LL} = 25.7$ dB were measured. The expected values for this configuration were $SNR_{UL} = 14.2$ dB, $SNR_{ML} = 23.4$ dB and $SNR_{LL} = 25.9$ dB.

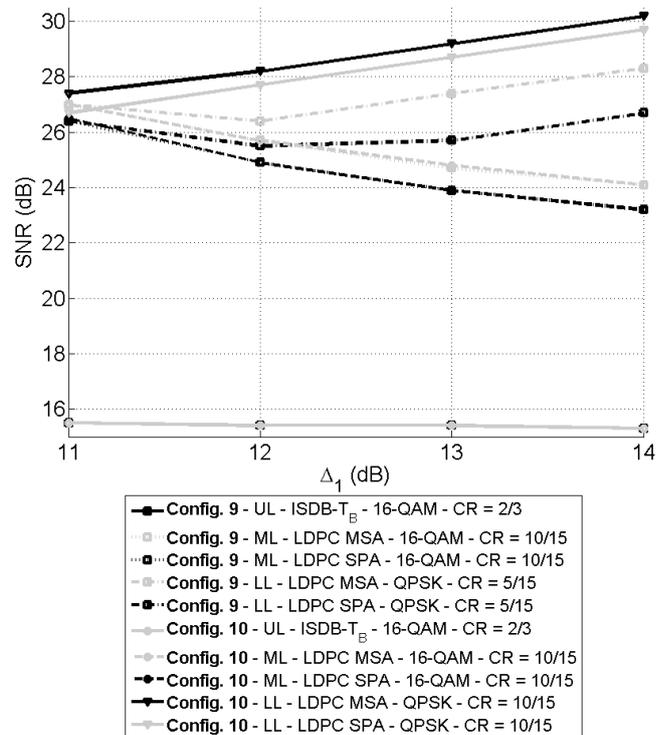


Fig. 10. Inverted 3-layer LDM with $\Delta_2 = 12$ dB - SNR vs. Δ_1 results.

6.5 Results Discussion

One of the advantages of using the LDM technique is the possibility of varying the Δ values, so that the configuration is adequate to fulfill the system requirements. In the case of the 3-layer LDM, these variations can be made using Δ_2 and Δ_1 . This was done to generate the results shown in Figs. 6, 7, 8, 9 and 10.

Among the various alternatives and tested configurations, there are some that showed an interesting performance, for example, the LDM configuration number 6 shown in Fig. 8, with $\Delta_2 = 12$ dB, $\Delta_1 = 5$ dB and LDPC SPA, where the values $SNR_{UL} = 15.7$ dB, $SNR_{ML} = 21.7$ dB and $SNR_{LL} = 27.5$ dB were measured. The total bit rate of this configuration is 30.1 Mbps and is equal to the total bit rate of LDM configuration number 2 shown in Fig. 6, with $\Delta = 12$ dB, where the values $SNR_{UL} = 15.6$ dB and $SNR_{LL} = 26.3$ dB were measured.

Although the 3-layer LDM result for the LL is not better than the 2-layer LDM, it is necessary to consider the new possibilities that arise with the use of ML, since it becomes possible a more modular reception and, with the use of Scalable High-Efficiency Video Coding (SHVC) that is the scalable extension of the High Efficiency Video Coding (HEVC) standard, it is possible to treat the LL data as a complement to the ML. Thus, the ML becomes the base layer and the LL is used as the improvement layer [33].

Table 3 [52], [53] shows the required bit rate values for 720p60, 1080p60, 1440p60 and 2160p60, using H.264 - Advanced Video Coding (AVC), H.265 - HEVC and H.266 - Versatile Video Coding (VVC) video coding methods.

Although the bit rate of the QPSK used in the 3-layer LDM seems low, it is necessary to consider the evolution of video encoders [54]. The use of HEVC and its scalability extension can be considered, as well as a more efficient model such as the VVC. The VVC is planned to be the next video compression standard by the Joint Video Experts Team (JVET) and it is supposed to save around 50% of the bit rate while maintaining the same visual quality compared to its predecessor the HEVC [55]. The VVC not only targets high resolution content but also modern video formats like 360°, High Dynamic Range (HDR), among others [56]. The HDR provides a viewing experience that scales the brightness range per pixel to offer a more realistic or a more vivid image. An additional 20% to 30% bit rate load is required in comparison with the results shown in Tab. 3 [52], [53].

Using modern video coding methods, such as the VVC, the values shown in the Tab. 3 [52], [53] and the 2-layer LDM configuration number 2, it is possible to transmit a High Definition (HD) content in the UL ($SNR_{UL} = 15.6$ dB) and a 2160p60 HDR content in the LL ($SNR_{LL} = 26.3$ dB).

Using the 3-layer LDM configuration number 6, there are two reception possibilities: 1) Receive only the UL, with $SNR_{UL} = 15.7$ dB and the ML with $SNR_{ML} = 21.7$ dB, enabling the transmission of HD content in the UL and 1080p60 HDR content in the ML. 2) Receive the three layers, with $SNR_{LL} = 27.5$ dB, enabling the transmission of HD content in the UL and 2160p60 HDR content aggregating the ML and LL bit rates.

This possibility of receiving two image quality options, depending on the received signal SNR threshold, guarantees the addition of modularity in the 3-layer LDM system, when it is compared to the 2-layer LDM. In other words, with a SNR of 21.7 dB and the 2-layer LDM configuration 2, it is only possible to receive the UL signal. In the case of the 3-layer LDM configuration 6, it is possible to receive the UL and the ML signals.

Considering the options for the system with inverted robustness hierarchy, shown in Figs. 9 and 10, an interesting configuration to be analyzed is the LDM configuration number 10 shown in Fig. 10, with $\Delta_2 = 12$ dB, $\Delta_1 = 12$ dB and LDPC SPA, where the values $SNR_{UL} = 15.4$ dB, $SNR_{ML} = 24.9$ dB and $SNR_{LL} = 27.7$ dB were measured. The total bit rate of this configuration is 30.1 Mbps and is equal to the total bit rate of the 2-layer LDM configuration number 2, with $\Delta = 12$ dB, where the values $SNR_{UL} = 15.6$ dB and $SNR_{LL} = 26.3$ dB were measured.

Similar to the 3-layer LDM, using the inverted 3-layer LDM configuration number 10, there are two reception possibilities: 1) Receive only the UL and the ML, with $SNR_{UL} = 15.4$ dB and $SNR_{ML} = 24.9$ dB, respectively, enabling the transmission of HD content in the UL and 2160p60 content in the ML. 2) Receive the three layers, with $SNR_{LL} = 27.7$ dB, enabling the transmission of HD content in the UL and 2160p60 HDR content aggregating the ML and LL bit rates. Also for this case, with a SNR of 24.9 dB and the 2-layer LDM configuration 2, it is only possible to receive the UL signal. In the case of the inverted 3-layer LDM configuration 10, it is possible to receive the UL and the ML signals.

Video Quality		Required Bit Rates [Mbps]		
		H.264 (AVC)	H.265 (HEVC)	H.266 (VVC)
720p60	Offline	1.7 ~ 2.5	1.3 ~ 1.9	0.7 ~ 1.1
	Live	3.4 ~ 5.1	2.5 ~ 3.8	1.4 ~ 2.1
1080p60	Offline	3.4 ~ 5.1	2.5 ~ 3.8	1.4 ~ 2.1
	Live	6.8 ~ 10.2	5.0 ~ 7.5	2.8 ~ 4.2
1440p60	Offline	6.8 ~ 10.2	5.0 ~ 7.5	2.8 ~ 4.2
	Live	13.5 ~ 20.5	10.0 ~ 15.0	5.6 ~ 8.4
2160p60	Offline	13.5 ~ 20.5	10.0 ~ 15.0	5.6 ~ 8.4
	Live	27.0 ~ 41.0	20.0 ~ 30.0	11.2 ~ 16.8

Tab. 3. Required bit rates for AVC, HEVC and VVC video coding methods. [52], [53].

7. Conclusion

The proposed 3-layer LDM can be used as an alternative process to migrate the Digital Terrestrial Television Broadcasting (DTTB) in a country. The UL is still compatible with ISDB-T_B and the ML and LL use better methods of coding, modulation and interleaving. A custom frame size of 19968 bits is used, in order to guarantee synchronism between the layers. The results displayed for the UL were obtained by performing tests using commercial receivers. Therefore, ensuring the backward compatibility of the proposed system.

Along with the implementation of the 3-layer LDM broadcast system, an alternative configuration with an inverted robustness hierarchy was also proposed and simulated, using a higher order constellation in ML and a lower bit rate configuration in LL.

The results presented in this paper show that the use of the LDM with three layers is feasible. It demonstrates the possibility of a software implementation of LDM transmitter and receiver using LDPC codes in ML and LL. The decoding performance has been enhanced by replacing the MSA with the SPA decoder.

In addition to the measured results, a mathematical representation of the proposed 3-layer system was developed, based on the traditional 2-layer system. Therefore, a theoretical operational analysis of the 3-layer LDM broadcast system was possible.

The main advantages of adding ML to the system are: the increase in bit rate, when compared to a system without LDM, and the addition of modularity, when compared to a 2-layer LDM.

As future work, it is possible to perform the tests that were done in this work, but considering multipath channels, for the 2-layer LDM and the different configurations of the 3-layer LDM. In addition, a more detailed analysis of the cancellation process delay is important and can provide new ideas and implementations that allow the reduction of this delay, such as the use of different techniques to perform the cancellation stages.

Acknowledgments

This work was supported in part by the Coordination for the Improvement of Higher Education Personnel (CAPES), National Council for Scientific and Technological Development (CNPq) and MackPesquisa.

The authors would like to thank PPGEEC and their colleagues at Mackenzie's Digital TV Research Laboratory.

References

- [1] WU, Y., HIRAKAWA, S., REIMERS, U. H., et al. Overview of digital television development worldwide. *Proceedings of the IEEE*, 2006, vol. 94, no. 1, p. 8–21. DOI: 10.1109/JPROC.2005.861000
- [2] WU, Y., RONG, B., SALEHIAN, K., et al. Cloud transmission: a new spectrum-reuse friendly digital terrestrial broadcasting transmission system. *IEEE Transactions on Broadcasting*, 2012, vol. 58, no. 3, p. 329–337. DOI: 10.1109/TBC.2012.2199598
- [3] EL-HAJJAR, M., HANZO, L. A survey of digital television broadcast transmission techniques. *IEEE Communications Surveys Tutorials*, 2013, vol. 15, no. 4, p. 1924–1949. DOI: 10.1109/SURV.2013.030713.00220
- [4] ZHANG, L., LI, W., WU, Y., et al. Layered-division-multiplexing: Theory and practice. *IEEE Transactions on Broadcasting*, 2016, vol. 62, no. 1, p. 216–232. DOI: 10.1109/TBC.2015.2505408
- [5] MONTALBÁN, J., ZHANG, L., GIL, U., et al. Cloud transmission: System performance and application scenarios. *IEEE Transactions on Broadcasting*, 2014, vol. 60, no. 2, p. 170–184. DOI: 10.1109/TBC.2014.2304153
- [6] DIONÍSIO, V. M., AKAMINE, C. Comparison of terrestrial DTV systems: ISDB-TB and ATSC 3.0. *SET International Journal of Broadcast Engineering*, 2017, vol. 3, no. 3, p. 8–14. DOI: 10.18580/setijbe.2017.1
- [7] GALLAGER, R. Low-density parity-check codes. *IRE Transactions on Information Theory*, 1962, vol. 8, no. 1, p. 21–28. DOI: 10.1109/TIT.1962.1057683
- [8] DIGITAL TERRESTRIAL MULTIMEDIA BROADCAST (DTMB). *Framing Structure, Channel Coding and Modulation for Digital Television Terrestrial Broadcasting System - GB Standard 20600-2006 (national standard)*. [Online] Cited 2020-12-14. Available at: <https://www.chinesestandard.net/PDF/English.aspx/GB20600-2006>
- [9] EUROPEAN TELECOMMUNICATIONS STANDARDS INSTITUTE (ETSI). *Digital Video Broadcasting (DVB); Second Generation Framing Structure, Channel Coding and Modulation Systems for Broadcasting, Interactive Service, News Gathering and Other Broadband Satellite Applications (DVB-S2) - ETSI EN Standard 302 307 (standard)*. [Online] Cited 2020-12-14. Available at: https://www.etsi.org/deliver/etsi_en/302300_302399/302307/01.03.01_60/en_302307v010301p.pdf
- [10] EUROPEAN TELECOMMUNICATIONS STANDARDS INSTITUTE (ETSI). *Digital Video Broadcasting (DVB); Frame Structure, Channel Coding and Modulation for a Second Generation Digital Terrestrial Television Broadcasting System (DVB-T2) - ETSI EN Standard 302 755 (standard)*. [Online] Cited 2020-12-14. Available at: https://www.etsi.org/deliver/etsi_en/302700_302799/302755/01.03.01_60/en_302755v010301p.pdf
- [11] EUROPEAN TELECOMMUNICATIONS STANDARDS INSTITUTE (ETSI). *Digital Video Broadcasting (DVB); Next Generation Broadcasting System to Handheld, Physical Layer Specification (DVB-NGH) - DVB document A160 (standard)*. [Online] Cited 2020-12-14. Available at: https://dvb.org/wp-content/uploads/2019/12/A160_DVB-NGH_Spec.pdf
- [12] ADVANCED TELEVISION SYSTEMS COMMITTEE (ATSC). *ATSC Standard: Physical Layer Protocol (A/322) - Doc. A/322:2017 (standard)*. [Online] Cited 2020-12-14. Available at: <https://www.atsc.org/wp-content/uploads/2016/10/A322-2017a-Physical-Layer-Protocol-1.pdf>
- [13] MACKAY, D. J. C., WILSON, S. T., DAVEY, M. C. Comparison of constructions of irregular gallager codes. *IEEE Transactions on Communications*, 1999, vol. 47, no. 10, p. 1449–1454. DOI: 10.1109/26.795809
- [14] FOSSORIER, M. P. C., MIHALJEVIC, M., IMAI, H. Reduced complexity iterative decoding of low-density parity check codes based on belief propagation. *IEEE Transactions on Communications*, 1999, vol. 47, no. 5, p. 673–680. DOI: 10.1109/26.768759

- [15] MYUNG, S., PARK, S., KIM, K., et al. Offset and normalized min-sum algorithms for ATSC 3.0 LDPC decoder. *IEEE Transactions on Broadcasting*, 2017, vol. 63, no. 4, p. 734–739. DOI: 10.1109/TBC.2017.2686011
- [16] RABAÇA, R. S., OLIVEIRA, G. H. M. G. d., JERJI, F., et al. Implementation of a real-time ISDB-TB LDM receiver using SDR. In *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. Jeju (South Korea), 2019, p. 1–6. DOI: 10.1109/BMSB47279.2019.8971858
- [17] ASSOCIATION OF RADIO INDUSTRIES AND BUSINESSES (ARIB). *Transmission System for Digital Terrestrial Broadcasting - STD-B31 - V1.6 E2 (standard)*. [Online] Cited 2020-12-14. Available at: https://www.arib.or.jp/english/html/overview/doc/6-STD-B31v1_6-E2.pdf
- [18] BRAZILIAN ASSOCIATION OF TECHNICAL STANDARDS (ABNT). *NBR 15601: Digital terrestrial television - Transmission system (standard)*. (in Portuguese). [Online] Cited 2020-12-14. Available at: <https://www.normas.com.br/visualizar/abnt-nbr-nm/26689/abnt-nbr15601-televisao-digital-terrestre-sistema-de-transmissao>
- [19] MONTALBAN, J., RONG, B., PARK, S. I., et al. Cloud transmission: System simulation and performance analysis. In *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. London (UK), 2013, p. 1–5. DOI: 10.1109/BMSB.2013.6621714
- [20] DA SILVA, L. F., AKAMINE, C., MACIEL, Y. P., et al. A proposal to use cloud transmission technique into the ISDB-T system. In *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting*. Ghent (Belgium), 2015, p. 1–5. DOI: 10.1109/BMSB.2015.7177246
- [21] MARANHÃO GARCIA DE OLIVEIRA, G. H., AKAMINE, C., MACIEL, Y. P. Implementation of ISDB-T LDM broadcast system using LDPC codes. In *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. Nara (Japan), 2016, p. 1–4. DOI: 10.1109/BMSB.2016.7521986
- [22] RABAÇA, R. S., AKAMINE, C., MARANHÃO GARCIA DE OLIVEIRA, G. H., et al. Implementation of LDM/ISDB-T broadcast system using diversity at reception. In *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. Cagliari (Italy), 2017, p. 1–4. DOI: 10.1109/BMSB.2017.7986130
- [23] RABAÇA, R. S., AKAMINE, C., MARANHÃO GARCIA DE OLIVEIRA, G. H., et al. Robustness against the effects of multipath in an ISDB-T LDM broadcast system using diversity at reception. *SET International Journal of Broadcast Engineering*, 2017, vol. 3, no. 3, p. 36–43. DOI: 10.18580/setijbe.2017.5
- [24] RABAÇA, R. S., MARANHÃO GARCIA DE OLIVEIRA, G. H., GANZAROLI, G. R., et al. Implementation of an ISDB-TB LDM broadcast system using the BICM stage of ATSC 3.0 on enhanced layer and diversity at reception. In *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. Valencia (Spain), 2018, p. 1–6. DOI: 10.1109/BMSB.2018.8436637
- [25] MONTALBAN, J., ANGULO, I., VELEZ, M., et al. Error propagation in the cancellation stage for a multi-layer signal reception. In *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. Beijing (China), 2014, p. 1–5. DOI: 10.1109/BMSB.2014.6873554
- [26] ZHANG, L., WU, Y., LI, W., et al. Enhanced DFT-based channel estimation for LDM systems over SFN channels. In *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. Ghent (Belgium), 2015, p. 1–6. DOI: 10.1109/BMSB.2015.7177253
- [27] MONTALBAN, J., IRADIER, E., ANGUEIRA, P., et al. Channel estimation: Key factor for LDM based local content delivery on SFNs. In *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. Valencia (Spain), 2018, p. 1–6. DOI: 10.1109/BMSB.2018.8436729
- [28] MONTALBAN, J., IRADIER, E., ROMERO, D., et al. New semi-blind channel estimation for LDM-LSI. In *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. Jeju (South Korea), 2019, p. 1–6. DOI: 10.1109/BMSB47279.2019.8971906
- [29] MONTALBAN, J., IRADIER, E., FANARI, L., et al. Improved semi-blind channel estimation with time domain cancellation for LDM-LSI. *IEEE Transactions on Broadcasting*, 2020, vol. 66, no. 3, p. 613–619. DOI: 10.1109/TBC.2020.2984995
- [30] REGUEIRO, C., BARRUECO, J., MONTALBÁN, J., et al. Enhanced DFT-based channel estimation for LDM systems over SFN channels. In *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. Ghent (Belgium), 2015, p. 1–6. DOI: 10.1109/BMSB.2015.7177224
- [31] MISRA, K., SEGALL, A., ZHAO, J., et al. Spatially scalable HEVC for layered division multiplexing in broadcast. In *2017 Data Compression Conference (DCC)*. Snowbird (USA), 2017, p. 3–12. DOI: 10.1109/DCC.2017.81
- [32] LEE, J., PARK, S. I., KWON, S., et al. Scalable HEVC over layered division multiplexing for the next generation terrestrial broadcasting. In *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. Cagliari (Italy), 2017, p. 1–4. DOI: 10.1109/BMSB.2017.7986176
- [33] LEE, J., PARK, S. I., KWON, S., et al. Efficient transmission of multiple broadcasting services using LDM and SHVC. *IEEE Transactions on Broadcasting*, 2018, vol. 64, no. 2, p. 177–187. DOI: 10.1109/TBC.2017.2755264
- [34] GÓMEZ-BARQUERO, D., SIMEONE, O. LDM Versus FDM/TDM for unequal error protection in terrestrial broadcasting systems: An information-theoretic view. *IEEE Transactions on Broadcasting*, 2015, vol. 61, no. 4, p. 571–579. DOI: 10.1109/TBC.2015.2459665
- [35] MOUHOUCHE, B., BARJAU, C., LEE, H. Design of non uniform constellations for layered division multiplexing. In *IEEE International Symposium on Signal Processing and Information Technology (ISSPIT)*. Abu Dhabi (United Arab Emirates), 2015, p. 247–251. DOI: 10.1109/ISSPIT.2015.7394337.
- [36] KIM, P., PARK, S., KIM, H., et al. Layered division multiplexing for satellite broadcasting system. In *International Conference on Information and Communication Technology Convergence (ICTC)*. Jeju (South Korea), 2016, p. 1224–1226. DOI: 10.1109/ICTC.2016.7763413.
- [37] GARRO, E., GIMENEZ, J. J., KLENNER, P., et al. Information-theoretic analysis and performance evaluation of optimal demappers for multi-layer broadcast systems. *IEEE Transactions on Broadcasting*, 2018, vol. 64, no. 4, p. 781–790. DOI: 10.1109/TBC.2018.2799300
- [38] GARRO, E., BARJAU, C., GÓMEZ-BARQUERO, D., et al. Layered division multiplexing with distributed multiple-input single-output schemes. *IEEE Transactions on Broadcasting*, 2019, vol. 65, no. 1, p. 30–39. DOI: 10.1109/TBC.2018.2823643
- [39] KIM, H., KIM, J., PARK, S. I., et al. Capacity analysis for LDM-based multiple-PLP configurations in ATSC 3.0. In *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. Jeju (South Korea), 2019, p. 1–5. DOI: 10.1109/BMSB47279.2019.8971903

- [40] LEE, J., PARK, S. I., KWON, S., et al. Layered division multiplexing for ATSC 3.0: Implementation and memory use aspects. *IEEE Transactions on Broadcasting*, 2019, vol. 65, no. 3, p. 496–503. DOI: 10.1109/TBC.2019.2897750
- [41] GARRO, E., BARJAU, C., GÓMEZ-BARQUERO, D., et al. Study on the optimum co-located MIMO scheme for LDM in ATSC 3.0: Use cases and core layer performance. In *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. Valencia (Spain), 2018, p. 1–4. DOI: 10.1109/BMSB.2018.8436920
- [42] PARK, S., LEE, J., LIM, B., et al. Field comparison tests of LDM and TDM in ATSC 3.0. *IEEE Transactions on Broadcasting*, 2018, vol. 64, no. 3, p. 637–647. DOI: 10.1109/TBC.2017.2755375
- [43] MYUNG, S., KIM, K., LEE, J., et al. Efficient decoding of LDM core layer at fixed receivers in ATSC 3.0. *IEEE Transactions on Broadcasting*, 2017, vol. 63, no. 4, p. 727–733. DOI: 10.1109/TBC.2017.2731040
- [44] HWANG, Y., CHO, S., MYUNG, S., et al. Efficient decoding schemes of LDPC codes for the layered-division multiplexing systems in ATSC 3.0. *IEEE Transactions on Broadcasting*, 2017, vol. 63, no. 1, p. 1–10. DOI: 10.1109/TBC.2016.2606896
- [45] CHO, S., HWANG, Y., MYUNG, S., et al. Low-complexity decoding algorithms for the LDM core layer at fixed receivers in ATSC 3.0. *IEEE Transactions on Broadcasting*, 2017, vol. 63, no. 1, p. 293–303. DOI: 10.1109/TBC.2016.2606879
- [46] ZHANG, L., LI, W., WU, Y., et al. Two-layer mobile service performance in LDM-based ATSC 3.0 system. In *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. Nara (Japan), 2016, p. 1–7. DOI: 10.1109/BMSB.2016.7521990
- [47] LIU, L., XU, Y., WU, Y., et al. Capacity analysis of 3-layer layered division multiplexing system. In *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. Jeju (South Korea), 2019, p. 1–5. DOI: 10.1109/BMSB47279.2019.8971843
- [48] BAE, J., KWON, S., KIM, Y., et al. Reception complexity and power consumption reduction with ASK in 3-layer LDM. In *IEEE 9th International Conference on Consumer Electronics (ICCE)*. Berlin (Germany), 2019, p. 152–157. DOI: 10.1109/ICCE-Berlin47944.2019.8966160
- [49] LARROCA, F., FLORES-GURIDI, P., GÓMEZ, G., et al. An open and free ISDB-T full seg receiver implemented in GNU radio. In *Wireless Innovation Forum Conference on Wireless Communications Technologies and Software Defined Radio (WinnComm 16)*. Virginia (USA), 2019, p. 1–10.
- [50] BEDICKS, G., YAMADA, F., SUKYS, F., et al. Results of the ISDB-T system tests, as part of digital TV study carried out in Brazil. *IEEE Transactions on Broadcasting*, 2006, vol. 52, no. 1, p. 38–44. DOI: 10.1109/TBC.2005.856729
- [51] NORDIG. *NorDig Unified Test Plan for Integrated Receiver Decoders for use in Cable, Satellite, Terrestrial and IP-Based Networks - ver 2.6.0 (manual)*. [Online] Cited 2020-12-14. Available at: https://nordig.org/wp-content/uploads/2017/12/NorDig-Unified_Test_Plan_ver_2.6.0.pdf
- [52] BRAZILIAN SOCIETY OF TELEVISION ENGINEERING (SET). *Integrating HEVC Video Compression with a High Dynamic Range Video Pipeline - SET Magazine - SET EXPO 2016 (technical report)*. [Online] Cited 2020-12-14. Available at: https://set.org.br/artigos/ed162/paper_smpte.pdf
- [53] SIQUEIRA, Í., CORREA, G., GRELLERT, M. Rate-distortion and complexity comparison of HEVC and VVC video encoders. In *IEEE 11th Latin American Symposium on Circuits & Systems (LASCAS)*. San Jose (Costa Rica), 2020, p. 1–4. DOI: 10.1109/LASCAS45839.2020.9069036
- [54] KUFA, J., KALLER, O., ZACH, O., et al. Objective models for performance comparison of compression algorithms for 3DTV. *Radioengineering*, 2019, vol. 28, no. 1, p. 207–219. DOI: 10.13164/re.2019.0207
- [55] INTERNATIONAL TELECOMMUNICATION UNION - TELECOMMUNICATION STANDARDIZATION SECTOR (ITU-T). *High Efficiency Video Coding - Recommendation ITU-T H.265 (manual)*. [Online] Cited 2020-12-14. Available at: <https://www.itu.int/ITU-T/recommendations/rec.aspx?rec=14107&lang=en>
- [56] INTERNATIONAL TELECOMMUNICATION UNION - TELECOMMUNICATION STANDARDIZATION SECTOR (ITU-T). *Versatile Video Coding - Recommendation ITU-T H.266 (manual)*. [Online] Cited 2020-12-14. Available at: <https://www.itu.int/ITU-T/recommendations/rec.aspx?id=14336>

About the Authors ...

Ricardo S. RABAÇA was born in 1990. He received the B.S. and M.S. degrees in Electrical Engineering from the Mackenzie Presbyterian University, São Paulo, Brazil, in 2013 and 2017, respectively. He is currently pursuing a Ph.D. degree in Electrical and Computation Engineering at Mackenzie Presbyterian University. Since 2016 he has been a post-grad Researcher with the Digital TV Research Laboratory at Mackenzie Presbyterian University. His fields of study are telecommunications, broadcasting and Software Defined Radio.

Fadi JERJI received a B.S. degree in Computer Engineering in 2010 and an M.S. degree in Electrical and Computation Engineering from Mackenzie Presbyterian University, São Paulo, Brazil, in 2019. He is currently pursuing a Ph.D. degree in Electrical and Computation Engineering at Mackenzie Presbyterian University. Since 2017 he has been a post-grad Researcher with the Digital TV Research Laboratory at Mackenzie Presbyterian University. He is also an Assistant Professor with the Electrical Engineering Department at Mackenzie Presbyterian University.

Cristiano AKAMINE (corresponding author) received a Ph.D. degree in Electrical Engineering from the State University of Campinas, Brazil, in 2011. He is a Professor at Mackenzie Presbyterian University, where he is a Coordinator of the Digital TV Research Laboratory. He is a member of the Board of the Brazilian Digital Terrestrial Television Forum and Society of Brazilian Broadcast Engineers (SET). He works with the ISDB-T_B broadcasting standardization and holds several patents and intellectual property licenses. He also has published numerous articles and has a Brazilian scientific grant of Productivity and Technological Development and Innovative Extension-Level 2 from the National Council of Technological and Scientific Development. He has also served as a reviewer for several periodicals and conferences and has participated as a Guest Editor in the Special Issue Point-to-Multipoint Communications and Broadcasting in 5G of IEEE Communications Magazine.