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J. Montalban et al., "Performance Study of Layered Division Multiplexing Based on SDR Platform," in IEEE Transactions on Broadcasting, vol. 61, no. 3, pp. 436-444, Sept. 2015, doi: 10.1109/TBC.2015.2432463.

Performance Study of Layered Division Multiplexing Based on SDR Platform

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***Abstract*— Two of the main drawbacks of the current broadcasting services are, on the one hand, the lack of flexibility to adapt to the new generation systems requirements, and on the other hand, the incapability of taking a piece of the current mobile services market. In this paper, Layered Division Multiplexing (LDM), which grew out of the concept of Cloud Txn, is presented as a very promising technique for answering those challenges and enhancing the capacity of broadcasting systems. The major contribution of this work is to present the first comprehensive study of the LDM performance behavior. In particular, in this paper, the theoretical considerations of the LDM implementation are completed with the first computer based simulations and laboratory tests, covering a wide range of stationary channels and the mobile TU-6 channel. The results will support LDM as a strong candidate for multiplexing different services in the next generation broadcasting systems, increasing both flexibility and performance.**

***Index Terms*—Cloud Txn, Layered Division Multiplexing, LDM, SDR, Spectrum Efficiency.**

I. Introduction

The dawn of the new century has brought a substantial revolution to the broadcasting world, changing the traditional way in which this technology has been understood during the last decades. On the one hand, the increased pressure for further attributions of the broadcast spectrum to other technologies has fostered the research on the field of more flexible usages of the spectrum for the next generation broadcasting systems. On the other hand, it is expected that the global mobile data traffic will increase 11-fold between 2014 and 2018, and thus, the users' expectations are continuously increasing, looking for higher quality services.

This work has been financially supported in part by the University of the Basque Country UPV/EHU (UFI 11/30), by the Basque Government (IT-683-13 and SAIOTEK), by the Spanish Ministry of Science and Innovation under the project NG-RADIATE (TEC2009-14201), by the Spanish Ministry of Economy and Competitiveness under the project HEDYT-GBB (TEC2012-33302) and the European Regional Development Fund (ERDF).

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In addition, there are other communication sectors willing to take advantage of the situation, increasing the pressure for further spectrum attributions of the current broadcasting frequency band [1]. As a consequence, the new generation standards, such as ATSC 3.0, have included in their call for proposals the imperative need for designing more spectral friendly and flexible systems [2][3].

The capability of simultaneously delivering services with different capacities, in particular mobile/indoor and HDTV, or even mobile/indoor and UHDTV, is one the most relevant use cases for Next Generation DTT [4]. In Europe, up to now, the second generation DVB standard family had solved this issue through the implementation of different Physical Layer Pipes (PLP) or the insertion of the mobile service within the Future Extension Frames (FEF) of the stationary services [5]. Nonetheless, even though each solution has its own particularities, both are based on Time Division Multiplexing (TDM). Another example of combined mobile and stationary services is ISDB, where Frequency Division Multiplexing (FDM) is used for delivering different contents within the same frame [6].

Most recently, Layered Division Multiplexing, which grew out from the Cloud Txn concept [7][8], has been presented as a promising candidate for the next generation standards. LDM is the sum of two synchronized signals (in time and frequency), which are broadcasted on the same RF television channel.

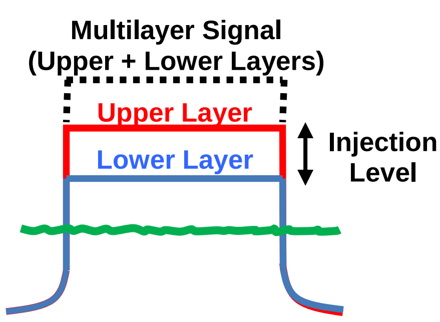

Fig. 1. LDM system: Hierarchical spectrum re-use to improve spectrum efficiency.

For instance, it is possible to combine on the same channel a signal targeting mobile services (Upper Layer, UL), and certain dBs below UL, another signal (Lower Layer, LL), where LL could be a DVB-T2 signal or another signal format for delivering high capacity services (See Fig. 1). As matter of fact, it has already been theoretically demonstrated that LDM shows higher spectrum efficiency than TDM and FDM techniques [9]. It should be mentioned that injection levels between data streams are flexible and represent the power level of the Lower Layer relative to the Upper Layer. The modulation and channel coding applied to each data stream can be changed according to the required robustness for the different reception conditions.

The major contribution of this paper is supporting the LDM theoretical performance with a practical study based on comprehensive computer simulations and laboratory tests.

The paper is organized as follows. Section II summarizes the main theoretical considerations for the LDM implementation and presents the performance gain with respect to TDM/FDM. Then, Section III describes the architecture of the transmitter and Section IV provides details about the possible receiver configurations. Section V explains the different analysis set-ups, and afterwards, Section VI and VII present both the stationary and mobile results. Eventually, Section VIII highlights the main conclusions and contributions of the paper.

II. Theoretical Considerations for LDM Implementation

This section summarizes the main theoretical concepts behind the layered division multiplexing technique [8][9][10] and provides a comparison with hierarchical modulation techniques [11][12].

Any means of delivering multiple layered services that share 100% the time and spectrum resources of a single RF channel involves potential interlayer interference. The lower layer signal acts as an interference source to the upper layer, reducing its noise tolerance capacity. Meanwhile, assuming a fixed total transmission power, adding the lower layer signal will also reduce the transmission power of the upper layer. Therefore, there is a two-fold impact from the lower layer signal to the upper layer signal: acting as a noise interference source and reducing the transmission power. In [8], the authors presented the theoretical formulas for obtaining the Signal to Noise Ratio (SNR) thresholds of Upper and Lower Layers. In TABLE 1, the LDM vs TDM performance comparison in [8] has been extended for the Rayleigh channel. It is important to note that for rich-scattering channels the gain is maintained or even increased.

TABLE 1. Performance comparison of LDM vs. TDM for Rayleigh Channels.

LDM (-5 dB injection)		**Stationary 50% Mobile 50%**		**Stationary 67.7% Mobile 33.3%**	
Data Rate	**SNR**	**Data Rate**	**SNR**	**Data Rate**	**SNR**
1.95 Mbps QPSK 3/15	-1.8 dB	1.93 Mbps QPSK 6/15	0.9 dB	2.15 Mbps QPSK10/15	5.7 dB
14.53 Mbps 16Q 3/4	19.6 dB	14.52 Mbps 256Q 3/4	22.6 dB	14.52 Mbps 64Q 3/4	17.7 dB
19.36 Mbps 64Q 2/3	22.3 dB	-	N.A.	19.36 Mbps 256Q 3/4	22.6 dB
25.81 Mbps 256Q 2/3	26.5 dB	-	N.A.	-	N.A

The LDM total gain (UL+LL) is about 5dB, and what is more important, the mobile/indoor gain ranges from 3 to 7 dB,i.e., 2 to 5 times power gain.

In the recent history of broadcasting, there are other systems that have merged two components on the transmitted signal in the form of hierarchical transmission. For instance, DVB-T or DVB-NGH have some working modes based on hierarchical modulation, which enable two layers with the same information message to be transmitted with different robustness [13]. Fig. 2 shows an example of a DVB-T hierarchical 64-QAM constellation with an embedded QPSK stream. In a 64 QAM constellation, 6 bits per 64QAM symbol can be coded. In hierarchical modulation, the 2 most significant bits (MSB) correspond to a QPSK service embedded in the 64QAM one [14].

LDM can be understood as a generalization of the hierarchical modulation concept, where the final scheme offers some substantial differences when compared to the DVB hierarchical modulation.

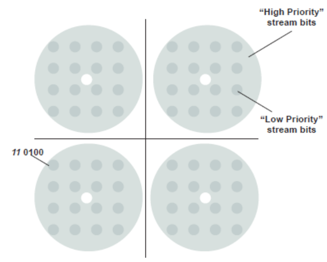

Fig. 2. DVB-T Hierarchical 64QAM constellation with an embedded QPSK (Source: [14]).

First, in LDM, the lower layer insertion is done at cell level, which is an OFDM carrier sub-channel carrying a constellation data point. Therefore, it is possible to have different transmission chains for each layer. That is to say, in the LDM system, the upper and lower layers may have different bit/cell and even time interleavers. This is a clear advantage as both layers are targeting different services, and thus, they have different requirements. In DVB-T, by contrast, the hierarchical insertion is done at bit level within the BICM, in such a way that both streams share the same transmission modules.

Second, in LDM, multilayer constellation points might not be in the same quadrant as the corresponding upper layer constellation point. That is to say, depending on the combination of upper and lower layer constellations and the injection level, multilayer constellation points corresponding to an upper layer constellation point of a certain quadrant may cross over to adjacent quadrants. Fig. 3 shows the multi-layer constellation for a 16-QAM LL signal; where for each UL quadrant a coded color-marker has been assigned. Thus, the black-triangle marker is associated with the upper left quadrant whereas the red-circle marks the lower right points. It can be clearly seen how some points of the lower layer constellation cross to other quadrants, and therefore, this is not the case of a classical hierarchical modulation.

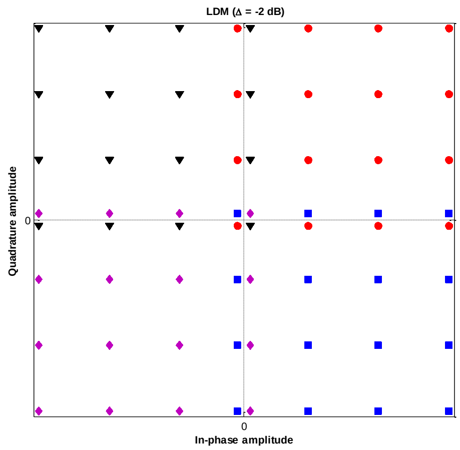

Fig. 3. Example of LDM multilayer Constellation. UL QPSK, LL 64QAM, injection level -3 dB.

III. LDM Transmitter

In an LDM transmitter, the major parts of the transmission modules are shared by both layers, and therefore, there is no significant complexity increase. A detailed block diagram of the transmitter is shown in Fig. 4.

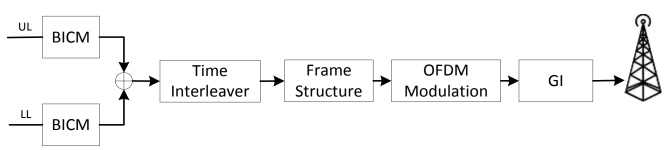

Fig. 4. LDM transmitter system diagram.

The first important outcome is that each stream has its own BICM module, and consequently, data streams can be separately configured taking into account the different services that they target. As previously mentioned, in this architecture, the injection level (Δ) is the key parameter indicating how deep the LL is embedded, and how the total transmission power is distributed between the two layered signals. What is more, assuming that the system total power is P_s, and the injection level Δ, the layers transmission power can be simplified as seen in (1) and (2), being $P_s = P_{UL} + P_{LL}$.

$$P_{UL} = \frac{10^{\frac{\Delta}{10}}}{1+10^{\frac{\Delta}{10}}} \quad (1)$$

$$P_{LL} = \frac{1}{1+10^{\frac{\Delta}{10}}} \quad (2)$$

For instance, a -4 dB injection level indicates that the UL signal is transmitted with the 72% of the total power, whereas the LL signal is transmitted with the 28%.

IV. LDM Receiver

A. *Upper layer-only reception*

For a receiver that is designed to receive only the mobile (upper) layer signal, the receiver system can be really simple. The key is that only the mobile service decoder is required, without the need of additional stream decoders and re-modulations. This single-layer receiver is energy efficient and easily integrated into portable and handheld devices. The implementation of robust LDPC codes can solve the inter-carrier interference problem, and therefore, low-complexity channel estimation and equalization algorithms are used[8]..

B. *Upper and lower layer reception*

From Fig. 5 it can be seen that for each additional layer decoding capability, a re-modulation/cancellation path and a decoding block is needed, whereas the equalization and synchronization blocks will work for all layers.

It is clear that, to perform the signal cancellation, the receiver first needs to recover the UL transmission symbols. The best way to assure that there will be no errors in the upper layer stream is to rebuild the mobile service transmission signal. Although this cancellation processing involves additional complexity to perform channel decoding and re-encoding, it provides the most reliable UL signal estimate.

Nevertheless, it is important to note that, when there is sufficient SNR to decode the LL signal, UL signal is at very high SNR condition, and thus, the LDPC decoder will require very few iterations to converge.

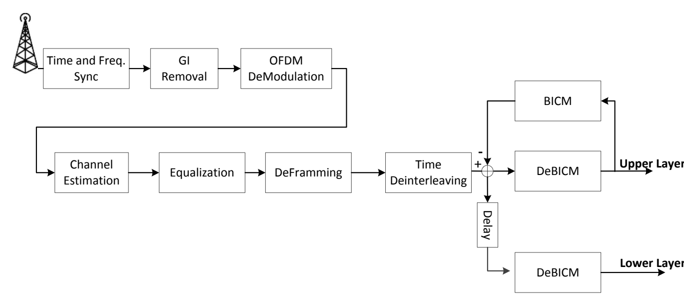

Fig. 5. General block diagram of an LDM receiver.

V. Evaluation

Once it has been theoretically proved that LDM can offer a significant performance gain when compared with other multiplexing techniques, the next step is to move to a more practical test/study platform, which will offer not only computer based ideal results, but also HW performance indicators. This methodology consists of two steps: first, the system performance is characterized by computer simulations, and second, laboratory measurements are carried out to account for practical receiver degradation. In both cases, the LDM performance will be compared with the Single Layer (SL) performance. This section describes the methods, set-ups and parameters associated to both computer simulations and laboratory measurements. The main parameters for the performance study are gathered in TABLE 2.

TABLE 2. Main parameters for the test/evaluation platform.

	Computer Simulation	Laboratory Test
FFT Size	16 K	
Guard Interval	1/8	
Bandwidth	6 MHz	
Pilot Pattern	PP1,PP2	
Injection level Δ	-4 dB, -5 dB	
Pilot Boosting	2.5 dB	
Time Interleaving	Block Time Interleaver (250 ms)	
Frame Length	250 ms	
Static Channels	AWGN,RICE, RAYLEIGH,0dBECHO	
Mobile Channels	TU-6@(5,50,75,100 Hz)	
Simulation Step	0.1 dB	0.2 dB

The FFT size is set up to 16K and the guard interval is defined as 1/8. This configuration allows the reception of echoes reflected from 90 km away without Inter Symbol Interference (ISI) in a 6 MHz channel. Accordingly, the densest PP2/PP1 pilot patterns are implemented, with different power boosting. In TABLE 3, the pilot boosting penalties according to the formula presented in [5] are calculated.

TABLE 3. Pilot boosting penalty for different signal configurations (FFT 16K).

SL		LDM ($\Delta = -4dB$)		LDM($\Delta = -5dB$)	
PP1	**PP2**	**PP1**	**PP2**	**PP1**	**PP2**
0.41 dB	0.38 dB	0.18 dB	0.17 dB	0.17 dB	0.15 dB

The signals will be tested against the channel models widely used in terrestrial broadcast standardization processes [3][5]. In the laboratory trials, the 0dB echo channel has been slightly modified introducing 1 dB attenuation to the delayed path, to remove possible performance degradation due to the very challenging carrier recovery. In the results section, this case has been marked with (*). Regarding the pilot pattern, it requires the usage of the densest PP1 together with a two dimensional LS estimation (time-domain interpolation), whereas for the rest of them PP2 has been selected.

Finally, in TABLE 4 the selected configuration modes are gathered. These modes attempt to cover a wide range of services, from the most robust mobile/indoor services (1.83-3.07 Mbps) to the most capacity demanding stationary services (16.63-27.82 Mbps).

The throughput is calculated for a 6 MHz channel taking into account the signal overhead due to the signaling data and frame structure. The first three cases are going to be used to test the single layer case, whereas a combination of the two more robust codes [16] and the three high capacity configurations are considered for LDM.

TABLE 4. LDM configurations and associated capacities.

Const.	CR	Bit Rate (Mbps)
QPSK	3/15	1.95
QPSK	4/15	2.56
QPSK	5/15	3.21
16-QAM	3/4	14.53
64-QAM	2/3	19.36
256-QAM	2/3	25.81

A. *Computer Simulations*

The transmission block diagram is depicted in Fig. 4 (Option A). The transmitter can convey either a SL signal or an LDM signal depending on the selected configuration. In this case, the lower layer is a DVB-T2 signal [13]. The generated signal is always a random PRBS, and the signaling is also based on DVB-T2, but it includes some modifications to make it LDM compatible.

Regarding the receiver, Fig. 5 shows the main block diagram for both the SL and LDM approaches. In addition to the common modules, it also includes the frequency domain cancellation algorithm presented in [8][10] for LDM reception. Channel estimation is based on a frequency domain DFT interpolation, plus an additional time-domain Wiener filtering. The time filtering window is 10 tap long and the negative symmetric algorithm has been used for padding the estimated LS pilots.

Regarding the Quality of Service (QoS), the signal reception will be considered error free when the BER value at the outer coder output is lower than 10^{-6} [13]. For stationary channels, the Gaussian noise is injected in the time domain, after estimating the overall signal power. Nevertheless, when dealing with mobile channels, for each receiving speed ten different channel realizations are averaged; and secondly, the noise is injected symbol by symbol in the frequency domain.

B. *Laboratory Tests*

A further step into the system analysis is developed in this set-up, where non-ideal transmission conditions are included: transmitted signal MER, clock error values, quantification errors, and TX/RX sampling rate differences. First, Fig. **6** depicts the block diagram of the transmitter side. The first half of the process is SW based, where the signals are generated in a PC running a modified version of the LDM platform explained before.

The channel model is applied also as one of the processing modules of the SW platform. The HW part consists of a general purpose Vector Signal Generator (VSG), namely the Anritsu MG 3700A model. This model has the capability to add two different sources (signal and AWGN) and modulate them into the selected RF channel.

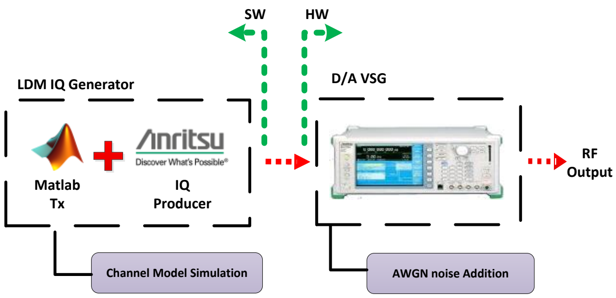

Fig. 6. Laboratory trials transmitter block diagram.

The block diagram of the receiver part is depicted in Fig. 6. At the receiver side, the generated signal is recorded by the Anritsu MS2690A Vector Signal Analyzer (VSA), which digitalizes the signal fed into the RF input. The used sampling rate is 25 Mbps with 16 bit resolution, and the measured internal noise of the analyzer is -131 dBm. The signal is sampled according to the predefined sampling rate and stored into the internal HD. From now on, the SW based part starts, which basically consists in a SDR receiver. This SDR receiver post-processes all the signals that have been previously recorded. This SDR receiver is an evolution of a SW receiver developed for DVB-T2. The implemented channel estimation and carrier recovery methods can be found in [17].

In this laboratory tests, it is considered that there is an erroneous reception when there is at least one erroneous FEC block per frame within the analyzed 5 seconds signal. Finally, when mobile channels are analyzed, the noise is injected symbol by symbol in the frequency domain, guaranteeing a controlled constant relation between the signal and noise powers.

VI. Stationary Results Analysis

The performance evaluation starts with the stationary channels, which include the challenging indoor portable and 0dBECHO among others. In this case, both SL and LDM cases are going to be compared in order to assure that there are no extra losses in the LDM case.

A. *Single Layer*

To begin with, TABLE 5 shows the SNR thresholds over the stationary channels when ideal channel estimation is assumed [2][5]. It is important to note that these receiving thresholds are the lowest boundaries against which the results including real channel estimation and laboratory HW equipment will be compared.

TABLE 5. Single layer thresholds for stationary channels with ideal channel estimation (required SNR to achieve BER=$1x10^{-6}$).

		AWGN	RICE	Rayleigh	0 dB Echo
QPSK	3/15	-4.3 dB	-4.2 dB	-3.6 dB	-3.9 dB
	4/15	-2.9 dB	-2.7 dB	-2.0 dB	-2.3 dB
	5/15	-1.7 dB	-1.5 dB	-0.5 dB	-0.9 dB

Due to the robustness of the LDPCs, the difference between the AWGN channel and the most challenging Rayleigh channel ranges from 0.4 dB to 0.8 dB.

In Fig. 7, these ideal values (solid lines) are completed with the receiving thresholds including computer based real channel estimation (dashed lines) and laboratory HW trials (dotted lines).

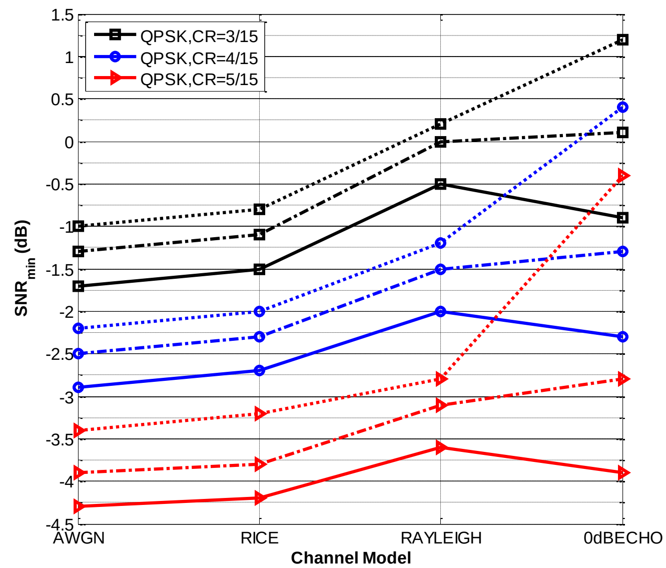

Fig. 7. Stationary channels: receiving thresholds performance losses for SL. Simulations with ideal channel estimation (solid lines), real channel estimation (dashed) and laboratory HW trials (dotted).

The idea behind this comparison is to identify the degradation boundaries in the single layer case. The first conclusion is that all the signal configurations show almost the same performance degradation for each channel in the three different set ups. What is more, the degradation (both due to real channel estimation or HW implementation) is maintained for all the channels, with the exception of the 0dB Echo.

In general, the channel estimation loss (solid lines vs dashed lines) is about 0.4-0.6 dB for the first three channels, whereas this value increases up to about 1 dB for the 0 dB Echo.

Regarding the laboratory HW measurements, for the AWGN, Rice and Rayleigh channels, the extra degradation is within 0.5 dB. What is more, the performance penalty remains almost constant for all the different stationary channels, meaning that the developed SDR LDM receiver performance is within the implementation impairments.

However, as expected, the 0 dB Echo channel offers the highest loss, as it presents the most difficult equalizing conditions. In particular, QPSK-CR=3/15 shows the worst performance with a degradation of about 2.4 dB. Apart from that, it is important to note that for an ideal case, Rayleigh is more critical than 0 dB Echo, but once channel estimation and carrier recovery are implemented, the 0 dB Echo is more challenging.

It is important to note that for the first two cases, when CR={3,4}/15 are used, the final SNR threshold remains negative or close to zero, and therefore, the system will be able to withstand a noise power which is actually higher than the transmitted signal power. Thus, these two combinations are the most suitable ones to be used as an upper layer for the LDM multiplexing.

B. Layered Division Multiplexing

First of all, TABLE 6 and TABLE 7 gather the computer based receiving thresholds with ideal channel estimation for the selected configurations, when the injection level values are -4 and -5 dB respectively, and when a code rate of 3/15 or 4/15 is selected for the UL.

TABLE 6. Stationary channels: receiving thresholds for LDM services (injection level -4 dB, UL {CR=3/15,4/15) with ideal channel estimation.

		AWGN	RICE	Rayleigh	0 dB Echo
QPSK	3/15	-2.1 dB	-2.0 dB	-0.9 dB	-0.4 dB
QPSK	4/15	-0.4 dB	-0.1 dB	1.3 dB	0.8 dB
16QAM	3/4	15.5 dB	16.0 dB	18.8 dB	18.7 dB
64QAM	2/3	18.9 dB	19.3 dB	21.5 dB	21.3 dB
256QAM	2/3	23.2 dB	23.5 dB	25.7 dB	25.8 dB

TABLE 7. Stationary channels: receiving thresholds for LDM services (injection level -5 dB, UL {CR=3/15,4/15) with ideal channel estimation.

		AWGN	RICE	Rayleigh	0 dB Echo
QPSK	3/15	-2.6 dB	-2.4 dB	-1.5 dB	-1.8 dB
QPSK	4/15	-0.8 dB	0.6 dB	0.5 dB	0.0 dB
16QAM	3/4	16.2 dB	16.7 dB	19.6 dB	19.4 dB
64QAM	2/3	19.6 dB	20.0 dB	22.2 dB	22.0 dB
256QAM	2/3	23.9 dB	24.3 dB	26.5 dB	26.5 dB

The upper layer SNR results are always around 0 dB, whereas the lower layer provides a wide range of values for different capacities, which can be adjusted with the injection level.

The next step is to provide more realistic receiving thresholds, where the computer based results including channel estimation and laboratory HW results are compared with the ideal simulation case. The main objective is to prove that the LDM implementation losses are the same as in the previously analyzed SL case.

First of all, the UL results for both -4 dB and -5 dB are plotted in Fig. 8. As expected, the channel estimation degradation for the upper layer is low (< 0.3 dB) for both injection levels (-4/-5 dB) and for the first three considered channels, but it increases up to 1 dB for the most challenging 0 dB Echo channel. As a matter of fact, this performance degradation is smaller than in the SL case, due to the fact that the pilot boosting penalty is smaller as the absolute amplitude value of the carriers has been maintained (see TABLE 3). Nevertheless, if the boosting penalty is taken into account, the losses are very well aligned with the SL case. Regarding the HW degradation (dotted lines), the values range from 0.2 dB to 0.5 dB in the first three types of channels, but they increase up to 1.5 dB in the case of 0 dB Echo. Again, the losses are very well aligned with the single layer case.

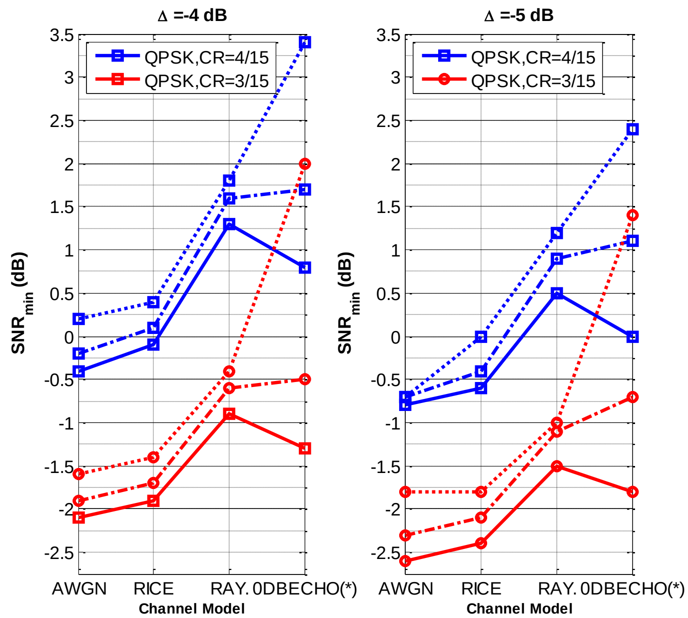

Fig. 8. Stationary channels: receiving thresholds performance losses for LDM (UL). Simulations with ideal channel estimation (solid lines), real channel estimation (dashed) and laboratory HW trials (dotted).

The next step is to study the lower layer performance to probe that there is no additional degradation due to the cancellation process. The receiving thresholds for both injection levels are depicted in Fig. 9. When the computer simulations including channel estimation results for -4 dB and -5 dB injection levels are compared, it can be seen that the LL channel estimation performance is not affected by injection level, and thus, this is another reason to assume that the cancellation process is not critical. The performance losses are between 0.3-0.6 dB for the first three cases and the difference with the ideal conditions may grow up to 1.3 dB for the 0 dB Echo case. Finally, it can be stated that, in general, the laboratory results show reasonable performance losses when compared to simulation results. As the differences are within 0.8 dB, it is shown that the obtained performance losses are very similar to the single layer case. Nevertheless, it is important to note that the 0 dB Echo is the most critical channel, with a maximum degradation of 1.5 dB for the 256QAM, CR=2/3 case.

Summarizing, it may be concluded that the channel degradation penalty associated to channel estimation errors is maintained for an LDM system when its performance is compared to the SL case, and what is more, the same applies for HW implementation losses.

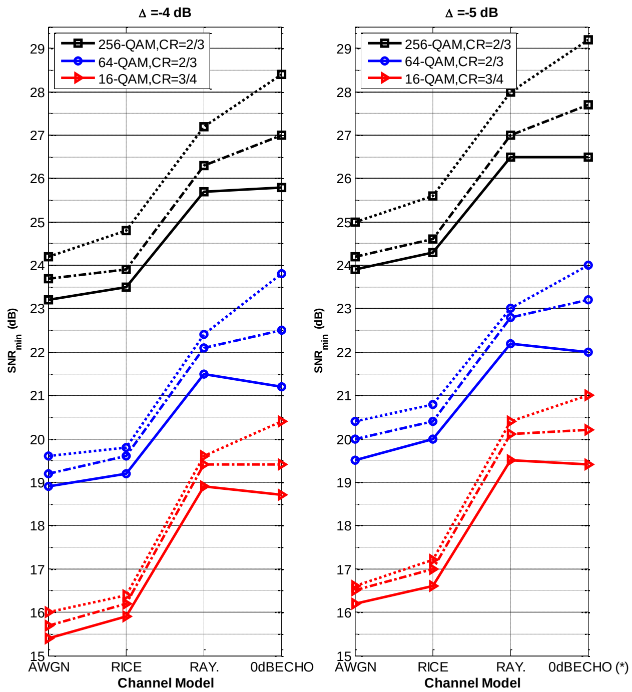

Fig. 9. Stationary channels: receiving thresholds performance losses for LDM (LL). Simulations with ideal channel estimation (solid lines), real channel estimation (dashed) and laboratory HW trials (dotted).

VII. MOBILE RESULTS ANALYSIS

A. *Single Layer*

The first objective of this section is twofold. First of all, it should be confirmed that the ICI distortion can be overcome with strong FEC; and second, it should be proved that, as a consequence, large sized FFT can be used for mobile channels [15]. In addition, the degradation shown in this section for real channel estimation and HW implementation will be used for comparison purposes with the LDM mobile case. The idea is to show that there is no extra degradation due to the layered multiplexing technique. In order to cover the most common cases, 4 different Doppler frequencies are assumed (5, 50, 75 and 100 Hz), which correspond with 3 km/h (handheld device), 90 km/h (semi-urban environment), 135 km/h (highway reception) and 180 km/h (high-speed case) in a 600 MHz channel.

For comparison purposes, in Fig. 10 the results provided by the three different measurement set-ups have been gathered: the solid and dashed lines representing computer based simulations with ideal and real channel estimation, and finally, dotted lines for laboratory trials.

The first important outcome is that, as expected, for all the cases, the receiving SNR difference between the 5 Hz and 100 Hz is at most 1 dB, meaning that when the signal configuration is robust enough the performance degradation due to the loss of carrier orthogonality (ICI) is substantially reduced. Second, it can be seen that the degradation due to channel estimation (solid vs. dashed lines) is maintained for all the different configurations, ranging from about 0.5 dB for the 5 Hz case to 0.9 dB for the 100 Hz case. Finally, the performance loss increase due to HW implementation is always lower than 1dB, and consequently, the difference with the theoretical threshold is lower than 2 dB.

Analyzing these results, another important conclusion is that the idea of using large sized FFTs has been confirmed, providing that the proposed FECs are robust enough. This will be a key point for LDM implementation. In this multiplexing scheme, both layers share the same FFT size, and therefore, the use of large sized FFTs will significantly reduce the overhead due to the guard interval.

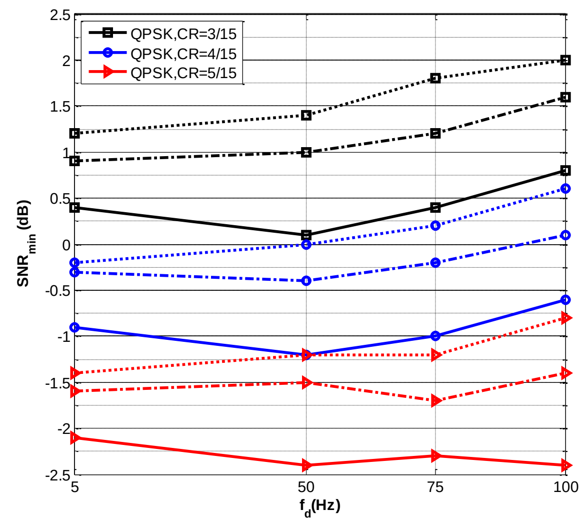

Fig. 10. Mobile channels: receiving thresholds performance losses for SL. Simulations with ideal channel estimation (solid lines), real channel estimation (dashed) and laboratory HW trials (dotted).

B. *Layered Division Multiplexing*

LDM is a multiplexing technique that can enhance the performance of the mobile service (upper layer), with a small degradation on the high-capacity service (lower layer). Previously, it has been theoretically proved that LDM shows a 3-7 dB gain for mobile services. The aim of this section is to compare the implementation losses of LDM with SL under mobile scenarios, in order to prove that this gain should be also maintained under more realistic scenarios.

Fig. 11 gathers the LDM upper layer performances for the different test scenarios, with the aim of studying the performance degradation of the system. The red color represents the most robust case (QPSK, CR=3/15), whereas the blue lines are associated with a higher capacity service (QPSK, CR=4/15).

The main contribution of these results is to prove that the same conclusions obtained in the single layer case are consistent with the LDM case. First of all, for the computer based simulations, both with ideal and real channel estimation, the difference between handheld speed (5Hz) and high-speed cases (100Hz) are at most 1 dB. Consequently, the UL is robust enough to withstand the Doppler noise due to the receiver time variability, even if large sized FFTs are used.

Regarding the laboratory test results, for the -5 dB injection range, the HW extra losses are also between 0.2 dB and 1 dB as in the single layer case. Nevertheless, for the -4 dB case, for 100 Hz, this degradation may be increased up to 2 dB (QPSK, CR 4/15), while for the rest of the cases is still smaller than 1 dB.

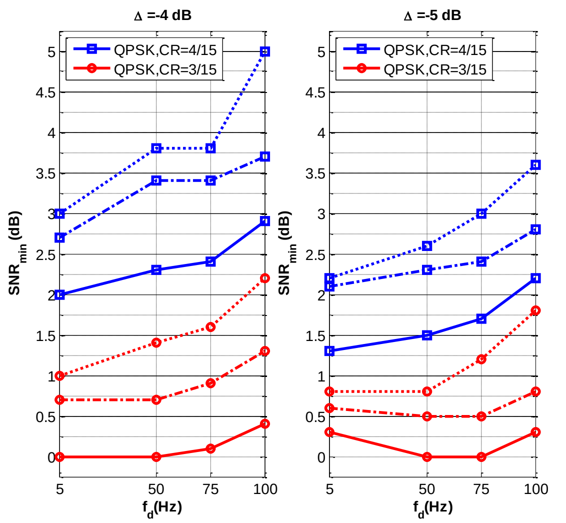

Fig. 11. Mobile channels: receiving thresholds performance losses for LDM (UL). Simulations with ideal channel estimation (solid lines), real channel estimation (dashed) and laboratory HW trials (dotted).

In short, the LDM mobile degradations are well aligned with the single layer results, and therefore, it is clearly shown that there is no extra loss for employing the LDM technique. What is more, the same channel estimation and equalization techniques applied in the single layer system can be used, and therefore, the theoretical gain should be maintained.

VIII. Conclusions

LDM is a new multiplexing technique, which grew out the Could-Txn concept, for simultaneously transmitting stationary and mobile services. This paper provides an exhaustive performance analysis of this technology highlighting its main differences with other techniques, such as the hierarchical modulation.

After proving theoretically the performance gain when compared with TDM/FDM for rich scattering channels, computer simulations have been carried out to confirm the threshold values for both layers forming the LDM ensemble. These thresholds have been presented for both stationary and mobile channels. It has been shown that the cancellation stage performs well even for the most demanding and challenging channels. Finally, another major contribution has been to prove that large sized FFTs can be used in LDM, as the UL signal can be decoded over mobile environments using a 16K signal (with maximum Doppler Frequencies up to 100 Hz).

It has been also shown that LDM hardware implementation losses are less than 1.7 dB for most stationary cases. In the mobile channels, HW performance loss strongly depends on the implemented configuration; the more robust the signal is, the less it is affected. This difference is lower than 2 dB for the vast majority of the cases up to a maximum Doppler frequency of 75 Hz. The LDM implementation losses are the same as in the SL case, which represents either FDM or TDM cases, where services are decoded independently.

Work is being carried towards the implementation of the more efficient Non-Uniform constellations and other potential improvements, in order to improve the LDM signal performance. In addition, the optimization of the injection levels (difference between upper and lower layers) and different constellation cancellation, demapping and decoding is still an open interesting topic for further research.

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