LDM Versus FDM/TDM for Unequal Error Protection in Terrestrial Broadcasting Systems: An Information-Theoretic View

David Gómez-Barquero and Osvaldo Simeone

***Abstract*—In this paper, power-based layer-division multiplexing (LDM) is studied as a means to provide unequal error protection in digital terrestrial television (DTT) systems by adopting an information-theoretic approach. LDM can potentially offer fundamental performance gains as compared to traditional time-division multiplexing (TDM) or frequency-division multiplexing due to the reuse by all information layers of all the available time-frequency resources. The main use case of LDM for terrestrial broadcasting is the simultaneous provision of fixed and mobile services in the same channel. Since most DTT networks worldwide are dimensioned for fixed rooftop reception, this paper illustrates the performance comparison between LDM and F/TDM in terms of the capacity-coverage tradeoff of the mobile service for a given reduction of the capacity of the fixed service while keeping the coverage of the fixed service constant. A mathematical formulation, and corresponding numerical results, are provided for different fading channels, including single-input single-output, single-input multiple-output, multiple-input single-output, and multiple-input multiple-output antenna systems, and accounting also for the impact of non-ideal channel coding.**

***Index Terms*—ATSC 3.0, digital terrestrial broadcasting, FDM, LDM, TDM, UEP.**

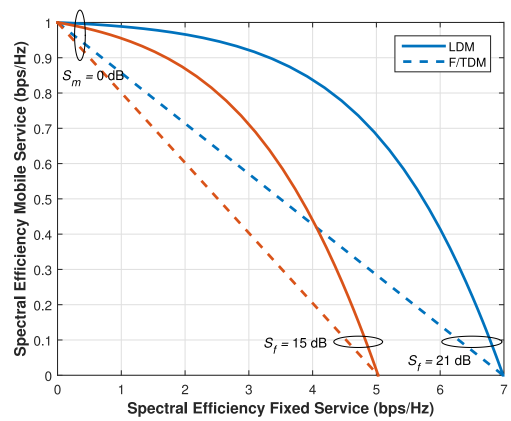

Fig. 1. Region of simultaneously achievable pairs of spectral efficiencies for fixed and mobile transmissions using ideal codes over a Gaussian noise channel with SNR for the mobile users, S_m, equal to 0 dB, and 15 and 21 dB SNR for the fixed users, S_f.

I. Introduction

POWER-based Layer-Division Multiplexing (LDM) has been recently proposed as a key technology for next-generation digital terrestrial television (DTT) standards to simultaneously provide fixed and mobile services in the same radio frequency (RF) channel [1], [2]. LDM may outperform traditional approaches as Frequency-Division Multiplexing (FDM) and Time-Division Multiplexing (TDM) by multiplexing the fixed and mobile information layers at different power levels across all available time-frequency resources. This potential advantage comes at the cost of an increased power consumption of mobile receivers, which operate during all the time and across the available frequency bandwidth, and an increased complexity of the fixed receivers, which need to perform interference cancelation by decoding the mobile layer prior to decoding the intended fixed information layer.

In information theory, LDM has been known to strictly outperform F/TDM for unequal error protection (UEP) in the presence of Gaussian noise since the seminal work by Bergmans and Cover [3], as illustrated in Fig. 1. We recall that UEP refers to the transmission of information layers encoded by means of codes with different error-correcting capabilities so that they can be decoded at different signal-to-noise ratio (SNR) levels. In Fig. 1, it can be seen that the gain of LDM increases with the difference in the SNR of the two layers, also known as the UEP ratio. Moreover, in [4], it was shown that TDM can actually outperform LDM in the presence of suboptimal channel coding, as characterized by an SNR gap to channel capacity. This aspect, along with the reduced receiver complexity and the appealing simplicity of FDM and TDM, are probably the reasons why LDM has not yet been implemented in any wireless commercial system. However, its recent application for DTT has renewed its interest, making it one of the current hot topics in terrestrial broadcasting [5].

LDM with two layers fits very well the use case of simultaneous transmission of fixed and mobile services in DTT networks [6]. The first (upper) layer is intended for the mobile

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users, and is encoded with a powerful low-rate forward error correction (FEC) code so that the mobile receivers can decode even at SNR thresholds below 0 dB [7]. The second (lower) layer is instead intended for fixed service. Fixed receivers need to decode and cancel the upper (mobile) layer before decoding the lower (fixed) layer. While this decoding comes at the cost of additional computational complexity, fixed receivers do not have the battery power constraints of mobile users. Moreover, they are characterized by operating SNRs around 15 to 20 dB [8], that are significantly larger than the decoding threshold of the mobile layer, hence potentially decreasing the computational burden (i.e., by reducing the number of decoding iterations of a turbo or LDPC decoder). Also, the utilization of the same OFDM waveform structure (i.e., FFT size, cyclic prefix and pilot pattern) for the two layers greatly simplifies the LDM signal detection and cancelation at the receivers [9].

Most DTT networks worldwide are dimensioned for fixed rooftop reception. By transmitting mobile services in-band within the same RF channel, mobile services can be easily and gradually introduced reusing the existing content, infrastructure and spectrum, without the need of deploying a dedicated mobile DTT network. The introduction of mobile services is envisaged to entail a controlled capacity reduction of the fixed service without affecting the fixed coverage. Moreover, due to the large differences in the link budget [10], mobile services are expected to be provided in a best-effort coverage fashion (e.g., with some degree of indoor penetration, but not full indoor coverage) [8].

In this letter, we take an information-theoretic approach to the study of the performance comparison between LDM and F/TDM as a mean to provide UEP in DTT systems. A mathematical formulation is provided for fading channels, including SISO (Single-Input Single-Output), SIMO (Single-Input Multiple-Output), MISO (Multiple-Input Single-Output) and MIMO (Multiple-Input Multiple-Output) antenna systems, and accounting also for non-ideal channel coding.

The primary contribution of this paper is the analysis of the coverage-capacity performance of the mobile service for a given reduction of the capacity of the fixed service while keeping constant the coverage level of the fixed service. This presentation of the results is novel, and provides a comprehensive understanding of the potential gain that can be achieved by introducing mobile services in existing DTT networks dimensioned for fixed rooftop reception via LDM. To the best of our knowledge, the only information-theoretic analysis applied to DTT in the literature is [9], which is, however, restricted to SISO Gaussian channels and ideal channel coding. Furthermore, reference [9] presents an illustrative but reduced set of capacity-coverage results which do not shed light on the regime of interest of guaranteed fixed coverage with controlled fixed capacity reduction. As a final remark, we point out that fixed users could experience an increased service capacity by using scalable video coding [11], whereby the mobile service layer carries a basic version of the content [12]. A small reduction of the fixed coverage may be acceptable in this case, because out of coverage fixed users would still be able to receive the basic content. Scalable video coding has not been considered in the paper it has a similar impact for both LDM and F/TDM.

The rest of the paper is structured as follows. Section II describes the system model. Section III details performance metrics and key equations required to analyze LDM and F/TDM in fading channel models. Section IV presents and discusses numerical results in terms of coverage-capacity performance. The letter is concluded in Section V.

II. System Model

In this section, we describe the deployment scenario, the channel model, the signal model for F/TDM and LDM, and the assumptions made regarding channel coding and MIMO transmission.

A. Deployment Scenario

We consider a DTT network in which a transmitter, equipped with possibly multiple antennas, simultaneously provides service to fixed and mobile users over a given coverage area in an RF channel. The analysis and results also apply to a Single Frequency Network (SFN) formed by multiple transmitters with the same total number of transmit antennas. We denote as M_t the number of transmit antennas, and with M_m and M_f the number of receive antennas at the mobile and fixed users, respectively.

The mobile and fixed users are characterized by their average SNR threshold per receive antenna, S_m and S_f, respectively, in linear units, that define the coverage of the two services for single layer F/TDM. This is in the sense that all mobile, or fixed, users with an SNR per receive antenna higher or equal to S_m, or S_f, are considered to be within the covered area of the network. We assume throughout the standard operating condition $S_m \leq S_f$. It should be pointed out that the SNRs S_m and S_f are averages with respect to multipath (fast) fading. Coverage reduction due to shadowing is conventionally accounted for by adding a power margin that guarantees a desired outage coverage probability, e.g., 9 dB for 95% probability at cell edge [10].

We define as R_m and R_f the mobile and fixed spectral efficiencies in bps/Hz, respectively, and we assume the conventional condition $0 < R_m \leq R_f$. We also introduce the parameter r, with $0 \leq r \leq 1$, to measure the capacity reduction for the fixed service incurred as a result of the introduction of the mobile service. This is in the sense that the capacity of the fixed user is reduced to $(1 - r)$ times the level that would be achieved in the absence of the mobile service. More discussion on the spectral efficiency metrics can be found in the next subsection.

B. Channel Model

Assuming OFDM transmission, as commonly used in DTT systems [8], the $M_u \times 1$ signal received at a given subcarrier by the fixed ($u = f$) or mobile ($u = m$) user is given as

$$\mathbf{y}_u = \sqrt{S_u}\mathbf{H}_u\mathbf{x} + \mathbf{z}_u, \quad (1)$$

where we do not indicate the subcarrier index for simplicity of notation; the $M_u \times M_t$ channel matrix $\mathbf{H}_u$ characterizes the effect of fast fading for the transmission to user $u \in \{f, m\}$; the $M_t \times 1$ vector $\mathbf{x}$ is the signal transmitted on the given subcarrier, which we assume to have unit power (i.e., $E[||\mathbf{x}||^2] = 1$) so that the total transmitted power remains constant for any number of transmit antennas; and $\mathbf{z}_u$ is the additive Gaussian noise with zero mean and identity covariance matrix, i.e., $\mathbf{z}_u \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$.

We generally allow channel matrices $\mathbf{H}_f$ and $\mathbf{H}_m$ to have different statistics, e.g., Rice for fixed users and Rayleigh for mobile users. Moreover, the channel matrices are assumed to vary according to stationary ergodic processes within each coding block, which may span multiple OFDM symbols. This channel model is well suited for systems characterized by sufficient time-frequency diversity [14], and is hence appropriate for terrestrial broadcasting since the time-frequency diversity of broadcast channels is considerably larger than that of mobile communication systems, especially in the time domain. For instance, typical time interleaving depths for the current state-of-the art DTT technology, DVB-T2 (Digital Video Broadcasting - Terrestrial Second Generation) [15], range between 80 and 250 ms over bandwidths of 6 to 8 MHz [16] (with cyclic prefix of up to 700 μs in 6 MHz channels). More specific assumptions will be detailed in Section III. Accordingly, we will consider as the capacity metric of interest the ergodic spectral efficiency, which is the spectral efficiency that can be attained in the presence of ergodic fading models.

The channel matrices are assumed to be known to the corresponding receivers but not to the transmitter. This is consistent with broadcasting systems due to the lack of an uplink channel, but it implies ideal channel estimation at the receiver side. Practical channel estimation is generally accounted for in the so-called implementation margin [15], which reflects the SNR increase required by receivers due to non-ideal channel estimation and synchronization. This margin should be taken into account by the broadcaster when designing and deploying the network. However, for LDM a non-ideal channel estimation introduces cross-layer interference from the upper to the lower layer [13]. This interference can be modeled as a worst-case additional white Gaussian noise as further discussed below.

C. Signal Model

For F/TDM, OFDM subcarriers are allocated between the fixed and mobile services so as to guarantee a given fixed capacity reduction r of the fixed user at the given SNR coverage S_f. Each OFDM subcarrier is hence either allocated to the fixed or to the mobile service.

For LDM, instead, the transmitted signal is the superposition over all available frequency and time resources of the upper layer $\mathbf{x}_{ul}$, intended for the mobile service, and the lower layer $\mathbf{x}_{ll}$, intended for the fixed service, as

$$\mathbf{x} = \sqrt{\rho_{ul}}\mathbf{x}_{ul} + \sqrt{\rho_{ll}}\mathbf{x}_{ll}, \tag{2}$$

where we impose the power normalization $E[||\mathbf{x}_{ul}||^2] = E[||\mathbf{x}_{ll}||^2] = 1$, and the fraction of the total power allocated to the mobile and fixed layers are defined, respectively, as ρ_{ul} and ρ_{ll}, with $\rho_{ll} + \rho_{ul} = 1$. The power allocation between the two layers is controlled by the so-called injection level, IL, which determines the power difference between the two layers. Following the terminology used in [9], the injection level IL is defined so that the fraction of the total power allocated to the mobile and fixed layers are given, respectively, as

$$\rho_{ul} = \frac{10^{IL/10}}{1 + 10^{IL/10}}. \tag{3}$$

and

$$\rho_{ll} = \frac{1}{1 + 10^{IL/10}}. \tag{4}$$

The larger is the injection level, the more power is allocated to the mobile service at the expense of reducing the power of the fixed service. For a given fixed capacity reduction r, an injection level IL can be found that results in the desired capacity reduction and keeps constant the fixed coverage. The calculation of the injection level is elaborated on Section III.

The lower (fixed) layer $\mathbf{x}_{ll}$ is treated as interference when decoding of the upper (mobile) layer $\mathbf{x}_{ul}$ at both the fixed and mobile users. Moreover, if successfully decoded at the fixed user, the upper layer $\mathbf{x}_{ul}$ is canceled from the received signal. This cancelation introduces cross-layer interference if channel estimation is not ideal, hence increasing the noise level for decoding of the lower layer. In fact, if cancelation is performed as

$$\mathbf{y}_f - \sqrt{\rho_{ul}}\hat{\mathbf{H}}_f\mathbf{x}_{ul}, \tag{5}$$

where $\hat{\mathbf{H}}_f$ is the channel estimate of the fixed channel, Eq. (1) yields an effective noise $\mathbf{z}+\rho_{ul}(\mathbf{H}_f-\hat{\mathbf{H}}_f)\mathbf{x}_{ul}$. Therefore, for the decoding of the lower layer, the interference depends on the injection level IL and the channel estimation error. Since current implementations can provide a channel estimation MSE lower than -30 dB for fixed reception [9], the latter contribution is not significant at practical SNR levels and is henceforth not explicitly considered.

D. Channel Coding

State-of-the-art DTT technologies employ rather long FEC codewords spanning, e.g., 16,200 and 64,800 bits [15], hence making asymptotic information-theoretic results relevant as performance benchmarks [17]. In order to account for the any residual channel coding suboptimality, following [4], we define as λ_m and λ_f the SNR gaps to capacity for the mobile service and fixed services, respectively, with $0 < \lambda_m, \lambda_f \leq 1$, with 1 (0 dB) denoting an ideal code. Note that, in coded modulation schemes such as Bit Interleaved Coded Modulation (BICM), this gap depends not only on the practical FEC codes used, but also on the bit interleavers and modulations. For instance, non-uniform constellations have been recently proposed for next-generation terrestrial broadcasting to reduce the gap to the Shannon limit, see, e.g., [18]. As a final remark, the implementation margin due to non-ideal channel estimation and synchronization may not be included in λ_m and λ_f, but is instead addressed by the broadcaster by increasing the operating SNR, thus reducing the coverage for the desired transmission rate or increasing the transmit power [10].

E. MIMO Transmission

MIMO is a key technology which is currently being considered for next generation terrestrial broadcasting systems in order to increase the capacity without any additional requirements on bandwidth and transmission power [5]. Multiple transmission elements can be realized by means of antennas with cross-polar (horizontal and vertical) polarization, which are instrumental in retaining full spatial multiplexing capabilities in line-of-sight conditions [19].

Since the MIMO gain increases as a function of the SNR [19], the potential benefit of MIMO is expected to be greater for rooftop reception than for mobile and portable reception. Based on this, for the fixed service, and hence for the lower layer, we assume throughout that a capacity-achieving MIMO space-time/frequency scheme is adopted, under the standard practice in broadcasting of equal power allocation across the transmit antennas[1]. We observe that the capacity-achieving scheme depends on the number of antennas at the transmitter and receiver side. For instance, if $N_t = N_f$, Spatial Multiplexing (SM) achieves capacity. We refer to [20] also for further discussion on capacity-achieving schemes. We also emphasize that we allow for capacity-achieving space-time/frequency schemes to operate with given SNR gaps to capacity as discussed above. Finally, we point to [21] for a discussion on the first standardized 2×2 MIMO terrestrial broadcasting scheme in DVB-NGH (Digital Video Broadcasting - Next Generation Handheld) [22], known as enhanced spatial multiplexing with phase hopping.

For the mobile service, in line with current standardization proposals [22], we consider three possibilities: (*i*) orthogonal space-time block coding, such as Alamouti coding for $N_t = 2$ and $N_m = 1$; (*ii*) frequency pre-distortion schemes, where the same signal is sent across all transmitting antenna elements with a different pre-distortion sequence, such as enhanced SFN (eSFN) [23]; (*iii*) capacity-achieving coding, such as SM [21]. Note that, by definition, the last scheme outperforms the previous two, which are considered here due to their simpler implementation that has made them preferred candidates for standardization [19]. We also observe that the main benefit of frequency pre-distortion schemes such as eSFN is that the pilot density does not need to be increased, as opposed to orthogonal space-time block coding schemes such as Alamouti [23]. Finally, we observe that MISO Alamouti coding is implemented in actual terrestrial broadcasting standards in the frequency domain [15], [22], although in the following we will use the more common terminology of space-time coding.

III. LDM VS. FDM/TDM FOR UEP INFORMATION-THEORETIC ANALYSIS

In this section, we provide a mathematical framework for the evaluation of the performance of F/TDM and LDM for the simultaneous provision of mobile and fixed services in the same time-frequency resources. As discussed in the previous section, we assume the capacity-achieving transmission scheme, as determined by the number of antennas, for the lower layer (fixed service), and we treat orthogonal space-time block coding, frequency pre-distortion and capacity-achieving schemes for the upper layer in separate subsections. Throughout, the derived equations apply to any number of antennas N_t, N_f and N_m and hence to SISO, SIMO, MISO and MIMO. Moreover, the derivation of the spectral efficiency formulas follow from standard information theoretic arguments that are only mentioned here when additional details are needed with respect to standard treatments as in the textbook [24].

A. Performance Metrics

In this subsection, we consider orthogonal space-time coding for the upper layer. We recall that, when $N_t = 2$, orthogonal space-time coding amounts to Alamouti coding, which achieves a maximum rate of one. The rate of an orthogonal block space-time code measures the number of information symbols per transmitted symbol. Generalizing to larger N_t, orthogonal block space-time block codes are known to have maximal rate [25]

$$R_{STC}(N_t) = \frac{N_t/2 + 1}{N_t} \tag{6}$$

for N_t even and

$$R_{STC}(N_t) = \frac{(N_t+1)/2+1}{N_t+1} \tag{7}$$

for N_t odd.

For reasons that will be clarified below, here we assume that the channel matrices satisfy the following stochastic dominance assumption:

$$\Pr\left[||[\mathbf{H}_f]_{n_m}||^2 \geq x\right] \geq \Pr\left[||[\mathbf{H}_m]_{n_m}||^2 \geq x\right] \tag{8}$$

for all $x \geq 0$, where $[\mathbf{H}]_{n_m}$ represents the n_mth row of the channel matrix $\mathbf{H}$. This is satisfied, for instance, if both channels have the same statistics, or in the conventional case of i.i.d. Rice fading channels for the fixed service and i.i.d. Rayleigh channels for the mobile channel with the same average power [26].

1) F/TDM: Given a fixed capacity reduction r, the ergodic spectral efficiency achievable by the fixed service is given by

$$R_f^{F/TDM} = (1-r)E\left[\log\det\left(\mathbf{I} + \lambda_f \frac{S_f}{N_t}\mathbf{H}_f\mathbf{H}_f^T\right)\right], \tag{9}$$

since, apart from the $(1-r)$ term, this is the expression of the capacity with SNR gap λ_f on the fixed channel in the presence of equal power allocation across the antennas (see, e.g., [20]). Note that this expression holds irrespective of the transmission scheme used by the mobile user. Assuming that the mobile layer uses orthogonal space-time block coding and maximum ratio combining (MRC) at the receiver side for processing of the signals received by multiple antennas, the ergodic spectral efficiency can be written as [20]

$$R_m^{F/TDM} = rR_{STC}(N_t)E\left[\log\left(1 + \lambda_m \frac{S_m}{N_t}||\mathbf{H}_m||^2\right)\right]. \tag{10}$$

[1] In the case of correlated channel matrices, equal power allocation may not be optimal, see, e.g., [20].

2) LDM: For a given injection level *IL*, and hence given a power allocation (ρ_{ul}, ρ_{ll}), the mobile spectral efficiency obtained with LDM, orthogonal space-time block coding and MRC at the receiving end, can be calculated as

$$R_m^{LDM} = R_{STC}(N_t) \cdot \cdot E\left[\log\left(1 + \lambda_m \sum_{n_m=1}^{N_m} \frac{\rho_{ul}\frac{S_m}{N_t}||[\mathbf{H}_m]_{n_m}||^2}{1+\rho_{ll}\frac{S_m}{N_t}||[\mathbf{H}_m]_{n_m}||^2}\right)\right]. \quad (11)$$

A proof of this fact can be found in Appendix A. We observe that the denominator in the expression (11) represents the interference from the lower layer when decoding the upper layer.

Due to the assumption (8) of stochastic dominance on the channel matrices $\mathbf{H}_f$ and $\mathbf{H}_m$, along with the mentioned assumption $S_m \leq S_f$, it can be proved that the transmission rate given by Eq. (11) can be decoded also by the fixed user (see Appendix B). Therefore, given a fixed capacity reduction r, the injection level *IL* is calculated by evaluating ρ_{ll} (see (4)) as

$$\rho_{ll} = \min\left\{\rho_{ll} \geq 0 : R_f^{LDM} \geq (1-r)E\left[\log\det\left(\mathbf{I} + \lambda_f \frac{S_f}{N_t}\mathbf{H}_f\mathbf{H}_f^T\right)\right]\right\}, \quad (12)$$

where the fixed-user spectral efficiency is calculated, similar to (9), as

$$R_f^{LDM} = E\left[\log\det\left(\mathbf{I} + \lambda_f \rho_{ll}\frac{S_f}{N_t}\mathbf{H}_f\mathbf{H}_f^T\right)\right]. \quad (13)$$

The condition (12) ensures that the fixed spectral efficiency is no smaller than a fraction $(1-r)$ of the spectral efficiency that would be attained in the absence of the fixed service.

B. Frequency Pre-Distortion at the Upper Layer

In this subsection, we consider a frequency pre-distortion scheme such as eSFN [23] for the upper layer. For analogous reasons as in the previous section, here we assume that the channel matrices satisfy the stochastic dominance assumption (8), in which, however, $[\mathbf{H}]_{n_m}$ should be interpreted as the sum of the elements of the n_mth row of the channel matrix $\mathbf{H}$. This sum represents the fact that the (same) signal transmitted by all transmit antennas is received by the n_mth receive antenna at the mobile with an equivalent channel gain equal to the sum $[\mathbf{H}]_{n_m}$. Based on this consideration and following the same arguments as in the previous subsection, it can be seen that the formulas derived for orthogonal space-time block coding are valid also for eSFN with the following two caveats: (*i*) In (11), it should be set $R_{STC}(N_t) = 1$ since frequency pre-distortion schemes come with no rate loss; (*ii*) The notation $[\mathbf{H}]_{n_m}$ should be interpreted as the sum of the elements of the n_mth row of the channel matrix $\mathbf{H}$.

C. Capacity-Achieving Transmission at the Upper Layer

In this subsection, we consider the ideal case in which capacity-achieving transmission strategies, such as SM for $N_t = N_m$ [21], are used at both upper and lower layers (with possible SNR gaps). Unlike the previous two subsections, here we make the simplifying assumption that the channel matrices for fixed and mobile users have the same statistics. Stochastic dominance conditions, such as (8), that guarantee decoding of the upper layer at the fixed user as long as successful decoding occurs at the lower layers could be identified as done for the schemes considered above. However, this would require a more technical discussion that is deemed to be out of the scope of this contribution. We refer to [26] for some discussion on related ongoing research.

1) F/TDM: The ergodic spectral efficiency achievable by the fixed service, $R_f^{F/TDM}$, is the same described in the previous subsection and is given by Eq. (9). The ergodic spectral for the mobile service is similarly calculated as

$$R_m^{F/TDM} = rE\left[\log\det\left(\mathbf{I} + \lambda_m \frac{S_m}{N_t}\mathbf{H}_m\mathbf{H}_m^T\right)\right]. \quad (14)$$

2) LDM: Accounting for the interference caused by the lower layer, the ergodic spectral efficiency for the mobile service is given by (see, e.g., [27])

$$R_m^{LDM} = E\left[\log\det\left(\mathbf{I} + \lambda_m\rho_{ul}\frac{S_m}{N_t}\mathbf{H}_m\mathbf{H}_m^T \cdot \cdot\left(\mathbf{I} + \rho_{ll}\frac{S_m}{N_t}\mathbf{H}_m\mathbf{H}_m^T\right)^{-1}\right)\right], \quad (15)$$

where matrix that is inverted accounts for the interference from the lower layer.

Under the said assumption on the channel matrices, and recalling the assumed inequality $S_m \leq S_f$, the upper layer can be decoded also at the fixed service, and hence the ergodic spectral efficiency can be calculated using (12) and (13).

IV. Results and Discussion

In this section, we present numerical results so as to provide insights into the performance comparison of LDM and F/TDM as means to provide mobile and fixed DTT services in the same RF channel. The comparison is performed in terms of the *trade-off between capacity, as measured by the spectral efficiency, and coverage, as determined by the SNR S_m, for the mobile service, given a tolerated fixed capacity reduction r at a given coverage SNR S_f*. We first present illustrative results for the case of a single transmit antenna and up to two receive antennas for both ideal channel coding, that is, with $\lambda_m = \lambda_f = 0$ dB, and practical channel coding with an SNR gap to capacity. Finally, we present some illustrative results for the case of two transmit antennas with ideal and practical channel coding. We note that a deployment with two transmit and two receive antennas correspond to the most common envisaged implementation for MIMO DTT systems [19].

A. Single Transmit Antenna, Ideal Channel Coding

In this subsection and the next, we set $N_t = 1$ and assume an i.i.d. Rayleigh channel for the mobile users and an i.i.d. Rice channel for the fixed users with a line-of-sight K-factor of 10 dB. Note that this assumption satisfies the condition (8). Moreover, we focus here on ideal channel codes, i.e., we set $\lambda_m = \lambda_f = 0$ dB.

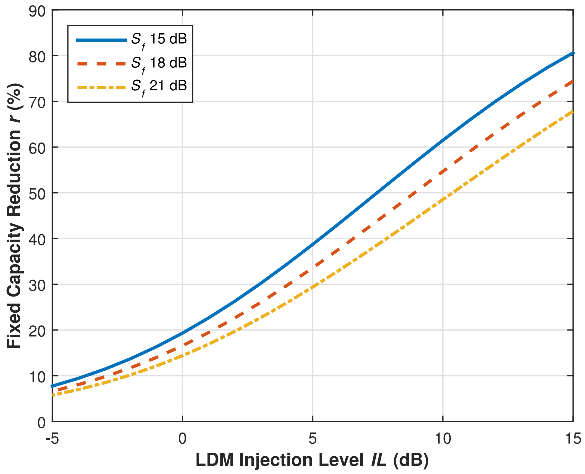

Fig. 2. Reduction of the capacity of the fixed service with LDM as a function of the injection level for different values of the fixed SNR S_f ($N_t = N_f = 1$, $\lambda_f = 0$ dB).

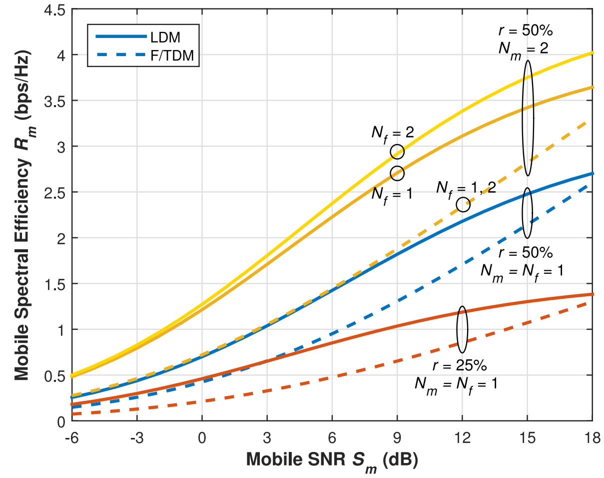

Fig. 3. Mobile capacity-coverage trade-off for LDM and F/TDM for $r = 25\%$ and $r = 50\%$ capacity reduction of the fixed service ($N_t = 1$, $N_f = 1$, $\lambda_m = \lambda_f = 0$ dB, $S_f = 18$ dB).

We first investigate the effect of the injection level on the capacity reduction r for the fixed service when using LDM. To this end, Fig. 2 shows the capacity reduction r of the fixed service with LDM for $N_f = 1$ as a function of the injection level for three S_f values, namely 15, 18 and 21 dB. Note that S_f =15 dB is the operating point of the first-generation DTT standard ATSC, and S_f =18 dB is the most common operating point for the DTT networks deployed in Europe, and it may also be representative for next generation ATSC systems due to improvements in receiver technology (e.g., noise factor) [8]. It is seen that a larger injection level, and hence a larger power allocation to the mobile service, clearly decreases the fraction of fixed capacity $(1 - r)$ that can be achieved for any given fixed coverage (we note that negative values of the injection level imply that more power is allocated to the fixed service than to the mobile service). Moreover, for a given capacity reduction of the fixed service r, the required injection level is seen to increase with the fixed SNR S_f. In particular, for realistic values of injection level, from 3 to 10 dB, the required value is observed to be about 1 dB larger for every 3 dB increase in S_f.

As a result of the discussion above, the LDM gain compared to F/TDM is expected to increase with the fixed SNR S_f, since the cross-layer interference of the fixed service on the mobile service is reduced for a larger injection level. We observe that an increase in the fixed SNR can also be achieved by increasing the number N_f of receive antennas at the fixed user. In fact, with MRC the average received SNR increases by a factor N_f. Therefore, as also further discussed below, the LDM gain is expected to grow with the number N_f of receive antennas. We also note that this argument does not apply to an increase in the number N_t of transmit antennas, which does not cause an increase in the average received SNR under the given assumption of no channel state information at the transmitter.

Fig. 3 shows the capacity-coverage trade-off of the mobile service for LDM and F/TDM for either one or two receive antennas at the fixed and mobile users, and for two different values of the reduction r of the fixed service capacity, namely $r = 25\%$ and $r = 50\%$. Note that, for $N_f = 1$, the injection level values required for LDM to achieve those capacity reductions are 2.7 dB and 8.9 dB, respectively, from Fig. 2. The figure shows that LDM outperforms F/TDM in all cases under the assumption of ideal channel coding. That is, for a given operating SNR S_m of the mobile service, LDM provides a mobile spectral efficiency increase over F/TDM (*capacity gain*); and, conversely, for a given target spectral efficiency of the mobile service, LDM provides a reduction in the required SNR S_m (*coverage gain*). As explained, the reason for this gain is the more efficient use of the available frequency and time resources of LDM, despite the interference introduced by the upper layer on the lower layer. It is also interesting to note that the coverage gain is larger for smaller values of the capacity reduction of the fixed service, e.g., for $N_f = N_m = 1$, the maximum coverage gain in Fig. 3 is 6.0 dB for $r = 25\%$, and 3.9 dB for $r = 50\%$.

Another important conclusion from Fig. 3 is that, when the mobile users have multiple antennas, LDM provides larger gains over F/TDM, yielding capacity gains even for $S_m = S_f = 15$ dB. The reason is that MRC across the receive antennas at the mobile user produces an increase of the signal-to-interference plus noise ratio (SINR), where interference accounts for the lower layer, and not merely an increase in the SNR. This translates into an increase in the channel capacity, as demonstrated with a simple argument in Appendix C.

B. Single Transmit Antenna, Practical Channel Coding

Fig. 4 shows the mobile spectral efficiency difference between LDM and F/TDM for $N_t = 1$ as a function of SNR of the mobile service for practical codes with an SNR loss factor $\lambda_m = \lambda_f$ of -1 dB and -3 dB. The case with ideal channel coding ($\lambda_m = \lambda_f = 0$ dB) is also shown as a reference.

In the figure, it can be seen that, when considering practical channel coding, F/TDM can actually outperform LDM in some cases. The loss is observed when the mobile SNR, S_m, is close to the fixed SNR, S_f, that is, when the UEP ratio is small. Nevertheless, state-of-the art terrestrial broadcasting

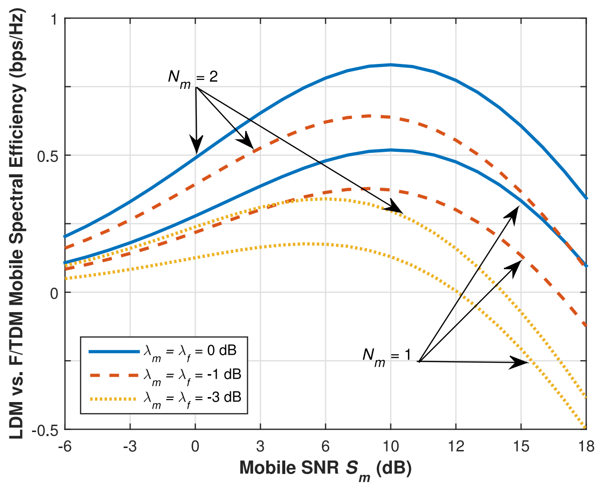

Fig. 4. Mobile spectral efficiency difference between LDM and F/TDM as a function of the mobile SNR for $r = 50\%$ reduction of the fixed capacity and ideal ($\lambda_m = \lambda_f = 0$ dB) and practical channel coding with $\lambda_m = \lambda_f = -1$ dB, -3 dB ($N_f = 1$, $S_f = 18$ dB).

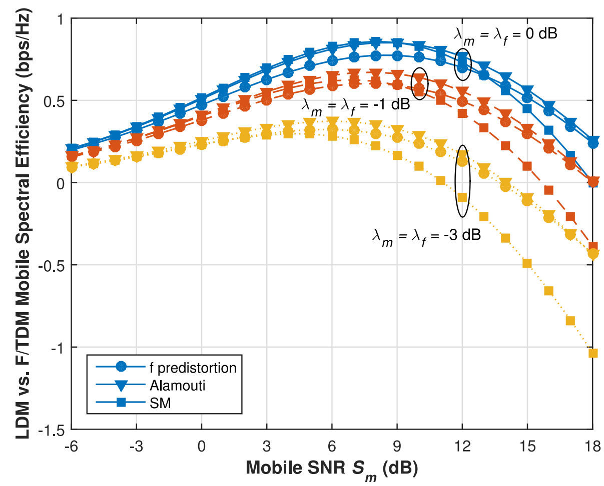

Fig. 6. Mobile spectral efficiency difference between LDM and F/TDM as a function of the mobile SNR for $r = 50\%$ reduction of the fixed capacity and ideal ($\lambda_m = \lambda_f = 0$ dB) and practical channel coding with $\lambda_m = \lambda_f = -1$ dB, -3 dB ($N_t = 2$, $N_f = 2$, $N_m = 2$, $S_f = 18$ dB).

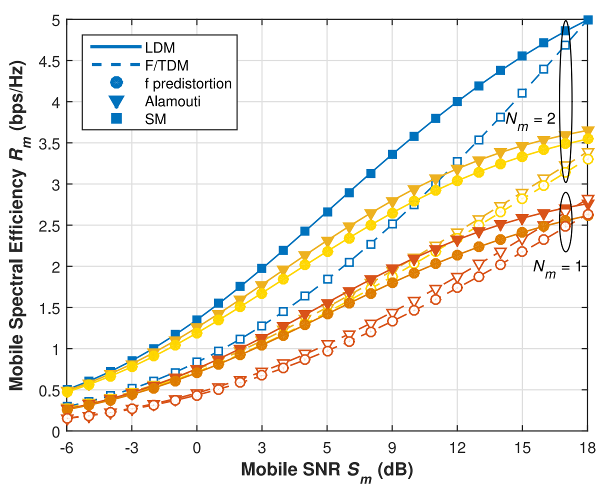

Fig. 5. Mobile capacity-coverage tradeoff for LDM and F/TDM for $r = 50\%$ fixed capacity reduction ($N_t = 2$, $N_f = 2$, $S_f = 18$ dB, $\lambda_m = \lambda_f = 0$ dB).

systems currently perform very close to the ideal limit, about 1 dB in AWGN channel [15]; and, although the gap to channel capacity is larger for Rayleigh channel [22], next-generation systems will further reduce the gap, including very low SNR values [18]. Hence, a figure of $\lambda_m = \lambda_f = -1$ dB may be realistic for both layers. For these values of the SNR gaps, LDM outperforms F/TDM in all the scenarios considered in Fig. 4.

C. Multiple Transmit Antennas, Ideal Channel Coding

Fig. 5 illustrates the capacity-coverage trade-off of the mobile service as a function of the SNR S_m in case the transmitter has $N_t = 2$ antennas. For the mobile service, we consider the performance with Alamouti coding, frequency pre-distortion (eSFN) and SM. As discussed, for the fixed service, capacity-achieving schemes are assumed throughout (i.e., SM). In the figure, it can be seen that the capacity gain provided by SM can only be leveraged for medium-to-high SNRs. For very low SNRs of around 0 dB, the performance is closely matched by Alamouti, which allows for a simpler receiver implementation. It can also be observed that Alamouti slightly outperforms frequency pre-distortion. As mentioned, the main benefit of frequency pre-distortion schemes such as frequency pre-distortion is that the pilot density does not need to be increased [23]. However, if the two LDM layers share the pilot sub-carriers [9], this would not represent an additional overhead if the lower layer already uses them for spatial multiplexing, and hence Alamouti should be preferred [28], although the difference compared to a frequency pre-distortion scheme is quite small.

D. Multiple Transmit Antennas, Practical Channel Coding

Fig. 6 shows the spectral efficiency difference between LDM and F/TDM with practical channel coding for a 2×2 MIMO system where spatial multiplexing is used for the fixed service, and Alamouti, frequency pre-distortion (eSFN) or spatial multiplexing is adopted for the mobile service. In the figure, it can be observed that F/TDM can outperform LDM when considering non-ideal channel coding if the UEP ratio between the SNR of the fixed and mobile users is not big enough, as shown for one transmit antenna in Fig. 4. It can be also appreciated that the gain of LDM is slightly larger for Alamouti, and smallest for spatial multiplexing.

V. Conclusion

In this paper we have analyzed from an information-theory point of view the potential gain of LDM versus FDM/TDM as means to provide mobile and fixed services in the same RF channel in digital terrestrial broadcasting systems. The obtained results demonstrate that, under the assumption of ideal channel coding, LDM outperforms FDM/TDM in both capacity and coverage performance of the mobile service, in the regime of a given capacity reduction of the fixed service with a constant fixed service coverage. For realistic channel coding implementations, with a gap to Shannon capacity of 1 dB, LDM still outperforms FDM/TDM. Another interesting conclusion of this study is that the performance gain of LDM increases with the number of receive antennas at both fixed and mobile users. Moreover, regarding the use of 2×2 MIMO, the adoption of Alamouti for the mobile (upper) layer is seen to be preferred when considering the performance-complexity trade-off, although the difference compared to frequency pre-distortion schemes is quite small.

VI. Appendix A: Derivation of Eq. (11)

We concentrate here on the special case $N_t = 2$ in order to simplify the notation. The proof for any N_t follows along the same lines. For the case $N_t = 2$, the Alamouti scheme is used for the upper layer. Alamouti operates across two successive channel uses, i.e., subcarriers, say $j = 1, 2$. The signal received in a channel use, i.e., subcarrier, j, at user $u \in \{f, m\}$ can be written, from (1) and (2), as

$$\mathbf{y}_u[j] = \sqrt{\rho_{ul} S_u}\mathbf{H}_u\mathbf{x}_{ul}[j] + \underbrace{\left(\sqrt{\rho_{ll} S_u}\mathbf{H}_u\mathbf{x}_{ll}[j] + \mathbf{z}_u[j]\right)}_{\mathbf{z}_{eff,u}[j]},$$

where we have emphasized that dependence on j of the transmitted signals and noise and we have assumed that the channel does not change in the block of two subcarriers over which Alamouti coding takes place. When decoding the upper layer, the lower layer signal $\mathbf{x}_{ll}[j]$ is treated as complex Gaussian noise with zero mean, covariance matrix $\mathbf{I}/2$, where the factor $1/2$ accounts for the power allocation across the two antennas, and independent across j. As a result, the effective noise observed at each receive antenna n_u, namely $[\mathbf{z}_{eff,u}[j]]_{n_u}$ is Gaussian with zero mean and power equal to $1 + \rho_{ll} S_u ||[\mathbf{H}_m]_{n_m}||^2/2$. Note that the effective noise is correlated across the receive antennas. Here we neglect this correlation, hence obtaining a lower bound on the maximum achievable rate (see, e.g., [27]).

The signal received across the two channel uses $j = 1, 2$ at any antenna n_u can be written, following, e.g., [24], as

$$\begin{bmatrix} [\mathbf{y}_u[1]]_{n_u} \\ [\mathbf{y}_u[2]]^*_{n_u} \end{bmatrix} = \sqrt{\rho_{ul} S_u}\begin{bmatrix} [\mathbf{H}_u]_{n_u,1} & [\mathbf{H}_u]_{n_u,2} \\ [\mathbf{H}_u]^*_{n_u,2} & -[\mathbf{H}_u]^*_{n_u,1} \end{bmatrix}\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} + \begin{bmatrix} [\mathbf{z}_{eff,u}[1]]_{n_u} \\ [\mathbf{z}_{eff,u}[2]]_{n_u} \end{bmatrix},$$

where $[u_1 \; u_2]^T$ is the vector of information symbols transmitted by the Alamouti scheme with power 1/2. Then, projecting into the kth column of the channel matrix, we obtain the signal [24]

$$\sqrt{\rho_{ul} S_u}||[\mathbf{H}_m]_{n_m}||^2 u_k + w_k,$$

where the noise w_k has power $1 + \rho_{ll} S_u ||[\mathbf{H}_m]_{n_m}||^2/2$. The resulting SNR is hence $\rho_{ul} S_u ||[\mathbf{H}_m]_{n_m}||^2/(2(1 + \rho_{ll} S_u ||[\mathbf{H}_m]_{n_m}||^2/2))$. Performing MRC across the receive antennas – the effect of which is to obtain an SNR equal to the sum of the SNRs at the individual antennas (e.g., [24]) – completes the proof.

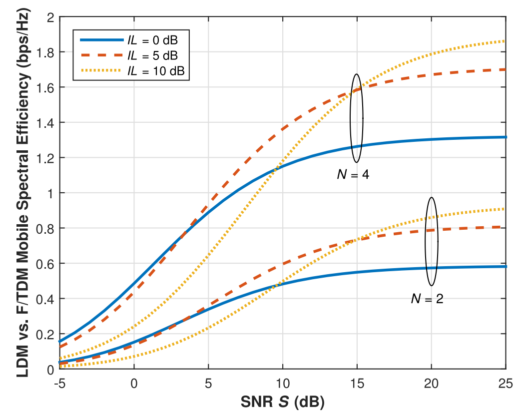

Fig. 7. Total spectral efficiency difference between LDM and F/TDM ($N_t = 1$, $N_m = N_f = N$, $S_m = S_f = S$).

VII. Appendix B: Upper Layer Decoding for the Fixed Users

In order to prove that the upper layer can be decoded at the fixed user as long as it can be decoded at the mobile user, one needs to ensure that the right-hand side of (11) is no smaller when evaluated by substituting the fixed channel matrix $\mathbf{H}_f$ to the mobile channel matrix $\mathbf{H}_m$. To see this, note that the quantity being averaged in (11) is a non-decreasing function of each norm $||[\mathbf{H}_u]_{n_m}||^2$. Therefore, condition (8), along with $S_m \leq S_f$, guarantees that the average with respect to $\mathbf{H}_f$ can be no smaller than that over the mobile channel matrix $\mathbf{H}_m$. Note that the same argument applies to both orthogonal space-time coding and frequency pre-distortion schemes. Moreover, using the same line of reasoning, one can conclude that the upper layer can be decoded at the fixed user as long as it can be decoded at the mobile user, under the assumption of equal channel matrix distributions, also for the case of capacity-achieving schemes at the upper layer.

VIII. Appendix C: LDM Gain for SIMO

In this appendix, we provide a simple argument to demonstrate that the gains of LDM over F/TDM increase with the number N_m of receive antennas at the mobile user. We consider the case $N_t = 1$, $N_f = N_m = N$ and $S_m = S_f = S$ with ideal channel coding, and focus on a simple AWGN model in which the channel gains are equal to one for all channels. This is done in order to make the argument more transparent. MRC is carried out at the mobile user across the receive antennas.

For F/TDM, under the said assumption, the total spectral efficiency $R_m^{F/TDM} + R_f^{F/TDM}$ can be easily calculated, from (10) and (9), as $\log(1 + SN)$ for any r. Instead, for LDM, the total spectral efficiency$R_m^{LDM} + R_f^{LDM}$ is given, from (11) and (13), as

$$\log\left(1 + N\frac{\rho_{ul} S}{1 + \rho_{ll} S}\right) + \log(1 + \rho_{ll} NS).$$

showing that the difference between the LDM and F/TDM spectral efficiencies is given by

$$\log\left(1 + N\frac{\rho_{ul} S}{1 + \rho_{ll} S}\right) + \log\left(\frac{1 + \rho_{ll} NS}{1 + NS}\right).$$

Fig. 7 illustrates that the difference is always positive, and that it increases with the number of receive antennas and the SNR, although the gain as a function of the SNR tends to saturate.

REFERENCES

[1] Y. Wu, B. Rong, K. Salehian, and G. Gagnon, "Cloud transmission: A new spectrum-reuse friendly digital terrestrial broadcasting transmission system," *IEEE Trans. Broadcast.*, vol. 58, no. 3, pp. 329–337, Sep. 2012.

[2] J. Montalban *et al.*, "Cloud transmission: System performance and application scenarios," *IEEE Trans. Broadcast.*, vol. 60, no. 2, pp. 170–184, Jun. 2014.

[3] P. P. Bergmans and T. M. Cover, "Cooperative broadcasting," *IEEE Trans. Inf. Theory*, vol. 20, no. 3, pp. 317–324, May 1974.

[4] S. Gadkari and K. Rose, "Time-division versus superposition coded modulation schemes for unequal error protection," *IEEE Trans. Commun.*, vol. 47, no. 3, pp. 370–379, Mar. 1999.

[5] W. Zhang, Y. Wu, N. Hur, T. Ikeda, and P. Xia, "FOBTV: Worldwide efforts in developing next-generation broadcasting system," *IEEE Trans. Broadcast.*, vol. 60, no. 2, pp. 154–159, Mar. 2014.

[6] J. Montalban *et al.*, "Performance study of layered division multiplexing based on SDR platform," *IEEE Trans. Broadcast.*, vol. 62, no. 3, p. 9, Sep. 2016.

[7] S.-I. Park, H. M. Kim, Y. Wu, and J. Kim, "A newly designed quarter-rate QC-LDPC code for the cloud transmission system," *IEEE Trans. Broadcast.*, vol. 59, no. 1, pp. 155–159, Mar. 2013.

[8] D. Gómez-Barquero, Ed., *Next Generation Mobile Broadcasting*. Boca Raton, FL, USA: CRC Press, 2013.

[9] L. Zhang *et al.*, "Channel capacity distribution of layer-division-multiplexing system for next generation digital broadcasting transmission," in *Proc. IEEE BMSB*, Beijing, China, 2014, pp. 1–6.

[10] "Frequency and network planning aspects of DVB-T2," Eur. Broadcast. Union, Geneva, Switzerland, Tech. Rep. 3348, Oct. 2014.

[11] Y. Ye and P. Andrivon, "The scalable extensions of HEVC for ultra-high-definition video delivery," *IEEE Multimedia Mag.*, vol. 21, no. 3, pp. 58–64, Jul. 2014.

[12] C. Regueiro *et al.*, "SHVC and LDM techniques for HD/UHD TV indoor reception," in *Proc. IEEE BMSB*, Ghent, Belgium, 2015, pp. 1–6.

[13] J. Montalban *et al.*, "Error propagation in the cancellation stage for a multi-layer signal reception," in *Proc. IEEE BMSB*, Beijing, China, 2014, pp. 1–5.

[14] A. Lozano and N. Jindal, "Are yesterday's information-theoretic fading models and performance metrics adequate for the analysis of today's wireless systems?" *IEEE Commun. Mag.*, vol. 50, no. 11, pp. 210–217, Nov. 2012.

[15] I. Eizmendi *et al.*, "DVB-T2: The second generation of terrestrial digital video broadcasting system," *IEEE Trans. Broadcast.*, vol. 60, no. 2, pp. 258–271, Jun. 2014.

[16] D. Gozalvez, D. Gómez-Barquero, I. Eizmendi, G. Berjón-Eriz, and M. Vélez, "DVB-T2 for mobile and mobile DVB-T2 (T2-lite)," in *Next Generation Mobile Broadcasting*. Boca Raton, FL, USA: CRC Press, 2013, pp. 151–183.

[17] Y. Polyanskiy, H. V. Poor, and S. Verdu, "Channel coding rate in the finite blocklength regime," *IEEE Trans. Inf. Theory*, vol. 56, no. 5, pp. 2307–2359, May 2010.

[18] L. Michael and D. Gómez-Barquero, "Modulation and coding for ATSC 3.0," in *Proc. IEEE BMSB*, Ghent, Belgium, 2015, pp. 1–5.

[19] P. Moss and T. Y. Poon, "Overview of the multiple-input multiple-output terrestrial profile of DVB-NGH," in *Next Generation Mobile Broadcasting*. Boca Raton, FL, USA: CRC Press, 2013, pp. 549–579.

[20] A. Goldsmith, A. J. Syed, J. Nihar, and V. Sriram, "Capacity limits of MIMO channels," *IEEE J. Sel. Areas Commun.*, vol. 21, no. 5, pp. 684–702, Jun. 2003.

[21] D. Vargas, D. Gozalvez, D. Gómez-Barquero, and N. Cardona, "MIMO for DVB-NGH, the next generation mobile TV broadcasting," *IEEE Commun. Mag.*, vol. 51, no. 7, pp. 130–137, Jul. 2013.

[22] D. Gómez-Barquero, C. Douillard, P. Moss, and V. Mignone, "DVB-NGH: The next generation of digital broadcast services to handheld devices," *IEEE Trans. Broadcast.*, vol. 60, no. 2, pp. 246–257, Jun. 2014.

[23] J. Robert and J. Zollner, "Multiple-input single-output antenna schemes for DVB-NGH," in *Next Generation Mobile Broadcasting*. Boca Raton, FL, USA: CRC Press, 2013, pp. 581–607.

[24] D. Tse and P. Wisvanath, *Fundamentals of Wireless Communications*. Cambridge, U.K.: Cambridge Univ. Press, 2005.

[25] K. Lu, F. Shengli, and X. Xiang-Gen, "Closed-form designs of complex orthogonal space-time block codes of rates (k+1)/(2k) for 2k-1 or 2k transmit antennas," *IEEE Trans. Inf. Theory*, vol. 51, no. 12, pp. 4340–4347, Dec. 2005.

[26] C. Tepedelenlioglu, R. Adithya, and Y. Zhang, "Applications of stochastic ordering to wireless communications," *IEEE Trans. Wireless Commun.*, vol. 10, no. 12, pp. 4249–4257, Dec. 2011.

[27] A. El Gamal and Y.-H. Kim, *Network Information Theory*. Cambridge, U.K.: Cambridge Univ. Press, 2011.

[28] S.-H. Chang, M. Rim, P. C. Cosman, and L. B. Milstein, "Superposition MIMO coding for the broadcast of layered sources," *IEEE Trans. Commun.*, vol. 59, no. 12, pp. 3240–3248, Dec. 2011.

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