Vargas, D.; Kim, Y.; Bajcsy, J.; Gómez Barquero, D.; Cardona Marcet, N. (2015). A MIMO-Channel-Precoding Scheme for Next Generation Terrestrial Broadcast TV Systems. IEEE Transactions on Broadcasting. 61(3):445-456. doi:10.1109/TBC.2015.2450431.

A MIMO-Channel-Precoding Scheme for Next Generation Terrestrial Broadcast TV Systems

David Vargas, Yong Jin Daniel Kim, Jan Bajcsy, David Gómez-Barquero, and Narcís Cardona

***Abstract*—To cope with increasing demands for spectral efficiency, Multiple-Input Multiple-Output (MIMO) technology is being considered for next generation terrestrial broadcasting television systems. In this paper we propose a MIMO channel-precoder that utilizes channel statistical structure and is suitable for terrestrial broadcasting systems, while being potentially transparent to the receivers. The performance of the channel-precoder is evaluated in a wide set of channel scenarios and mismatched channel conditions, a typical situation in the broadcast set-up. Capacity results show performance improvements in the case of strong line-of-sight scenarios with correlated antenna components and resilience against mismatched condition. Finally, we present bit-error-rate simulation results for state-of-the-art digital terrestrial broadcast systems based on DVB-NGH to compare the performance of SISO, $2{\times}2$ and $4{\times}2$ MIMO systems and proposed MIMO channel-precoder.**

***Index Terms*—Multiple-Input Multiple-Output (MIMO) channels, MIMO capacity and precoding, DVB, DVB-NGH, terrestrial broadcasting.**

I. INTRODUCTION

TODAY, terrestrial broadcasting technologies are facing a new era in which the spectrum efficiency is forced to be significantly enhanced due to increasing scarcity and cost of wireless bandwidth as well as high data rate content such as HDTV (High Definition TV), the incoming UHDTV (Ultra-High Definition TV), and the pressure for all SDTV (Standard Definition TV) services to be converted to HDTV. Future digital terrestrial TV broadcasting systems are expected to reach not only traditional rooftop receivers, but also portable and mobile terminals. In the last category, smart-phones and tablet computers face an exploding demand for mobile data traffic which is estimated to increase 10-folds between 2014 and 2019 [1]. These key drivers motivate the development of new digital terrestrial TV standards which rely on employing state of the art technologies.

MIMO is a key technology for future broadcasting systems which increases the capacity and the signal resilience without any additional requirements on bandwidth or increased transmission power. DVB-NGH (Digital Video Broadcasting - Next Generation Handheld) is the first TV broadcasting system to incorporate multi-antenna technology exploiting benefits of the MIMO channel [2], [3]. Similarly, other standardization forums such as ATSC (Advanced Television Systems Committee), ISDB (Integrated Services Digital Broadcasting), and DVB with a future extension of DVB-T2 (Second Generation Terrestrial) are also considering the use of MIMO technology. In mobile reception scenarios, MIMO has a potential of up to 80% capacity increase over Single-Input Single-Output (SISO) with DVB-NGH [2], while thanks to introduction of MIMO, even higher capacity gains are expected in fixed rooftop reception due to higher signal strength levels [4].

Presently, 2×2 and 4×2 antenna configurations are being considered in the broadcast TV standardization forums. Cross-polar arrangement (antennas with orthogonal polarization) is the preferred antenna configuration for digital terrestrial TV. When compared with the co-polar counterpart (antennas with the same polarization), cross-polar antennas provide higher multiplexing gains in line-of-sight (LOS) conditions, due to orthogonal nature of the cross-polar channel [5]–[7], and are feasible for small handset devices. In the ultra-high frequency range, the antenna separation required in the co-polar case to provide sufficiently uncorrelated fading signal may exceed typical handheld device sizes.

Increased data rates in MIMO systems are allowed through spatial multiplexing (SM) gain that is utilized by sending independent data streams across different transmit antennas. The performance of spatial multiplexing MIMO can be enhanced by linearly combining the data streams across the transmit antennas, known as precoding. DVB-NGH has applied precoding to improve performance in mobile broadcast channels for 2×2 MIMO. Precoder design in this system has been numerically assessed in terms of bit-error-rate (BER) criteria, which requires the simulation of the complete system chain (i.e., including MIMO demodulation and channel decoding) and dependent of specific system parameters such as constellation order and code rate [8].

In this paper, we propose an information theoretical approach to design channel-precoders that aim to maximize the *ergodic capacity* of the MIMO broadcasting system which depends only on the channel model and the target CNR (carrier to noise ratio). The proposed channel-precoder for arbitrary number of transmit and receive antennas utilizes channel statistical structure and is suitable for terrestrial broadcasting systems,

Manuscript received April 11, 2014; revised February 1, 2015 and May 4, 2015; accepted June 16 2015.

D. Vargas, D. Gómez-Barquero, and N. Cardona are with the Instituto de Telecomunicaciones y Aplicaciones Multimedia (iTEAM) of the Universitat Politècnica de València, 46022 Valencia, Spain (email: davarpa@iteam.upv.es; dagobar@iteam.upv.es; ncardona@iteam.upv.es).

Y. J. D. Kim was with with the Department of Electrical and Computer Engineering, McGill University, 3480 University St., Montréal, Québec, Canada H3A 2A7. He is now with the Department of Electrical and Computer Engineering, Rose-Hulman Institute of Technology, Terre Haute, IN 47803 USA (e-mail: kim2@rose-hulman.edu.)

J. Bajcsy is with the Department of Electrical and Computer Engineering, McGill University, 3480 University St., Montréal, Québec, Canada H3A 2A7 (email:jan.bajcsy@mcgill.ca).

Part of the work of D. Vargas has been funded by the Erasmus Mundus Programme of the European Commission under the Transatlantic Partnership for Excellence in Engineering - TEE Project.

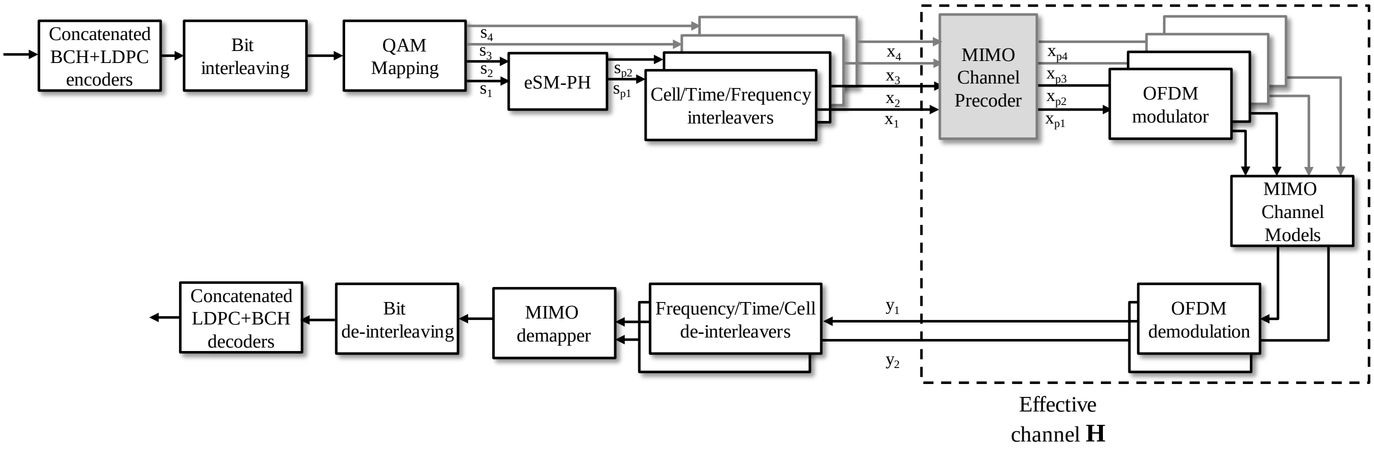


Figure 1. Transmit to receive diagram block based on DVB-NGH 2×2 MIMO system and 4×2 MIMO extended physical layer. Proposed channel-precoder is included at the transmitter in shaded box.

while being potentially transparent to the receivers. We focus on channel-precoding design and performance assessment for MIMO technology in terrestrial broadcasting systems in case of fixed rooftop and portable outdoor reception channels. The specific contributions of this work are as follows.

- First, we propose a MIMO channel-precoder designs that is novel in the terrestrial MIMO broadcasting setting. These precoder has the potential to further increase the channel capacity when compared to equivalent unprecoded MIMO set-up.
- Secondly, we determine the capacity improvements for recently considered 2×2 and 4×2 MIMO terrestrial broadcasting systems over currently deployed SISO terrestrial broadcasting. Obtained results show that SISO ergodic capacity can be increased by about 75% for both channel with 2×2 MIMO, but only a minor additional improvement compared to 2×2 MIMO can be achieved with 4×2 MIMO in the CNR range of interest.
- Then, the performance of the proposed channel-precoder is evaluated for fixed and portable channels and various reception conditions. A mismatched analysis allows to evaluate the performance of the precoder when the channel statistics do not match the precoder, a typical situation in the broadcast set-up. Capacity results present performance enhancements in scenarios with strong line-of-sight and correlated antenna component, and resilience in mismatched condition.
- Finally, we present bit-error-rate (BER) simulation results for SISO, MIMO setups and MIMO channel-precoders, considering the state-of-the-art DVB-NGH physical layer system. For the 2×2 MIMO systems, we utilize the MIMO profile of DVB-NGH, while for the 4×2 MIMO, we develop an extension of the DVB-NGH architecture to 4 independent transmitted data streams. With extensive simulation results we evaluate the performance improvements and degadations of the proposed MIMO channel-precoder in multiple environments.

The rest of this paper is organized as follows. Section II describes the system model with transmit and receiver architectures based on DVB physical layer, and rooftop and portable outdoor reception channel models. The optimization process for MIMO channel-precoders is included in Section III. Numerical evaluations in terms of channel capacity and BER with a system based on DVB-NGH physical layer are illustrated in Section IV. Section V discusses implementation aspects of channel-precoders for next generation broadcasting systems and finally Section VI presents the conclusions.

II. SYSTEM MODEL

The system model employed in this paper with the transmitter and the receiver is illustrated in Fig. 1, where the transmitter is based on DVB-NGH physical layer standard specification. In this paper we study two transmitter configurations with two and four transmit aerials. While the two transmit antennas case is included in DVB-NGH standard, the four transmit antennas case is an extension of DVB-NGH physical layer. Additionally, in shaded color, an optional MIMO channel-precoder is included at the transmitter side. The channel model represents a fixed rooftop and portable outdoor reception environments. A detailed explanation of different blocks is given in the next subsections.

A. Considered Transmit Architectures

As specified in [9], the incoming bit stream is first encoded by the concatenation of a BCH (Bose-Chaudhuri-Hocquenghem) and LDPC (Low-Density-Parity-Check) codes and passed through a bit interleaver that allows decorrelating the error events at the receiver. Specifically for DVB-NGH MIMO, the bit interleaver was designed to exploit the quasi-cyclic structure of the LDPC codes exhibiting low complexity, low latency, and fully parallel design easing the implementation of iterative structures.

The interleaved code bits are then multiplexed into one data stream (layer) per transmit antenna following a Gray labelling. Subsequently, in the case of two transmit antennas, the modulated data streams are processed by the eSM-PH (enhanced Spatial Multiplexing - Phase Hopping) processing block. The eSM-PH block weights and combines each layer according to a specified rotation angle, and additionally, a periodical phase hopping term is added to the second transmit antenna to randomize the code structure and avoid the negative effect of certain channel realizations [10]. The eSM-PH processing for two transmit antennas is expressed in the following matrix form [8]:

$$\begin{bmatrix} s_{p1} \\ s_{p2} \end{bmatrix} = \sqrt{2} \begin{bmatrix} 1 & 0 \\ 0 & e^{j\phi(n)} \end{bmatrix} \begin{bmatrix} \sqrt{\beta} & 0 \\ 0 & \sqrt{1-\beta} \end{bmatrix} \begin{bmatrix} \cos\theta & \sin\theta \\ \sin\theta & -\cos\theta \end{bmatrix} \begin{bmatrix} \sqrt{\alpha} & 0 \\ 0 & \sqrt{1-\alpha} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix}, \quad (1)$$

where s_1, s_2, s_{p1}, and s_{p2} are the input/output constellation symbols to the eSM-PH precoding, β is the factor that controls the power at the output of each transmit antenna, θ is the angle of the rotation matrix, α is the factor that controls the power allocated to each data stream, and $\phi(n)$ is the phase hopping term at the n^{th} QAM symbol within an LDPC codeword. The eSM-PH precoder is designed for 6 , 8, and 10 bits per channel use (bpcu) which correspond to the following constellations in the first and second transmit antennas: QPSK+16QAM, 16QAM+16QAM, and 16QAM+64QAM. In addition to ease the time-multiplexing in the same RF channel of SISO and MIMO transmissions, three possible values of power imbalance (β) are defined: 0 dB, 3 dB and 6 dB. This deliberate transmitted power imbalance provides a reasonable coverage reduction for single antenna terminals while eSM-PH codes are optimized to maintain good performance in this situation. Specific eSM-PH parameters can be found in [8]. In this paper we focus on the case where both transmit antennas have the same power. The design of precoders with intentional power imbalance is out of the scope of this paper.

In case of four transmit antennas, the transmitter spatially multiplexes the four modulated data streams s_1, s_2, s_3, s_4 which are passed directly to the cell interleaver operating at codeword level. The cell interleaver applies a different pseudo-random permutation for every codeword to ensure a uniform distribution of the channel fading realizations. Then, the time interleaver interlaces symbols from several codewords over various OFDM symbols to provide protection against selective fading. After time interleaving, the frequency interleaver operates on an OFDM level and its function is two-fold. First it mixes up symbols from various services and secondly, it applies a pseudo-random permutation to break the structured nature of the time interleaver output.

Here, the proposed MIMO channel-precoder gives the option of combining the samples among transmit layers according to a specific channel-precoding matrix per OFDM carrier, so that

$$\mathbf{x}_{\mathrm{p}} = \Gamma \mathbf{x}, \quad (2)$$

where Γ is the channel-precoder matrix derived and discussed in further detail in Section III, and $\mathbf{x}$ and $\mathbf{x}_{\mathrm{p}}$ are input/output symbol vectors to the channel-precoder with size $N_r{\times}1$, where N_r is the number of receive antennas.

Finally, before transmission across the cross-polarized antennas, the signal is passed from frequency to time domain by IFFT operation plus guard interval insertion, which composes the OFDM modulator.

B. MIMO Channel and Models

We first consider the set-up where the transmitted signal passes by a multipath (i.e., frequency-selective) and static (i.e., time-invariant) cross-polarized MIMO channel. The cross-polar channel can be expressed in general form [11]:

$$\mathbf{H} = \sqrt{\frac{K}{1+K}}\bar{\mathbf{H}}_{\times} + \sqrt{\frac{1}{1+K}}\tilde{\mathbf{H}}_{\times}. \quad (3)$$

In equation (3), $\bar{\mathbf{H}}_{\times}$ and $\tilde{\mathbf{H}}_{\times}$ are the LOS and NLOS (non-line-of-sight) channel components which take into account local scatters and the K factor describes the power ratio between them. $\bar{\mathbf{H}}_{\times}$ and $\tilde{\mathbf{H}}_{\times}$ can be decomposed into $\bar{\mathbf{H}}_{\times} = \bar{\mathbf{X}} \odot \bar{\mathbf{H}}$ and $\tilde{\mathbf{H}}_{\times} = \tilde{\mathbf{X}} \odot \tilde{\mathbf{H}}$ to explicitly describe the depolarization effects[1]. The $\bar{\mathbf{X}}$ and $\tilde{\mathbf{X}}$ matrices describe the energy coupling between cross-polarized paths. In the fixed rooftop and portable outdoor channel models considered in this paper, the cross-polar ratio for the vertical and horizontal polarizations has the same value, i.e. same signal leakage from vertical to horizontal polarization and from horizontal to vertical polarization. When the MIMO paths are correlated due to the environment, the matrices $\bar{\mathbf{H}}$ and $\tilde{\mathbf{H}}$ have the following expression:

$$\begin{aligned} \mathrm{vec}(\tilde{\mathbf{H}}) &= \tilde{\mathbf{R}}^{1/2}\mathrm{vec}(\tilde{\mathbf{H}}_w) \\ \mathrm{vec}(\bar{\mathbf{H}}) &= \bar{\mathbf{R}}^{1/2}\mathrm{vec}(\bar{\mathbf{H}}_w) \end{aligned}, \quad (4)$$

where $\tilde{\mathbf{R}}$ and $\bar{\mathbf{R}}$ are the $N_t N_r{\times}N_t N_r$ covariance matrices (with N_t being the number of transmit antennas) which describe the correlation between the channel paths of the LOS and NLOS components, respectively. The terms $\tilde{\mathbf{R}}^{1/2}$ and $\bar{\mathbf{R}}^{1/2}$ are the Cholesky decomposition of the covariance matrices and $\tilde{\mathbf{H}}_w$ and $\bar{\mathbf{H}}_w$ are i.i.d zero-mean complex Gaussian random matrices of size $N_r \times N_t$.

1) Modified Guilford Rooftop Channel Model - MGM: This channel characterizes a rooftop reception environment, based on the model in [12] and extracted from a channel sounding campaign in Guildford, UK [13] of a MIMO 2×2 channel with cross-polar antennas arrangement. The MGM (Modified Guilford Channel) in [14] is made up of 8 taps with different values of delay and power gain. While the first tap is Rice distributed with K factor, the rest are Rayleigh distributed. Each tap has a specific X factor (cross-polar power ratio) describing the energy coupling between cross-polarized paths. The model also exhibits spatial correlation between the antennas represented with a covariance matrix per tap. The MGM is characterized by a prominent LOS component with low X values, i.e., low coupling between vertical an horizontal components. The overall values for the K and X factors are 5 and 0.03, respectively. The transmit antennas are co-located in a single transmitter site which cause at the receiver locations impinging signals with same strengths, arriving at the same time, and with no frequency offsets due to a common transmit local oscillator [10].

2) Next Generation Handheld Portable Outdoor channel model - NGH PO: The MIMO NGH channel models [15] characterize mobile and portable reception and extracted from a measurement that took place in Helsinki (Finland) 2010.

---

[1] Operator $\odot$ represents the Hadamard of element-wise multiplication

These models were used during the DVB-NGH standardization process to evaluate performance of the MIMO schemes in realistic scenarios. Three scenarios are defined, outdoor mobile model, outdoor portable model and an indoor portable model. While for the mobile case user velocities of 60 km/h and 350 km/h are defined, the portable case considers 3 km/h and 0 km/h. In this paper we select the NGH portable outdoor model with 0 km/h. As the MGM model, the NGH-PO has a power delay profile of 8 taps where the first one is a complete LOS and the rest of the taps are Rayleigh distributed. Similarly to MGM model, the NGH-PO also includes a X factor and correlation between antennas. However, the NGH-PO model has lower K factor, higher X factor (i.e., more coupling between polarizations) and higher covariance matrix than the MGM model. In particular, the K and X factors take the values of 1 and 0.25, respectively.

3) Channel Model Extension to Four Transmit Antennas: In this case we consider four transmit antennas in the same tower with two horizontal and two vertical antennas. The 4×2 MIMO channel models are formed by two correlated independent instances of the $2{\times}2$ MIMO channels previously described. At the time of writing this paper no channel characterization is available for 4×2 MIMO broadcast channels and specific values need to be confirmed with data extracted from measurement campaigns. For the second 2×2 MIMO NLOS and LOS components, the terms $\tilde{\mathbf{H}}_w$ and $\bar{\mathbf{H}}_w$ are replaced with $\dot{\mathbf{H}}_w$ and $\ddot{\mathbf{H}}_w$ where

$$\begin{aligned} \mathrm{vec}(\dot{\mathbf{H}}_w) &= \beta \mathrm{vec}(\tilde{\mathbf{H}}_w) + \sqrt{1-\beta^2}\mathrm{vec}(\hat{\mathbf{H}}_w), \\ \mathrm{vec}(\ddot{\mathbf{H}}_w) &= \gamma \mathrm{vec}(\bar{\mathbf{H}}_w) + \sqrt{1-\gamma^2}\mathrm{vec}(\check{\mathbf{H}}_w) \end{aligned} \tag{5}$$

where $\hat{\mathbf{H}}_w$ and $\check{\mathbf{H}}_w$ are independent instances of i.i.d zero-mean complex Gaussian random matrices. The MGM model suggests a $\beta = 0.5$ value for the NLOS. In this paper we will study different correlation values γ for the LOS in the $[0, 1]$ range. Although the correlation between channel components from different polarizations is low [11], higher correlation values are observed between channel components with the same polarization [16]. Furthermore, strong LOS scenarios produces high correlated channels components [17], [18].

C. Receiver Architecture

The signal distorted by the channel is received by two cross-polarized antennas. Referring to Fig. 1, the received streams are first processed by the OFDM demodulator, which essentially discards the guard interval and performs an FFT. In the baseband, the complex output vector of the OFDM demodulator is given by $\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w}$, where $\mathbf{H}$ is the $N_r{\times}N_t$ channel matrix in frequency domain, $\mathbf{x}$ is the $N_t{\times}1$ transmitted vector, and $\mathbf{w} \sim \mathcal{CN}(\mathbf{0}, \sigma^2\mathbf{I})$ is $N_r \times 1$ additive circularly symmetric complex Gaussian noise, where σ^2 is the noise power. In Fig. 1, this *effective channel* $\mathbf{H}$ is denoted by the dashed box. In this paper we assume perfect knowledge of CSI (channel state information) at the receiver side. However, a practical receiver implementation estimates the channel response from each transmit antenna with known orthogonal pilot signals sent multiplexed with the data [19]. Therefore, the receiver needs to estimate four and eight channel responses for the $2{\times}2$ and 4×2 schemes, respectively[2]. The two received streams are then frequency, time and cell de-interleaved to undo the transmitter operations and fed to the MIMO demodulator which provides soft information about the transmitted code bits. We note that in the case of two transmit antennas with eSM-PH, the MIMO demodulator takes into account eSM-PH processing. LLRs (Log-Likelihood Ratios) for the transmitted code bits are calculated using the received data streams and CSI. Next, the LLRs are de-interleaved and processed by the LDPC decoder that runs several iterations of the sum-product algorithm before outputting its decisions to the BCH decoder.

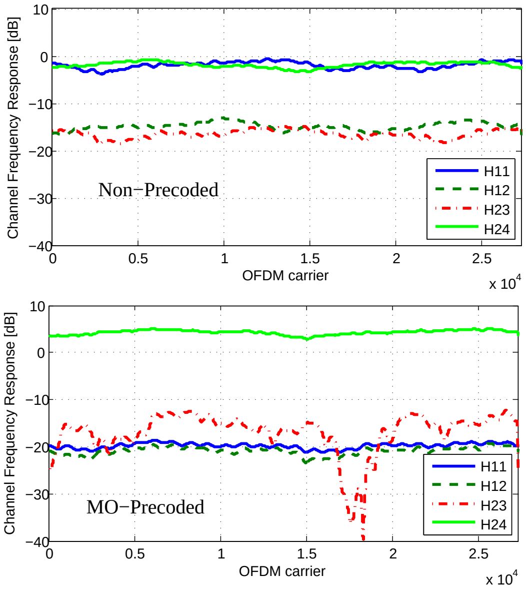


Figure 2. Channel frequency responses of a MIMO $4{\times}2$ without precoding (top) and with precoding (bottom) in the MGM channel model.

III. DESIGN OF MIMO-CHANNEL-PRECODERS FOR DIGITAL TERRESTRIAL TV SYSTEMS

Due to the lack of feedback channel from the receiver to the transmitter - as in cellular systems - and differing channel realizations at different locations of the broadcasting network, conventional MIMO-precoding that maximizes capacity of individual MIMO link cannot be employed in the broadcasting system. On the contrary, our precoding design exploits common statistical structure found in the overall broadcast network such as statistical distribution of the channel, correlation between antennas, and LOS conditions. Our precoder design aims to maximize the *ergodic capacity* of the MIMO broadcasting system and depends only on the channel model and the target CNR.

---

[2] Compared with SISO, the amount of pilot information has to be doubled and quadrupled for $2{\times}2$ and $4{\times}2$ MIMO schemes, respectively. This amount of pilot information reduces significantly the available spectral efficiency in mobile scenarios since denser patterns are needed to sample the time-variant channel, e.g., 8, 3% and 16, 6% of pilots assumed for SISO and MIMO 2×2 in DVB-NGH, respectively. This situation improves in static/portable reception (as the one studied in this paper) where sparser pilot patterns can be supported due to time-invariability of the channel e.g.,1% for SISO DVB-T2 UK mode, 2% for $2{\times}2$ MIMO, and 4% for $4{\times}2$ MIMO.

Table I
SIMULATION PARAMETERS.

System Parameters	**Value**
FFT size	32K
Guard interval	1/128
LDPC block length	16200 bits
Code rate	5/15, 8/15, and 11/15
Constellation	256QAM - SISO 16QAM - MIMO 2×2 QPSK - MIMO 4×2
Mapping	Gray labelling
Channel estimation	perfect receive CSI

We first recall the ergodic capacity of MIMO channel with no information at the transmitter, perfect CSI at the receiver and zero-mean Gaussian distributed inputs as [20]:

$$C = E_{\mathbf{H}}\{\log_2 \det\left(\mathbf{I}_{N_r} + \frac{\rho}{N_t}\mathbf{H}\mathbf{H}^\dagger\right)\}, \tag{6}$$

where ρ is the CNR in linear units, $\mathbf{I}_{N_r}$ is the identity matrix of size $N_r \times N_r$, the superscript † denotes the conjugate transposition, and the statistical expectation operator E is over all possible channel realizations. Equation (6) provides with the maximum achievable system rate with diminishing error probability as the transmission duration tends to infinity. This definition is convenient for fast fading channels or for long codeword transmission in which the channel can be assumed to be sufficiently averaged.

The previous definition assumed perfect CSI at the receiver with no information at the transmitter. However, the broadcast network tends to exhibit common channel characteristics such as predominant LOS (i.e., high K factor) in rooftop environment, or correlation between antenna paths [4]. Inspired by [20]–[24], we design MIMO channel-precoder that attempts to adapt the transmission signal characteristics to the channel statistics to increase the ergodic capacity in MIMO digital terrestrial TV systems. Our approach of exploiting the channel statistics can provide significant capacity improvements for users with strong LOS component and/or correlation among antennas, while preserving similar area coverage for receivers with dominant multipath environment, i.e., low K factor, and uncorrelated antenna paths. The optimization problem is mathematically defined as:

$$\begin{aligned} &\underset{\mathbf{Q}\succeq 0 \ s.t.}{\text{maximize}} \qquad E_{\mathbf{H}}\{\log_2 \det\left(\mathbf{I}_{N_r} + \frac{\rho}{N_t}\mathbf{H}\mathbf{Q}\mathbf{H}^\dagger\right)\} \\ &\text{trace}(\mathbf{Q}) = N_t \end{aligned} \tag{7}$$

where the statistical expectation is over all realizations of MIMO channel $\mathbf{H}$, and $\mathbf{Q}$ is the covariance matrix of the transmitted vector $\mathbf{x}$. While the first constraint keeps the positive semi-definite property of the covariance matrix, the second constraint maintains constant sum power for any transmit antenna dimension, i.e., $\text{trace}(\mathbf{Q})/N_t = 1$. With strong error correcting codes, such as LDPC codes used in the considered MIMO system, capacity optimization criterion is the preferred metric [22].

Once the capacity maximizing $\mathbf{Q}$ is obtained from (7), it can be further decomposed into $\mathbf{Q} = \mathbf{U}\Lambda\mathbf{U}^\dagger$ by the eigen-decomposition [25], where $\mathbf{U}$ is the unitary matrix whose columns are the eigenvectors of $\mathbf{Q}$, and Λ is the diagonal matrix whose diagonal entries are the corresponding non-negative real eigenvalues. Consequently, the optimal channel-precoder which maximizes the system ergodic capacity is given by:

$$\Gamma = \mathbf{U}\boldsymbol{\Lambda}^{\frac{1}{2}}, \tag{8}$$

and the carrier input to OFDM modulator in Fig. 1 is precoded as $\mathbf{x}_{\mathrm{p}} = \Gamma\mathbf{x}$. With the precoding, the power per transmit antenna is given by $\text{diag}\left(E\{\mathbf{x}_p\mathbf{x}_p^\dagger\}\right)$ where

$$\begin{aligned} E\{\mathbf{x}_p\mathbf{x}_p^\dagger\} &= E\{\Gamma\mathbf{x}\mathbf{x}^\dagger\Gamma^\dagger\} = \Gamma E\{\mathbf{x}\mathbf{x}^\dagger\}\Gamma^\dagger \\ &= \Gamma\Gamma^\dagger = \mathbf{U}\boldsymbol{\Lambda}^{\frac{1}{2}}\Lambda^{\frac{1}{2}}\mathbf{U}^\dagger = \mathbf{Q} \end{aligned} \tag{9}$$

because for $i.i.d.$ column vector $\mathbf{x}$, $E\{\mathbf{x}\mathbf{x}^\dagger\} = \mathbf{I}_{N_t}$. Thus, the power allocation per transmit antenna in this precoded MIMO system is given by $\text{diag}\left(\mathbf{Q}\right)/N_t$. Consequently, this channel-precoding allocates different power per transmit antenna. However, for all the solutions proposed in this paper, the maximum power imbalance between any pair of transmit antennas is lower than 0.5 dB that can be considered negligible.

Equation (7) describes a convex optimization problem because log-determinant is a concave function over positive semi-definite matrices and expectation is a linear operator. Hence the optimal value can be calculated numerically by using standard convex optimization techniques [26]. Direct computation of the optimization problem, however, is still computationally expensive due to the large degrees of freedom in the MIMO-channel matrix $\mathbf{H}$ found in the broadcasting systems. Consequently, we propose below a semi-analytical solution with low computational complexity, to obtain MIMO channel-precoders based on ergodic capacity[3] for a generic MIMO transmission system of dimension $N_t \times N_r$.

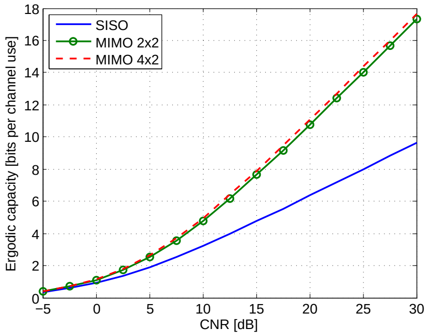
1) MIMO-Channel-Precoder Based on Mean-Optimality: Now we derive a new channel-precoder - as the best of our knowledge - with near-optimal performance in the considered broadcast TV channel. This method is based on averaging per-channel-realization optimal covariance matrices. First, slightly abusing terminology, let $\tilde{\mathbf{H}}$ be a possible channel realization. For this specific channel realization, the solution $\tilde{\mathbf{U}}$ matrix is given by the eigenvector matrix of $\tilde{\mathbf{H}}^\dagger\tilde{\mathbf{H}}$ and the solution $\tilde{\boldsymbol{\Lambda}}$ matrix is given by the following water-filling solution:

$$\tilde{\lambda}_k = \max\left(\mu - \frac{\sigma^2}{\tilde{d}_k}, 0\right), \quad k = 1, 2, \ldots, N_t, \tag{10}$$

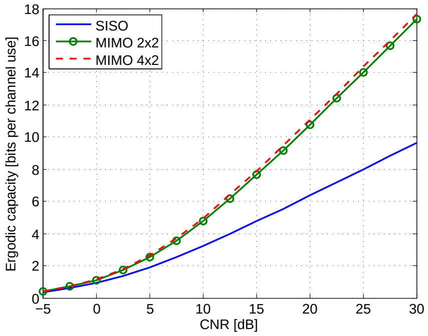
where $\tilde{\lambda}_k$ is the k^{th} diagonal entry of $\tilde{\boldsymbol{\Lambda}}$, $\tilde{d}_k$ is k^{th} eigenvalue of $\tilde{\mathbf{H}}^\dagger\tilde{\mathbf{H}}$, σ^2 is the noise power, and water-filling parameter

---

[3] For the case of quasi-static or slow fading, in which one codeword is affected by one channel realization, the appropiate measure is the ϵ-outage capacity with the following expression: $C_\epsilon \triangleq \sup\{R \mid \Pr\{C_{\mathbf{H}} < R\} < \epsilon\}$ where $C_{\mathbf{H}}$ is the capacity of a specific channel realization, and $\Pr\{C_{\mathbf{H}} < R\}$ is the probability that $C_{\mathbf{H}}$ is lower than rate R. The ϵ-outage capacity can be interpreted as the minimum rate C_ϵ that can be achieved at the $(1-\epsilon)\,100\%$ of the channel realizations. The optimization of channel-precoders based on outage capacity requires a different approach to the one proposed in this paper and is thus beyond the scope of this paper. For the interested reader references [27] and [28] provide results related to the optimization of transmission techniques based on outage capacity.

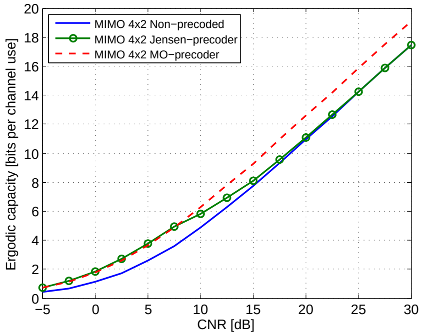


(a) MGM channel model.

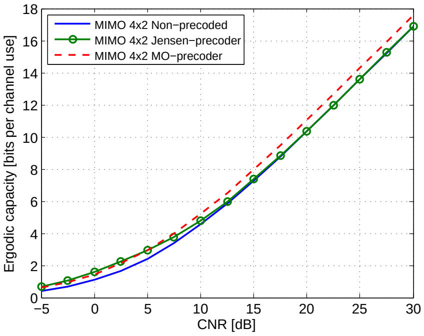


(b) NGH-PO channel model.

Figure 3. Ergodic capacity in bits per channel use vs. the CNR in dB for MGM (a) and NGH-PO (b) channel models with SISO, MIMO 2×2 and MIMO 4×2. For the MIMO 4×2 channels the LOS correlation $\gamma=0$, i.e., no correlation. (Note that the gain of MIMO 4×2 over MIMO 2×2 is higher for the NGH-PO channel.)



(a) MGM channel model.



(b) NGH-PO channel model.

Figure 4. Ergodic capacity in bits per channel use vs. CNR in dB for MGM (a) and NGH-PO (b) channels with 4×2 MIMO and LOS correlation $\gamma=1$. Unprecoded system, precoded MIMO with Jensen and MO precoders are illustrated. (Note that in this case of full LOS correlation, the precoding gains are higher for the MGM channel model.)

μ is chosen such that $\tilde{\lambda}_1+\tilde{\lambda}_2+\ldots+\tilde{\lambda}_{N_t}=N_t$. The *mean-optimal* covariance matrix is then obtained by averaging along all per-channel optimal covariance matrices:

$$\mathbf{Q}_{\mathrm{MO}}=E\{\tilde{\mathbf{U}}\tilde{\mathbf{\Lambda}}\tilde{\mathbf{U}}^{\dagger}\}, \tag{11}$$

where the statistical expectation is over all possible channel realizations. The resulting MIMO-channel-precoder for the mean-optimal solution is given by

$$\Gamma_{\mathrm{MO}}=\mathbf{U}_{\mathrm{MO}}\mathbf{\Lambda}_{\mathrm{MO}}^{\frac{1}{2}}, \tag{12}$$

where $\mathbf{U}_{\mathrm{MO}}$ and $\mathbf{\Lambda}_{\mathrm{MO}}$ are the eigenvector and eigenvalue matrices, respectively, of the mean-optimal covariance matrix $\mathbf{Q}_{\mathrm{MO}}$. The proposed algorithm has low computational complexity and it is a simple tool to optimize the performance of generic MIMO channels which exhibit any kind of correlation between antennas and/or LOS condition.

Fig. 2 shows sample channel frequency responses of a MIMO 4×2 without (top) and with precoding (bottom) under the MGM channel. The precoder does not affect significantly the selectivity of the channel response but modifies the mean power of the effective received channels.

2) MIMO-Channel-Precoder Based on Jensen's Inequality: For comparison and completeness, we have also considered a MIMO precoder based on Jensen's inequality [29], which was previously used for precoder designs in cellular systems with feedbacks [22]. This second precoder is used for the first time for digital broadcasting TV systems. In this design, instead of maximizing the ergodic capacity expression in (7), we maximize a tractable upperbound obtained through the following derivation:

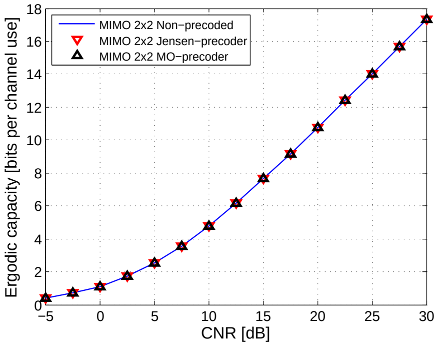
$$\begin{aligned} &E\{\log_2\det\left(\mathbf{I}_{N_r}+\frac{\rho}{N_t}\mathbf{H}\mathbf{Q}\mathbf{H}^{\dagger}\right)\} \\ &=E\{\log_2\det\left(\mathbf{I}_{N_t}+\frac{\rho}{N_t}\mathbf{H}^{\dagger}\mathbf{H}\mathbf{Q}\right)\} \qquad (13) \\ &\le\log_2\det\left(\mathbf{I}_{N_t}+\frac{\rho}{N_t}E\{\mathbf{H}^{\dagger}\mathbf{H}\}\mathbf{Q}\right), \qquad (14) \end{aligned}$$

where (13) is due to log-determinant identity, $\log\det(\mathbf{I}+\mathbf{A}\mathbf{B})=\log\det(\mathbf{I}+\mathbf{B}\mathbf{A})$, and (14) follows from the Jensen's inequality and the concavity of the log-determinant function over positive semi-definite matrices. Optimizing (14) can be done through well known waterfilling algorithm [29]. Consequently, the solution $\mathbf{U}_{\mathrm{J}}$ matrix is given by the eigenvector matrix of $E\{\mathbf{H}^{\dagger}\mathbf{H}\}$ and the solution Λ_{J} matrix is given by the water-filling solution:

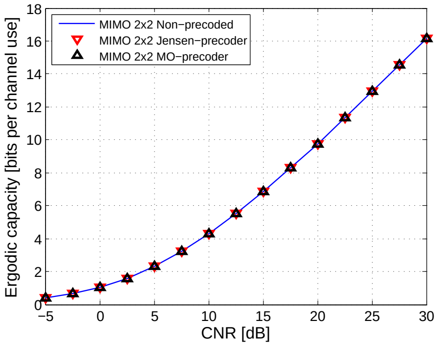
$$\lambda_k=\max\left(\mu-\frac{\sigma^2}{\alpha_k},0\right),\quad k=1,2,\ldots,N_t, \tag{15}$$

where λ_k is k^{th} diagonal entry of Λ_{J}, α_k is the k^{th} eigenvalue of $E\{\mathbf{H}^{\dagger}\mathbf{H}\}$, σ^2 is the noise power, and water-filling parameter μ is chosen such that $\lambda_1+\lambda_2+\ldots+\lambda_{N_t}=N_t$. Finally, the MIMO-channel-precoder solution based on Jensen's inequality is given by:

$$\Gamma_{\mathrm{J}}=\mathbf{U}_{\mathrm{J}}\mathbf{\Lambda}_{\mathrm{J}}^{\frac{1}{2}}. \tag{16}$$



(a) MGM channel model.



(b) NGH-PO channel model.

Figure 5. Ergodic capacity in bits per channel use vs. CNR in dB for MGM (a) and NGH-PO (b) channels with 2×2 MIMO. Unprecoded system, precoded MIMO with Jensen and MO precoders are illustrated.

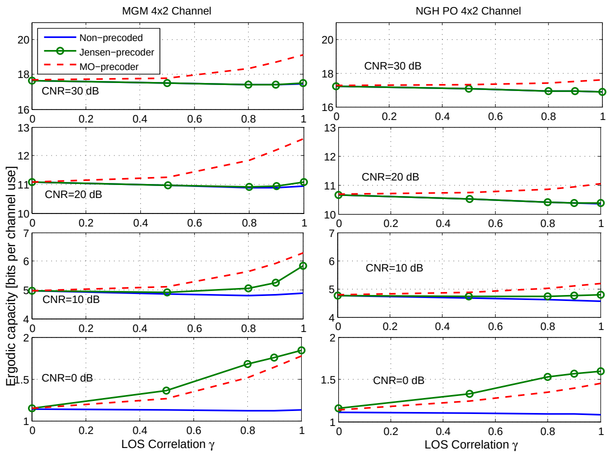


Figure 6. Ergodic capacity in bits per channel use vs. LOS correlation γ with 4×2 MIMO for MGM (left) and NGH-PO (right) channels and CNR values of 0, 10, 20 and 30 dB. Unprecoded system, precoded MIMO with Jensen and MO precoders are illustrated. Channel-precoders are designed for every case of LOS correlation γ and target CNR (matched case with channel statistics).

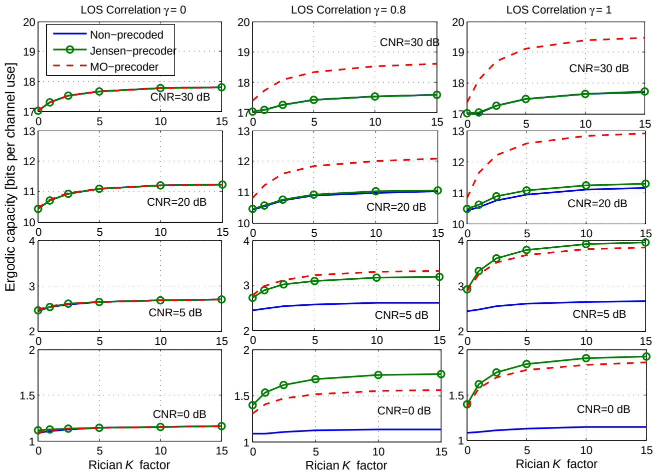


Figure 7. Ergodic capacity in bits per channel use vs. Riciean K factor with 4×2 MIMO under MGM channels and CNR values of 0, 5, 20 and 30 dB. Three values of LOS correlation γ are studied, $\gamma = 0$, $\gamma = 0.8$ and $\gamma = 1$. Unprecoded system, precoded MIMO with Jensen and MO precoders are illustrated. Jensen and MO precoders are designed for every target CNR and fixed $K = 5$ (MGM parameter) - mismatched case with the true channel statistics.

This precoding maximizes (14) instead of the ergodic capacity, and consequently leads to a tractable lowerbound to the true channel-precoding capacity.

Channel-precoders in (7), (12), and (16) improve performance of the transmission in ergodic sense. In the broadcasting set-up the multiple receiving users can suffer different propagation conditions. Therefore, in the next sections we evaluate the channel-precoders performance (gains and degradations) with various channel environments and channel-precoder missmatched condition, i.e., channel statistics differ from the ones used to optimized the channel-precoders.

IV. Performance Gains for MIMO and Channel-Precoding in Digital Terrestrial TV

In this section we provide capacity and physical layer simulation results to evaluate the performance gains thanks to MIMO and proposed MIMO channel-precoding in digital terrestrial TV systems in various environments.

A. MIMO Capacity Benefits

Fig. 3 shows the ergodic capacity in bits per channel use vs. the CNR in dB for the *effective channel* for the considered SISO, MIMO 2×2 and MIMO 4×2 transmission discussed in Section II. We use the MGM and NGH-PO channels described in II-B1 and II-B2, respectively. For both channels, using 2×2 MIMO increases the capacity of SISO at all CNRs, however, the gains start to be significant in the medium to high CNR range ($10-30$ dB) due to array, diversity and especially multiplexing gains. Further increasing the number of transmit antennas to 4 does not provide significant improvement in both channels. This is due to no additional multiplexing gain is achieved, and only additional diversity is obtained [30]. However, the gain of MIMO 4×2 over MIMO 2×2 is higher for the NGH-PO channel. This is because of the higher X value in the NGH-PO channel which provides higher diversity gain.

B. Additional Capacity Gains from MIMO Precoding

Fig. 4 shows the ergodic capacity in bits per channel use vs. CNR in dB for 4×2 MIMO system with no precoding, Jensen-precoder and the MO (Mean-Optimality) precoder under MGM (a) and NGH-PO (b) channels. Channel-precoding

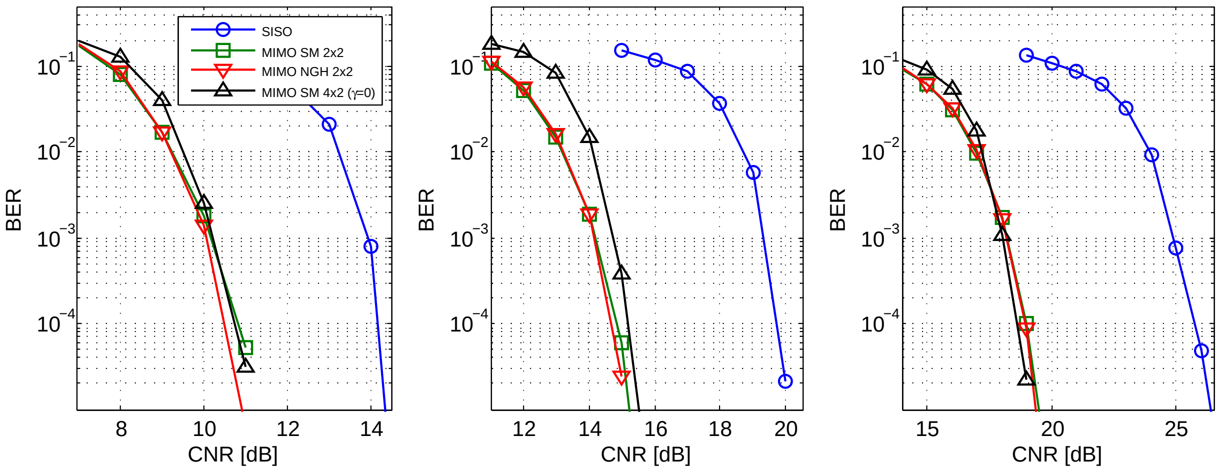


Figure 8. Bit error rate vs. CNR in dB for NGH-PO channel model with code-rates 5/15 (left), 8/15 (center) and 11/15 (right). SISO, unprecoded MIMO with spatial multiplexing (SM) 2×2, MIMO with NGH precoding 2×2 and unprecoded MIMO with spatial multiplexing 4×2 are illustrated.

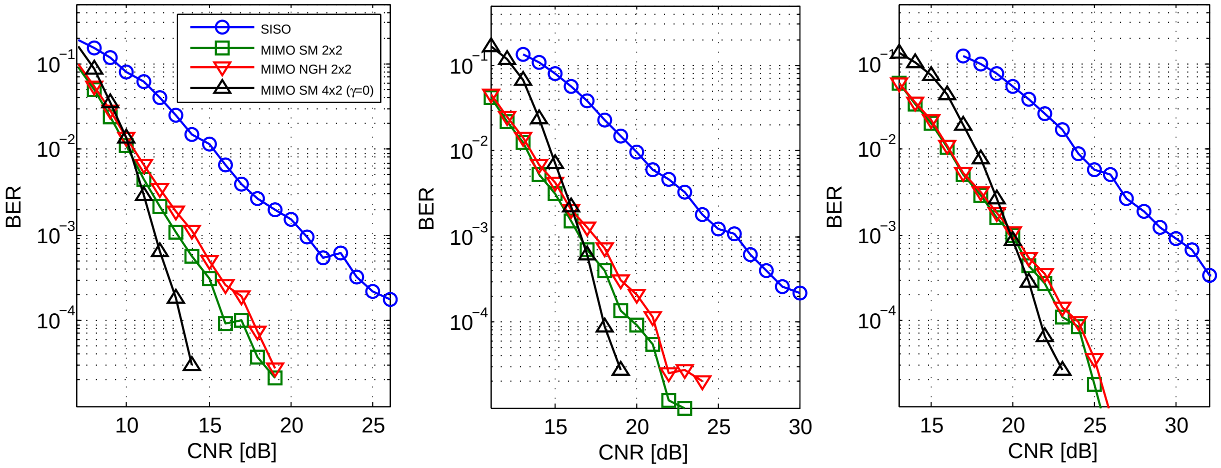


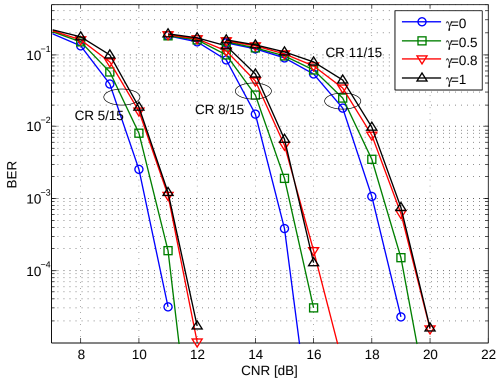
Figure 9. Bit error rate vs. CNR in dB for MGM channel model with code-rates 5/15 (left), 8/15 (center) and 11/15 (right). SISO, unprecoded MIMO with spatial multiplexing (SM) 2×2, MIMO with NGH precoding 2×2 and unprecoded MIMO with spatial multiplexing 4×2 are illustrated.

is optimized for this specific channel statistics with full LOS correlation, i.e., $\gamma = 1$. It can observed that, compared to the unprecoded 4×2 MIMO, the MO-precoder 4×2 MIMO provides an extra 1.6 bits per channel use under MGM channel and an extra 0.7 bits per channel use uder NGH-PO channel at 25 dB of CNR. On the other hand, while the channel-precoder solution based on Jensen's inequality outperforms unprecoded system and MO-precoder at low CNRs, it converges to unprecoded system at high CNRs.

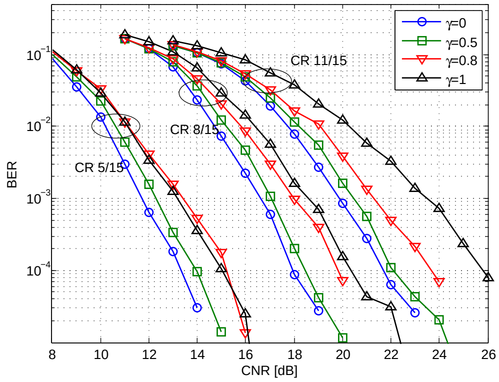
Results in Fig. 5 present 2×2 MIMO performance where the use of Jensen and MO precoders show no enhancement at all CNRs. This is due to the low correlation of the MIMO paths in the 2×2 case. More generally, the performance of channel-precoding in MIMO systems with the same number of transmit and receive antennas converges to an unprecoded system as the CNR increases [22].

In Fig. 6 we present the ergodic capacity in bits per channel use for unprecoded and precoded 4×2 MIMO system against the LOS correlation parameter γ under MGM channel (left) and the NGH-PO channels (right). Here, the channel-precoders are designed for every γ value and target CNR of 0, 10, 20 and 30 dB. Therefore, Fig. 6 analyzes the performance when the channel statistics match the channel-precoder. Here, for both channels and CNRs the channel-precoding gain over unprecoded system increases with increasing γ factor, and furthermore higher gains are achieved for the MGM channel. Note that the ergodic capacity with channel-precoding converges to unprecoded system at $\gamma = 0$, i.e., no LOS correlation between the two 2×2 MIMO channels. At low CNRs, Jensen precoder has the best performance but converges to an unprecoded system as as the CNR increases. On the other hand, the MO-precoder outperforms unprecoded system for medium to high γ values and for all studied CNRs. It is worth noting that higher ergodic capacity can be achieved in a system with channel-precoding and correlated LOS than in an unprecoded system with uncorrelated LOS. Similar conclusion can be extracted from reference [31] for a 4×2 MIMO system.

Next, Fig. 7 presents ergodic capacity in bits per channel use vs. the Ricean K factor of the MGM channel with 4×2 MIMO system and CNR values of 0, 5, 20 and 30 dB. Three values of LOS correlation γ are studied, $\gamma = 0$ (no

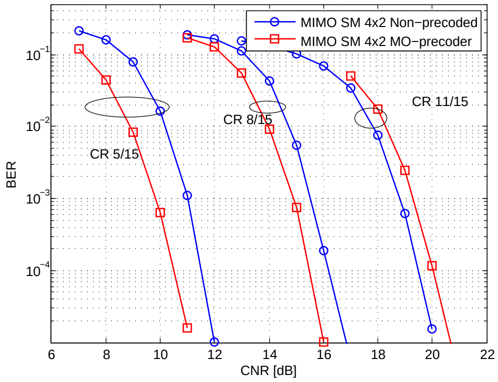


(a) NGH-PO channel model.

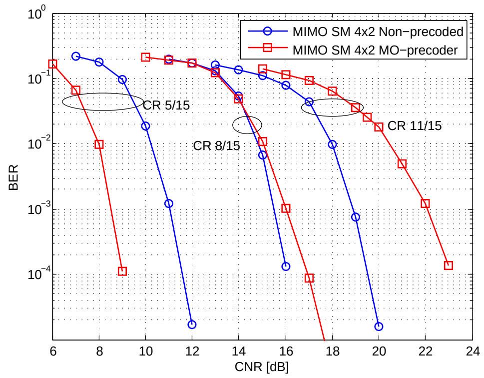


(b) MGM channel model.

Figure 10. Bit error rate vs. CNR for NGH-PO (upper) and MGM (bottom) channel models with code-rates 5/15, 8/15 and 11/15. Unprecoded MIMO with spatial multiplexing 4×2 with different LOS correlation γ values is illustrated.



(a) LOS correlation $\gamma = 0.8$.



(b) LOS correlation $\gamma = 1.0$.

Figure 11. Bit error rate vs. CNR in dB for NGH-PO channel model with code-rates 5/15, 8/15 and 11/15. MIMO with simple spatial multiplexing 4×2 and MIMO with simple spatial multiplexing 4×2 with MO-precoder for $\gamma = 0.8$ (upper) and $\gamma = 1.0$ (bottom).

correlation), $\gamma = 0.8$ (medium to strong correlation) and $\gamma = 1$ (full correlation). The performance of the channel-precoders is studied in mismatched condition, i.e., the channel statistics differ from the ones used to design the precoders. In the case of $\gamma = 0$, channel-precoders have the same performance to unprecoded system at all studied CNRs and K values. For the other two γ cases, the ergodic capacity of channel-precoding increases with increasing K factor. As observed in Fig. 4(a) Jensen precoder outperforms MO precoder at low CNRs while MO-precoder outperforms Jensen precoder at higher CNRs. In this mismatched analysis we can observe that channel-precoders still provide better performance than unprecoded system even in the event of mismatched K. Note that in the extreme case of $K = 0$ the channel-precoders still provide an improvement. This is is because, even though there is no LOS component in the channel, the channel-precoders are able to exploit the correlation of the NLOS component.

C. BER Performance for Different Transceiver Designs

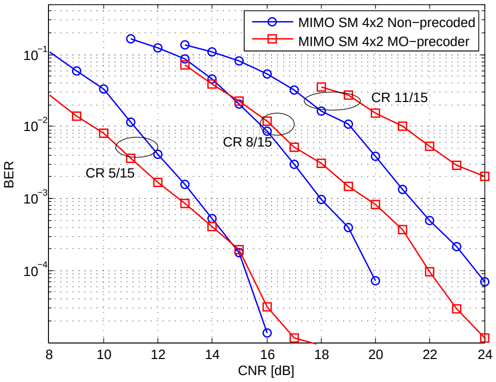
To complement the channel capacity results presented in the previous subsections, we have also simulated BER performance of the considered MIMO systems described in Section II.

We used the MGM rooftop and NGH-PO MIMO cross-polar channel as described in Section II-B with values of K and X defined in Subsection II-B2 and Subsection II-B1. Further simulation parameters are specified in Table I, where the precoded MIMO systems used the designed MO-precoder with fixed channel paramters (fixed K, X and LOS correlation γ factors). Perfect CSI at the receiver side is assumed. We select code-rates $5/15$, $8/15$ and $11/15$ to evaluate the performance of the different schemes at low, mid and high code-rates. Additionally, we use on each transmit antenna a 256QAM constellation for SISO, 16QAM constellation for 2×2 MIMO, and QPSK constellation for 4×2 MIMO. In particular, 8 bits are transmitted per channel use for all antenna configurations with an effective rate of 2.58, 4.18 and 5.78 bits per channel use, respectively when taking into account error control coding[4].

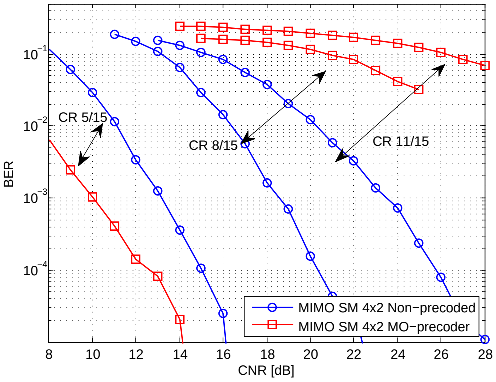
First in Fig. 8 and Fig. 9 we compare the performance of SISO, MIMO SM (unprecoded) 2×2, MIMO eSM-PH (NGH precoding) 2×2 and unprecoded 4×2 MIMO with LDPC code rates of $5/15$ (left), $8/15$ (center) and $11/15$ (right) under NGH-PO (Fig. 8) and MGM (Fig. 9) channels. For the unprecoded MIMO SM 4×2 case, both channels have zero LOS correlation ($\gamma = 0$). For both channels, MIMO schemes show a significant gain compared to SISO. Applying NGH precoding to MIMO 2×2 provides an advantage over the unprecoded case in the NGH-PO channel (since NGH precoding was optimized

---

[4] This spectral efficiency does not take into account the loss due to signalling, synchronization, pilot insertion, and guard interval.



(a) LOS correlation $\gamma = 0.8$.



(b) LOS correlation $\gamma = 1.0$.

Figure 12. Bit error rate vs. CNR in dB for MGM channel model with code-rates 5/15, 8/15 and 11/15. MIMO with simple spatial multiplexing $4{\times}2$ and MIMO with simple spatial multiplexing $4{\times}2$ with MO-precoder for $\gamma = 0.8$ (upper) and $\gamma = 1.0$ (bottom).

for this channel), but it does not for the MGM channel. It is interesting that while MIMO NGH 2×2 provides better or similar performance to unprecoded $4{\times}2$ MIMO in the NGH-PO channel, for the MGM channel MIMO 4×2 outperforms MIMO NGH $2{\times}2$.

Here, in Fig. 10 we investigate the unprecoded $4{\times}2$ MIMO performance degradation due to LOS correlation under MGM (top) and NGH-PO (bottom) channels . One can observe that the performance degrades with increasing γ factor for both channels. However, this degradation is higher in the MGM channel.

In Fig. 11 and Fig. 12 we compare the performance of $4{\times}2$ MIMO with the MO-precoder and the unprecoded case in the NGH-PO and MGM channels, respectively. LOS correlation values $\gamma = 0.8$ and $\gamma = 1.0$ are included. In both channels we can observe that MO-precoding provides improved or similar performance to unprecoded system at code rate $5/15$ but incurs in an increasing performance degradation with increasing code rate.

To explain the performance dependence with the code rate of the MO-precoding, we present in Fig. 13 the probability density function (pdf) of the LLR values at the output of the MIMO demodulator for a MIMO 4×2 with and without MO-precoding under the MGM channel model with 15 dB (top) and 25 dB (bottom). First, it can be observed that MO-precoding affects the distribution of LLR values. With precoding, the LLRs take, with high probability, either small (i.e., low bit reliability) or high absolute values (i.e., high bit reliability). Without precoding the LLR values are more uniformly distributed. The strong reliability for some of the LLR values with precoding can be connected with the improved performance at low code-rates. When channel coding is used, previous works in [32], [33] have shown that while diversity techniques improve performance at high code-rates, they can degrade the performance at low code-rates. MO-precoding reduces the diversity of the LLR values in favour of enhancing the reliability of some of the transmitted bits, which can be exploited by the diversity of the channel code at low code-rates.

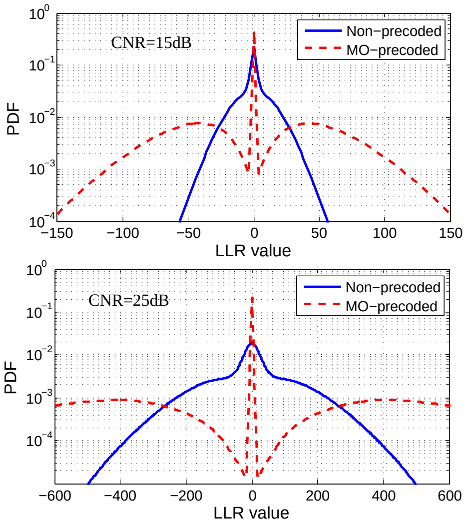


Figure 13. Probability density function of the LLR values for MIMO 4×2 without precoding and with MO-precoding under MGM channel with 15 dB (upper) and 25 dB (bottom) of received CNR.

Finally, in Fig. 14 the performance of MO-precoder 4×2 MIMO is analysed in the case of mismatch condition with K factor where the precoder statistics and true channel statistics differ. This is common situation in the broadcasting set-up since different users can experience channels with different reception conditions and therefore different channel statistics. Here, we compare the gain over unprecoded 4×2 MIMO in the NGH-PO channel with two values of γ equal to 0.8 and 1.0. We study the performance of code rate $5/15$ since higher ones provided poor performance for channel-precoding. The gain increases for both values of γ with increasing K factor. It is interesting to note that for this low code-rate even in the extreme case of $K = 0$ (where there is no LOS component) the channel-precoder still provides a gain of about 0.5 dB. This is because the precoder is still able to exploit the covariance matrix of the NLOS components which also has some degree of correlation (cf. section II-B3).

V. Implementation Aspects

Transmission techniques transparent to receiver terminals provides flexibility to network operators for the introduction of new schemes to the existing receiving population in its network. Transparency for channel-precoding can be achieved

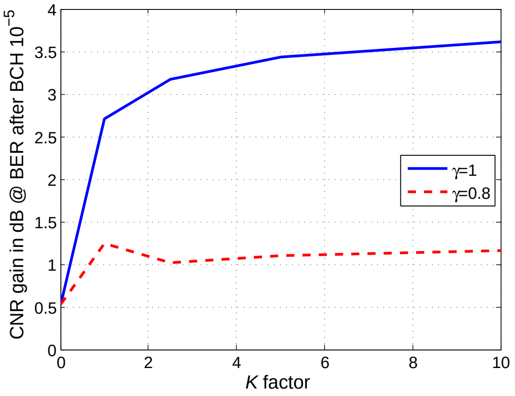


Figure 14. CNR gain in dB vs. K factor for MIMO 4×2 with MO-precoder over MIMO 4×2 without precoding in NGH-PO channel with code-rate $5/15$. MO precoder is designed for fixed $K = 5$, (mismatched case).

by placing it after the insertion of the pilot symbols which are required to estimate the channel response at the receiver. In this case, the receiver needs to estimate the effective channel formed by the combination of the precoder plus channel. If the channel-precoding varies along the frequency domain it can impose a performance degradation if the resulting channel selectivity cannot be estimated at the receiver. To overcome this, the channel-precoder can be placed before the pilot insertion removing transparency to receiver terminals. Here, the receiver estimates the true channel response and the demodulation process takes into account the precoding applied at the transmitter end. Alternatively, a precoder with no variation in frequency domain could be transparent to receivers and without imposing an additional distortion to the channel frequency response.

If channel-precoder is designed in a per carrier basis, different powers are allocated along the carriers in frequency domain. For the solutions reported in Section III, the maximum power variance in frequency direction is lower than -40 dB which can be considered is sufficiently low. To remove any power variation in frequency domain of the transmitted signal a single channel-precoder could be designed at the cost of some performance loss.

The complexity at the transmitter side due to precoding is a per carrier complex matrix multiplication of dimension $N_t{\times}N_t$ by $N_t \times 1$. Similarly, the receiver needs to perform a matrix multiplication of dimension $N_r \times N_t$ by $N_t \times N_t$. If channel-precoding is designed per carrier, the coefficients can be stored at both the transmitter and receiver in a look-up table. When the inclusion of channel-precoding is transparent to receivers, there is not any associated complexity increase at the receiver end.

VI. CONCLUSION

In this paper we have derived a MIMO channel-precoder that exploits the specific channel statistics such as correlation between antennas or/and the LOS component which frequently happens in digital terrestrial TV broadcasting systems. The channel-precoder performance has been evaluated in a wide set of scenarios and mismatched channel conditions with channel models extracted from channel sounding campaigns characterizing MIMO cross-polar transmission in the UHF bands. Numerical evaluations show that, for the considered 4×2 MIMO systems, the proposed channel-precoding can provide significant capacity improvements for users with strong LOS component and correlated MIMO paths, while preserving similar area coverage for receivers with dominant multipath and uncorrelated components. Furthermore, the proposed transmission technique is potentially transparent to consumer receivers easing the implementation with digital terrestrial TV networks employing MIMO.

Finally, we have assessed the performance of practical MIMO systems and compared it against SISO using the DVB-NGH physical layer. Our results show that for the 2×2 MIMO scheme based on DVB-NGH and for an extended version with spatial multiplexing to support 4 transmit antennas, MIMO can provide significant CNR reductions. Comparison of unprecoded 4×2 MIMO against MIMO eSM-PH 2×2 shows that while using 4 transmit antennas improves the performance under the fixed rooftop channel, it loses performance in the portable outdoor environment. For the proposed MIMO precoder system, performance evaluation show that for low code rates, enhancements can be achieved in the case of strong LOS correlation and resilience against mismatched condition with the channel statistics, a typical situation in the broadcast set-up. These results show that the capacity gains due to precoding can be translated into lower error rates or increased coverage in MIMO-based digital terrestrial TV.

ACKNOWLEDGMENT

The authors would like to thank the anonymous reviewers for their valuable comments which increased the paper quality and interest. Special thanks goes to Peter Moss - formerly BBC R&D - for his valuable comments to this paper.

REFERENCES

[1] "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2014–2019," White Paper, CISCO, 2015.

[2] D. Vargas, D. Gozálvez, D. Gómez-Barquero, and N. Cardona, "MIMO for DVB-NGH, the Next Generation Mobile TV Broadcasting," *IEEE Communications Magazine*, vol. 51, no. 7, pp. 130–137, July 2013.

[3] D. Gómez-Barquero, C. Douillard, P. Moss, and V. Mignone, "DVB-NGH: The Next Generation of Digital Broadcast Services to Handheld Devices," *IEEE Transactions on Broadcasting*, vol. 60, no. 2, pp. 246–257, June 2014.

[4] P. Moss and T. Y. Poon, "Overview of the Multiple-Input Multiple-Output Terrestrial Profile of DVB-NGH," in *Next Generation Mobile Broadcasting*, D. Gomez-Barquero, Ed. Boca Raton, FL, USA: CRC Press, 2013, pp. 549–580.

[5] R. Nabar, H. Bolcskei, V. Erceg, D. Gesbert, and A. Paulraj, "Performance of Multiantenna Signaling Techniques in the Presence of Polarization Diversity," *IEEE Trans. Signal Processing*, vol. 50, no. 10, pp. 2553–2562, Oct. 2002.

[6] C. Gomez-Calero, L. Navarrete, L. De-Haro, and R. Martinez, "A 2x2 MIMO DVB-T2 System: Design, New Channel Estimation Scheme and Measurements With Polarization Diversity," *IEEE Transactions on Broadcasting*, vol. 56, no. 2, pp. 184–192, June 2010.

[7] J.-S. Han, J.-S. Baek, and J.-S. Seo, "MIMO-OFDM Transceivers With Dual-Polarized Division Multiplexing and Diversity for Multimedia Broadcasting Services," *IEEE Transactions on Broadcasting*, vol. 59, no. 1, pp. 174–182, March 2013.

[8] D. Vargas, S. Moon, W.-S. Ko, and D. Gómez-Barquero, “Enhanced MIMO Spatial Multiplexing with Phase Hopping for DVB-NGH,” in *Next Generation Mobile Broadcasting*, D. Gomez-Barquero, Ed. Boca Raton, FL, USA: CRC Press, 2013, pp. 609–634.

[9] Eizmendi *et al.*, “DVB-T2: The Second Generation of Terrestrial Digital Video Broadcasting System,” *IEEE Transactions on Broadcasting*, vol. 60, no. 2, pp. 258–271, June 2014.

[10] *Implementation guidelines for a second generation digital terrestrial television broadcasting system (DVB-T2)*, ETSI Std. TR 102 831, Rev. 0.10.4, 2010.

[11] F. Quitin, “Channel modeling for polarized MIMO systems,” Ph.D. dissertation, Université Libre de Bruxelles/Université catholique de Louvain, 2011.

[12] P. Moss, “2-by-2 MIMO Fixed Reception Channel Model for Dual-Polar Terrestrial Transmission,” White Paper, British Broadcasting Corporation, 2008.

[13] J. Boyer, P. G. Brown, K. Hayler, M. L. Garcia, J. D. Mitchell, P. N. Moss, and M. J. Thorp, “MIMO for Broadcast-Results from a High-Power UK Trial,” White Paper, British Broadcasting Corporation, 2007.

[14] P. Moss, “MIMO Technology in Broadcasting - and an Application in Programme-Making,” in *2nd IEEE Broadcast Technology Society Gold Workshop on Next Generation Broadcasting*, Cagliari, March 2013.

[15] P. Moss, T. Y. Poon, and J. Boyer, “A simple model of the UHF cross-polar terrestrial channel for DVB-NGH,” White Paper, British Broadcasting Corporation, 2011.

[16] X. Zhang and X. Zhou, *LTE-Advanced Air Interface Technology*. CRC Press, 2012.

[17] N. Czink, “The random-cluster model - a stochastic MIMO channel model for broadband communication systems of the 3rd generation and beyond,” Ph.D. dissertation, Institut für Nachrichtentechnik und Hochfrequenztechnik, Vienna University of Technology, 2007.

[18] L. Jiang, V. Jungnickel, S. Jaeckel, L. Thiele, and A. Brylka, “Correlation analysis of multiple-input multiple-output channels with cross-polarized antennas,” in *14th Asia-Pacific Conference on Communications, 2008. APCC 2008*, Oct 2008, pp. 1–5.

[19] J.-S. Baek and J.-S. Seo, “Efficient Pilot Patterns and Channel Estimations for MIMO-OFDM Systems,” *IEEE Transactions on Broadcasting*, vol. 58, no. 4, pp. 648–653, Dec. 2012.

[20] E. Telatar, “Capacity of multi-antenna Gaussian channels,” *European Trans. Telecomm.*, vol. 10, no. 6, pp. 585–596, Nov. 1999.

[21] H. Sampath and A. Paulraj, “Linear Precoding for Space-Time Coded Systems with Known Fading Correlations,” *IEEE Communications Letters*, vol. 6, no. 6, pp. 239–241, June 2002.

[22] M. Vu and A. Paulraj, “MIMO Wireless Linear Precoding,” *IEEE Signal Processing Magazine*, vol. 24, no. 5, pp. 86–105, October 2007.

[23] S. Zhou and G. Giannakis, “Optimal Transmitter Eigen-Beamforming and Space-Time Block Coding Based on Channel Mean Feedback,” *IEEE Transactions on Signal Processing*, vol. 50, no. 10, pp. 2599–2613, October 2002.

[24] D. Love, R. Heath, V. K. N. Lau, D. Gesbert, B. Rao, and M. Andrews, “An Overview of Limited Feedback in Wireless Communication Systems,” *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 8, pp. 1341–1365, October 2008.

[25] G. H. Golub and C. F. Van Loan, *Matrix Computations*, 3rd ed. Baltimore: Johns Hopkins University Press, 1996.

[26] S. P. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge University Press, 2004.

[27] E. Jorswieck and H. Boche, “Behavior of outage probability in MISO systems with no channel state information at the transmitter,” in *Proceedings IEEE Information Theory Workshop*, March 2003, pp. 353–356.

[28] B. Varadarajan and J. Barry, “The outage capacity of linear space-time codes,” *IEEE Transactions on Wireless Communications*, vol. 4, no. 6, pp. 2642–2648, Nov. 2005.

[29] T. M. Cover and J. A. Thomas, *Elements of Information Theory*. New York: Wiley, 1991.

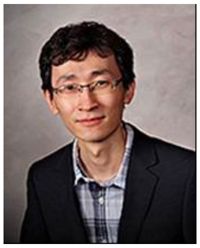
[30] D. Tse and P. Viswanath, *Fundamentals of Wireless Communications*. Cambridge University Press, 2005.

[31] M. Vu and A. Paulraj, “On the capacity of MIMO Wireless Channels with Dynamic CSIT,” *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 7, pp. 1269–1283, September 2007.

[32] R. Kobeissi, S. Sezginer, and F. Buda, “Downlink Performance Analysis of Full-Rate STCs in 2x2 MIMO WiMAX Systems,” in *Proceedings IEEE Vehicular Technology Conference (VTC)*, April 2009, pp. 1–5.

[33] S. Moon, W.-S. Ko, D. Vargas, D. Gozalvez, M. Nisar, and V. Pauli, “Enhanced Spatial Multiplexing for Rate-2 MIMO of DVB-NGH System,” in *Proccedings of 19th International Conference on Telecommunications (ICT), 2012*, April 2012, pp. 1–5.

David Vargas received his M.Sc. degree in Telecommunication engineering from Universitat Politècnica de València (UPV), Spain in 2009. During his studies he spent one year at the University of Turku (UTU), Finland. Currently he is pursuing a Ph.D. degree at the Mobile Communications Group at the Institute of Telecommunications and Multimedia Applications (iTEAM), UPV. He has been a guest researcher in the summer of 2011 at the Vienna University of Technology, Austria, during 2013 at McGill University, Montreal, Canada, and a research intern in 2015 at BBC Research & Development, London, UK. He has participated in the standardization process of the next generation mobile broadcasting standard DVB-NGH and is currently an active participant in the standardization process of the next-generation terrestrial broadcasting standard ATSC 3.0. His research interests include multi-antenna communications, signal processing for communications, and digital broadcasting.



Yong Jin Daniel Kim received his M. Eng. and Ph. D. degrees in electrical and computer engineering from McGill University, Quebec, Canada, in 2007 and 2014, respectively. Since 2014, he is an assistant professor in the department of Electrical and Computer Engineering at Rose-Hulman Institute of Technology, Terre Haute, Indiana. His current research interests include digital communications, network information theory and coding, and stochastic signal processing.

Jan Bajcsy photograph and biography not available at the time of publication.

David Gómez-Barquero received the double M.Sc. degrees in telecommunications engineering from the Universitat Politécnica de Valéncia (UPV), Spain, and the University of Gävle, Sweden, in 2004, and the Ph.D. degree in telecommunications from the UPV in 2009. He is a Senior Researcher (Ramon & Cajal Fellow) with the Institute of Telecommunications and Multimedia Applications, UPV, where he leads a research group working on next generation broadcasting technologies. He is currently a Research Scholar with the New Jersey Institute of Technology, Newark, NJ, USA. Previously, he hold visiting research appointments at Ericsson Eurolab, Germany, the Royal Institute of Technology, Sweden, the University of Turku, Finland, the Technical University of Braunschweig, Germany, the Fraunhofer Heinrich Hertz Institute, Germany, and the Sergio Arboleda University of Bogota, Colombia. Since 2008, he has been actively participating in the European Digital Television Standardization Forum DVB in different topics such as upper layer forward error correction, DVB-T2, T2-Lite, and DVB-NGH. In 2013, he joined the U.S. Digital Television Standardization Forum ATSC to work on ATSC 3.0, where he is the Vice-Chairman of the Modulation and Coding Ad-Hoc Group. He is the Editor of the book entitled Next Generation Mobile Broadcasting (CRC Press).

Narcís Cardona was born in Barcelona, Spain. He received the M.S. degree in Communications Engineering from the ETSI Telecommunications at the Polytechnic University of Catalunya in 1990, and the Ph.D. in Telecommunications from the Polytechnic University of Valencia in 1995. Since October 1990, he is with the Communications Department of the Polytechnic University of Valencia (UPVLC). Prof Cardona is in head of the Mobile Communications Group at the UPVLC, with 30 researchers including assistant professors & research fellows. Additionally he is the Director of the Mobile Communications Master Degree (since 2006) and Vice-Director of the Research Institute of Telecommunications and Multimedia Applications (iTEAM) since 2004. Prof Cardona has led and participated to National research projects and to European projects, Networks of Excellence and other research forums, always in Mobile Communications aspects. At European scale, he has been Vice-Chairman of COST273 Action, Chair of the WG3 of COST2100 in the area of Radio Access Networks, and he is currently the Chairman of the EU Action COST IC1004 since May 2011. Prof Cardona is also member of the Steering Board of METIS (7FP), also on Future Mobile Communications Technologies. From his research work, Prof Cardona has authored 8 patents, several books and above 160 research papers. His current areas of interest include mobile channel characterisation; planning and optimisation tools for cellular systems, RRM techniques applied to personal communications and broadcast cellular hybrid networks.