MIMO for ATSC 3.0

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***Abstract*—This paper provides an overview of the optional MIMO (Multiple-Input Multiple-Output) antenna scheme adopted in ATSC 3.0 to improve robustness or increase capacity via additional spatial diversity and multiplexing by sending two data streams in a single radio frequency channel. Although it is not directly specified, it is expected in practice to use cross-polarized 2x2 MIMO (i.e., horizontal and vertical polarization) to retain multiplexing capabilities in line-of-sight conditions. MIMO allows overcoming the channel capacity limit of single antenna wireless communications in a given channel bandwidth without any increase in the total transmission power. But in the U.S. MIMO can actually provide a larger comparative gain because it would be allowed to increase the total transmit power, by transmitting the nominal transmit power in each polarization. Hence, in addition to the MIMO gains (array, diversity and spatial multiplexing), MIMO could exploit an additional 3 dB power gain. The MIMO scheme adopted in ATSC 3.0 re-uses the SISO (Single-Input Single-Output) antenna baseline constellations, and hence it introduces the use of MIMO with non-uniform constellations.**

***Index Terms*—ATSC 3.0, MIMO, DTT, spatial multiplexing.**

I. Introduction

MIMO (Multiple-Input Multiple-Output) antenna technology has been introduced in many wireless communications technologies such as WiFi, WiMAX and 4G LTE to improve the transmission robustness via additional spatial diversity, or to increase capacity by sending multiple data streams in the same bandwidth via spatial multiplexing [1]. While SIMO (Single-Input Multiple-Output) exploits diversity and array gains, MISO (Multiple-Input Single-Output) only retains the spatial diversity gain. The spatial multiplexing gain is achieved only in the case of MIMO, and it allows MIMO to overcome the capacity limit of single transmit antenna wireless communications in a given channel bandwidth without any increase in the total transmission power [2].

Terrestrial MIMO broadcasting in the UHF (Ultra-High Frequency) band requires co-located[1] antennas with cross-polar (horizontal and vertical) polarization to retain full spatial multiplexing capabilities in line-of-sight conditions [3]. Another important difference of terrestrial MIMO broadcasting compared to unicast wireless communications systems is that it is not possible to share the Channel State Information (CSI) of the receivers with the transmitter, which reduces the potential gain. Nevertheless, the potential MIMO gain in terrestrial broadcasting is still very important, especially for medium and high signal-to-noise ratios (SNR) [4]. Also, the channel precoder may be optimized according to broadcast channel statistics by linearly combining the data streams across the transmit antennas [5].

MIMO for terrestrial broadcast has been demonstrated in field tests by the public broadcasters BBC (UK) [6] and NHK (Japan) [7]. The DVB-NGH technical specification [8] was the first terrestrial broadcasting standard that allows for the optional use of MIMO [9], although the technology has not been yet proved in the field, and field measurements were used to develop representative channel models for pedestrian outdoor, indoor, and mobile reception [4].

This paper provides an overview of the optional MIMO antenna system adopted in ATSC 3.0 intended for 2x2 cross-polarized MIMO [10]. This means that at least two antenna aerials with horizontal and vertical polarization are present at both transmitter and receiver side. The transmitter must include individually-fed cross-polar antennas, and the receiver must include a cross-polar pair of antennas and two tuners in order to receive and decode the MIMO signal.

MIMO may become a key technology for ATSC 3.0 because the current commercial state-of-the-art digital terrestrial television (DTT) standard, DVB-T2 [11], does not include this feature. Considering the relevance of maximizing the broadcast spectrum efficiency due to the rapidly growing demand for wireless broadband services [12], MIMO is the most convincing technology that brings huge benefit in this aspect. Furthermore, in the U.S. MIMO can actually provide a larger comparative gain because the regulation allows to increase the total transmit power by transmitting the nominal transmit power in each polarization. Hence, in addition to the MIMO gain, it could exploit a 3 dB power gain. MIMO is also an effective way to impose the use of two antennas at the receivers, which results on average in another 3 dB gain compared to SISO for cross-polarized transmissions.

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[1] It should be pointed out that MIMO with two separately located antennas spanned across two broadcast towers is a MISO Single Frequency Network (SFN) with receivers with two antennas and a single demodulator, and cannot exploit spatial multiplexing due to the resulting power imbalances.

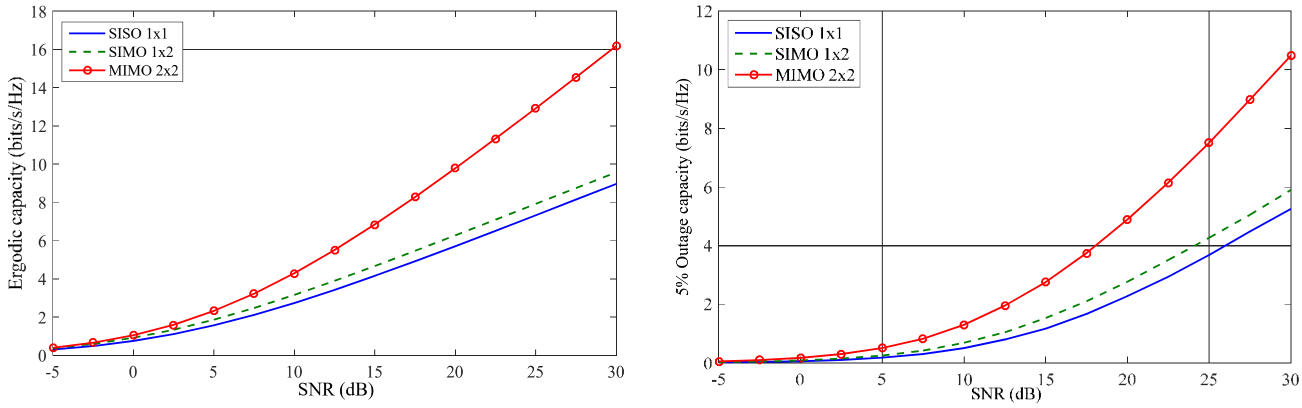

Fig. 1. Ergodic capacity for a mobile DVB-NGH channel model (left) and 5% outage capacity for fixed rooftop MGM channel model (right). The fixed rooftop model includes a 9 dB lognormal fading margin in the CNR. This means that SNRs in the MGM channel (right) are 9 dB higher than the required SNR for the system modulation and coding, which correspond to the SNR-axis in the DVB-NGH channel (left). SNR values of 24 and 27 dB correspond to SNR thresholds of 15 dB and 18 dB, respectively.

The rest of the paper is structured as follows. Section II provides some basics about the MIMO channel capacity gain and implementation aspects. Section III describes the MIMO transmission chain adopted in ATSC 3.0. Section IV provides illustrative performance simulation results. The paper is concluded in Section V, where a brief discussion about the potential introduction of MIMO in the U.S. is given.

II. MIMO BASICS

A. *MIMO Gain*

The implementation of MIMO provides three different types of gains: array gain, diversity gain, and multiplexing gain [9]. The array gain is due to the coherent combination of the received signals with several antennas (for co-polar antennas, this gain equals 3 dB every time the number of antennas is doubled). The diversity gain is due to the fact of having several spatial branches (with independent fading) between the transmitter and receiver. And the multiplexing gain allows transmitting more than one data stream.

Fig. 1 shows the channel capacity for SISO, SIMO with two receive antennas, and MIMO with two transmit and two receive antennas, in the mobile DVB-NGH channel [4] (user speed 60km/h) with ergodic capacity and the modified Guildford channel model (MGM) from BBC for fixed rooftop reception [3, 6, 13] with 5% outage capacity. Both models have been specifically developed for terrestrial broadcasting based on field measurements. While ergodic capacity is an appropriate metric for mobile broadcasting applications, the ε-outage capacity [2] is more suited for fixed broadcasting applications. The outage capacity can be mathematically expressed as:

$$C_\varepsilon \cong \max\{ R \mid \Pr(C_{\mathbf{H}} < R) \le \varepsilon \} \quad (1)$$

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 the rate R. The ε-outage capacity in (1) can be interpreted as the minimum rate C_ε that can be achieved the (1- ε)·100% of the channel realizations, or in the specific case of the MGM of the receiving population.

In Fig. 1, it can be seen that the MIMO capacity increases with the SNR at a higher rate than SISO and SIMO schemes. This difference in spectral efficiency increases with increasing SNR and is due to multiplexing gain for a MIMO channel employing multiple transmit and receive antennas with independent information streams. The gain depends also on the particular channel. The predicted MIMO benefit over SISO for the fixed rooftop model is about 100% for SNRs ranging between 24 and 27 dB. Small portable devices with built-in antennas might not get as much received signal strength. However, increased diversity due to multiple antennas at low SNR levels provides very significant gains in relative terms. In particular, the DVB-NGH mobile model gives a gain of 40%, 48% and 57%, for 0, 5 and 10 dB SNR, respectively.

Regarding the additional gain that may be achieved by doubling the total transmit power with MIMO, the BBC fixed channel model yields an extra 50% gain due to the 3 dB power increase for a SISO SNR of 24 dB (40% for 27 dB SNR). For mobile reception, the gain increases in 92%, 71% and 54%, for 0, 5 and 10 dB SISO SNR, respectively.

Finally, it should be pointed out that MIMO requires the use of twice the pilots compared to SISO for the same performance in terms of echo tolerance and Doppler [15]. Hence, the additional pilot overhead should be taken into account to derive the final gain.

B. *MIMO Implementation*

There are important implementation implications on both transmit and receive sides when deploying MIMO.

For the transmitter side, there are: (i) new antenna(s), (ii) additional cabling, and (iii) second transmit data stream (amplifier, up-converter, etc.). The modulator outputs two baseband signals (one for each antenna), and then the whole RF chain needs to be doubled. If MIMO is used to increase the total transmission power, it would naturally imply additional capital and operational costs.

For the receiver the implications are: (i) cross-polarized antennas, (ii) two tuners, and (iii) higher constellation demapper complexity [16]. If MIMO is used to increase the overall system capacity, the receiver naturally has to support the increased peak data rates. It should be pointed out that a receiver with two tuners supporting channel bonding [17] would pave the way for advanced MIMO receivers, since a channel bonding receiver requires two tuners and the capability of supporting

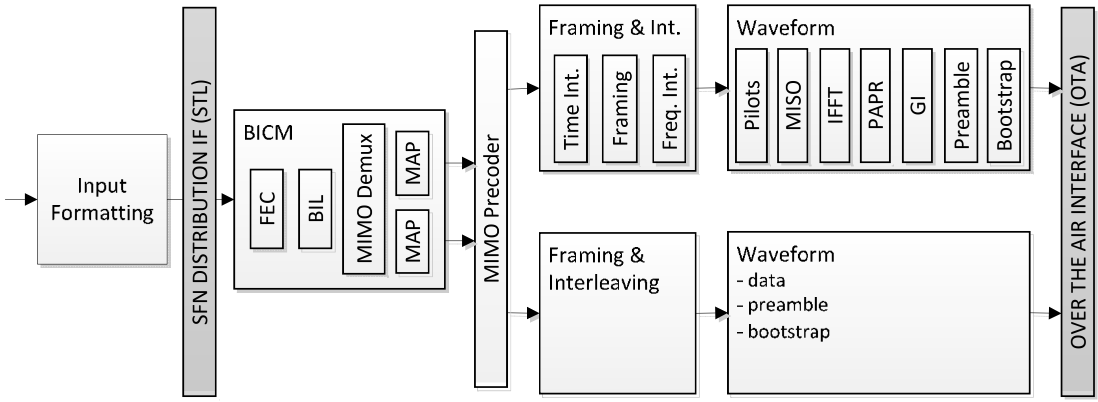

Fig. 2. MIMO transmit block diagram in ATSC 3.0. Acronyms: IF (interface), STL (studio transmitter link), FEC (forward error correction), BIL (bit interleaver), MIMO Demux (MIMO antenna stream demultiplexer), MAP (constellation mapper), MISO (Multiple-Input Single-Output), PAPR (Peak-to-Average Power Ratio), GI (Guard Interval).

increased (in particular, doubled) peak data rates. The implementation of MIMO for fixed rooftop reception also requires that the receiver installation accommodates the reception of the two streams to the demodulator, which may require substantial changes in existing installations based on single antenna reception.

III. ATSC 3.0 MIMO System Overview

Fig. 2 depicts the ATSC 3.0 MIMO transmission chain, where two MIMO blocks can be identified: the MIMO demultiplexer and the MIMO precoder. Naturally, all blocks, which are carried out after the generation of the two MIMO streams in the MIMO demultiplexer, are doubled, one block for each antenna (e.g., constellation mapper, framing and interleaving, and waveform generation).

The MIMO transmission chain re-uses all the blocks from the SISO baseline [10], including forward error correction (FEC) codes, bit interleavers (BIL), constellations[2], frequency and time interleavers, etc. The same time and frequency interleaving configuration should be applied to both MIMO streams. The only two differences compared to the SISO baseline are that specific pilot patterns have been defined for MIMO, and that MIMO requires twice the time interleaver memory as SISO. The MIMO pilot patterns achieve the same performance in terms of echo tolerance and Doppler as for SISO. The doubling of the time interleaving memory is due to the fact that the SISO memory requirement applies to the memory of each antenna, providing the same time interleaving trade-off as for SISO.

MIMO processing in ATSC 3.0 is only applicable to the data path, and it is not applied to the bootstrap, which is the entry point to the ATSC 3.0 system, and to the preamble with layer-1 (L1) signaling information [19]. The use of MIMO is signaled in the preamble. The use of mixed SISO and MIMO frames in the same RF channel is possible in ATSC 3.0, and it is also signaled in the preamble.

The use of MIMO with channel bonding [17], constellation superposition (Layered Division Multiplexing, LDM) [20], and the peak-to-average power ratio (PAPR) reduction technique

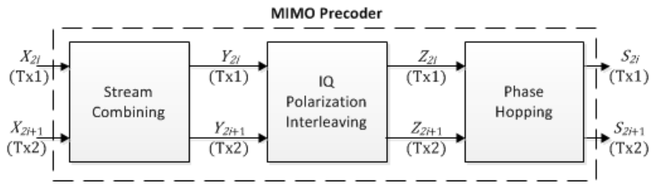

Fig. 3. ATSC 3.0 MIMO precoder sub-block diagram consisting of stream combination, IQ polarization interleaving and phase hopping.

ACE (Active Constellation Extension) is not defined in the ATSC 3.0 specification. The use of MISO with Transmit Diversity Code Filter Sets (TDCFS) may be optionally applied with a unique code applied per station or per-antenna [21].

A. *MIMO Demultiplex*

The antenna stream demultiplexer distributes the output bits from the bit interleaver into two constellation mappers, one for each transmit antenna. The output bits are alternatively distributed to the mappers in groups, and the group size corresponds to the number of bits per constellation symbol (cell). That is, the demultiplexer is equivalent to an even/odd cell demultiplexer but implemented at the bit level.

B. *MIMO Precoder*

Fig. 3 illustrates the MIMO precoder, which is based on Spatial Multiplexing (SM) and consists of three different steps:

- Stream combining.
- I/Q polarization interleaving.
- Phase hopping.

The MIMO precoder acts on a pair of input constellation symbols (X_{2i}, X_{2i+1}), where i is the index of the cell pair within the FEC codeword, and creates a pair of outputs constellation symbols (S_{2i}, S_{2i+1}). Encoded cell pairs are transmitted on the same OFDM symbol and carrier from transmitter #1 (Tx1) and transmitter #2 (Tx2), respectively.

The MIMO precoding is applied at data physical layer pipe (PLP) level, and each of the three sub-blocks of the MIMO precoder can be optionally activated (and their use is signaling in the L1). This allows the possibility of configuring the precoder in a transparent way in the transmission chain, such

[2] The MIMO scheme adopted in ATSC 3.0 re-uses the SISO antenna baseline constellations, and hence it introduces the use of MIMO with Non-Uniform Constellations (NUC). In addition to QPSK, ATSC 3.0 has adopted two-dimensional NUC (2D-NUC) for 16-, 64- and 256-point constellations, and one-dimensional NUCs (1D-NUC) for 1024- (1k) and 4096-point (4k) constellations [18].

TABLE I
ROTATION ANGLE FOR THE STREAM COMBINING OF THE MIMO PRECODER

Coding Rate	QPSK	16QAM	64QAM, 256AM, 1024QAM,4086QAM
2/15	0°	0°	0°
3/15	0°	0°	0°
4/15	0°	0°	0°
5/15	0°	0°	0°
6/15	15°	0°	0°
7/15	15°	0°	0°
8/15	20°	0°	0°
9/15	20°	0°	0°
10/15	25°	0°	0°
11/15	25°	15°	0°
12/15	25°	15°	0°
13/15	30°	15°	0°

that the output pair cells are exactly the input pair cells. This particular case is known as plain spatial multiplexing.

$$S_{2i}(\text{Tx1}) = Z_{2i}(\text{Tx1}) = Y_{2i}(\text{Tx1}) = X_{2i}(\text{Tx1}) \quad (2)$$

$$S_{2i+1}(\text{Tx2}) = Z_{2i+1}(\text{Tx2}) = Y_{2i+1}(\text{Tx2}) = X_{2i+1}(\text{Tx2}) \quad (3)$$

The next sub-sections describe the signal processing performed at each sub-block of the precoder when they are used. If not used, the output pair cells are exactly the input pair cells.

1) Antenna Stream Combination

The stream combining consists on a linear combination of the pair of input constellation symbols based on a rotation matrix with angle θ. It improves the spatial diversity under spatially correlated channels because symbols are not transmitted only from one of the transmitted antennas [2]. The presence of correlation in the MIMO terrestrial broadcast channel is common in line-of-sight conditions [26]. The scheme adopted in ATSC 3.0 is similar to the precoder adopted in DVB-NGH [22]. The operation is mathematically expressed as follows:

$$\begin{bmatrix} Y_{2i}(\text{Tx1}) \\ Y_{2i+1}(\text{Tx2}) \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ \sin\theta & -\cos\theta \end{bmatrix} \begin{bmatrix} X_{2i}(\text{Tx1}) \\ X_{2i+1}(\text{Tx2}) \end{bmatrix} \quad (4)$$

The value of the rotation angle θ is fixed and its value depends on the modulation and coding (ModCod) used in the PLP.

Table I shows the rotation angle θ for each coding rate for QPSK and 16QAM. The rotation angles have been selected to improve the performance in scenarios where there is a power imbalance (PI) between the receive antennas. This imbalance could be produced at the transmit side, but also due to the channel impairments. In the performance evaluations, no gain was observed for higher order constellations due to rotation. It should also be pointed out that if there is no power imbalance, the optimum rotation angle is 0° for all ModCods.

2) I/Q Polarization Interleaving

The I/Q polarization interleaver is simply a switching interleaving operation, such that the output cells consist of the real (In-phase) component of one input symbol and the imaginary (Quadrature) component of the other input symbol. The I/Q polarization interleaving is described by the following equations:

$$Z_{2i}(\text{Tx1}) = Re\{Y_{2i}(\text{Tx1})\} + j \cdot Im\{Y_{2i+1}(\text{Tx2})\} \quad (5)$$

$$Z_{2i+1}(\text{Tx2}) = Re\{Y_{2i+1}(\text{Tx2})\} + j \cdot Im\{Y_{2i}(\text{Tx1})\} \quad (6)$$

TABLE II
MIMO SCATTERED PILOT SCHEMES AND EQUIVALENT SISO PILOT SCHEMES

MIMO pilot scheme	D_X	D_Y	Equivalent SISO pilot scheme	Overhead
MIMO6_2	6	2	SP3_2	16.66%
MIMO6_4	6	4	SP3_4	8.33%
MIMO12_2	12	2	SP6_2	12.5%
MIMO12_4	12	4	SP6_4	6.25%
MIMO16_2	16	2	SP8_2	8.33%
MIMO16_4	16	4	SP8_4	4.16%
MIMO24_2	24	2	SP12_2	4.16%
MIMO24_4	24	4	SP12_4	2.08%

D_X and D_Y are the separation of pilot bearing carriers in the frequency and time direction, respectively.

The I/Q polarization interleaving provides an additional diversity gain because each constellation symbol is transmitted over the two polarizations.

3) Phase Hopping

The phase hopping consists of a phase rotation to the symbols of the second transmit antenna. This may slightly degrade the performance under some specific channel conditions, but it improves overall performance by improving worst-channel phase correlated conditions [23].

The same phase hopping term from DVB-NGH [22] has been adopted for ATSC 3.0. The operation is mathematically expressed as:

$$\begin{bmatrix} S_{2i}(\text{Tx1}) \\ S_{2i+1}(\text{Tx2}) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & e^{j\phi(i)} \end{bmatrix} \begin{bmatrix} Z_{2i}(\text{Tx1}) \\ Z_{2i+1}(\text{Tx2}) \end{bmatrix} \quad (7)$$

where ϕ is the phase rotation angle, defined by the following equation:

$$\phi(i) = \frac{2\pi}{N} i, (N = 9), i = 0, \dots, \frac{N_{cells}}{2} - 1 \quad (8)$$

where N_{cells} is the number of cells per FEC codeword. The phase rotation is initialized to 0º at the beginning of each FEC block and is incremented by 2π/9 for every cell pair.

C. MIMO Pilots

1) Pilot Schemes

ATSC 3.0 defines twelve MIMO pilot schemes, four less than the number of SISO patterns. All MIMO patterns have equivalent SISO patterns, such that MIMO keeps the same Doppler and echo tolerance. This implies that the overall pilot density for MIMO is doubled so that the receiver is able to estimate the MIMO channel from each transmit antenna with the same accuracy in frequency and time.

Table II shows the parameters defining the MIMO scattered pilot patterns, the equivalent SISO pilot schemes, and the resulting pilot overhead. The terminology employed for the MIMO pilot patterns is MIMO*a*_*b*, where $a = D_X$ (separation of pilot carriers in the frequency direction) and $b = D_Y$ (number of symbols forming one scattered pilot sequence, i.e., separation of pilot carriers in the time direction) per transmit antenna. It should be pointed out that the same restrictions for the MIMO pilot schemes in terms of the FFT and the GI apply as for SISO [14].

Fig. 4 illustrates two examples of MIMO scattered pilot schemes. Continual pilots and reserved carriers are not shown. In the figure, it can be seen that pilots are assigned to two pilot groups, namely group 1 and group 2. In MIMO the phases of the scattered, continual, edge, frame-start and frame-closing pilots may be modified compared to SISO, according to the MIMO pilot antenna encoding scheme. Two algorithms are defined for ATSC 3.0, namely:

- Walsh-Hadamard encoding.
- Null pilots encoding.

Only one pilot algorithm may be used in a given frame. Each algorithm applies a specific signal processing to each pilot group in each antenna, and they are briefly described next. The null pilots encoding might be more suited for static channel conditions (e.g., for fixed roof-top reception) while the Walsh-Hadamard pilot encoding might be more suited for mobile channels. The reason is that the pilot spacing in time direction is increased to $2D_Y$ for the null pilots encoding compared to a pilot spacing of D_Y for the Walsh-Hadamard pilot encoding. For fast varying channel conditions, it is more challenging for the channel estimation to follow these channel variations if the pilot spacing in time direction is increased.

2) *Walsh-Hadamard Pilot Encoding*

With Walsh-Hadamard MIMO pilot encoding, the phases of the scattered, continual, edge, frame-start and frame closing pilots for group 2 are modified in the signal transmitted from antenna #2. Both antennas shall transmit in all pilot positions. This scheme is used in DVB-T2 for MISO Alamouti [24], and it was also adopted in DVB-NGH [4].

The scattered pilots from antenna #2 are inverted compared to antenna #1 on alternate scattered pilot bearing carriers. The few continual pilots from transmitters in antenna #2 falling on scattered-pilot-bearing carriers are inverted compared to antenna #1 on carriers for which the scattered pilots are inverted, whereas continual pilots on non-scattered-pilot-bearing carriers are not inverted. It should be noted that those cells which would be both a continual and a scattered pilot are treated as scattered pilots. Regarding the edge pilots antenna #2, they are inverted compared to antenna #1 on odd numbered OFDM symbols. Finally, the frame start and boundary pilots from antenna #2 are inverted compared to antenna #1 on alternate scattered pilot bearing carriers.

3) *Null Pilots Encoding*

With MIMO null pilot encoding, the amplitudes of the scattered, continual, edge, frame-start and frame-closing pilots are modified in the signal transmitted from both transmit antennas #1 and #2. In opposition to Walsh-Hadamard encoding, with null pilots encoding each antenna transmits only on pilots belonging to one single group (either group 1 or group 2) with 3 dB increased transmit power to compensate for the null pilots not transmitted in the other group. The null pilots are inserted in the scattered pilots from antenna #1 on alternate scattered-pilot-bearing carriers and OFDM symbols.

IV. Performance Simulation

In this section we provide some illustrative physical layer performance simulation results about the overall performance of the MIMO scheme of ATSC 3.0, the use of non-uniform constellations for MIMO, and two of the signal processing algorithms of the MIMO precoder: antenna stream combination and phase hopping. Additional parameters are detailed next. A low-density parity-check (LDPC) code length of 64800 bits was used. Bit, time and frequency interleavers from the specification were also employed. The proposed criterion is to select the SNR that provides a bit error rate (BER) of 10^{-4}.

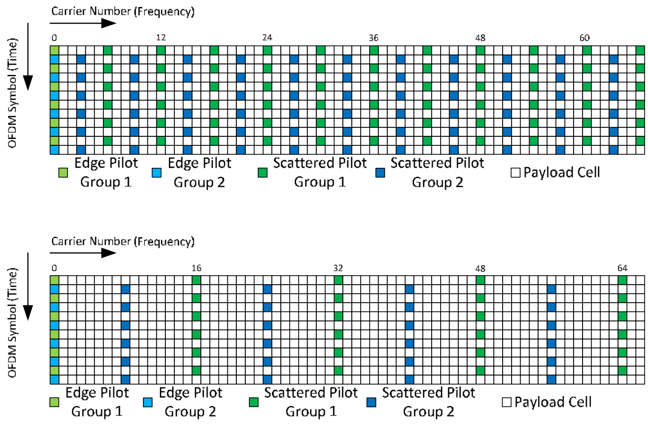

Fig. 4. Illustrations of the MIMO scattered pilot patterns: MIMO6_2 (top), and MIMO16_2 (bottom).

A. *Overall Performance*

Fig. 5 shows the simulated MIMO performance of ATSC 3.0 compared to SISO for the mobile DVB-NGH channel [4] and the MGM fixed rooftop channel model [13]. The upper bounds of Fig. 1 are also shown for comparison. For the NGH mobile channel, QPSK, 16QAM and 64QAM constellations and a pilot pattern SP6_2 have been considered in the simulations. The considered constellations for the MGM fixed channel range from 64QAM up to 4096QAM (4kQAM) [18], and the pilot pattern used is SP12_4. For each constellation, four representative coding rates have been considered: 2/15, 6/15, 10/15 and 13/15 [25]. For MIMO, a maximum-likelihood (ML) demapper has been employed for simulations up to 64QAM and a minimum mean-square error (MMSE) demapper for higher order constellations in order to reduce the complexity burden. The equivalent pilot patterns for MIMO can be easily found in Table II.

In Fig. 5 it can be noted that the MIMO gains are larger for the fixed MGM channel compared to the NGH mobile channel. In the figure, we can also observe that the difference to the theoretical limit is higher for the MGM channel, especially at low SNRs. For instance, using 16NUC in each antenna, the difference to the theoretical limit is 3.6 and 7.9 dB for low and high CRs respectively. On the other hand, this difference becomes higher for the MGM channel, with 5.7 and 7.5 dB for low and high CRs respectively. In addition, the use of MMSE demapping implies a significant performance loss compared to the optimum ML.

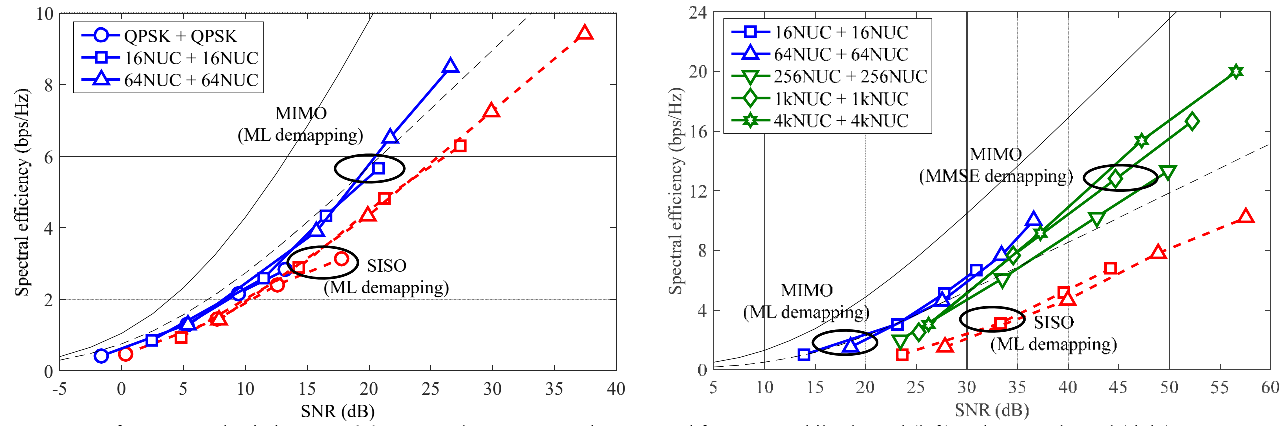

Fig. 5. MIMO performance and gain in ATSC 3.0 compared to SISO. Results presented for NGH mobile channel (left) and MGM channel (right).

MIMO channel depending on SNR and angle of departure: without phase hopping. System optimization would be possible only for a particular angle of arrival.

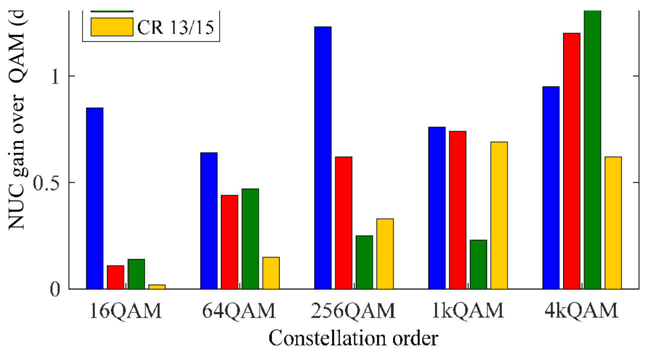

Fig. 6. Gain of non-uniform constellations compared to uniform constellations for MIMO.

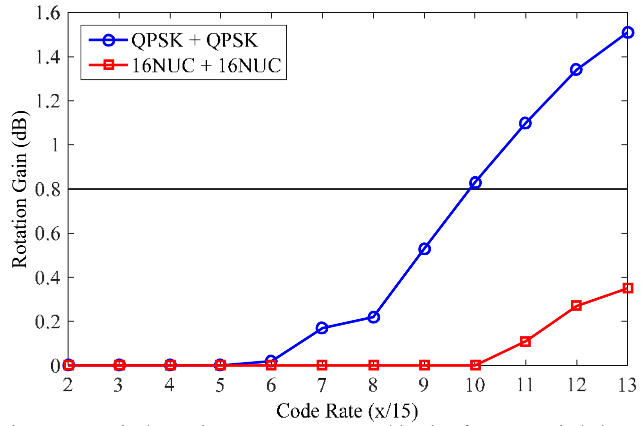

Fig. 7. SNR gain due to the antenna stream combination for a power imbalance of 9 dB. NGH mobile channel mode for QPSK and 16QAM.

B. *Non-Uniform Constellations for MIMO*

Fig. 6 depicts the SNR gain of NUCs over uniform QAM constellations for four representative coding rates 2/15, 6/15, 10/15 and 13/15 in the MGM fixed rooftop channel model [13]. The MMSE demapper is used for all constellations in this case. High SNR gains are achieved especially for high constellation orders and low coding rates. However, it should be stressed that the constellations of ATSC 3.0 have been optimized for SISO [18], and hence the MIMO performance is not optimal. Further optimization may be possible e.g., considering a different SNR range and channel models.

C. *Precoder – Antenna Stream Combination*

Fig. 7 shows the SNR gain obtained with the rotation angles shown in Table I for QPSK and 16QAM in the NGH mobile channel [4] with a power imbalance of 9 dB. The gain increases with the coding rate and low modulation orders, achieving a maximum SNR gain of up to 1.5 dB for QPSK 13/15. With a lower power imbalance, the selected angles still are optimum, but the gain decreases. For instance, the obtained gain with QPSK 13/15 is reduced to 0.63 dB and 0.2 dB with power imbalances of 6 dB and 3 dB respectively. As mentioned in Section III, if there is no power imbalance there is no SNR gain due to the antenna stream combination, and the optimum rotation angle is 0 dB for all cases.

D. *Precoder – Phase Hopping*

Fig. 8 shows the BER performance of (2x2)-sheer spatial multiplexing using non-uniform 16QAM with the baseline LDPC long code of code rate 9/15 and corresponding bit-interleaver over a fully correlated MIMO channel representing worst case line-of sight channel conditions. Here, the channel matrix is modelled as:

$$\boldsymbol{H} = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & e^{j\Phi_t} \end{bmatrix}. \tag{8}$$

The underlying assumptions for this model are uniform linear antenna arrays at transmitter and receiver with planar wave propagation in-between. The angle of departure from the transmitter is denoted by Φ_t.

Fig. 8 illustrates the dependence of the system performance on the angle of departure (AOD), where particular angles, e.g., $\Phi_t = 0°$ and $\Phi_t = 90°$, prove to have a catastrophic effect. In the absence of spatial precoding and phase hopping this is due to the independence of the transmitted streams resulting in erased or severely attenuated constellation points at the receiver.

Apparent from Fig. 8 is also that optimization of spatial precoding for this scenario will be optimal only for a limited range of angles of departure and suboptimal for others. The remedy is the combination of spatial precoding and phase hopping and their effect on the performance is shown in Fig. 9. The simulation parameters are identical to those for sheer SM in Fig. 8, but in addition precoding with antenna stream combination and phase hopping is employed. It is evident that precoding provide sufficient means to spread a FEC codeword over both data streams in such a way that degenerate received constellation points are mitigated and that ultimately the performance is rendered independent from the angle of departure.

V. Conclusions and Outlook

This paper provides an overview of the optional MIMO cross-polarized MIMO scheme adopted in ATSC 3.0. The MIMO scheme of ATSC 3.0 re-uses as much as possible the ATSC 3.0 SISO baseline specification, and it has been defined such that it is not outperformed by the SISO baseline in any aspects (e.g., time interleaving trade-off and echo resilience and Doppler performance). The MIMO scheme is very flexible, with several signal processing algorithms possible for the precoder (antenna stream combining, I/Q polarization interleaving, and phase hopping), the MIMO pilot encoding scheme (Walsh-Hadamard and null pilots), and with twelve different scattered pilot patterns. ATSC 3.0 also introduces the use of MIMO with non-uniform constellations, improving the transmission robustness compared to the use of uniform constellations.

MIMO is a promising technique to overcome the capacity limit of single antenna communications, and allows for terrestrial broadcasting to transmit two different data streams in the same radio frequency channel using simultaneously both horizontal and vertical polarizations. However, implementation requires important modifications at existing transmitter and fixed rooftop reception installations, and significantly more advanced receivers. Also, for low SNR regions there is smaller MIMO capacity gain compared to the high SNR region characteristic of fixed rooftop reception, although the relative gain at low SNR is very significant.

Nevertheless, in the U.S. MIMO can actually provide a larger comparative gain because the regulation allows to increase the total transmit power by transmitting the nominal transmit power in each polarization. Hence, in addition to the spatial multiplexing gain, MIMO can exploit a 3 dB power gain. MIMO is also an effective way to impose the use of two antennas at the receivers, which on average results in another 3 dB gain compared to SISO for cross-polarized transmissions. Also, the use of channel bonding will pave the way towards the implementation of MIMO receivers because it requires two tuners and support of twice the peak data rate, like MIMO but in two RF channels. For all these reasons, MIMO may become a key technology for ATSC 3.0, also taking into account that the current commercial state-of-the-art digital terrestrial television standard DVB-T2 does not include this feature.

VI. Note

It is noted that that some items referred to in this paper, in particular, the rotation angles of the antenna stream combiner module of the MIMO precoder, could be changed during the candidate standard phase of the ATSC 3.0 physical layer specification.

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