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Shaping duo binary turbo-coded BICM scheme for JPWL image transmission using a link adaptation strategy over wireless channels

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Abstract

In order to guarantee a robust transmission of JPWL (JPEG Wireless: Joint Photographic Experts Group Wireless) images through time and frequency selective wireless channels, an efficient adaptive communication strategy is proposed. It is based on an optimization of a closed-loop adaptive multiple-input multiple-output, orthogonal frequency division multiplexing (MIMO-OFDM) scheme associated with a shaping BICM (bit-interleaved coded modulation) technique composed of a duo binary turbo code (DBTC), high-order modulations such as 64–256 QAM (Quadrature Amplitude Modulation) and a shaping code. According to the CSI (channel state information) knowledge at the transmitter side, an algorithm based on unequal error protection (UEP) and unequal power allocation (UPA) is used to select the transmitter key parameters (source/channel encoder rate, modulation order, power, number of quality layers and number of iterations of the Turbo decoder) to achieve the target Quality of Service (QoS). The proposed DBTC-shaping BICM scheme reaches a shaping gain of 1.2 dB for a 256 QAM modulation over a SISO Gaussian channel, whereas only 0.7 dB of shaping gain can be achieved in a scheme that uses the LDPC shaping BICM scheme for the same modulation order. Based on a DBTC shaping BICM scheme and an adaptive algorithm, the proposed MIMO-OFDM strategy achieves better performance compared to a strategy using an iterative process between an RS (Reed-Solomon) and arithmetic decoders. As a result, and on the one hand, a gain of 5.38 dB can be achieved in terms of PSNR (peak signal-to-noise ratio). On the other hand, a gain of 78% in terms of power consumption is obtained for the same QoS level. Moreover, the adaptive number of iterations in the proposed strategy can minimize the computational complexity of the turbo decoding compared to a scheme using four iterations whatever the channel conditions.

Keywords: JPWL image, Realistic wireless channel, Duo binary turbo code, Shaping BICM, MIMO-OFDM, Link adaptation, High-order modulations

1 Introduction

Recently, important improvements have been done in digital transmissions over wireless channels. In a highly interconnected world, the demand for more efficient communication protocols is crucial. Wireless transmissions are characterized by their severe

constraints (limited bandwidth, multipath phenomenon, Doppler effect, etc.). In the case of image transmission, the robust system that would be developed in order to overcome the constraints of the wireless channel should allow the transmission of high-quality (high-resolution) images with a good QoS, whatever the transmission conditions and under a power budget constraint.

1.1 Background

The transmission of compressed images through wireless channels needs robustness against transmission errors. In the case of the JPEG 2000 standard, robust tools are provided for image compression [1]. However, a single erroneous bit can cause the decoding of a bad sequence. In order to cope with transmission errors, channel codes are used in association with UEP and UPA strategies. The JPEG2000 Wireless (JPWL) standard [2] is an extension of the JPEG 2000 standard. It proposes specific robust tools, such as powerful error correcting codes (ECCs), UEP and UPA. In the context of JPWL image transmission, several works that use UEP and/or UPA strategies with ECC like Reed–Solomon codes (RS), turbo codes, low-density parity-check (LDPC) codes, etc., have been proposed. In [3–5], the ECCs are used with UEP and/or UPA strategies for the transmission of quality layers. These works improve the transmission robustness of JPWL images compared to equal error protection (EEP) schemes, but they only cover transmissions over Gaussian or non-frequency selective Rayleigh channels. Reference [6] presents a novel UPA algorithm using OFDM, in order to minimize the total image distortion over frequency selective fading channels. This optimization algorithm exploits the hierarchical structure of the JPEG2000 images, the channel state information and the distortion model to allocate optimal values of power, thus minimizing image distortion. It is worth mentioning that in the previously cited works, a single-input single-output (SISO) channel is used. However, the use of the MIMO (multiple-input multiple-output) technology ensures an efficient use of spatial diversity.

The increasing number of antennas makes it possible to achieve higher data rates and allows increasing the number of users. Moreover, the hierarchy of JPWL images content is well adapted to the structure of MIMO systems, which can be decomposed into several hierarchical SISO sub-channels by using precoder solutions. Each quality layer will be transmitted over a SISO sub-channel using the UEP and/or UPA strategies. Several precoding algorithms are proposed in this context. In [7–10] and [11], the precoders allocate the power emission on the sub-channels in order to maximize a particular criterion such as SNR (signal-to-noise ratio) or channel capacity. By using precoders' solutions, an improvement of the performance is obtained, but the hierarchy of the JPWL content is not taken into account in these optimization methods. In [12], a link adaptation scheme in a closed-loop MIMO-OFDM system is proposed. This scheme takes into account the content of the JPWL images, and all the transmission parameters (transmitted power, source/channel coder rates and modulation order) are considered in the optimization process. The precoding coefficients used in [12] are predefined to allocate the power for each sub-channel, allowing a maximization of the received quality layers under a target BER (bit error rate) constraint. Several other works using link adaptation schemes for wireless JPEG 2000 image transmission can be found in [13–15]. In these findings, a Reed–Solomon (RS) code with hard decoding is used for the optimization of

the image transmission. However, the drawback of these works is that the compressed image transmission over a wireless channel requires a low BER to avoid transmission errors, which requires more transmission power. In [16], an approach for image transmission over a realistic MIMO-OFDM channel using a link adaptation scheme including a serial concatenation of a soft-input soft-output RS decoder and an arithmetic decoder is proposed. The soft decoding allows relaxing the constraint on the SNR. In this case, less power is used to achieve the target BER. Consequently, more quality layers can be transmitted, improving the quality of the received JPWL images.

The purpose of studies presented in [12, 16] is to have provide a good QoS whatever the channel conditions. That is why the optimization algorithm relies on the bit-rate/distortion optimization process used in the JPWL standard which selects the optimal parameters allowing to reach the target QoS. The JPWL image quality is improved by minimizing the distortion of this image and maximizing the number of transmitted quality layers.

The soft iterative decoder used in [16] improves the performance comparing to the work in [12]. In contrast, it does not allow the transmission of images at high spectral efficiency and in particular for poor channel conditions. The BICM strategy [17] allows the combination of powerful ECC with high-order modulations. It gives an efficient system leading to both high spectral efficiency and high performance, with a reasonable complexity [18]. The good performance brought by the BICM technique can be improved by using the constellation shaping technique. In this case, the constellation points approach a Gaussian distribution at the channel input. As a consequence, an improvement of the performance can be achieved with a minimization of the average transmission power [19]. This is very important in the case of JPWL image transmission because the residual power allows the transmission of more quality layers, thus maximizing the visual image quality.

Several powerful ECCs can be used with the shaping BICM strategy such as the turbo code. For example, in [20] and [21], a turbo code is used in a BICM shaping constellation scheme. By using this approach, an improvement in terms of BER has been obtained where a target BER can be reached with less power compared to the BICM scheme without constellation shaping. The shaping techniques used in [20] and [21] require more puncturing in order to keep the same overall system rate. This can affect the turbo decoding pattern. In this case, it is necessary to search for other ECCs that overcome this problem. The DBTC adopted in DVB-RCT/RCS [22, 23] and the low-density parity check code (LDPC) adopted in the DVB-S2 [24] present a better performance compared to the classical turbo code. The authors of [25] present a comparison study between the DBTC and the LDPC code in a SISO scheme. These two codes show excellent performance in terms of BER and a high degree of flexibility in terms of block sizes and code rates. Concerning the BER performance, for a rate of 1/2, for instance, the DBTC outperforms the LDPC code for block lengths up to N=1728 bits (0.2 dB gain over LDPC for N = 576 bits). For a block length greater than N = 1728 bits, the LDPC code starts to outperform the DBTC (0.1 dB better for N = 4308 bits). It is also mentioned in [25] that even with the complexity of the DBTC decoding compared to the LDPC decoding, the DBTC presents a better complexity-performance trade-off for lower block lengths. In [26], another comparative study is performed between the DBTC and the LDPC codes

in a MIMO-OFDM scheme. This study confirms the results presented in [25]. In addition to this, the DBTC code shows better performance compared to the LDPC code for high modulation orders. The LDPC code is used in many shaping schemes such as in [27, 28] where a shaping code is used to achieve a non-uniform constellation. Recently, several strategies have been used to construct shaping LDPC-coded modulations. In [29], distribution matching (DM) rules are used to build a shaping LDPC-coded modulation scheme for optical fiber systems. Also, the authors of [30] use a tree LDPC-based signal shaping to construct a shaping LDPC-coded modulation scheme. In these works ([27–30]), even with the use of higher block lengths (33,480 bits in [29] and 10,000 bits in [30]), only a shaping gain between 0.3 and 0.7 dB can be achieved for different modulation orders (16, 64 and 256 QAM). In the case of the work presented in [31], shaping gains between 0.5 and 1.2 dB are obtained for modulation orders of 16, 64 and 256 QAM. In this last work, the constellation shaping scheme is obtained by using the DBTC in association with a simple shaping code where a small block length (188 bytes) is used with higher modulation orders.

In the present work, a small block length of 188 bytes will be used with high modulation orders. Therefore, the use of the DBTC will be more efficient than the one with LDPC, thus yielding to a shaping BICM scheme with better performance. To minimize the complexity brought by DBTC decoding, an adaptive number of iterations will be used.

1.2 Contribution

In this paper, the link adaptation scheme introduced in [12] and [16] and the shaping BICM strategy proposed in [31] are investigated in order to achieve high visual image quality for the transmission of JPWL images over realistic wireless channels. The duo binary shaping BICM technique will allow to achieve low BERs at low SNRs even if high-order modulations are used in poor channel conditions, thus improving spectral efficiency and minimizing power consumption. This allows transmitting several quality layers of the JPWL image with less power. Thanks to the high spectral efficiency, more bits can be used for source coding which minimizes the distortion of the received JPWL images. Consequently, the visual image quality will be maximized.

The contribution of this paper can be decomposed into the three following parts :

- The duo binary shaping BICM technique is introduced in each SISO sub-channel to protect the quality layers resulting from the JPWL source coding. In the shaping BICM scheme, a simple shaping code is inserted between a variable rate DBTC and high-order QAM modulations (4, 16, 64 and 256 QAM).
- The DBTC decoding pattern, for which the complexity increases with the number of iterations, has to be optimized. In [16], the number of iterations is not considered in the adaptive optimization and it is fixed to four iterations. However, in good channel conditions a smaller number of iterations can be enough to achieve the target BER. In this case, an adaptive number of iterations is necessary to minimize the decoding complexity. So, a minimum number of iterations are favored.
- Finally, the optimization block determines the optimal parameters (source and channel code rates, modulation order, number of layers and number of iterations of the

DBTC decoding) before the transmission of the JPWL layers. Moreover, it allocates the necessary power for each sub-channel to maximize the visual quality of the received image.

The rest of the paper is organized as follows: In Sect. 2, the proposed strategy is presented. Section 3 is devoted to the simulation results and discussions. Finally, conclusions and perspectives are presented in Sect. 4.

2 The proposed strategy

The proposed strategy builds upon the works presented in [12, 16] and [31]. In this section, the strategy will be presented in 2 steps corresponding to the 2 schemes :

- Firstly, the SISO BICM constellation shaping scheme used in each sub-channel of the global MIMO-OFDM scheme.
- Secondly, the Global adaptive MIMO-OFDM scheme.

### 2.1 SISO BICM constellation shaping scheme

In order to have good performance at high spectral efficiency, a BICM scheme is used. Furthermore, the shaping constellation technique is introduced to improve the performance of this scheme to benefit from energy saving.

2.1.1 Transmission part of the proposed BICM constellation shaping scheme

Figure 1 presents the transmission part of the proposed BICM constellation shaping scheme. It corresponds to the BICM_CS block in the overall MIMO-OFDM scheme (Fig. 5). The data is first encoded using the DBTC. The resulting sequence is then passed through a serial-to-parallel converter forming *k* parallel sequences, which are then interleaved separately. The sequence number (*k*) corresponds to the number of bits of the QAM symbols.

$$k = log_2(M) \tag{1}$$

where M is the QAM modulation order.

Fig. 1 Transmitter block of the BICM constellation shaping scheme. The transmission part of the proposed SISO BICM constellation shaping scheme (the *i* th BICM_CS block in the transmission part of the global adaptive scheme)
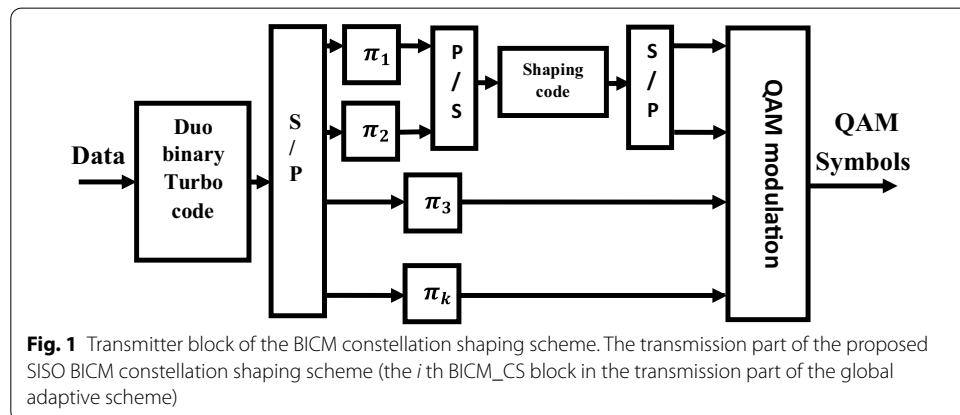
The two first sequences are then passed through a parallel-to-serial converter forming one sequence which is then treated by the shaping code. The sequence at the output of the shaping code is sent to a serial-to-parallel converter to form two sequences, which are concatenated with the others sequences to form the QAM symbols of the modulation block.

2.1.2 Duo binary turbo code (DBTC)

Figure 2 presents the 8-state DBTC, which is used in this paper. This code has been adopted for the DVB standard [22, 23]. It is built around 8-state duo-binary RSC (Recursive-Systematic Convolutional) encoders, having generator matrix $G = [15, 13]_8$. The data is first encoded in the natural order (switches in position 1). In the second step, it is encoded with an interleaved order provided by the time interleaver π (switch in position 2). It has been proved in [32] that the DBTC has better performance compared to the classical turbo code. In particular, it provides higher minimum distances, requires less puncturing for a given rate (lower sensitivity of the puncturing pattern), has higher throughput and reduced latency, ensures robust decoding and has better convergence. These improvements and especially the lower sensitivity of the puncturing pattern are very important when the shaping code is used. This last step requires an additional puncturing in order to keep the same overall system rate.
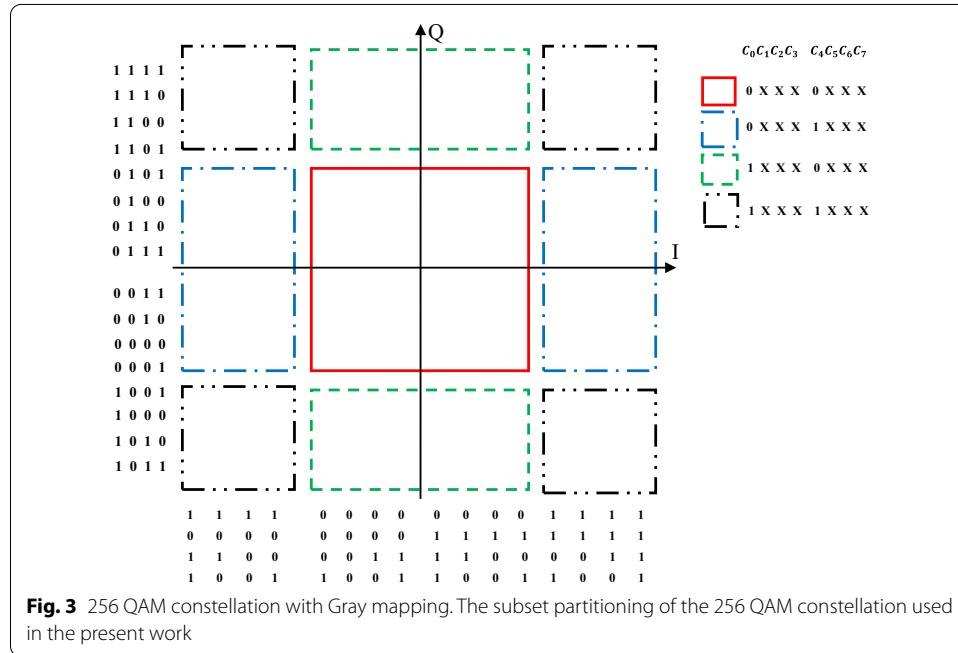
2.1.3 Shaping code

The simple shaping code of parameters 2 inputs and 4 outputs introduced in [31] is used in this study. Table 1 presents the input/output relationship of this shaping code. Its principle is that the number of zeros at the output is greater than the number of ones. This promotes the transmission of constellation symbols with lower power. In this case,

Fig. 2 Duo binary turbo code (DBTC). The 8-state duo binary turbo code used in the present paper
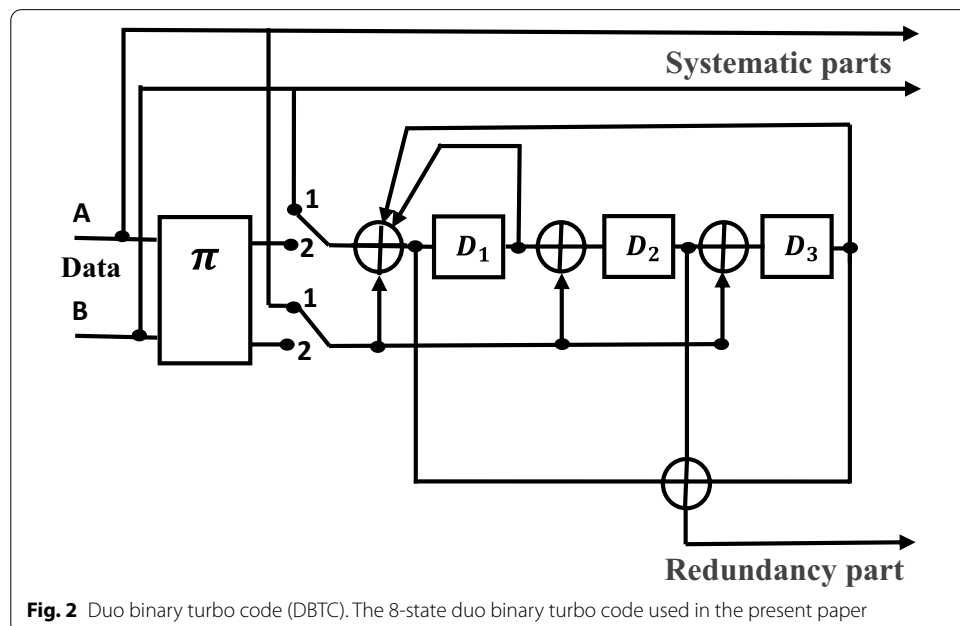
Table 1 Inputs/outputs of the shaping code (2,4)

Inputs	Outputs
00	00 00
01	01 00
10	10 00
11	00 10

Fig. 3 256 QAM constellation with Gray mapping. The subset partitioning of the 256 QAM constellation used in the present work

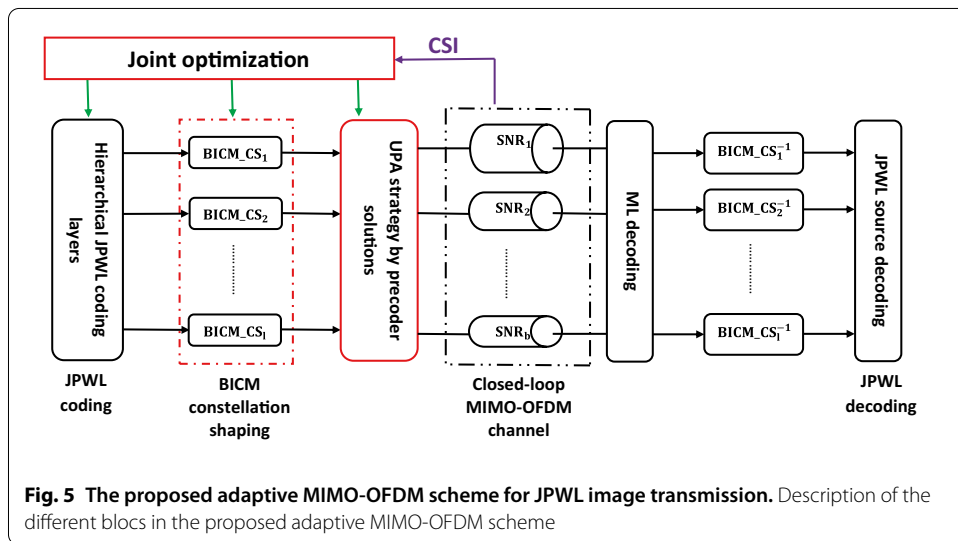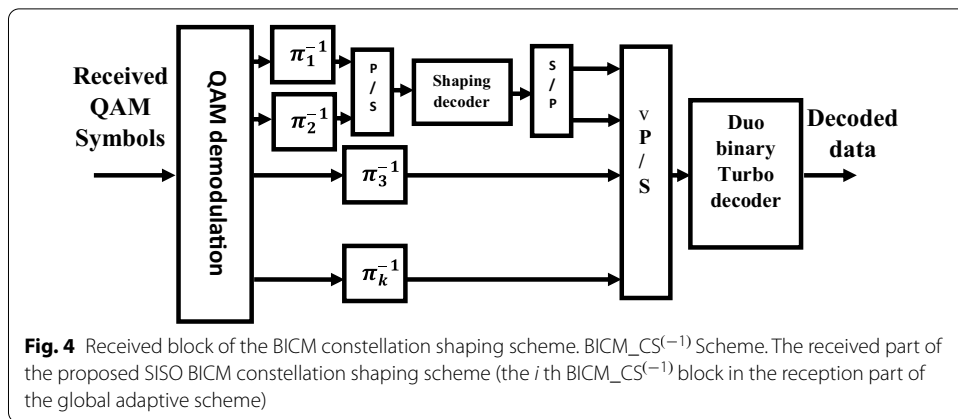a shaping gain in terms of BER is observed as well as a saving in the average transmitted power.

2.1.4 Shaping QAM constellation

In order to promote the transmission of the symbols with lower power, the QAM constellation is partitioned into four sub-constellations with increasing average power. Two data bits are used for the mapping of each sub-constellation. The sub-constellation with the lowest power symbols is mapped to 00, and the output of the shaping code adds the two bits that are used in the mapping of this sub-constellation [31]. Figure 3 presents the partitioning of the 256 QAM constellation.

The proposed shaping BICM strategy presents an important improvement in terms of BER and power saving. The unequal probability introduced by the shaping code allows to transmit the lower power QAM symbols more likely than the symbols with higher power, approaching a Gaussian distribution at the channel input. As a result, an important gain in terms of BER is obtained together with a saving in the average transmitted power.

In the case of JPWL images transmission, it is important to use high modulation orders. This allows to use more bits in the JPWL source coding. Therefore, the image

Fig. 4 Received block of the BICM constellation shaping scheme. BICM_CS$^{(-1)}$ Scheme. The received part of the proposed SISO BICM constellation shaping scheme (the *i* th BICM_CS$^{(-1)}$ block in the reception part of the global adaptive scheme)

Fig. 5 The proposed adaptive MIMO-OFDM scheme for JPWL image transmission. Description of the different blocs in the proposed adaptive MIMO-OFDM scheme

distortion will be minimized. Moreover, the proposed shaping BICM scheme allows achieving lower BERs at lower SNRs and to have a saving in the average transmission power, even when high modulation orders are used. The power saved can then be used to transmit more quality layers to improve the transmitted image visual quality.

2.1.5 Reception part of the proposed BICM constellation shaping scheme

Figure 4 presents the reception part of the proposed BICM constellation shaping scheme. It corresponds to the BICM_CS^{-1} block in the overall MIMO-OFDM scheme (Fig. 5). For each SISO sub-channel, a soft QAM demodulation is used to compute the log-likelihood ratio (LLR) of each received symbol. The first and second sequences are passed through a parallel-to-serial converter (P/S) to form one sequence that will be processed by the shaping decoder. The shaping decoder then uses the MAP algorithm to decode the received sequence and generates the estimation of the shaping sequence encoded at the transmitter side (see [20]). The resulting sequence is then passed through a S/P converter to form two sequences which are decoded with the other sequences by the DBTC decoder.

2.2 Adaptive MIMO-OFDM scheme for JPWL image transmission

In [12] and [16], the MIMO channel is decomposed into several uncorrelated SISO sub-channels with mean SNRs. According to the CSI knowledge at the transmitter side, the optimization block determines the number of sub-channels that can be used and, for each sub-channel, determines the optimal values of the modulation order, the rate of the channel coder and the source bit-rate to maximize the visual quality of the received JPWL images. At the reception side, a maximum likelihood decoder is used before the demodulation and the robust JPWL decoding. In the present work, the optimization scheme proposed in [12] and [16] was used with the duo binary BICM constellation shaping technique introduced in [31] for a closed-loop MIMO-OFDM scheme to ensure the best image quality at the receiver side. In the MIMO-OFDM scheme, each quality layer is transmitted over a SISO sub-channel and all the transmission parameters are considered in the optimization process. Figure 5 presents the different blocks of the proposed adaptive MIMO-OFDM scheme.

2.2.1 JPWL source coding

Source coding is compliant with the JPWL standard [1]. In [12], the transmitted image is coded using a single tile, where JPWL is used to code this image into 1 to 4 quality layers. To avoid transmission errors, the JPWL encoding is used with the following parameters [1]:

- "Start Of Packet" and "End of Packet Header" resynchronization markers,
- Main header protection and tile-part header protection predefined by the JPWL standard,
- The RS code is used with the rates defined by the JPWL standard to protect the data layers.

In this work, we use the same configuration as in [12] but without using RS code. Therefore, the resulting JPWL image contains only the main header, the tile-part header and the quality layers without any ECC-related redundancy.

2.2.2 Bit interleaved coded modulation with constellation shaping (BICM_CS)

Each quality layer is channel encoded separately by using the BICM constellation shaping scheme presented earlier. Figure 1 presents the scheme of the ith BICM_CS block. After QAM modulation, OFDM modulation is applied.

2.2.3 Decoding of the received image

At the receiver side, the OFDM demodulation is firstly applied, then a maximum likelihood decoder is used. After this, each received quality layer is passed through the decoding part of the BICM constellation shaping (BICM_CS^{-1}). To form the bit sequence that will be decoded by the JPWL decoder. Finally, a hard decision is carried out after DBTC decoding.

2.2.4 Formalization of the optimization problem

The main objective of the proposed scheme is to ensure the best QoS under a power budget for JPWL image transmission. The JPWL images are coded using a hierarchical structure with unequal importance. An optimization strategy that minimizes the bit rate/distortion is also used to obtain the best visual quality of these images. Moreover, the decoding of a given quality layer depends on the correct decoding of the preceding layer. For that reason, it is useless to allocate the power for a given quality layer, if this power is not enough for the correct decoding of the preceding layer. Hence, the highest importance layer is favored. The next layers are only considered if there is remaining power.

In the proposed work, before performing the coding of the JPWL images, an optimization block defines the optimal parameters to achieve the best QoS, taking into account the constraint on the CSI knowledge and the power budget. The best QoS can be obtained by minimizing the image distortion which is given according to the bit-rate/distortion optimization method of the JPWL standard. The image distortion is minimized by maximizing the number of bits used for source coding. Moreover, the QoS is improved by maximizing the number of transmitted quality layers.

$$Max(QoS) \begin{cases} Max(\beta_{s,i \in \{1,...l\}}) \\ Max(l) \end{cases} \tag{2}$$

- *Max*: maximize.
- $\beta_{s,i}$ is the number of bits used for source coding for the i th quality layer.
- l is the number of quality layers that can be transmitted.

The optimization process can be realized under the following constraints;

$$\begin{cases} Rate : \beta_{s,i} + \beta_{c,i} \leq \beta_i \\ QoS : BER_i \leq B \\ Power : \sum_{i \in (1,...l)} P_i^2 \leq E_T \\ With \begin{cases} \beta_i = S_{max} N \log_2(M_i) \\ \beta_{c,i} = \beta_{s,i}(\frac{1}{RT_i} - 1) \\ l \leq Nsc \end{cases} \end{cases} \tag{3}$$

where

- $\beta_{c,i}$ is the number of bits used for channel coding for the i th quality layer.
- BER_i is the bit error rate in the i th sub-channel and B is the target BER.
- P_i^2 and E_T are, respectively, the precoder coefficient for the i th sub-channel and the total power that can be used for image transmission.
- S_{max} is the maximum number of OFDM symbols that can be used in each sub-channel, N is the number of useful OFDM sub-carriers and M_i is the modulation order.
- Nsc is the number of SISO sub-channels that compose the MIMO channel (i.e., the maximum number of quality layer that can be used).

Relying on the CSI knowledge and the target BER (B) defined for each SISO sub-channel, the necessary power will be allocated to reach the target BER (target QoS).

Hence, a maximum number of quality layers (l) with the highest number of bits for source coding must be used with this power budget. To have this, less power must be used to achieve the target BER in the transmission of each quality layer, which can be obtained by the use of the shaping BICM strategy.

Concerning the maximization of the number of bits used for source coding, $\beta_{s,i}$ can be derived from equation (3) as follows:

$$\beta_{s,i} \leq RT_i S_{max} N \log_2(M_i) \tag{4}$$

In relation (4), S_{max} and N are fixed by the user. So, the maximization of $\beta_{s,i}$ leads to the maximization of M_i, which can be obtained by using high-order modulations, and/or the maximization of the turbo code rate RT_i, with the constraint on the total power and the channel CSI.

2.2.5 Proposed solutions for the optimization problem

The presented algorithm is based on the target BER fixed by the user and the constraint on the total power. The optimization block determines the number of quality layers that can be transmitted, and for each quality layer i defines the optimal configuration (the modulation order $M_{i\in(1,...l)}$, the turbo code rate $RT_{i\in(1,...l)}$ and the number of iterations $N\_It_{i\in(1,...l)}$ of the turbo decoding) in order to maximize the number of bits used for source coding.

The optimization algorithm starts by defining the SNR (the power) needed to achieve the target BER permitting to use a given BICM configuration (the configuration with the highest channel coding rate, the highest modulation order and the smallest number of iterations is favored) in the current sub-channel.
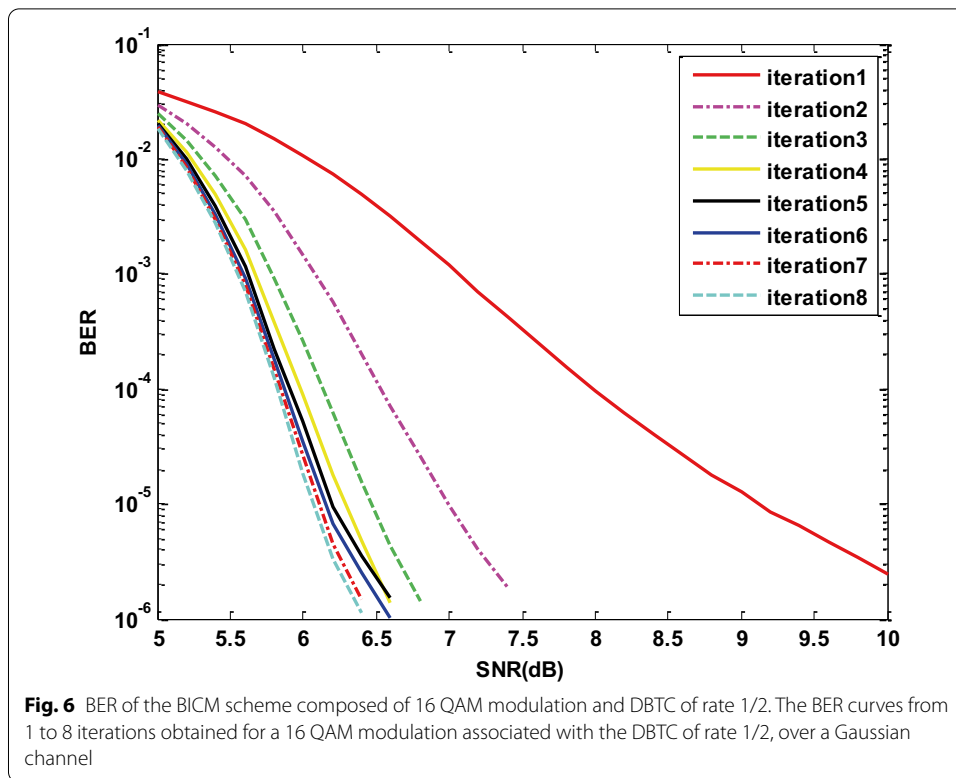
In the case of turbo decoding, the relationship between the SNR and the BER of a given configuration can be obtained from the BER curve. In this paper, due to the use of OFDM modulation which combats the channel frequency selectivity, each resulting SISO sub-channel can be considered as a Gaussian channel [33]. The BER curves for all used shaping BICM configurations are obtained by Monte Carlo simulations through a Gaussian channel. A MAP algorithm is used to perform DBTC decoding, using up to 8 iterations. Several block lengths can be used in the DBTC decoding. In this work, a block length of 188 bytes is used, but the strategy can be applied for any other block length.

As an example, Fig. 6 shows the obtained BER curves for a 16-QAM modulation associated with the DBTC of rate 1/2 over a Gaussian channel.

From the curves obtained by simulations, the SNR (SNR_T) allowing to achieve the target BER (BER_T) is defined for all the used configurations. So, based on the CSI knowledge for each sub-channel i, the power is allocated taking into account the constraint on the total power which is normalized to $E_T = 1$. For a given shaping BICM configuration, the $SNR_{T,i}$ that allows to achieve the target BER ($BER_{T,i}$) is the mean SNR (channel gain) of this sub-channel (SNR_i) weighted by the precoding coefficient P_i^2.

$$SNR_{T,i} = (P_i^2)(SNR_i) \tag{5}$$

The precoding coefficient P_i^2 can be calculated as follows:

Fig. 6 BER of the BICM scheme composed of 16 QAM modulation and DBTC of rate 1/2. The BER curves from 1 to 8 iterations obtained for a 16 QAM modulation associated with the DBTC of rate 1/2, over a Gaussian channel

$$P_i^2 = SNR_{T,i}/SNR_i \qquad (6)$$

As an example, let the mean SNR (channel gain) of the first sub-channel be $SNR_1 = 10$ dB. Using Fig. 6 and taking the BER curve obtained for one iteration, $BER_{T,1} = 10^{-5}$ is achieved at $SNR_{T,1} = 6.9$ dB. In this case, $SNR_{T,1} < SNR_1$ and the precoding coefficient can be calculated in order to allocate enough power.

Since $P_i^2 = SNR_{T,1}/SNR_1 = 4.9/10 = 0.49 < E_T$, this configuration (turbo code rate=1/2, 16 QAM modulation and 1 iteration in the turbo decoding) can be used for this sub-channel, and there is a residual power (Rp) value of $Rp = 1 - P_i^2 = 0.51$ that can be used for another sub-channel.

In the presented work, 4 modulation orders (4, 16, 64, 256 QAM) are considered with 4 different rates for the turbo code (1/2, 2/3, 3/4, 6/7) and with a maximum of 8 iterations in the turbo decoding. So, 128 BICM configurations can be obtained (see Fig. 7). These configurations are classified from 1 to 128 according to the modulation order, turbo code rate and number of iterations for the turbo decoding. In order to maximize the number of bits allocated for the source coding and to minimize the computational time in the turbo decoding, this ranking is carried out such as the configuration with a higher modulation order, higher turbo code rate and less iteration number is favored. It should be noted that the shaping code has been taken into consideration in these BICM configurations.
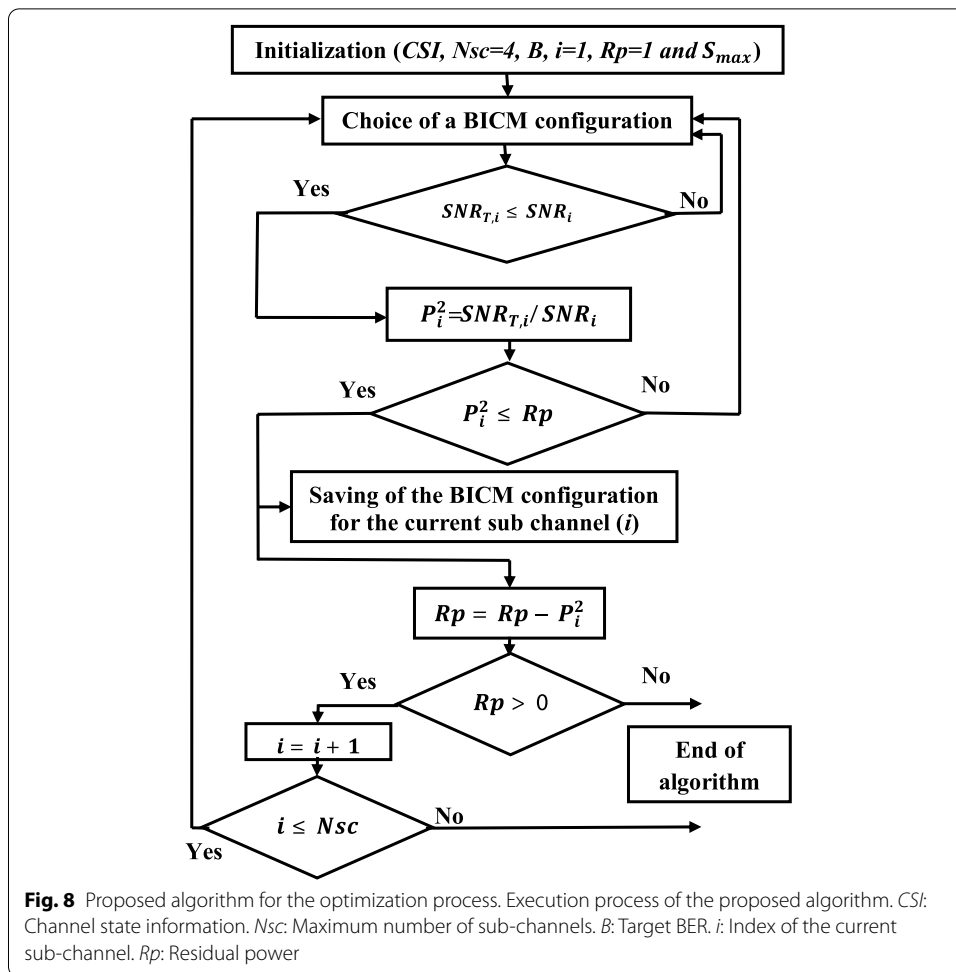
Once all the 128 configurations are defined with their corresponding BER curves, the proposed algorithm can be run as presented in Fig. 8.

Fig. 7 The 128 BICM possible configurations. The BICM configurations that can be obtained according to the modulation order, turbo code rate and number of iterations for the turbo decoding
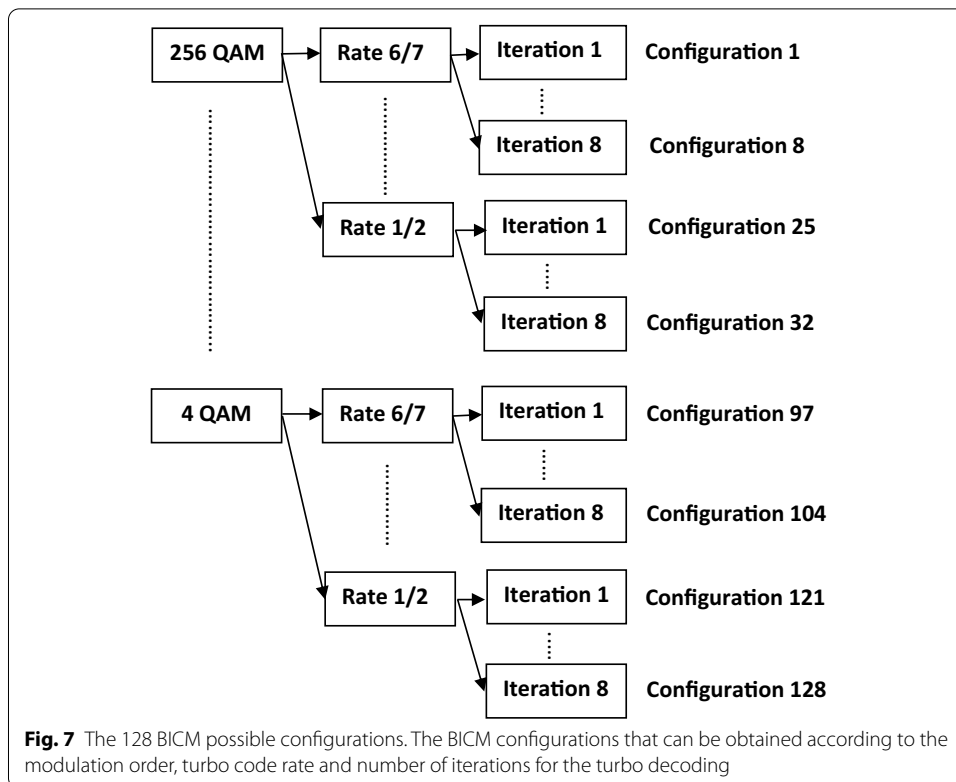
In the following, a 4x4 MIMO channel is considered, but the algorithm can handle more MIMO sub-channels. The target BER B and the maximum number of OFDM symbols S_{max} are defined by the user. The residual power (Rp) is initialized to 1.

According to the target BER B, a target SNR is defined for each shaping BICM configuration. Then, in the BICM configuration choice block, a configuration is chosen in order to be tested. The SNR of the current sub-channel is compared to the target SNR of the chosen configuration. If the channel gain is greater than the target SNR, the precoder coefficient (P_i^2) is calculated. If $P_i^2 \leq Rp$, the current configuration is validated, and the parameters of this configuration (modulation order, turbo code rate and number of iterations) are saved for the current sub-channel. Otherwise, the algorithm continues to the next configuration and so on, until a configuration can be satisfied. If no configuration can be found, the algorithm stops (i.e., the transmission of the JPWL image for this channel cannot be performed reliably). In order to decrease the number of configurations to be tested, the 128 BICM configurations are divided into four levels characterized by a SNR level, where each level contains 32 configurations. In this case, the channel gain is compared firstly to the SNR characterizing each level, and then, it is compared to the 32 configurations of the chosen level. Therefore, the maximum number of tested configurations is 36.

After the saving of the first sub-channel parameters, a test of the residual power Rp is performed. If $Rp > 0$, the next sub-channel is used to transmit the next quality layer. The program runs until the total power or all the sub-channels are used. Once

Fig. 8 Proposed algorithm for the optimization process. Execution process of the proposed algorithm. *CSI*: Channel state information. *Nsc*: Maximum number of sub-channels. *B*: Target BER. *i*: Index of the current sub-channel. *Rp*: Residual power
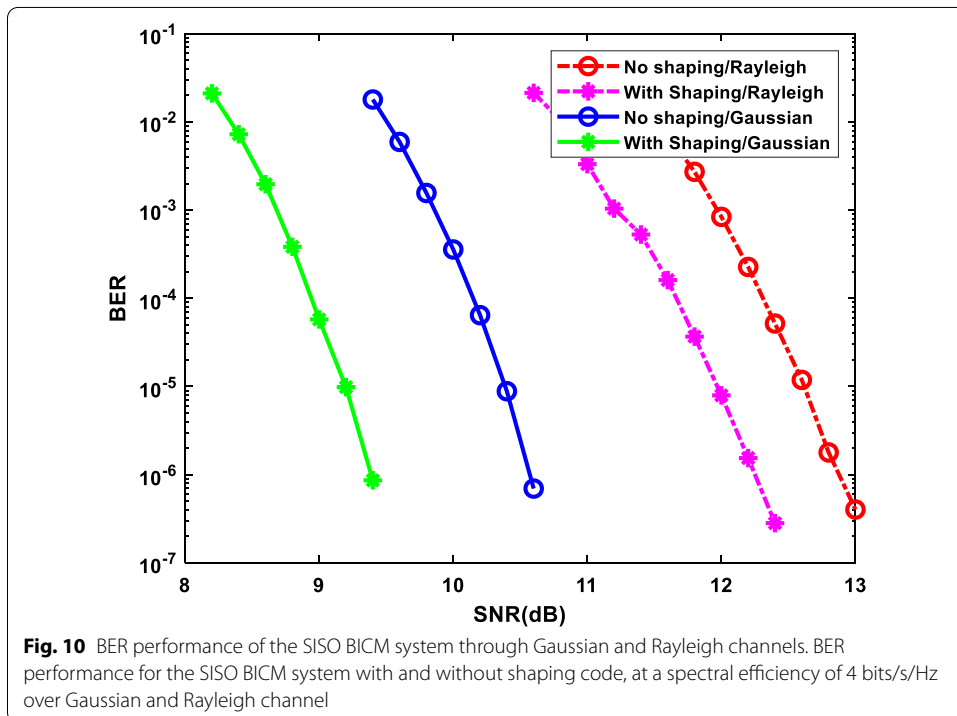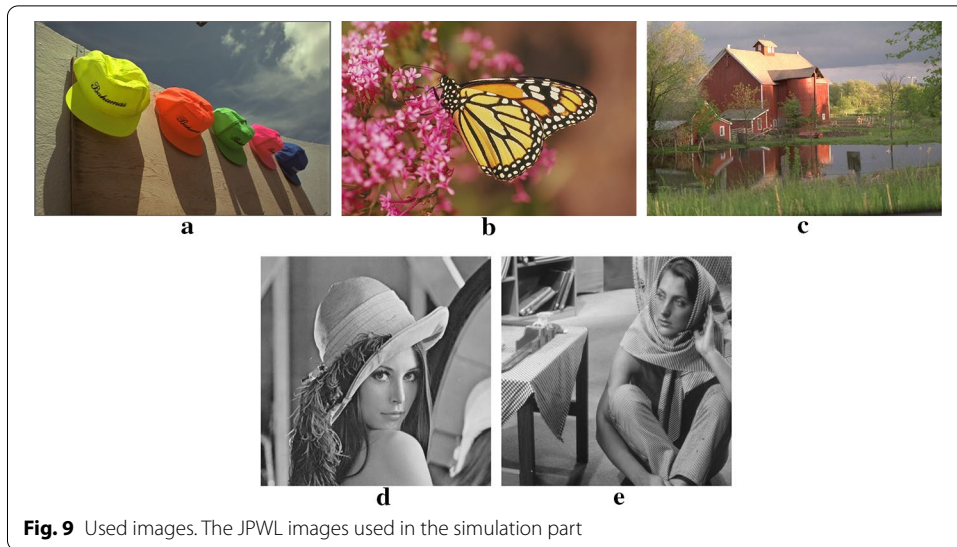
the optimal transmission parameters are defined, the JPWL image is coded and transmitted with these parameters through the MIMO channel.

3 Simulation results

Firstly, although we are in an OFDM configuration hypothesis, the robustness of the proposed SISO shaping BICM scheme is tested in terms of BER over Gaussian and Rayleigh channels. Secondly, the proposed adaptive strategy is tested over a realistic MIMO-OFDM channel. The performance is compared to the work proposed in [12] for the transmission of the following color images a: Caps, b: Monarch and c: House, respectively, shown in Fig. 9, and with the strategy proposed in [16] for gray images d: Lena and e: Barbara, respectively, shown in Fig. 9. The performance of the studied adaptive strategy is evaluated in terms of PSNR (peak signal-to-noise ratio) and SSIM (Structural SIMilarity) of the decoded images [34].

3.1 Performance of the shaping BICM scheme in SISO statistical channels

In this part, random bits sequences will be passed through the SISO shaping BICM scheme in order to compute the BER between the received and the transmitted sequences. Figure 10 presents the BER performance evaluated for the association of

Fig. 9 Used images. The JPWL images used in the simulation part

Fig. 10 BER performance of the SISO BICM system through Gaussian and Rayleigh channels. BER performance for the SISO BICM system with and without shaping code, at a spectral efficiency of 4 bits/s/Hz over Gaussian and Rayleigh channel

DBTC (rate = 1/2 and 188 bytes block length) and the 256 QAM modulation with and without the (2, 4) shaping code. Gaussian and Rayleigh channels are used.

From this figure, at a BER of $10^{(-5)}$, a shaping gain of 1.2 dB is obtained for the Gaussian channel. For the Rayleigh channel, the shaping gain is 0.6 dB. These gains are achieved when the proposed shaping BICM scheme is compared to the BICM scheme without shaping code. The proposed shaping BICM scheme presents a better performance compared to the BICM scheme without shaping code whatever the channel conditions. This is because the modulation symbols approach a Gaussian distribution at the

Table 2 Used parameters

Parameters	Values
QAM modulation orders	4, 16, 64 and 256
Turbo code rates	1/2, 2/3, 3/4 and 6/7
S_{max} per sub-channel	520 symbols OFDM
BER after channel decoding	$B = 10^{(-9)}$
Total power	$E_T = 1(normalized)$
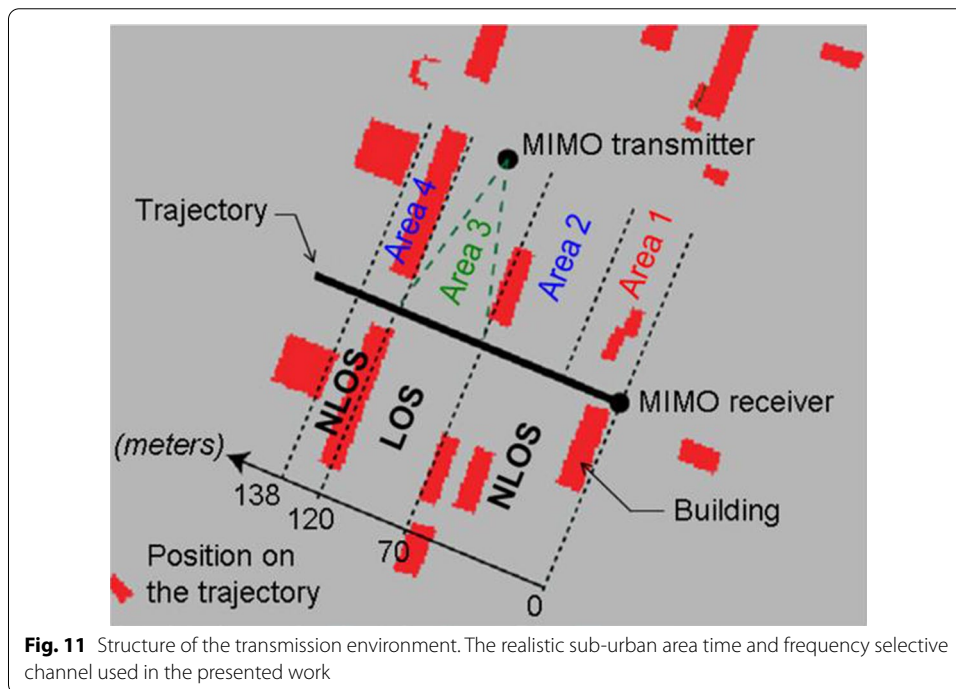
Fig. 11 Structure of the transmission environment. The realistic sub-urban area time and frequency selective channel used in the presented work

channel input. In addition to this, a saving on the average transmitted power of more than 47% is obtained. For more details, the reader can refer to [31].

3.2 Performance of the adaptive scheme for the realistic MIMO-OFDM channel

The used realistic suburban area time and frequency selective channel are presented in Fig. 11. The corresponding complex impulse responses have been obtained by a 3D ray tracing channel simulator developed in our laboratory [35]. By using a precoding solution [36], this MIMO channel is decomposed into *Nsc* parallel and independent SISO sub-channels with decreasing SNR orders. The precoder works as a pre-equalizer by adjusting the transmission power through an unequal power allocation strategy.

To compare the performance of the proposed adaptive strategy with the work presented in [12] and [16], the realistic MIMO channel is decomposed into 4 SISO sub-channels, thus allowing the transmission of 1–4 JPWL quality layers. The distances between the antennas are 0.4λ, where λ is the wavelength of the used high-frequency carrier. Frequency selectivity is overcome by the use of OFDM modulation. In the $BICM_{SC}$ block, the DBTC with variable rate is associated with several QAM modulation

orders. This gives high spectral efficiency when the channel conditions allow it. A lower spectral efficiency can be used in poor conditions. To improve the performance of the used BICM scheme, and to have a saving in the average transmitted power, the shaping code presented previously is introduced between the turbo code and the modulation. In the optimization process, the number of OFDM symbols used in the transmission is $S_{max} = 520$. The used images have bits-streams of sizes ranging from 10^4 to 10^5 bits. In this case, the B parameter must be: $B << 10^{-5}$. In [12], it was proved experimentally that $B = 10^{-9}$. In this work, we use the same value as in [12] for B. Concerning the CSI, one can use several schemes presented in the literature, for example, in [37, 38]. In this work, CSI is not totally known to the transmitter and the receiver as it is updated every 20 OFDM symbols.

Table 2 summarizes the used parameters:

The image is continuously transmitted over 2300 points of the realistic channel trajectory. The transmitter is static, and the receiver moves through a path of 138 m, sampled every λ with a mobility speed of 5 m/s. Figure 12 presents the variation of the total MIMO channel gain. From Fig. 12, it can be noticed that the transmission conditions evolve between poot (area 1), average (area 2 and 4) and good (area 3) conditions. The PSNR and SSIM results are calculated for each received image. These results are then averaged over a window of 20 values so that they are more readable (the window is chosen after testing different sizes as in [12]). In this simulation part, the performance is first studied for the color and gray images in terms of PSNR and SSIM. Secondly, the Monarch image is used to test the performance of the proposed scheme in terms of spectral efficiency and transmitted layers. After this, the power consumption and the visual comparison are tested. Finally, the performance is evaluated in terms of reliability of CSI information.

3.2.1 Performance in terms of PSNR and SSIM

Figure 13 presents the variation of the average PSNR for the Monarch image at each position of the reception trajectory. The Caps and House images exhibit the same

Fig. 12 Variation of the total MIMO 4 × 4 channel gain. The variation of the channel gain through the reception trajectory
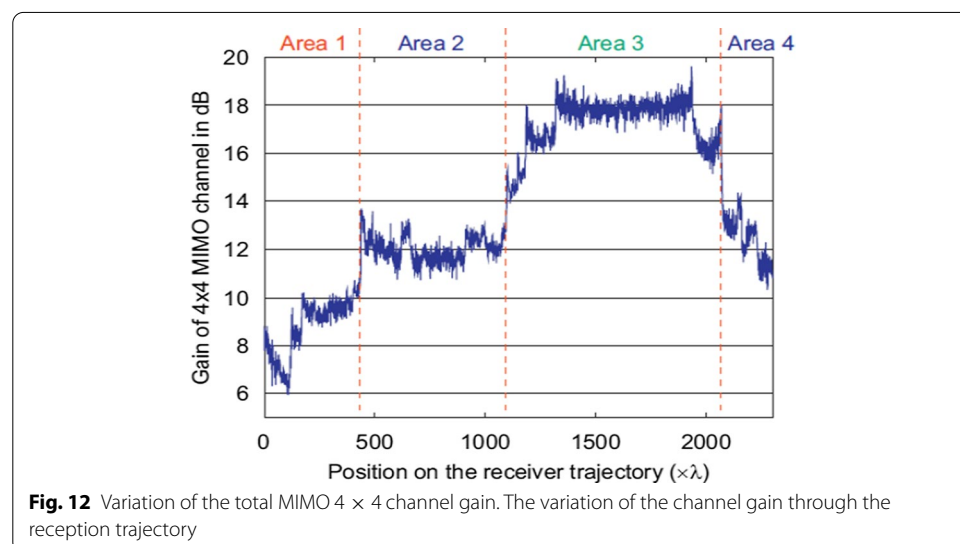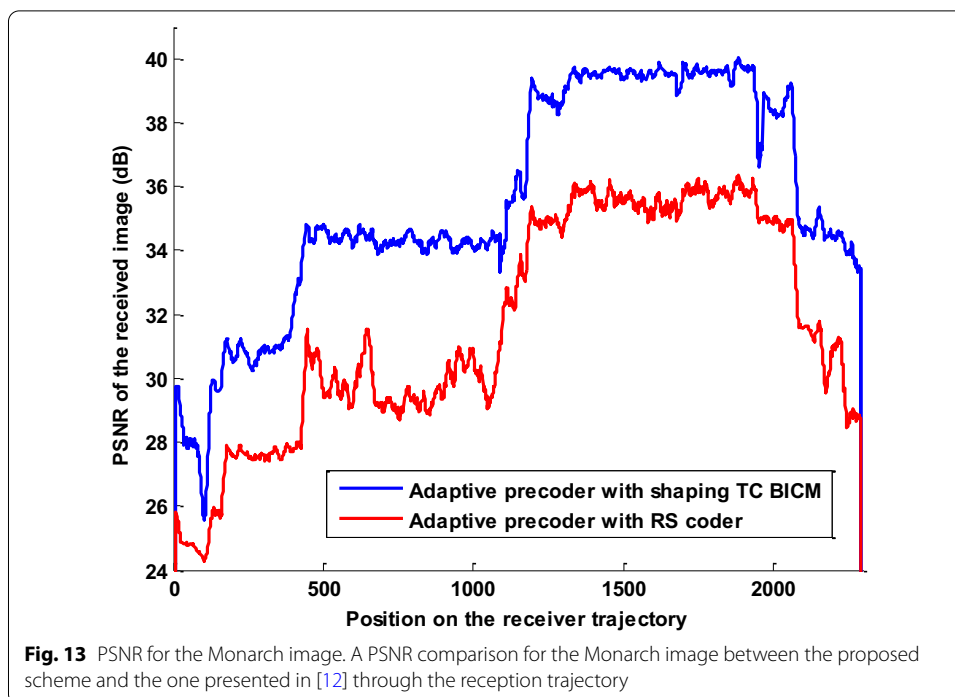
Fig. 13 PSNR for the Monarch image. A PSNR comparison for the Monarch image between the proposed scheme and the one presented in [12] through the reception trajectory

behavior as the Monarch image regarding the PSNR and SSIM curves. From this figure, it is observed that the proposed scheme improves the decoding PSNR of the JPWL compressed Monarch image. This is confirmed by the average performance in terms of the PSNR and SSIM for the Monarch image presented in Table 3. A gain of 3.44 dB, 4.34 dB and 3.73 dB is obtained, respectively, for the poor, average and good area conditions. The results are compared to those presented in [12].

The best performance presented by the proposed strategy, either for an increasing SNR or for a realistic MIMO channel, can be illustrated by the use of the shaping BICM. This allows to achieve low BERs at low SNRs with high spectral efficiency, and even in poor channel conditions. High-order modulations allows to maximize the total number (β_i) of bits that can be transmitted in each SISO sub-channel. Moreover, the redundancy bits are minimized by using a high rate turbo code. Hence, the number of bits allocated for source coding through all the channel areas is maximized, thus minimizing the distortion of the reconstructed JPWL images. With the proposed scheme, low SNRs are used to achieve the target BERs. In this case, there is enough remaining power that can be used to transmit more quality layers. As a result, higher PSNR values are obtained.

To visualize the effect of the shaping technique, a transmission of the Monarch image is performed with and without the shaping code presented earlier. In this simulation part, the DBTC rate = 1/2 and the QAM modulation is used with 4 orders (4, 16, 64 and 256).

Table 4 presents the gain in terms of PSNR when using the shaping technique. A gain of 0.68 dB, 0.81 dB and 0.25 dB is obtained compared to the system without shaping code for, respectively, the poor, average and good channel conditions. Using the shaping code technique, an improvement in the BER performance is obtained with a saving in the average transmitted power. This allows achieving the target BER at a lower SNR

compared to the scheme without shaping code and consequently transmitting more quality layers, thus improving the quality of the received JPWL image.

For the Caps and House images, a significant improvement in performance is also observed.

From Tables 5 and 6, a gain of 2.45 dB, 3.39 dB and 2.97 dB is obtained, respectively, for the poor, average and good areas of the simulation trajectory for the Caps image. The gains are 1.79 dB, 2.41 dB and 2.69 dB for the House image.

For the gray images, the performance of the proposed scheme is evaluated for the Lena and the Barbara images. Figure 14 presents the average PSNR of the Lena image at each position of the reception trajectory. Concerning the Barbara image, the same behavior is observed.
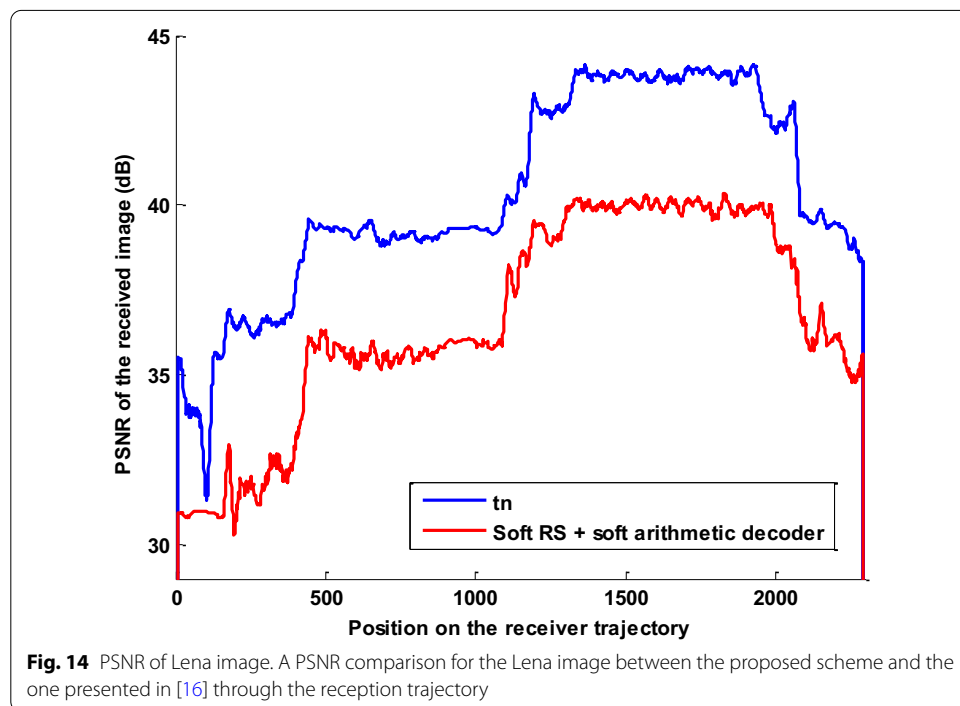

Fig. 14 PSNR of Lena image. A PSNR comparison for the Lena image between the proposed scheme and the one presented in [16] through the reception trajectory

Table 3 Average performance for the Monarch image in terms of PSNR (*dB*) and SSIM

	Area 1		Area 2 and 4		Area 3	
	PSNR	SSIM	PSNR	SSIM	PSNR	SSIM
With RS	26.68	0.83	30.01	0.88	35.20	0.93
With TC	30.12	0.89	34.35	0.93	38.93	0.95

Table 4 Average performance of Monarch image in terms of PSNR (dB) with and without shaping code

	Area 1	Area 2 and 4	Area 3
	PSNR	PSNR	PSNR
BICM without shaping	29.31	33.30	38.28
BICM With shaping	29.99	34.11	38.53

Table 5 Average performance for the Caps image in terms of PSNR (*dB*) and SSIM

	Area 1		Area 2 and 4		Area 3	
	PSNR	SSIM	PSNR	SSIM	PSNR	SSIM
With RS	30.95	0.84	33.55	0.89	37.99	0.944
With TC	33.44	0.88	36.94	0.93	40.96	0.96

Table 6 Average performance for the House image in terms of PSNR (*dB*) and SSIM

	Area 1		Area 2 and 4		Area 3	
	PSNR	SSIM	PSNR	SSIM	PSNR	SSIM
With RS	27.28	0.68	29.14	0.75	32.32	0.86
With TC	29.07	0.75	31.55	0.84	35.01	0.91

Table 7 Average performance of Lena image in terms of PSNR

	Area 1	Area 2 and 4	Area 3
	PSNR	PSNR	PSNR
RS + Arithmetic	31.67	35.78	39.60
Proposed scheme	35.82	39.23	43.25

Table 8 Average performance of Barbara image in terms of PSNR

	Area 1	Area 2 and 4	Area 3
	PSNR	PSNR	PSNR
RS + Arithmetic	25.90	30.30	36.10
Proposed scheme	30.42	35.68	41.36

From Fig. 14, it is clear that even with the use of an iterative soft decoder as in [16], the proposed scheme leads to a better PSNR value for the transmitted Lena and Barbara images than those obtained in [16]. From Tables 7 and 8, by using the proposed scheme and compared to the strategy used in [16], gains of 4.15 dB, 3.45 dB and 3.65 dB are obtained, respectively, at poor, average and good channel conditions for the Lena image (Table 7). For the Barbara image, gains of 4.52 dB, 5.38 dB and 5.26 dB are obtained, respectively, at poor, average and good channel conditions (Table 8).

The important gain in terms of PSNR obtained for the studied gray images can be illustrated as in the first configuration where the number of bits used for source coding is maximized and more quality layers are transmitted. This allows to minimize the distortion of the transmitted JPWL images.

3.2.2 Performance in terms of spectral efficiency and transmitted layers

Table 9 shows the results in terms of average modulation order which ranges from 4.83 to 6.82 for the poor, average and good channel conditions, respectively. This is to be compared to the modulation order values found in [12], which ranges from 2 to 5.29 for, respectively, the poor, average and good channel conditions.

Table 9 Average performance for the Monarch image in terms of modulation order

	Area 1	Area 2 and 4	Area 3
	Average (M)	Average (M)	Average (M)
With RS	2.00	2.66	5.29
With TC	4.83	5.13	6.82

Table 10 Average performance for the Monarch image in terms of number of transmitted layers

	Area 1	Area 2 and 4	Area 3
	Average (l)	Average (l)	Average (l)
With RS	1.67	2.67	3.13
With TC	2.04	3.00	3.97

It is clear that a high modulation order and consequently a high spectral efficiency are used in all channel conditions. This can be illustrated by the association of the turbo code and the shaping code (shaping BICM scheme) in the present work. In addition to this, the global rate (spectral efficiency) varies between 1 and 6.85 bit/s/Hz in the proposed study. However, in the scheme using the RS code, the global rate varies only between 1.42 and 5.19 bit/s/Hz. So, more variety in the global rate can be achieved with the proposed scheme, and therefore, the adaptive choice of these rates is more effective.
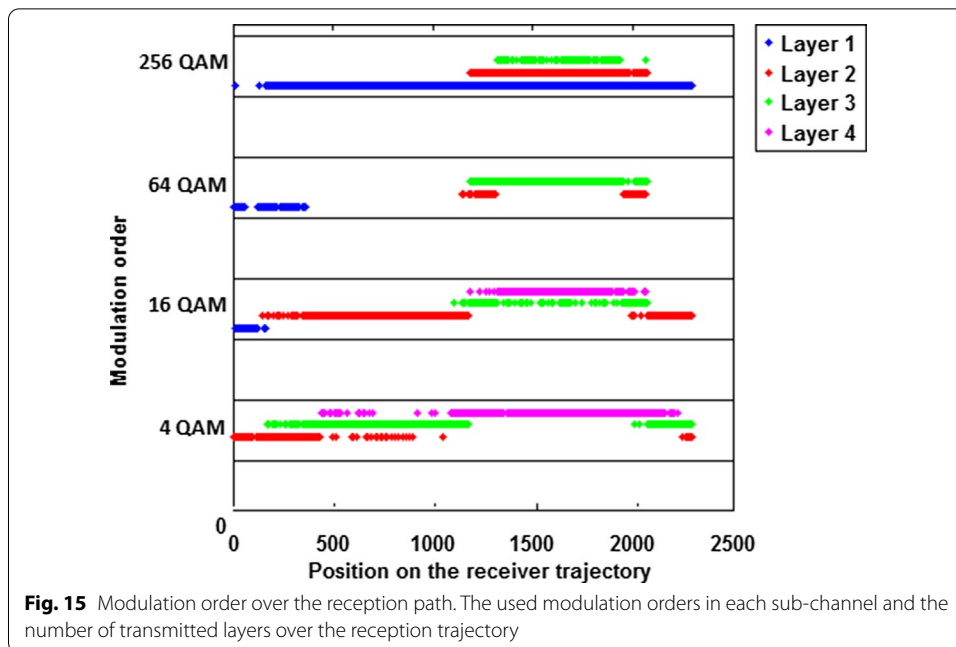
Table 10 presents the average number of transmitted layers. From this table, at least two quality layers are used in poor channel conditions, and approximately all the quality layers are used in good channel conditions. This is confirmed by Fig. 15, which presents the used modulation orders in each sub-channel and the number of transmitted layers.

In the adaptive strategy, a quality layer is transmitted when there is enough power to achieve the target BER. With the shaping duo binary turbo-coded BICM scheme, a low SNR and consequently a low power allow to achieve the target BER. For that reason, more quality layers can be used even at high spectral efficiency and for poor channel conditions.

3.2.3 Performance in terms of power consumption

In order to evaluate the power consumption, a comparison study is performed between the proposed strategy and the one in [16]. We transmit the Lena image using the same QoS as in [16]. Table 11 presents the average power consumption for the two schemes.

Compared to the scheme used in [16], it is seen from Table 11 that 64%, 89% and 91% of the power budget are consumed, respectively, in poor, average and good channel conditions. The proposed scheme uses only 21%, 18% and 13% of the power budget for, respectively, poor, average and good channel conditions. These results are obtained for the same configuration (modulation orders, number of transmitted quality layers and bit rate) leading to a comparable QoS in the two strategies. Consequently, the proposed strategy yields a power consumption gain of 43%, 71% and 78% for, respectively, poor, average and good channel conditions. In the proposed strategy, the efficiency of the shaping BICM technique used with the DBTC allows to use less power for the data transmission even if high modulation orders are used (orders over 64). Please note that

Fig. 15 Modulation order over the reception path. The used modulation orders in each sub-channel and the number of transmitted layers over the reception trajectory

in [16] the maximum modulation order is 64 QAM, and it is only used in good channel conditions. In the same conditions as in [16], the proposed scheme can reach the target QoS with less power.

It is necessary to note here that, with the important gain brought by the proposed strategy, the number of turbo iterations is less than 3 for poor channel conditions (area 1) and less than 2 in average and good channel conditions (areas 2, 3 and 4). This has to be compared with [16], where iterative decoding is performed in 4 iterations. A large number of decoding iterations imply a higher computation time. So, the use of adaptive iterations number allows us to reduce the decoding complexity.

3.2.4 Visual comparison

Figure 16 presents a visual comparison for the transmission of the Monarch and Barbara images. Figure 16a and b presents, respectively, the received Monarch images in poor channel conditions (area1) for the strategy proposed in [12] and the proposed scheme. (c) and (d) present, respectively, the received Barbara images in good channel (area3) conditions for the strategy used in [16] and the proposed strategy. It can be observed that the proposed scheme improves the visual quality of the received images.

3.2.5 Robustness according to the CSI estimation

At the end of this simulation part, a performance comparison of the proposed strategy is conducted when the CSI is updated after an increasing number of OFDM symbols. Figure 17 presents the PSNR for the Monarch image using the proposed scheme, in the case of perfect CSI, CSI updated every 20 OFDM symbols and 100 OFDM symbols. From this figure, the CSI knowledge affects the performance, and degradation in the PSNR is observed when the CSI is updated after an increasing number of OFDM symbols.

Fig. 16 Visual comparison for Monarch (**a**, **b**) and Lena (**c**, **d**). A visual comparison for the transmission of Monarch and Lena images
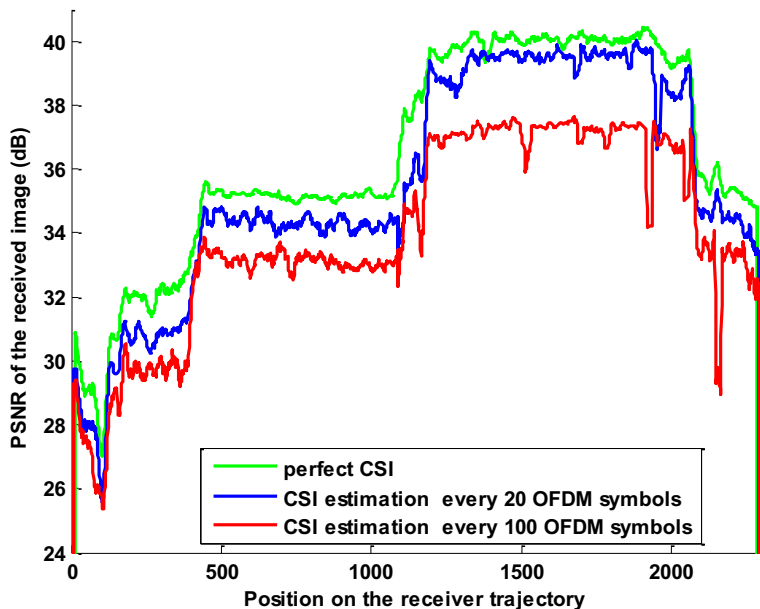
Fig. 17 PSNR of the Monarch image for different CSI levels. the PSNR of Monarch image obtained by using the proposed scheme for different CSI levels

Table 11 Average power consumption for the transmission of Lena image

	Area 1	Area 2 and 4	Area 3
	Power	Power	Power
Strategy in [16]	64%	89%	91%
Proposed strategy	21%	18%	13%

Table 12 Average performance of the Monarch image for different CSI levels

	Area 1	Areas 2 and 4	Area 3
	PSNR	PSNR	PSNR
Perfect CSI	31.29	35.24	39.75
CSI every 20 symbols	30.12	34.35	38.93
CSI every 100 symbols	29.20	33.09	36.80

From Table 12, degradations of 1.17 dB, 0.89 dB and 0.82 dB are observed, respectively, for poor, average and good channel conditions, when the perfect CSI is updated every 20 OFDM symbols. When it is updated every 100 OFDM symbols, the degradation becomes more important. For poor, average and good channel conditions, the degradation is, respectively, of about 2.09 dB, 2.15 dB and 2.95 dB. The unreliable CSI does not allow to allocate the optimal power in order to reach the target BER, which degrades the performance. In the proposed strategy, the turbo code used with the shaping BICM technique allows to approach the target BER even if the allocated power is not sufficient. In this case, the performance degradation is less noticeable.

4 Conclusion

The proposed scheme based on an optimization process between all the transmitter parameters (source and channel encoder rates, modulation order, quality layers and number of iterations) improves the quality of the received JPWL images, and a good QoS is obtained even for poor channel conditions. The DBTC shaping BICM scheme reaches a shaping gain of 1.2 dB compared to the scheme without shaping code. Therefore, higher-order modulations can be used for the transmission of JPWL images, in which less power is used to achieve the target QoS. This gives a power consumption gain of 78% if the same target QoS is fixed as in the strategy that uses iterative process between RS and arithmetic decoders. On the other hand, image distortion is minimized (a gain of 5.38 dB in PSNR is obtained), since a higher number of bits can be used for source coding, thus allowing the transmission of more quality layers. So, the gain provided by the proposed strategy can be either in terms of QoS, or in terms of power consumption for a comparable QoS. In addition to this, the adaptive iterations number in the proposed strategy can minimize the decoding complexity compared to strategy that uses RS and arithmetic decoders with 4 iterations whatever the channel conditions.

error protection; UEP: Unequal error protection; UPA: Unequal power allocation; PSNR: Peak signal-to-noise ratio; SNR: Signal-to-noise ratio.

Authors' contributions

A.H, B.S.B and C.P conceived of the presented idea. A.H, H.B and Y.P developed the theory and performed the computations. K.N. and C.C discussed the results and contributed to the final manuscript. All authors discussed the results and contributed to the final manuscript.

Availability of data and material

Data sharing not applicable to this paper as no datasets were generated or analyzed during the current study.

Declarations

Competing interests

The authors declare that they have no competing interests.

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