Improved Reception Schemes for Digital Video Broadcasting Based on Hierarchical Modulation

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Abstract. *In this paper, we first provide an overview of Hierarchical Modulation (HM) along with the opportunities offered by this modulation in the context of the recent Digital Video Broadcasting standard for Satellite to Handheld devices (DVB-SH). With HM, the binary data is partitioned into a "high-priority" (HP) and a "low-priority" (LP) bit stream that are separately and independently encoded before being mapped on non-uniformly spaced constellation points. We will show that the robustness of the HP stream is obtained at the expense of performance degradation of the less protected LP stream with respect to a non-hierarchical modulation. To overcome this inherent drawback of HM, we propose two different reception schemes for improving the bit error rate performance of the less protected LP stream, while keeping the HP decoding performance unchanged. The important point is that in one of the proposed reception schemes, the performance improvement is achieved together with the reduction of the receiver's complexity.*

Keywords

DVB-SH standard, non-uniform hierarchical modulation, turbo code, concatenated coding, improved iterative decoding.

1. Introduction

Novel wireless communication and multimedia services are being introduced almost daily and the demand for mixed traffic (e.g., voice, data, e-mail, Internet access, etc.) at higher data rates and higher quality connectivity, continue to grow. Digital broadcast systems have increasingly been deployed for various services such as terrestrial digital TV, digital radio, satellite TV and radio. Classical digital broadcast systems were designed with fixed modulation techniques, which had to guarantee reliable communication even with very hostile channel environment. Obviously, these schemes become spectrally inefficient when the wireless channel experiences deep fades. For this reason, some recent broadcast systems are designed with flexible transmission parameters such as the possibility of choosing among different constellations (e.g., QPSK, 8-PSK, 16-QAM, 64-QAM, etc.), and selecting error correction codes of different coding rates. In this way, the transmitter can switch to a modulation with a larger constellation and/or higher coding rate in the presence of favorable channel conditions. However, a disadvantage of such a scheme is that all receivers have to be designed with capability of receiving all supported transmission modes, and hence such receivers may be expensive to manufacture.

A major obstacle in increasing the spectral efficiency of fixed rate broadcast system is *backward compatibility*. More precisely, this means that the deployed classical receivers must continue to operate in the upgraded system in order to prevent prohibitive costs. Hierarchical modulation (HM) [1], [2], [3], [4] has been included in various standards, such as DVB-T [5] and very recently in DVB-SH standard proposal for mobile digital TV transmission [6] as a strong solution for increasing the data rate and the robustness of original broadcast systems. The advantage of HM is that the system is backward compatible, i.e., the upgrade is transparent to the receivers of the original system.

The basic idea behind HM consists in partitioning the initial binary stream into two parts: the *basic* or "high-priority" (HP) information and the *secondary* or "low-priority" (LP) information. The basic information is actually the data transmitted in the original system, whereas the secondary information is the additionally transmitted data in the upgraded system. In other words, the originally designed system transmits the basic information (HP) only, while the upgraded system using HM transmits both basic and secondary information. After channel encoding, the HP and the LP information are multiplexed into a single stream and mapped on non-uniformly spaced constellation points creating different levels of error protection. In a multiuser scenario, the HP information is to be received correctly by each user even in a very bad channel environment, while the LP information is mostly dedicated to users whose channels have better qualities and higher signal-to-noise ratios (SNR). Another interesting feature of HM is that the coverage areas for the LP and HP streams are of different sizes owing to the different susceptibility to noise of the two streams. It is important to notice that the enhanced protection provided

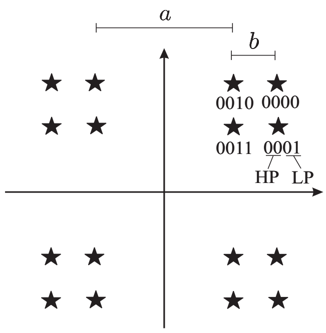

Fig. 1. Non-uniform hierarchical 16-QAM constellation with modulation parameter $\alpha \triangleq a/b$.

by HM for the HP stream is at the expense of lower noise immunity for the LP stream. In other words, the HP stream may require a considerably lower SNR in order to achieve the same bit error rate (BER) as that the LP stream. Consequently, in some situations, the required SNR for a reliable transmission of the LP stream may not be available. In [7], the authors propose a receiver that uses the reliable information on HP bits provided by the HP decoder to improve the decoding of the less protected LP stream.

In this paper, we first propose an overview of the new opportunities that HM provides in the context of the recent DVB-SH standard. Then we capitalize on the main challenge of HM and propose new reception schemes which processes and receives both HP and LP information with the objective of improving the BER performance of the less protected LP stream. At the receiver, we consider iterative soft-input soft-output (SISO) decoding which is an efficient technique when channel coding is used [8], [9]. This scheme is essentially composed of a detector (also called demapper) and a SISO channel decoder, exchanging soft probabilistic information with each other through several iterations. The hierarchical decoder is composed of two separate SISO decoders, one for each stream. In the first proposed receiver, the two decoders operate simultaneously and the LP decoder exploits the aforementioned iterative mechanism to improve the BER performance. As a second upgraded receiver, we propose a *sequential* decoding strategy (i.e., first HP and then LP decoding). This scheme exploits the reliability of the decoded HP bits to improve the accuracy of LP decoding thanks to the inherent dependency of the two streams due to the hierarchical constellation.

The organization of this paper is as follows. Section 2 presents the principle of hierarchical modulation along with the DVB-SH transmitter architecture [6] which uses hierarchical modulation. We also describe the basic receiver that will be used as a reference for performance comparison throughout the paper. Then we present some simulation results to demonstrate the opportunities provided by hierarchical modulation in the context of DVB-SH systems. In Section 3, we propose two upgraded receivers with the aim of improving the performance of the LP stream. Simulation results are presented in Section 4 comparing the performance obtained with the basic and with the two improved receivers. Different reception strategies are also compared in terms of their computational complexity. Finally, Section 5 concludes the paper.

2. Hierarchical Modulation and DVB-SH System Architecture

2.1 Hierarchical Modulation

Without loss of generality, we will explain the principle of HM using 16-QAM constellation. In the case of a non-hierarchical 16-QAM constellation, the binary data is grouped into groups of 4 bits and mapped to one of the 16 states in the complex plane. In hierarchical 16-QAM (16-HQAM), the assignment of the binary data to the permissible states is different than in the non-hierarchical 16-QAM. Fig. 1 depicts the 16-HQAM mapping. As shown, the 16-HQAM can be viewed as the combination of two QPSK modulation. This implies that two separate data streams are available for transmission. The first stream (called the high-priority or HP stream) which is mapped to the two most significant bits (MSB) of each state, indicates the index of the quadrant (1, 2, 3 or 4) in which the state is located. The second stream (called the low-priority or LP stream) which is mapped to the two least significant bits (LSB) of each state, indicates the location of a state within its quadrant.

We can now compare the 16-HQAM constellation with its non-hierarchical counterpart. As obvious from Fig. 1, the noise sensitivity of the HP stream (i.e., the two MSB of each state) is substantially lower than that of the 16-QAM modulation. This is due to the fact that the affiliation of two information bits to the quadrant index is less likely to become incorrectly detected when the transmission is corrupted by noise. More precisely, if a given state in a quadrant is incorrectly detected, the quadrant information is still correct. However, the LP stream is less robust to noise than an equivalent data stream in a non-hierarchical 16-QAM. Actually, the additional LP data stream imposes a penalty on the LP performance compared to the original QPSK modulation. This penalty can be analyzed in terms of the HM parameter $\alpha \triangleq a/b$. When $\alpha = 1$, one gets a standard 16-QAM modulation with a specific mapping (also called uniform HM). However, when α is increased, the four points in each quadrant form a “cloud” and in this case the HP information would be protected even further, at the expense of robustness of the LP stream.

The variable immunity to noise of the HP and LP streams can be used for the transmission of different kinds of programs with different coverage areas. More precisely, the HP and LP streams cover two distinguished areas. For instance, the more protected stream (HP), containing the basic information, would be received both by fixed and mobile receivers, in a larger area. On the other hand, the less protected stream (LP) would be received only by fixed receivers (e.g., in an indoor area) which have a higher antenna gain

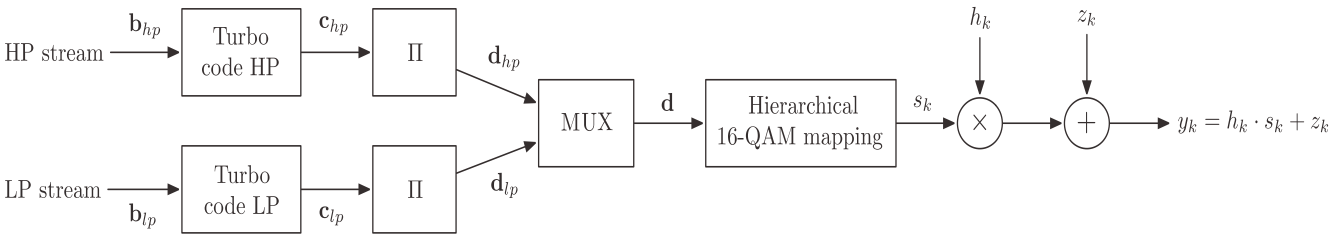

Fig. 2. Block diagram of the transmission scheme for the DVB-SH system using hierarchical modulation.

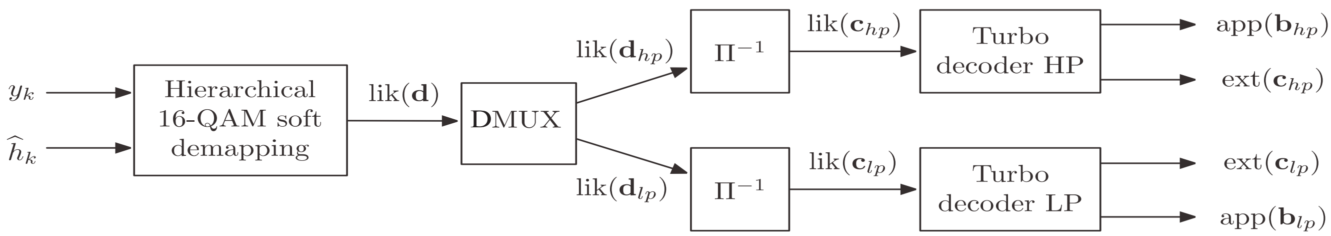

Fig. 3. Block diagram of the *basic* DVB-SH reception scheme.

and SNR. The HP coverage area can be further enlarged at the expense of the LP area, by choosing larger values of α.

2.2 DVB-SH System Architecture

We now describe the DVB-SH standard which has been recently proposed for multimedia services over hybrid satellite and terrestrial networks to a variety of mobile and fixed terminals. Target terminals include handheld (e.g., PDA, mobile phones), vehicle-mounted devices, laptops, etc., and stationary terminals [6].

The DVB-SH physical layer has two different transmission modes, the TDM mode and the OFDM mode [6]. In this work, we focus on the OFDM mode which supports hierarchical 16-QAM modulation. Fig. 2 depicts the functional block diagram of the transmitter proposed in [6] for DVB-SH in the OFDM mode. As shown, the HP and LP streams are *independently* encoded by their respective turbo encoder module. The channel encoding modules are state of the art and field-proven encoders (3GPP2 turbo code) supporting several coding rates thanks to different puncturing patterns. The two encoded streams are then interleaved, combined into a single stream, and mapped on non-uniformly spaced 16-HQAM constellation points. The modulated signal is then passed through an OFDM modulator and broadcasted over the multipath wireless channel. As mentioned in Subsection 2.1, HM protects better the HP stream than the LP stream. However, it is possible to increase further the error protection of the HP stream than those of the LP stream by employing a lower coding rate. Consequently, the HP stream may require a considerably lower SNR in order to provide the same quality of service (e.g., BER) as the LP stream.

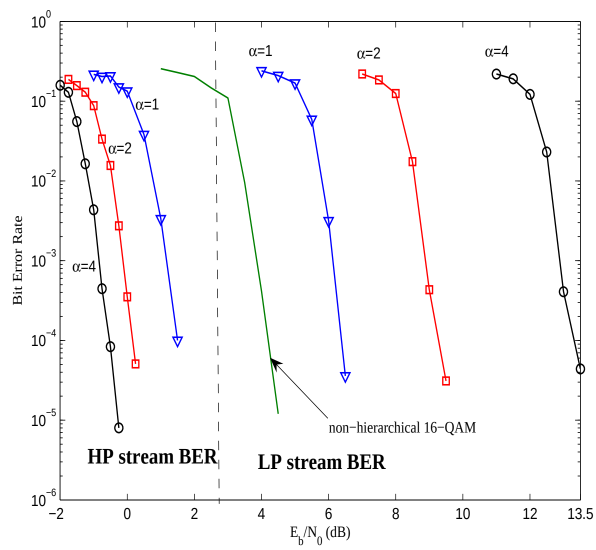

Fig. 4. DVB-SH system behavior for HP and LP streams in the case of hierarchical modulation for different values of parameter α with the *basic* receiver, $R_{hp} = R_{lp} = 1/3$, 8 turbo decoding iterations.

Since in the scheme presented in Fig. 2 the HP and the LP information are encoded *separately*, they can be decoded separately by two different turbo decoders. We refer to this approach as the *Basic* reception scheme. The block diagram of such a receiver is depicted in Fig. 3. As illustrated, the receiver is essentially composed of a soft demapper and two turbo decoders, one for each stream [10]. The HP and LP turbo decoders calculate the *a posteriori* probability (APP) and the *extrinsic* probability for the uncoded HP and LP stream, respectively.

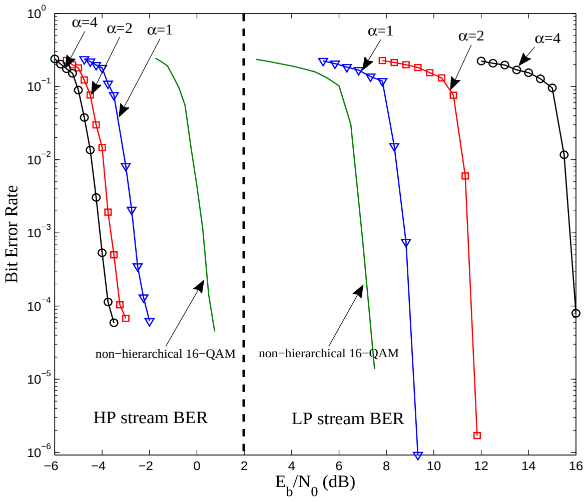

Fig. 5. DVB-SH system behavior for HP and LP streams in the case of hierarchical modulation for different values of parameter α with the *Basic* receiver, $R_{hp} = 1/5$, $R_{lp} = 2/5$, 8 turbo decoding iterations.

It is now relevant to compare the BER performance of a DVB-SH system using respectively a 16-HQAM and a non-hierarchical 16-QAM constellation. Fig. 4 shows the system behavior of hierarchical modulation for HP and LP streams in the case of a DVB-SH system using the transceiver presented in Figs. 2 and 3, where the HP and LP encoding rates, denoted respectively by R_{hp} and R_{lp} are both equal to $1/3$. For comparison, we have also reported the BER obtained with a non-hierarchical 16-QAM modulation. A first observation is that hierarchical modulation creates two levels of error protection. Compared with non-hierarchical modulation, the HP stream is highly protected while the LP stream BER is slightly degraded compared to its non-hierarchical variant. It can be also observed that the robustness of the HP stream is increased even further by increasing the parameter α. However, as depicted in Fig. 4, the main drawback of the *Basic* reception scheme is that when α increases, the LP stream requires a considerably larger SNR in order to achieve the same BER as that of the HP stream.

We have reported in Tab. 1 the relative gain (for the HP stream) and loss (for the LP stream) in SNR resulting from using a hierarchical 16-QAM rather than a non-hierarchical 16-QAM modulation, where the BER is equal to 10^{-5}. An interesting observation is that changing the parameter α from 2 to 4, leads to about 0.9 dB of SNR gain for the HP stream at the expense of about 4.5 dB of SNR loss for the LP stream, i.e., the sensitivity of the LP stream to noise seems to be larger when $\alpha = 4$.Similar plots are shown in Fig. 5 for the case where $R_{hp} = 1/5$ and $R_{lp} = 2/5$. These show the behavior of hierarchical modulation when the HP stream is transmitted with a greater error protection, i.e., with a lower coding rate, than the LP stream. Similarly we observe that the enhanced protection for the HP stream is at the expense of less protection for the LP stream (about 11 dB of SNR gap is observed between the HP and the LP BER performance for $\alpha = 1$).

Modulation	Gain (dB)	Loss (dB)	Diff. (dB)
Classical 16-QAM	0	0	0
16-HQAM ($\alpha = 1$)	2.5	2	+0.5
16-HQAM ($\alpha = 2$)	4	5	-1
16-HQAM ($\alpha = 4$)	4.9	9.5	-4.6

Tab. 1. Behavior comparison of 16-HQAM and non-hierarchical 16-QAM in DVB-SH systems.

3. Design of Improved Hierarchical Receivers

As shown in the previous section, an inherent drawback of HM is the performance degradation imposed on the LP stream. In what follows, we propose two upgraded reception schemes with the aim of improving the LP decoding performance.

3.1 Turbo-BICM Receiver

Our proposed receiver mainly consists in the combination of two sub-blocks, as shown in Fig. 6. The first sub-block, referred to as soft demodulator (also called demapper), produces bit metrics (probabilities and so called "*extrinsic information*") from the input symbols and the second one is a SISO decoder. The output of the SISO decoder is fed back to the soft demodulator and hence, each sub-block can take advantage of the quantities provided by the other sub-block as an *a priori* information.

Assume that the deployed OFDM modulator after 16-HQAM mapping in Fig. 2 uses N subcarriers through a frequency-selective multipath fading channel. At the receiver, after removing the cyclic prefix (CP) and performing fast Fourier transform (FFT), the received signal at the k-th subcarrier can be written as [11]:

$$y_k = H_k s_k + z_k, \quad k = 1, \ldots, N \tag{1}$$

where H_k is the channel frequency response coefficient, s_k is the complex hierarchical symbol, z_k is assumed to be zero-mean circularly symmetric complex Gaussian with distribution $z \sim \mathcal{N}_c(0, \sigma^2)$.

Let d_k^l be the l-th $(l = 1, \ldots, m)$ coded and interleaved bit corresponding to the hierarchical constellation symbol s_k, where m is such that 2^m is equal to the size of the constellation. We denote by $\gamma(d_k^l)$ and $\lambda(d_k^l)$ the extrinsic probability for the bit d_k^l at the demapper and the decoder output, respectively. Moreover, in this reception mechanism, the extrinsic probability provided by each subblock takes the place of the *a priori* probability for the other subblock.

Note that the main difference between the *Basic* receiver of Fig. 2 and this scheme, is that besides the *inner* iterations performed inside the SISO decoders (inherent to the

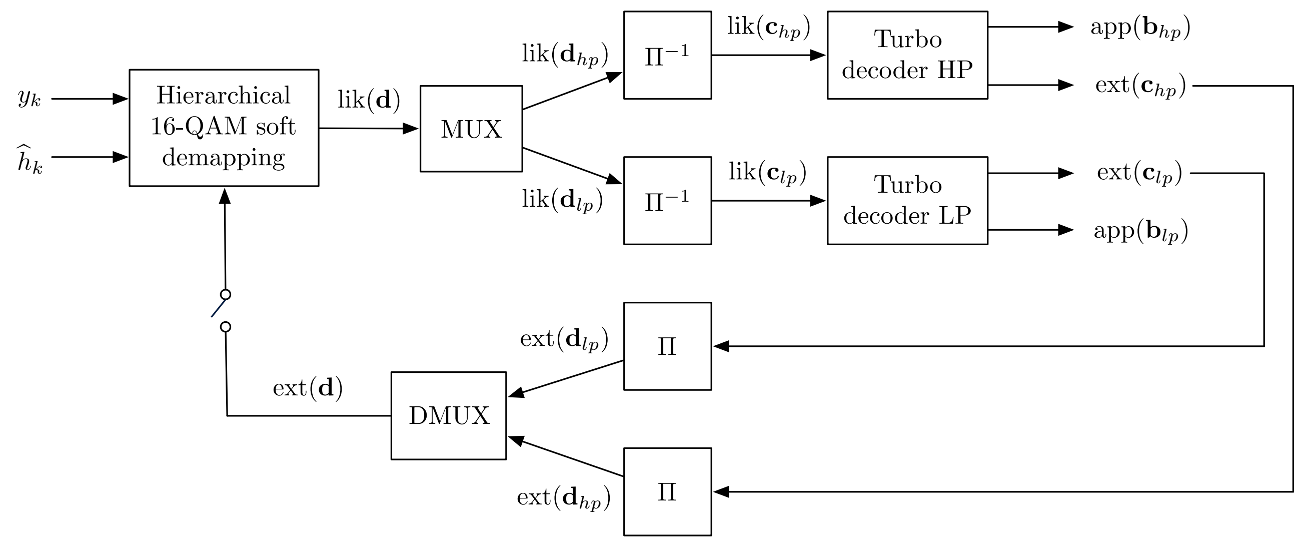

Fig. 6. Block diagram of the proposed *Turbo-BICM* reception scheme for hierarchical modulation.

decoding of turbo codes), the *Turbo-BICM* receiver performs some *outer* iterations involving the demodulator and the two SISO decoders (represented by the feedback in Fig. 6). In what follows, unless otherwise mentioned, by iteration we mean *outer* iteration. The demodulator extrinsic probability $\gamma(d_k^l)$ can be obtained as [12], [13]

$$\gamma(d_k^l) \propto \sum_{d_k^j \in \{0,1\}, j \neq l} e^{-\frac{1}{\sigma^2}|y_k - H_k s_k(d_k^1,\ldots,d_k^4)|^2} \prod_{j=1, j\neq l}^{m} \lambda(d_k^j). \quad (2)$$

Note that in this latter equation, the *a priori* probability of the bit d_k^l itself has been excluded, so as to let the exchange of *extrinsic* information between the channel decoder and the soft detector. Also, note that this term assumes independent coded bits d_k^l, which is a valid approximation for random interleaving of large size. At the first iteration, no *a priori* information is available on bits d_k^l, therefore the probabilities $\lambda(d_k^l)$ are set to $1/2$.

By successive application of equation (2), the soft demapper can calculate the vector of extrinsic probabilities $\gamma(\mathbf{d})$ corresponding to the compound sequence $\mathbf{d}$. The resulting vector is divided into the vectors $\gamma(\mathbf{d}_{lp})$ and $\gamma(\mathbf{d}_{hp})$ corresponding to the sequences $\mathbf{d}_{lp}$ and $\mathbf{d}_{hp}$, respectively. Each of the extrinsic vectors $\gamma(\mathbf{d}_{lp})$ and $\gamma(\mathbf{d}_{hp})$ is then de-interleaved as appropriate for the turbo decoding operation.

The overall process at the receiver consists in using (2) to regenerate the bit metrics and then alternating between demodulation and SISO decoding. After a given number of iterations, the information bits $\widehat{\mathbf{b}}_{hp}$ and $\widehat{\mathbf{b}}_{lp}$ are derived from hard thresholding the *a posteriori* probability vectors APP($\mathbf{b}_{hp}$) and APP($\mathbf{b}_{lp}$), respectively.

3.2 Sequential Receiver

We now describe the second solution proposed for improving the LP reception performance. The block diagram of the receiver is depicted in Fig. 7. As shown, this scheme differs from the *Turbo-BICM* receiver in that the two streams are decoded *sequentially*. The receiver starts by decoding the more protected HP stream. This part can be implemented by iterating demodulation and HP decoding. The main idea behind the *sequential* receiver is that the inherent reliability of the decoded HP bits can be used to help the decoding of the LP stream. This is because the affiliation of two bits to a quadrant is less likely to become disturbed and thus the decoded HP bits can be assumed perfectly correct at the SNR required for decoding the LP stream. This provides the LP stream demodulator with an *additional* information which is the is quadrant index where the complex symbol (more precisely the two LSB in each hierarchical symbol) is located.

The main advantage of this approach is that the hierarchical soft demapper is less sensitive to noise since, thanks to the quadrant information, the 16-HQAM constellation is transformed to the more robust QPSK constellation (see Fig. 1). Moreover, the receiver's complexity is reduced since the demodulator has to search among four QPSK constellation points rather than among sixteen 16-QAM constellation points (see the summation of equation (2)). One variant of this solution can be implemented by giving the soft *extrinsic* information for the HP stream to the LP demodulator instead of the hard estimated HP bits. However, this latter scheme requires a complete demapping (i.e., by using a 16-QAM constellation) for the LP stream. In this paper, for the sake of complexity reduction, we have adopted a sequential reception scheme that provides the hard HP bit stream.

By exploiting the quadrant information, the QPSK demodulator selects the correct quadrant and provides the a priori probabilities required for the LP SISO decoder. As shown in Fig. 7, this part of the receiver can itself be implemented by iterating demodulation and SISO decoding.

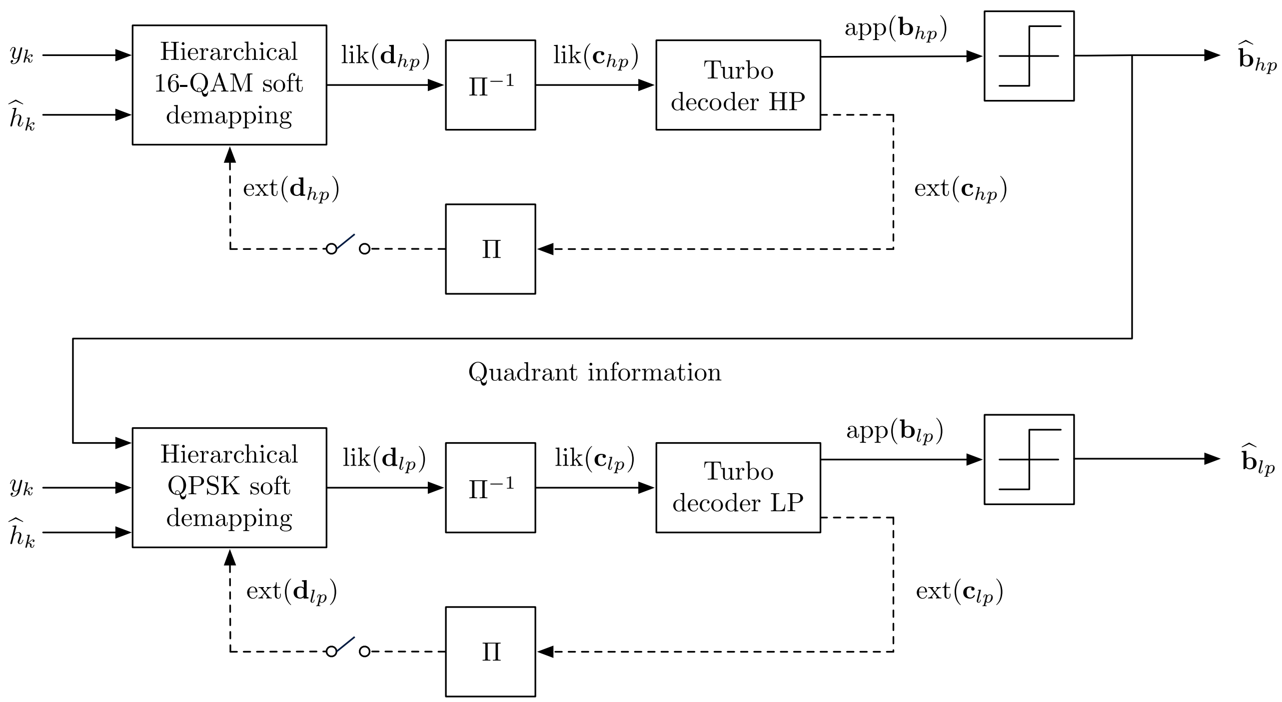

Fig. 7. Block diagram of the proposed *Sequential* reception scheme for hierarchical modulation.

4. Simulation Results

In this section, we provide numerical results to evaluate the performance improvement provided by the two proposed reception schemes in the presence of hierarchical modulation, in comparison with the *Basic* receiver. The transmitter adopted for all schemes is that depicted in Fig. 2. Throughout the simulations, each uncoded HP and LP packet has a length of $L_{hp} = L_{lp} = 1024$ bits. For HP and LP channel encoding, we consider a parallel turbo encoder with a common recursive systematic convolutional (RSC) constituent code with rate $1/3$ and constraint length 5, defined in octal form by $(37,21)_8$. All interleavers are pseudo-random and operate over their entire input sequence length. Data symbols belong to the hierarchical 16-HQAM constellation. One OFDM symbol is composed of 100 complex constellation symbol. Performance evaluation is performed over the uncorrelated Rayleigh fading channel. For each frame, a different realization of the channel has been drawn and remains constant during the whole frame. Moreover, the number of decoding iterations inside each turbo decoder is set to 8.

First the LP stream BER performance provided by the *Turbo-BICM* and the *Basic* reception schemes are compared. For keeping the decoding complexity comparable to that of the basic scheme, the *Turbo-BICM* decoder is implemented by performing only two pass of soft information exchange between the demodulator and the two SISO decoders. Fig. 8 shows that for $\alpha = 1$ (the least robust mode for the HP stream), the improvement in terms of required E_b/N_0 in order to attain a BER of 2×10^{-4} for the LP stream is about 0.6 dB, compared to the *Basic* receiver. Similar plots are shown in Figs. 9-10 for the case where α is equal to 2 and 4, respectively. We observe that when α increases, the amount of performance improvement is reduced compared to the case where $\alpha = 1$. Before explaining the reasons behind this observation, let us analyze the case of the proposed *Sequential* receiver.

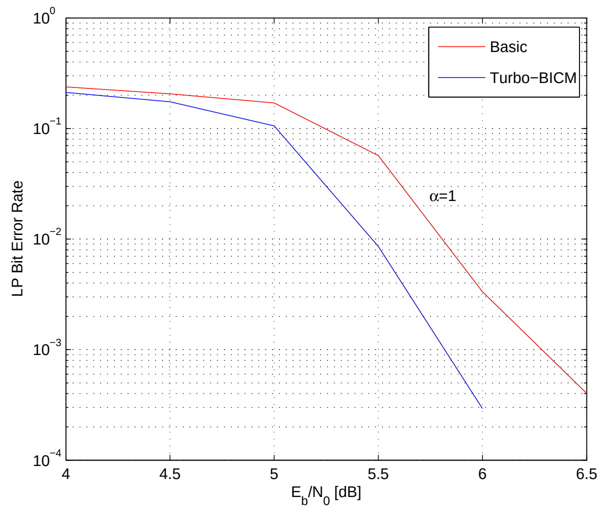

Fig. 8. Improvement of the LP stream BER performance with the proposed *Turbo-BICM* receiver, $\alpha = 1$.

Fig. 11 compares the LP stream BER of the *Sequential* and the *Basic* receivers when the HM parameter α is equal to 1. A first observation is that the amount of performance

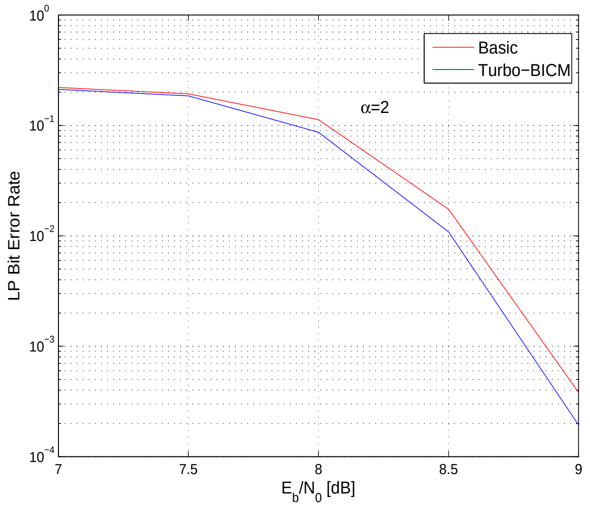

Fig. 9. Improvement of the LP stream BER performance with the proposed *Turbo-BICM* receiver, $\alpha = 2$.

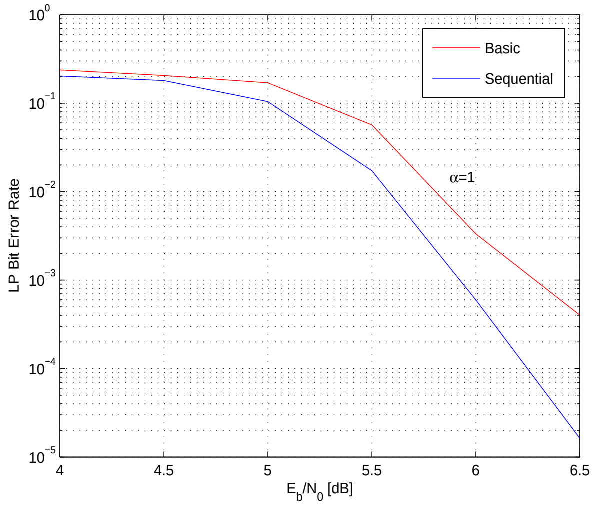

Fig. 11. Improvement of the LP stream BER performance with the proposed *Sequential* receiver, $\alpha = 1$.

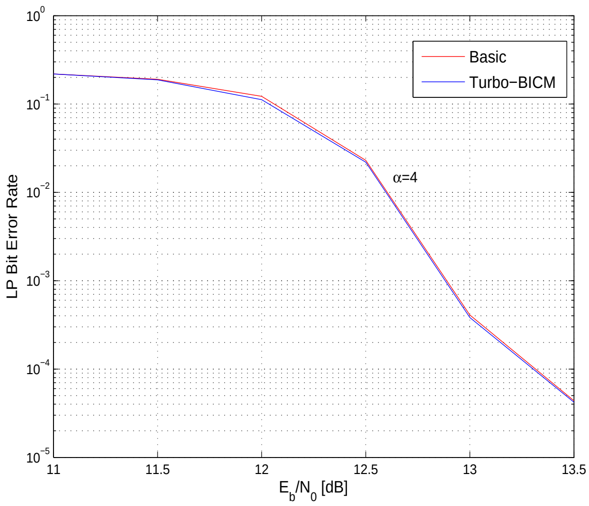

Fig. 10. Comparison of the LP stream BER performance achieved by the proposed *Turbo-BICM* receiver and the *Basic* receiver, $\alpha = 4$.

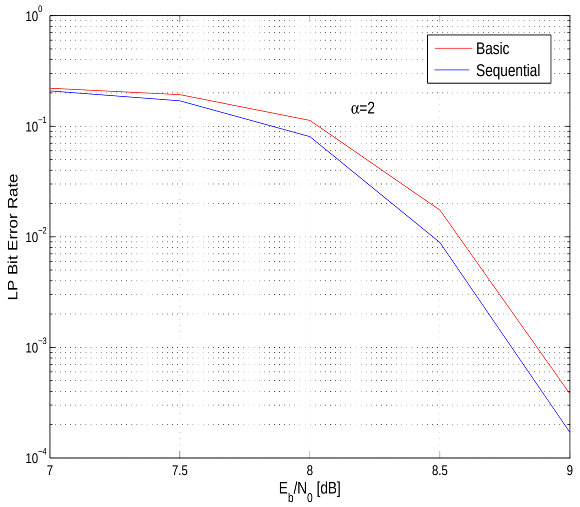

Fig. 12. Improvement of the LP stream BER performance with the proposed *Sequential* receiver, $\alpha = 2$.

improvement provided by the *Sequential* receiver is comparable to that provided by the *Turbo-BICM* receiver (almost 0.6 dB of SNR gain at a BER of 10^{-5}). Moreover, as discussed in Section 3.2, the improvement in the LP BER provided by the *Sequential* receiver is obtained together with a reduction in the demodulation complexity. Notice also that the results of Fig. 11 are obtained without any iteration between the demodulation and the SISO decoding process.

Obviously, the amount of performance improvement brought by this scheme can be even larger if one iterates demodulation and SISO decoding at the expense of increased receiver complexity.

Similar plots are shown in Fig. 12 for the case where α is equal to 2. We observe that the *Sequential* receiver still outperforms the *Basic* receiver but the amount of improvement is slightly reduced compared to the case where $\alpha = 1$. This is due to the fact that when α increases, the soft probabilistic information for the HP stream becomes more reliable. More precisely, the *Basic* scheme which processes the two streams simultaneously, is provided with a more reliable quadrant information and performs closer to the *Sequential* receiver which has the most precise quadrant information. In other words, decoding the LP stream when $\alpha = 1$ benefits more from the *Sequential* receiver than when $\alpha = 2$ or $\alpha = 4$.

Finally, note that in the two schemes proposed above, the performance of the HP stream remains unchanged compared to the *Basic* scheme.

5. Conclusion

The problem of signal detection in DVB-SH systems with hierarchical modulation was investigated. Hierarchical modulation can be effectively used to upgrade a digital broadcast system by creating different levels of error protection. It was shown that the enhanced protection offered by hierarchical modulation for the HP stream is at the price of lower noise immunity for the LP stream. The hierarchical modulation parameter α can be used to control the tradeoff between the penalty imposed on the LP stream and the protection of the HP stream. We proposed two reception schemes (called *Turbo-BICM* and *Sequential*) to improve the LP detection performance. The *Turbo-BICM* receiver led to an improvement of the LP stream BER thanks to the exchange of soft information between the demodulator and the two SISO decoders. Our numerical results indicated that the *Sequential* receiver can provide the same amount of performance improvement than the *Turbo-BICM* scheme. The amount of performance improvement provided by the *Sequential* receiver was shown to be more important when the HP stream is less protected (i.e., for small values of α). The important point is that the performance improvement brought by the *Sequential* decoder was obtained together with a reduction of the complexity at the receiver. Although the proposed receivers in this paper were able to improve the LP BER performance, the derivation of other encoding/decoding schemes providing further gain is an interesting research direction.

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