Rotated QAM constellations to improve BICM performance for DVB-T2

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Rotated QAM Constellations to Improve BICM Performance for DVB-T2

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***Abstract* — A technique intended to increase the diversity order of Bit-Interleaved Coded Modulations (BICM) over non Gaussian channels is presented. It introduces simple modifications to the mapper and to the corresponding demapper. They consist of a constellation rotation coupled with signal space component interleaving. Iterative processing at the receiver side can provide additional improvement to the BICM performance. This method has been shown to perform well over fading channels with or without erasures. It has been adopted for the 4-, 16-, 64- and 256-QAM constellations considered in the DVB-T2 standard. Resulting gains can vary from 0.2 dB to several dBs depending on the order of the constellation, the coding rate and the channel model.**

Keywords — Bit-interleaved coded modulation, constellation rotation, component delay, diversity, iterative demapping, fading and erasure channel.

I. INTRODUCTION

Next generation broadcast systems such as DVB-T2 should be designed to satisfy the need of high data rate transmissions through improving the robustness to severe channel conditions. Reliable transmissions over channels with deep fades requires the increase of the diversity order. The Bit-Interleaved Coded Modulation (BICM) principle [1] introduced by Zehavi in [2] currently represents the state-of-the-art in coded modulations over fading channels. The proposed technique intends to increase the diversity order of BICM through the introduction of modifications concerning mainly the mapper and the demapper. These modifications involve applying a rotation to the constellation and introducing interleaving between the in-phase and quadrature components of the transmitted signal.

This paper is organized as follows:

In section II, we start by a brief description of the BICM approach. Then, the proposed diversity increase technique is detailed.

In section III, ways to adapt the proposed technique to the context of DVB-T2 are elaborated.

Section IV shows simulation results of the improved system over channels well suited to DVB-T2.

Section V concludes the paper.

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II. INCREASING THE DIVERSITY ORDER OF BICM SCHEMES OVER FADING CHANNELS

A. *BICM System Description*

The BICM transmitter is described in Fig. 1. The information frame **u** is encoded via a binary outer Forward Error Correcting (FEC) code. The encoded sequence **c** is then interleaved at the bit level by π and the resulting interleaved sequence **v** is mapped to a succession of complex channel symbols **x**. At the signaling interval *t*, *m* bits of the interleaved sequence are mapped to symbol $x_t = (x_t^I, x_t^Q)$ chosen from a 2^m-ary constellation by an *m*-bit signal label. x_t^I and x_t^Q represent the in-phase and quadrature components of the constellation symbol.

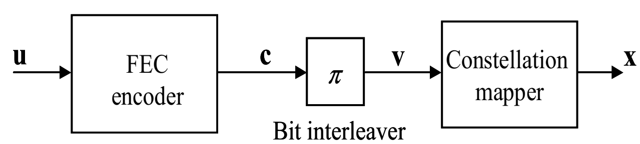

Figure 1. The BICM transmitter structure

At the receiver side, the demapper provides probabilities or log-likelihood ratios related to every bit of sequence **v**. After deinterleaving they constitute the input to the soft-input FEC decoder which delivers decisions related to the information sequence **u**.

We have proposed a technique to increase the diversity order of the BICM scheme described in Fig. 1. This technique relies on two tiers: correlating the in-phase I and quadrature Q components of the transmitted signal and making these two components fade independently.

B. *Correlating I and Q Components*

For QAM schemes, since Gray mapping is used, I and Q channels can be mapped separately as two independent PAMs. In the example of Fig. 2, bits S_1 and S_2 are mapped to the I channel independently of bits S_3 and S_4 which are mapped to the Q channel. Consequently, at the receiver side, all constellation points need both I and Q components to be identified and the estimation of I gives no information about Q and *vice-versa.*

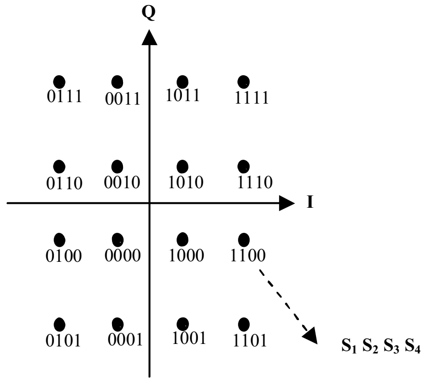

Figure 2. Example of 16-QAM Gray mapping.

In order to circumvent this natural independence, I and Q components have to be correlated for every constellation signal. This correlation could be obtained by changing the constellation mapping. However it has been stated in [3] that with strong FEC codes such as turbo or LDPC codes, best performance is obtained with Gray mapping. Then, a simple answer to the correlation issue involves applying a simple rotation to the constellation. This approach is a particular case of the multidimensional modulation schemes designed to optimize diversity order over fading channels and detailed in [4] and [5].

C. *Ensuring Independent Fading for I and Q Components*

When a constellation signal is submitted to a fading event, its I and Q coordinates fade identically. Thus, in case of severe fading, the information transmitted on I and Q channels suffers from an irreversible loss. A means of avoiding this loss involves making I and Q fade independently. Then, in most cases only half of the transmitted information is affected. When combined with the constellation rotation proposed in the previous section, this feature is expected to help the demodulator better recover the transmitted information.

One way to allow both component axes to fade independently is to introduce coordinate interleaving. This solution known as Signal Space Diversity (SSD) was first proposed as means of increasing diversity for trellis-coded modulations in [6]. Simplified component interleaving can be introduced depending on the fading channel model. In [7], the authors proposed the replacement of I and Q component interleaving by a simple time delay for one of the two component axes over uncorrelated flat Rayleigh fading channels.

D. *BICM Scheme with Signal Space Diversity (BICM-SSD)*

The transmitter and receiver structure of the proposed BICM-SSD scheme is presented in Fig. 3.

Due to the constellation rotation and the delay insertion, the binary information contained in each constellation point is transmitted twice over the channel. Consequently, the rotated constellation can be seen in a way as a repetition code proceeding at the constellation symbol level. From this point of view, the BICM transmitter of Fig. 3(a) becomes a serial concatenation of two codes separated by an interleaver. Therefore, at the receiver side, the conventional structure presented in Fig. 3(b) can be beneficially replaced by an iterative structure, as described in Fig. 4 in order to get additional gains. Extrinsic information related to every coded bit is then computed by the FEC decoder and fedback at the demapper input as *a priori* information.

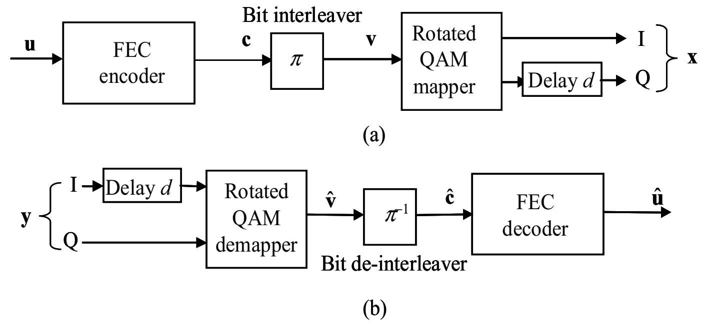

Figure 3. Structure of the proposed BICM-SSD scheme: (a) transmitter and (b) conventional receiver.

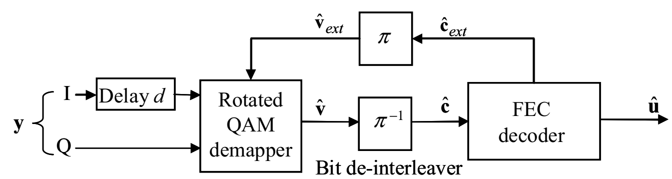

Figure 4. Iterative receiver structure for the proposed BICM-SSD scheme.

Such a BICM scheme with iterative demapping at the receiver has already been proposed in [8] for transmission over fading channels with a DVB-RCS turbo code [9] as a FEC code. A gain of 0.8 dB at a Bit Error Rate (BER) of 10^{-7} has been observed over Rayleigh fading channel for a rotated and Q-delayed 16-QAM and coding rate of $R = 1/2$.

E. *Impact on Complexity*

In the case of a classical non-rotated 2^m–QAM, the number of metrics to be computed at the demapper is $2\times 2^{m/2}$. Each metric is computed over one dimension corresponding to the in-phase I or quadrature Q component. This is due to the independence induced by the Gray mapping.

In the case of a rotated 2^m–QAM, the number of metrics to be computed at the demapper becomes 2^m. Due to the correlation between the I and Q components introduced by the rotation, each metric is now computed over two dimensions corresponding to the I and Q components of the rotated constellation signal.

The computational complexity is multiplied by a factor of $\sqrt{2^m}$ with respect to the classical demapper case.

III. Application to DVB-T2

A. DVB-T2 BICM Module and Channel Model

In the DVB-T2 baseline system architecture, the BICM module consists of a FEC encoder based on an outer BCH code and an inner LDPC code, followed by a bit interleaver and a constellation mapper that allows the encoded bits to be possibly mapped to a QPSK, a 16-QAM, a 64-QAM, or a 256-QAM constellation.

In the DVB-T2 context, the BICM module is followed by several levels of interleavers. At the constellation signal or cell level, a pseudo-random cell interleaver is combined with a row-column time interleaver in order to spread the constellation cells along several FEC codewords. A frequency interleaver is then applied to the OFDM cells within a single OFDM symbol in order to mitigate the effect of frequency selective fading.

Consequently, when only one transmitter is considered, the transmission channel model can be approximated by a flat fading Rayleigh model. Under coherent detection assumption, the received discrete time baseband complex signal y_t can be written as:

$$y_t = a_t x_t + n_t \tag{1}$$

where x_t is the complex signal transmitted at time t, a_t is a Rayleigh distributed fading coefficient with $E(a_t^2) = 1$ and n_t is a complex white Gaussian noise with spectral density $N_0 / 2$ in each component axis. Due to the different interleavers, consecutive fading coefficients are assumed uncorrelated.

In a single-frequency network, where several transmitters simultaneously send the same signal over the same frequency channel, some additional erasure events have to be taken into account in the channel model:

$$y_t = a_t e_t x_t + n_t \tag{2}$$

where e_t is a random discrete process taking a value of 0 with a probability of P_e and a value of 1 with a probability of $1 - P_e$. At the receiver side, the transmitted energy has to be normalized by a $\sqrt{1 - P_e}$ factor in order to cope with the loss of transmitted power. Erasure ratios up to 15 % corresponding to $P_e = 0.15$ have been considered in the context of DVB-T2.

The occurrence of erasure events sets a bound on the coding rate R. In fact, with an erasure probability of P_e a reliable coded transmission cannot be ensured with a redundancy ratio lower than P_e, or in other words with a coding rate greater than $1 - P_e$. This prevents the conventional system from operating at high coding rates in single-frequency networks.

B. Specificity of the Application to DVB-T2

The BICM-SSD principle had been originally devised for fading channels. However this technique turned out to be also well adapted to channels with erasures. As previously mentioned, due to the constellation rotation and the delay insertion, the binary information contained in each constellation point is transmitted twice over the channel. Conversely, each transmitted cell contains the information related to two different constellation points. Thus, when a transmitted cell is erased, the information related to the corresponding two constellation points can nevertheless be retrieved from non-erased cells.

In light of the presence of erasure events, some aspects of the BICM-SSD principle have to be reconsidered. In previous studies, the choice of the rotation angle α was based on maximizing the so-called *product distance* [5] in order to minimize the pairwise error probability between two different transmitted sequences. This criterion was derived for fading channels.

For the QAM modulations under study, it leads to $\alpha \approx 31.7°$. The second best value for 16-, 64-, and 256-QAM is $\alpha = 22.5° (\pi / 8)$. Unfortunately, this criterion is only valid for asymptotical performance, that is for high values of Signal-to-Noise Ratios (SNR). In practice, actual operating SNRs can be rather low, especially when a powerful FEC coding is considered. Consequently, the product distance criterion is suboptimal for the SNR region of interest and the angle values mentioned above do not lead to the best actual coded performance.

Moreover, for erased constellation points, the distances are no longer 2-dimensional because they are measured on the projection of the point on the non-erased axis, I or Q. In this case, a criterion based on a 1-dimensional distance should be introduced.

Finally, without going into details, the angle values adopted in the standard represent a compromise between the two criteria that suit the fading channels and the fading channels with erasures. They are given in Table I as a function of the modulation order.

TABLE I. Values of the Rotation Angle

Constellation	Rotation angle value in degree
QPSK	29.0
16-QAM	16.8
64-QAM	8.6
256-QAM	3.6

C. Performance Analysis of the Demapper

The potential improvement in error correcting performance of BICM-SSD with respect to a classical BICM can be inferred from the error rate curves at the output of the demapper. Fig. 5 compares the BER at the output of a classical 16-QAM demapper and at the output of a 16-QAM rotated and Q-delayed demapper over the flat fading Rayleigh channel. Two curves, labeled *genie-aided* have been added. They represent the performance of the demapper when error-free *a priori* information is provided to the demapper. These curves represent a lower bound on the BER achievable with an iterative receiver.

In the case of a non-iterative receiver, the curves of the classical and proposed demapper cross around an E_b/N_0 of 4 dB. Thus, an overall gain can be obtained provided that the FEC decoder operates at SNRs greater than the crossing value. Note that the potential gains increase with the operating SNR. As a direct consequence, larger gains are expected when the coding rate increases.

With the classical mapper/demapper, one can observe that the genie-aided curve is almost identical to the original one. This means that no significant improvement is expected if iterative demapping is implemented. On the contrary, with the proposed scheme, the genie-aided curve shows that an additional gain can be achieved with an iterative receiver. This gain allows the proposed demapper to perform better than the conventional one at all SNR values.

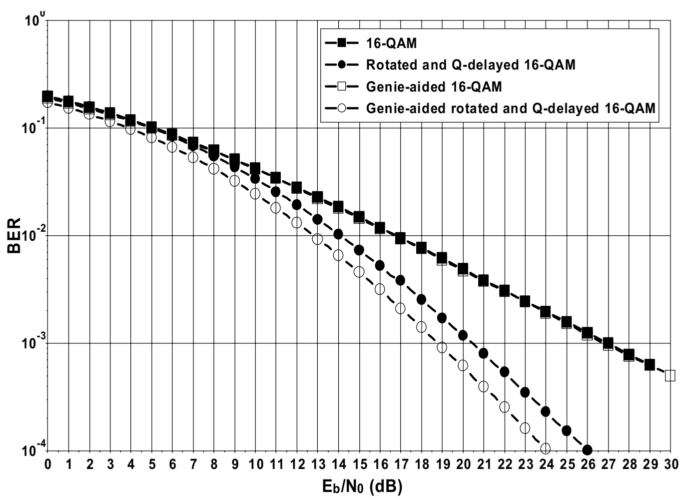

Figure 5. BER at the output of the 16-QAM demapper for a transmission over flat fading Rayleigh channel.

Fig. 6 extends the BER results of Fig. 5 to a transmission over a flat fading Rayleigh channel with 15% of erasures.

The improvement in performance due to the rotation of the constellation and the insertion of the component delay increases with respect to the classical demapper when the erasure ratio increases. This effect can be observed in Fig. 6. In addition, for a given coding rate *R*, the operating point is shifted to higher SNR values when the erasure ratio increases, predicting a larger gain.

When iterative demapping is used, the genie-aided curves of Fig. 6 predict a larger potential performance benefit when compared to the classical Rayleigh channel.

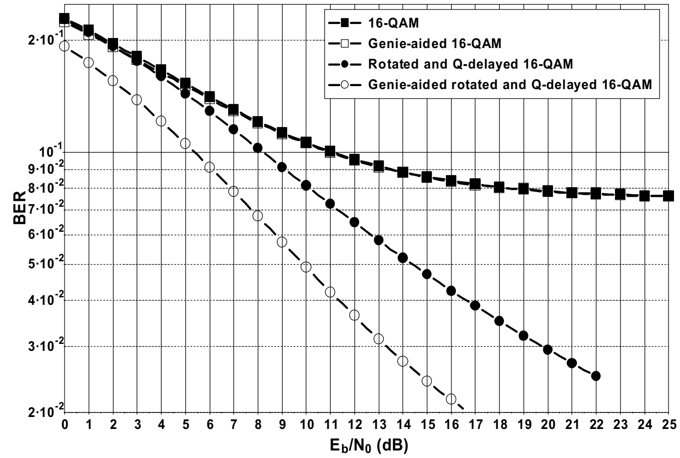

Figure 6. BER at the output of the 16-QAM demapper for a transmission over flat fading Rayleigh channel with 15% of erasures.

The error floor of the BER curve corresponding to the classical demapper predicts a limit on the operating point and consequently on the coding rate. On the contrary, when the rotation and the component delay are applied, no error floor is seen down to 2.10^{-2} predicting the possibility to operate at higher coding rates.

IV. SIMULATION RESULTS

Simulations were carried out in the context of the DVB-T2 transmission chain over two different channel types: the Rayleigh fading channel and the Rayleigh fading channel with erasures. A frame size of 64,800 bits corresponding to the one of the DVB-S2 code [10] adopted as well in DVB-T2 is used.

The LDPC decoder applies the sum-product algorithm [11] and a maximum of 50 iterations are performed for every decoded frame. Due to the error correcting capability of the additional BCH decoder, comparisons of different coded LDPC solutions are performed at a BER of 10^{-6}. The resulting number of errors at this BER level is assumed to be within reach of the BCH decoder correcting capability.

When iterative demapping is used, feedback to the demapper is performed every LDPC decoder iteration. This choice keeps the same maximum number of decoder iterations as the classical case. It has the advantage of offering the best error correcting performance while minimizing the impact on computation complexity.

The chosen value of the Q delay in the performed simulations is equal to one ($d = 1$) QAM symbol period. An S-random interleaver [12] was used as BICM interleaver.

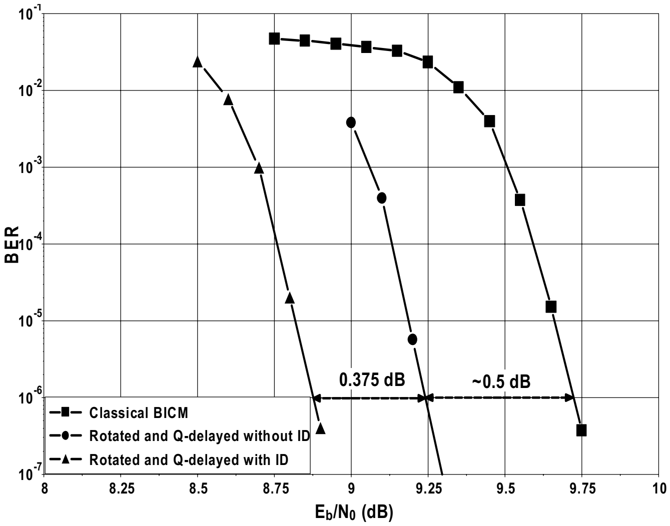

Figure 7. BER at the output of the LDPC decoder for the proposed demapper with and without iterative demapping compared to the classical BICM 16-QAM demapper. Code rate $R = 4/5$ and 64,800-bit frames. Transmission over flat fading Rayleigh channel.

The curves of Fig. 7 show that the proposed system outperforms the state-of-the-art BICM system. It has around 0.5 dB gain at a BER of 10^{-6} when the rotation and the Q-delay are applied. It reaches nearly 0.9 dB when iterative demapping is introduced. This improvement in performance can be predicted by the BER curves of Fig. 5. In fact, by taking into account the shift corresponding to the use of a code rate $R = 4/5$, these curves give an insight into the BER at the input of the LDPC decoder.

Note that in the case of the fading channel with erasures, a greater number of frames in error is needed in order to obtain a reliable BER curve without ruggedness due to the recurrence of burst errors. Typically, 100 frames in error were taken for the lowest points of the simulation results in Fig. 8 instead of 50 frames in error for the results in Fig. 7.

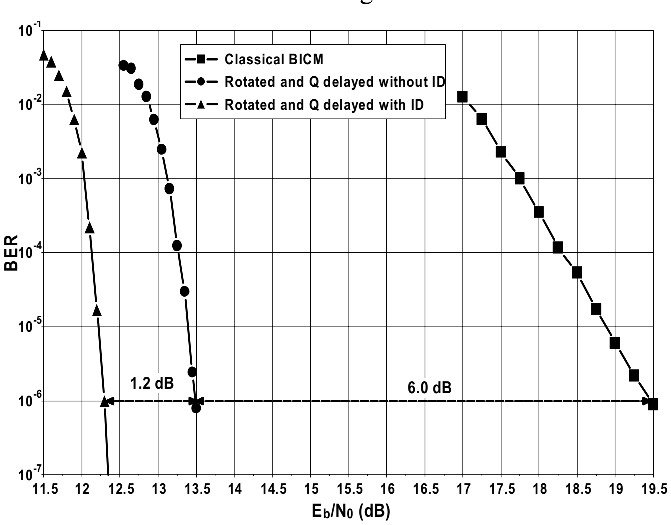

Figure 8. BER at the output of the LDPC decoder for the proposed demapper with and without iterative demapping compared to the classical BICM 16-QAM demapper. Code rate $R = 4/5$ and 64,800-bit frames. Transmission over Flat fading Rayleigh channel with 15% of erasures.

The simulation results plotted in Fig. 8 show a substantial improvement in performance for the proposed system with respect to the classical BICM over fading channels with 15% of erasures. The gain is 6.0 dB for the rotated and Q-delayed system. It reaches 7.2 dB when iterative demapping is introduced.

Note that the slope of the BER curve for the proposed system is steeper than the one of the classical BICM, predicting an increase in the performance gain with increasing E_b/N_0. This difference in the slopes can be explained by the improved diversity order due to the introduction of the rotation and the Q delay.

Another important aspect to be noted is the robustness of the proposed system with respect to erasure events. In fact from Fig. 7 and Fig. 8, a penalty of only 3.2 dB is observed at 10^{-6} of BER when the erasure ratio reaches 15%. This loss reaches 9.7 dB for the classical BICM system.

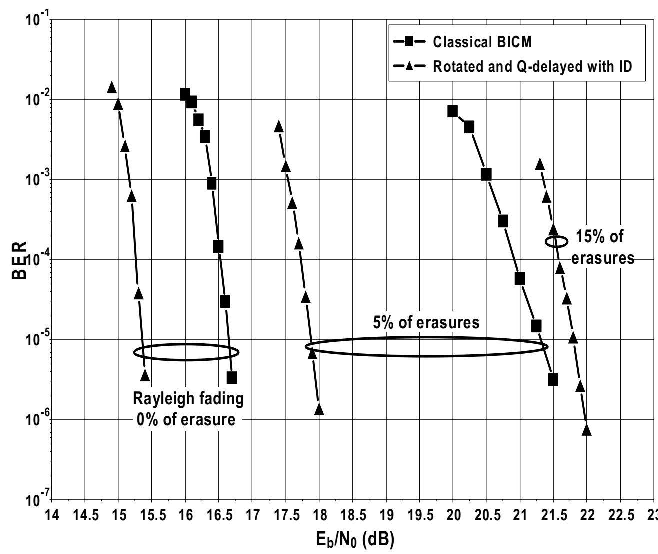

Figure 9. BER at the output of the LDPC decoder for the proposed demapper with iterative demapping compared to the classical BICM 64-QAM demapper. Code rate $R = 9/10$ and 64,800-bit frames. Transmission over flat fading Rayleigh channel, flat fading Rayleigh channel with 5% and 15% of erasures.

Fig. 9 shows BER curves over a flat fading Rayleigh channel without erasure, with 5% and 15% of erasures for a 64-QAM and a code rate of $R = 9/10$.

Comments regarding simulation results of Fig. 8 apply as well for the curves of Fig. 9. In fact, we can see that the gain increases with the erasure ratio and that the proposed system attains convergence with an erasure ratio beyond the redundancy rate of the LDPC code for the 15% erasure case. The classical BICM system has been omitted for the case of 15% of erasures. In fact, the decoder does not attain convergence since the erasure probability $P_e > 1\text{-}R$.

V. Conclusion

In this paper we have proposed an approach to increase the diversity order of coded modulations. It offers substantial gains with respect to classical BICM. It is well suited to severe channel conditions consequently improving the robustness of the receiver to deep fades and erasure events. It allows the transmission of reliable information for erasure ratios beyond the redundancy rate of the FEC code. Thanks to these advantages, this technique has been adopted in the second generation Digital Video Broadcasting-Terrestrial standard.

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