DESIGN OF ROTATED QAM MAPPER/DEMAPPER FOR THE DVB-T2 STANDARD

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ABSTRACT
Signal Space Diversity (SSD) has been lately adopted into the second generation of the terrestrial digital video broadcasting standard DVB-T2. While spectrally efficient, SSD improves the performance of QAM constellations over fading channels thanks to an increased diversity. In this paper, flexible mapper and demapper architectures for DVB-T2 standard are detailed. A detection based on the decomposition of the constellation into two-dimensional sub-regions in signal space associated to an algorithmic simplification constitute the main novelty of this work. They enable to strongly decrease the complexity of the demapper. The design and the FPGA prototyping of the resultant architecture are then described. Low architecture complexity and measured performance demonstrate the efficiency of the detection method.

Index Terms—DVB-T2, erasure channel, QAM, fading channel, demapper architectures, FPGA design and prototyping

1. INTRODUCTION
In light of the analogue switch off in several countries, the Digital Video Broadcasting (DVB) technical module has recently been adopted the second generation of terrestrial video broadcasting standard (DVB-T2). Next generation broadcasting systems should be designed to make full use of spectral resources while providing reliable transmissions in order to enable services like multichannel HDTV and innovative data casting services. The efficient usage of the radio spectrum can be achieved by the introduction of Single Frequency Networks (SFN) [1] where several transmitters simultaneously send the same signal over the same frequency channel. However, SFN entail undesirable effects on the transmission channel since their deployment leads to the introduction of deep fades. Reliable transmissions over deeply faded channels require an increase in the diversity order. The Bit-Interleaved Coded Modulation (BICM) principle [2] introduced by Zehavi in [3] currently represents the reference in coded modulations over fading channels.

The Signal Space Diversity (SSD) principle introduced in [4-5] improves the diversity order of BICM schemes over fading channels. It is divided into two steps. The first step consists of rotating the constellation in signal space following a particular angle value. The second step applies an interleaving of one of the In-phase (I) or Quadrature (Q) components of the signal with respect to the other. When concatenated with Forward Error Correcting (FEC) codes, modulations with SSD show an improvement in performance for high coding rates [6] over fading channels. In the presence of erasure events, BICM with SSD achieves higher spectral efficiencies beyond the redundancy ratio of the outer FEC [6]. In addition, improvement in performance by several dBs over severe channel conditions has been observed. The improved robustness to erasure events led to the adoption of QAM constellations with SSD in DVB-T2.

The application of SSD to QAM constellations has an important impact on the design of the mapper and its corresponding demapper. In fact when Gray mapping is used, applying a rotation to the signal constellation breaks the independence between the in-phase and quadrature components of the QAM. Consequently, the Maximum Likelihood (ML) QAM detector cannot apply two independent Pulse Amplitude Modulation (PAM) detectors anymore. Instead, both I and Q signal components are needed for the computation of the demapper metrics. For this reason, the design of high throughput, low complexity, low latency architectures for a BICM with SSD is a great challenge. In this paper, a novel detection method that reduces the demand of computational resources is presented. This method is based on the decomposition of the constellation into sub-regions in signal space.

The remainder of the paper is organized as follows. Section 2 recalls the basic principles of the BICM and SSD. Then, a simplified detection method is introduced in Section 3. The challenging issue of designing resultant demapper architecture is developed in Section 4. Finally, an implementation of the flexible demapper and its experimental setup onto FPGA devices are presented.

2. SYSTEM DESCRIPTION
2.1. Channel model
In this section, we describe the channel model used by the technical module of DVB-T2 in order to simulate the effect of erasure events. The model is a modified version of the classical Rayleigh fading channel. Assuming infinite length channel interleaving, erasure events can be modeled by a discrete random process $e_t$ taking value 0 with a probability of $P_e$ and value 1 with a probability of $1-P_e$. The received discrete time baseband complex signal $y_t$ becomes:

$$y_t = \rho_t e_t x_t + n_t$$  \hspace{1cm} (1)

where $x_t$ is the complex transmitted signal, $\rho_t$ is a Rayleigh
distributed fading coefficient with $E(\rho^2) = 1$, and $n_t$ is a complex Additive White Gaussian Noise (AWGN) with spectral density $N_0/2$ in each component axis. We assume coherent detection and perfect Channel State Information (CSI) knowledge so that $\rho$ and the phase of the signal are perfectly estimated and available at the receiver. When the channel is erasure free ($P_e = 0$), it becomes a classical Rayleigh fading channel.

### 2.2. BICM with SSD

The SSD principle consists of introducing modifications to the mapper and demapper as shown in Figure 1. The QAM constellation is rotated by an angle $\alpha$ and the component axes are interleaved [5]. The in-phase and quadrature components are therefore subject to two different fading coefficients increasing the degree of diversity of the BICM scheme.

![Fig. 1: the BICM with SSD structure (a) transmitter and (b) receiver](image)

The information frame $\mathbf{u}$ goes through the FEC encoder to generate the codeword $\mathbf{e}$. Afterwards, this sequence $\mathbf{e}$ is interleaved using the bit interleaver $\pi$ to generate the mapper input sequence $\mathbf{v}$. At time $t$, $m$ consecutive bits of the interleaved sequence $\mathbf{v}$ are mapped to complex symbol $x_t$ chosen from a $2^m$-ary rotated constellation $\mathcal{X}$ by an $m$-bit signal label $\mu_m : x_t = \{(x^I_t, x^Q_t) \in \mathcal{X}\}$

where $x^I_t$ and $x^Q_t$ represent the in-phase and quadrature components of $x_t = \mu_m(v_t)$. At the receiver side, the Log Likelihood Ratio (LLR) computation has to take into account the introduced modifications (cf. Figure 1(b)). For Gray-mapped QAM constellations, the demapper now calculates a two-dimensional squared Euclidean distance for the computation of the LLR $\hat{\nu}_t$ related to the $i^{th}$ bit of $v_t$. The resulting $\hat{\nu}_t$ becomes:

$$\hat{\nu}_t = \log \left( \frac{\sum_{x_t \in \mathcal{X}} P(x_t) \exp\left(\frac{-D_{ev}(x_t)}{2\sigma^2}\right)}{\sum_{x_t \in \mathcal{X}} P(x_t) \exp\left(\frac{-D_{ev}(x_t)}{2\sigma^2}\right)} \right)$$

where

$$D_{ev}(x_t) = \sqrt{\left(\mathbf{y}_{eq,t}^I - x^I_t\right)^2 + \left(\mathbf{y}_{eq,t}^Q - x^Q_t\right)^2}$$

$\mathbf{y}_{eq,t}^I, \mathbf{y}_{eq,t}^Q$ represent the in-phase and quadrature components of the equalized discrete time received complex baseband symbol $y_{eq,t}$. $\sigma^2$ is the channel noise variance and $\mathcal{X}$ represents the subset of constellation symbols whose $i^{th}$ bit is equal to $b, b \in \{0,1\}$. The a priori probability $P(x_t)$ is unavailable at the receiver, an equally likely assumption is made ($P(x_t) = \frac{1}{2^m}$). After de-interleaving, the LLRs of (3) are used as inputs to the decoder. When the received signal $y_t$ is erased, the LLR computation is updated accordingly. The corresponding squared Euclidean distance $\left(\mathbf{y}_{eq,t}^I - x_t\right)^2$ is replaced by 0 in (4).

### 3. SIMPLIFIED ROTATED DEMAPPER

The LLR computation of equ. (3) has to be simplified for hardware implementation. However, the piecewise linear approximation based directly on channel observations widely used for square QAM constellations is no longer applicable. In fact due to the rotation, both component axes (I and Q) are needed for the LLR computation of every transmitted bit. One efficient method to reduce complexity is the use of the Max-Log approximation:

$$\ln \left( \exp(a_1) + \cdots + \exp(a_k) \right) = \max_{i=1\cdots k}(a_i)$$

Equ. (3) becomes:

$$\hat{\nu}_t = \frac{1}{2\sigma^2} \left[ \min_{x_t \in \mathcal{X}} D_{ev}(x_t) - \min_{x_t \in \mathcal{X}} D_{ev}(x_t) \right]$$

Nevertheless, soft demapping is still demanding in computational complexity. For instance, 256 squared Euclidean distances have to be calculated, if we consider a 256-QAM constellation. It means that 1024 multipliers are necessary to perform this computation.

In order to reduce the number of squared Euclidean distance computations for high order QAM constellations, we propose a detection method based on the decomposition of the constellation into two-dimensional sub-regions in signal space. This leads to an LLR computation on a limited number of squared Euclidean distances of the original high order QAM constellation. We have also adapted the method to the case of a fading channel with erasures.

### 3.1 Constellation sub-regions in signal space

Equ. (6) is a function of two 2-dimensional (2D) squared Euclidean distances:

- From the received point (channel output) to the closest point where the considered bit is equal to 0
- From the received point to the closest point where the considered bit is equal to 1

Consequently, any sub-region should include the closest two points with values 0 and 1 for every LLR computation. A closer look at the Gray mapping of the constellation allows the partitioning of the constellation into sub-regions...
according to the sign of the received channel observation $y^I$ and $y^Q$.

$$
\begin{array}{c|c|c}
 & x^I \text{ for } v^I = 1 & x^I \text{ for } v^I = 0 \\
\hline
v^I & [-7.96, 0.06] & [0.06, 7.96] \\
v^J & [-4.01, 4.01] & [-7.96, -3.89] & [3.89, 7.96] \\
\end{array}
$$

Table 1: the interval of the I component $x^I$ where the 3 constellation bits $v^I$ take respectively the values 1 and 0.

If we consider the rotated 64-QAM case for example (Figure 2), table 1 shows the interval of the I component $x^I$ where the 3 constellation bits $v^I$ take respectively the values 1 and 0. Note that since the axes are symmetric with respect to the origin, the same reasoning applies to the Q component $x^Q$. From table 1, we can see that bit $v^0$ sets the critical condition on the delimitation of the sub-region since $v^I=1$ for all $x^I < 0$ (respectively $v^I=0$ for all $x^I > 0$). Consequently, a good choice for the sub-region where $x^I < 0$ would be $[-7.96, 1.90]$ (respectively $[-1.9, 7.96]$ for $x^I > 0$). Notice that in this sub-region, the condition on bits $v^J$ and $v^K$ is satisfied. The definition of the proposed sub-regions as a function of the sign of the received I and Q components is shown in Figure 2. When an erasure occurs, the detection by sub-regions is limited to the non-erased remaining axis following the preceding sub-region definition. We shall denote it by $1D$-region.

3.2 Impact on computational complexity and performance

Detection by sub-region selection denoted by $2D$-region significantly reduces the number of needed squared Euclidean distance computations for high order QAM constellations. In the case of 64-QAM, every sub-region contains 25 constellation points. This leads to a reduction of 60% in number of needed squared Euclidean distances (25 computations instead of 64). The complexity reduction increases with the order of the constellation. In fact, it reaches 69% for a 256-QAM.

Figures 3 and 4 show that detection by sub-region selection has no impact on the performance compared to the Max-log simplification.
4. DESIGN OF ROTATED MAPPER/DEMAPPER
In this section, generic rotated mapper and demapper architectures are detailed. The work is performed in the context of the SME42 project of the EUREKA’s Eurostars programme. The flexible architectures are dedicated to the four constellations of the DVB-T2 standard (QPSK, 16-QAM, 64-QAM and 256-QAM). Moreover, classical and rotated constellations can be processed by the architectures.

4.1. Generic mapper and demapper architectures
The mapper is composed of two main parts as shown in Figure 5. A first part corresponds to a classical mapping function that depends on the QAM mode. This function is done thanks to a LUT dedicated to each constellation. Then, four multipliers and two adders are necessary to apply the rotation to the constellation points. Indeed, two values can be processed in parallel. Two multiplexers are also required to select the final outputs as a function of the mapping mode (classical or rotated).

A flexible demapper architecture has also been designed for the DVB-T2 standard. The proposed architecture enables detection over classical Rayleigh fading channels and fading channels with erasures. The proposed 2D-region and 1D-region algorithms are chosen for 256 and 64-QAM over a fading channel with or without erasures respectively. On the other hand, a Max-Log computation is done for 16-QAM and QPSK. Indeed, the resources that are necessary for an architecture dedicated to the rotated 256-QAM, are sufficient for a demapping without sub-region selection of rotated 16-QAM and QPSK constellations. Note that the resources are also sufficient for a classical demapping of a 64-QAM constellation. But in this case, twice as much time is needed for the computation.

4.2. Approximation of the Euclidean distance computation
For the rotated demapping function, the most complex task is the computation of Euclidean distances. $2 \cdot \left(\log_2(M)/2 + 1\right)^2$ multiplications have to be performed if an M-QAM constellation is considered. We applied an approximation in order to eliminate the multiplier operations. The Euclidean distance is the distance between two points defined as $\sqrt{a^2 + b^2} = a \cdot \sqrt{1 + \left(b/a\right)^2}$. If we choose $a$ as the maximum of the two values, then the ratio $b/a$ is smaller than one. A linear approximation of the Euclidean distance can thus be performed as follows:

\[
F(a,b) = \sqrt{a^2 + b^2} \\
\text{if } \min(a,b) \leq \max(a,b)/4 \\
\quad \text{then } F(a,b) = \max(a,b) \\
\text{else } F(a,b) = \max(a,b) + (\min(a,b) - \max(a,b)/4)/2
\]

Figure 6 presents the exact computation and the approximated computation of the function $F(a,b)$. Note that the difference between the two curves is minor. Moreover, if a fixed-version of the function with 1 bit for the sign, 2 bits for the magnitude and 4 bits for the precision is considered, no significant relative error is observed.

The architecture of the Euclidean distance computation designed from the proposed approximation is given in Figure 7. Two comparators, one adder, one substrator and one multiplexer are used. As previously explained, we have chosen 7-bit data paths for this architecture.

4.3. Modules of the flexible rotated demapper
We have designed a flexible rotated demapper which contains: one ROM, nine core modules, one interconnection network, eight comparison modules and one LLR computation module. The top level scheme of the architecture is given in Figure 8. The ROM contains the I and Q component values for the four QAM modes. However, as the sub-region detection is applied for 256 and 64-QAM constellations, all the I and Q component values need not be saved. Actually, only values of region I and II separately (cf Figure 2) are stored in our design in the case of classical Rayleigh fading channel. However, the cumulative values of regions I and II are the ones to be...
stored in the case of a channel with erasure since the 1D-region algorithm is restricted to one remaining component. The values of region III and IV can be found by a sign inversion of the stored values.

Nine core modules are assigned in our architecture. They enable a parallel Euclidean distance computation for the received symbols. In fact, the highest complexity configuration is the 2D-region demapping for a 256-QAM. It needs 9 by 9 = 81 Euclidean distance computations. If the architecture computes 9 Euclidean distances in parallel, 9 period times are necessary to obtain the 81 values. In our point of view, this architectural solution offers a good trade-off between data rate and complexity.

It is possible to re-use this architecture for a fading channel with erasures. Indeed, the demapper needs to compute \( (\log_2(M)/2) \cdot (\log_2(M)/2 + 1) \) Euclidean distances if the 1D-region algorithm is applied. However, now every Euclidean distance depends only on one component of the received symbol (the non-erased one). In consequence, every core module computes two 1D Euclidean distances and then selects their minimum to send to the interconnection network module. This process is obtained thanks to the structure of the core module that enables to compute the two values \( X^e_l \) and \( X^o_l \) in parallel as shown in Figure 8. Following this reasoning, all the Euclidean distance values can be computed in 4 and 8 period times for the 64 and 256-QAM constellations respectively.

The interconnection network module is in charge of the distribution of the Euclidean distances and of the comparisons to get the minimum distances of each received symbol. It works according to the configuration of the previous modules. In our architecture, the ROM produces the constellation values row by row. This leads to two different kinds of elements, one to distribute and one to compare the Euclidean distance values to the two temporary minimum distances \( e^e_{bi} \) and \( e^o_{bi} \). 68 comparators are needed to do the task. Then, eight comparison modules are still necessary to obtain the final minimum of the Euclidean distances according to the mapping bit value one and zero. Each of which is composed of two comparators and two registers. The registers memorize the final minimum values \( e^e_{bi} \) and \( e^o_{bi} \). After all these steps, the LLRs are computed by two multiplexers, two multipliers and one subtractor.

5. LOGIC SYNTHESIS AND PROTOTYPING

The purpose of this section is to demonstrate the efficiency of the flexible rotated QAM demapper architecture that has been designed for the DVB-T2 standard.

5.1. FPGA implementation results

The flexible rotated QAM demapper was synthesized and implemented on a Virtex II Pro FPGA using Xilinx ISE tools. Computational resources of the demapper take up 791 slice Flip-Flops and 4,667 slice LUTs. It means that the occupation rates are about 2% and 17% of a Xilinx XC2VP30 FPGA for slice registers and slice LUTs, respectively. In addition, multiplication resources for the demapper module take up 20 DSP blocks. It represents 14% of the total DSP blocks available in the chosen device. No block memory resource is used in our design because the ROM module was mapped in slice LUTs. Note that these results are obtained thanks to the proposed demapping algorithms that enable to decrease the computational complexity. In particular, a reduction from 1024 to 20 the number of multipliers is achieved for the 256-QAM constellation. Received symbols are clocked with \( f_0 = 62 \) MHz resulting in an input data rate of 62 Msymbol/s and an output data rate of \( 62 \cdot \log_2(M) \) MLLR/s. The Virtex5 LX110 is the FPGA device chosen in the SME42 project where the frequency of the BICM receiver is set to be 100 MHz. Logic syntheses for this device show that this target frequency can be achieved by the proposed architectural solution.

In order to validate the flexible rotated QAM demapper, BER performance measures have to be carried out. For this reason, we have integrated a channel emulator from a classical Rayleigh fading channel adjusted to hardware implementation. The channel emulator is obtained from an AWGN generator of multiples variables. The hardware emulator is achieved using the Wallace method [8]. Moreover, erasure event modeling was added to the channel emulator as explained in section 2.1. This module needs 4,907 slice Flip-Flops and 6321 slice LUTs. In addition, 59 DSP resources are necessary for multiplications and 13 BlockRAMs are also assigned.

5.2. Experimental setup

The experimental setup is a development board XUP that contains a Xilinx XC2VP30 device. Figure 9 shows the different components of the experimental setup implemented onto the FPGA. A Pseudo Random Generator (PRG) sends out pseudo random data streams at each clock period \( f_0 \). This module is composed of flip-flops and XOR gates. The proposed flexible rotated mapper processes the data streams. Then, the noise generator described in the
previous section generates Rayleigh fading samples with or without erasures and adds them to the previous data streams. The reception part is composed of two elements: an equalizer and the flexible rotated demapper. Actually, an equalization has to be performed for the in-phase $Y_{eq}^I$ and quadrature $Y_{eq}^Q$ components of the received complex symbol. They depend on the received information $Y_I$ and $Y_Q$, the Rayleigh distributed fading coefficients $\rho_I$ and $\rho_Q$ and the channel noise variance $\sigma^2$ (cf equ. 6). BER measurement facilities are also implemented in the experimental setup in order to rapidly verify the demapping performance.

**CONCLUSION**

Signal Space Diversity has been adopted into the DVB-T2 standard. In this paper, a rotated demapper dedicated to the four constellations of the DVB-T2 standard is described. It enables detection over classical Rayleigh fading channels and fading channels with erasures. In addition, a prototype based on a FPGA device has been realized to demonstrate the efficient of the flexible architecture. The design of the BICM receiver with the LDPC decoder is currently under investigation to demonstrate the interest of a iterative BICM architecture.

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