Rotated Constellations for a Satellite Communication Link in a DVB-T2 context

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Abstract— **In this paper, the focus is on DVB-T2-like rotated constellations techniques applied to a satellite link for mobile services. Associated with signal space component interleaving, a QPSK constellation with rotation is evaluated over S-band satellite mobile channel with payload impairments. Channel capacity is first assessed showing an important potential for improvement. Largest gains are obtained for high spectral efficiency and for the cases with high level of impairments. Coded simulations show that rotated constellation can bring up to 1.5 dB gain for medium to high coding rates over a satellite to vehicle channel, confirming channel capacity predictions.**

Keywords— rotated constellations, DVB-T2, DVB-NGH, signal interleaving, satellite payload impairments, satellite mobile vehicular link

I. INTRODUCTION

The second generation of the Digital Video Broadcasting Terrestrial standard (DVB-T2) [1], shows excellent results over terrestrial channels, with limited mobility. To cope with higher mobility requirements with the possibility of covering a larger interval of signal to noise ratios and spectral efficiencies, DVB-NGH specifications have been drafted. They introduce advanced Multiple Input Multiple Output (MIMO) antennas schemes, low coding rates and a complementary satellite component for a larger coverage. Indeed, satellite transmission seems to be an attractive and efficient way to broadcast TV or radio over large areas. More recently, ITU studies [10] or 5GPP reflexion groups have promoted satellite as a service or a coverage complement of terrestrial systems. But for mass market considerations, use of very-well designed waveforms for satellite link [9] is not to consider, in the idea of having the same chipset for receiving terrestrial and satellite link. Non optimized transmission using a terrestrial standard with well choosen settings may be preferred. This thought may explain why in this paper, DVB-T2 transmission is studied on a satellite link. Thus, as rotated constellations are considered to improve the quality of transmission on terrestrial channels, purpose of this work is to assess if such technique may bring such benefits over satellite vehicular channel.

In a conventional Quadrature Amplitude Modulation (QAM), half of the information bits are carried by the I component and the remaining half by the Q component. When constellation rotation is considered, every constellation point in signal space has its own projection on the I and Q components separately. Therefore, information regarding all bits to be transmitted is carried over both I and Q components. Component interleaving is performed afterwards such that the I and Q signals carrying the information regarding one symbol are sent in a different time and over a different subcarrier of the DVB-T2 Orthogonal Frequency Division Multiplexing module. Now, if deep fading occurs at a particular time and frequency, it is highly unlikely that it would affect both I and Q components of the same symbol. Thanks to increased robustness, rotated constellations were adopted in the DVB-T2 and DVB-NGH standards [1] [2] [3].

Nevertheless, despite this adoption, no particular study on its potential benefits over a mobile satellite channel has been performed. In this paper, transmission from a geostationary satellite over S-band mobile propagation channel is studied. Roof top vehicular antenna affected by intermediate tree shadowing is considered at receiver side. The underlying channel aggregates propagation effects and payload impairments such as non-linearity effects, phase noise, and filtering.

The paper is organized as follows: first, the principle of constellation rotation is recalled in Section II. Then, the Land Mobile Satellite (LMS) three-state channel model over S-band is defined in Section III. It is followed by channel capacity computations for rotated and classical QPSK constellation in Section IV. Coded simulation results for a DVB-T2-like waveform with constellation rotation are provided in Section V. These simulations equally include satellite payload impairments. Section VI concludes the paper.

II. ON THE ROTATION OF CONSTELLATION PRINCIPLE

Assuming that a Rayleigh-like fading can occur independently on the phase and quadrature component of a constellation symbol, the situation depicted in Fig. 1 represents a typical study case for constellation rotation. Bit information is carried by both I and Q and therefore is not totally lost. Half of the total amount of transmitted bits would have been affected by deep fading in case of non-rotated constellation. Nonetheless, independent fading is assumed possible thanks to frequency/time I/Q interleaving.

 ISBN: 978-1-61208-348-3

Indeed, real propagation channel show correlation both in time and in frequency.

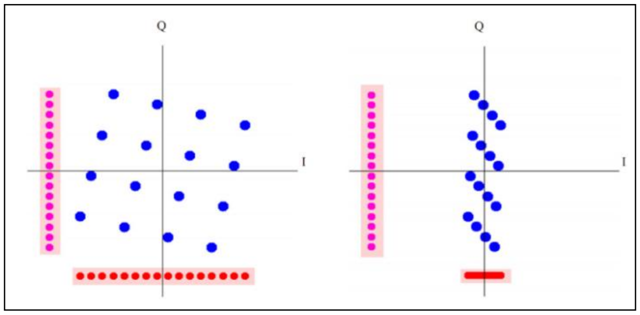

Figure 1. On the left hand side: rotated constellation without fading; on the rigth hand side: rotated constellation with fading on the I component.

The general architecture for a constellation rotation transmitter adopts a Bit Interleaved Coded Modulation scheme (BICM) [4] as depicted in Fig. 2. It is composed of the association of an outer error correcting code and a QAM mapper applying a constellation rotation and I/Q interleaving separated by a bit interleaver. The code represents a combination of a Bose-Chaudury-Hocquenghem (BCH) code and a Low Density Parity Check (LDPC) code. I/Q interleaving is performed in time an frequency via a set of cell, time and frequency interleaving as defined in the DVB-T2 standard [1]. Interleaved components are afterwards mapped to OFDM subcarriers according to the DVB-T2 frame builder.

Rotation angle Φ was chosen following a set of predefined optimization criteria related to the L-product distance [5] and signal space characteristics in case of deep fades [3]. The choice is assessed under a DVB-T2 context, considering that fading over I and Q component is uncorrelated. This condition is reached thanks to the long frequency and time interleavers adopted in the DVB-T2 standard. Adopted rotation angle values in this article, the same as in DVB-T2 thanks to the interleavers, are summarized in TABLE I.

TABLE I. ROTATION ANGLE FOR A DVB-T2 CONTEXT

Modulation	**QPSK**	**16-QAM**	**64-QAM**	**256-QAM**
Φ (degrees)	*29,0*	*16,8*	*8,6*	*3,6*

At the receiver side (see Fig. 3), one main difference exists when compared with a conventional bit interleaved coded modulation with an OFDM receiver. Log-likelihood ratios (LLRs) provided by the demapper are now computed over rotated symbols. This induces the use of a 2-component (in-phase and quadrature) demapper. Indeed, the Euclidean distance of received symbol now should be computed over the two projections over the I and Q axes as follows:

$$LLR(b_i) = ln \frac{\sum_{x \in C_i^1} exp\left(-\frac{|I-\rho_I I_x|^2+|Q-\rho_Q Q_x|^2}{2\sigma^2}\right)}{\sum_{x \in C_i^0} exp\left(-\frac{|I-\rho_I I_x|^2+|Q-\rho_Q Q_x|^2}{2\sigma^2}\right)} \quad (1)$$

where x is a symbol of the QAM constellation, C_i^j represent the symbols of the constellation carrying the bit b_i when b_i is equal to *j*, I and Q are the received in phase and quadrature components, $\rho_{I/Q}$ is the fading on the I or Q component, $2\sigma^2$ is the Additive White Gaussian (AWGN) noise variance, I_x and Q_x denote the reference symbols of the rotated QAM constellation.

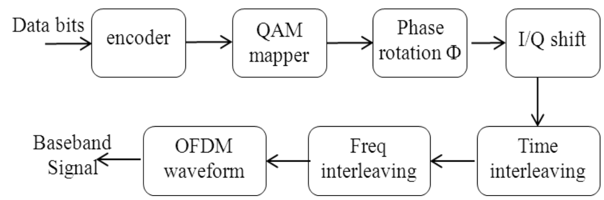

Figure 2. General architecture for an OFDM transmitter with a rotation of constellation

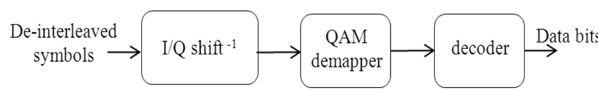

Figure 3. Processing at the receiver for rotated constellations.

III. S-BAND 3 STATES MODEL

This model detailed in [6] has been widely used since the 90's. It is fully empirical (or equivalently statistical) and relies on a specific S-band measurements dataset including various environments (open, intermediate tree shadow, heavy tree shadow, suburban, urban). Basically, it divides the LMS propagation channel into 3 shadowing states:

- State 1 : "LOS" -Line of Sight-
- State 2 : "Shadowing", corresponding typically to isolated trees in suburban areas
- State 3 : "Heavy Shadowing/Blockage" corresponding typically to houses in suburban areas.

In the generative model, the state change (large scale) is synthesised using a 3-state Markov chain whose input parameters are the initial state vector and the transition matrix. Two more input parameters have also been added:

- Each state is assumed to have a minimum length ("state length")
- A transition between two states happens over a given transition distance ("state transition length").

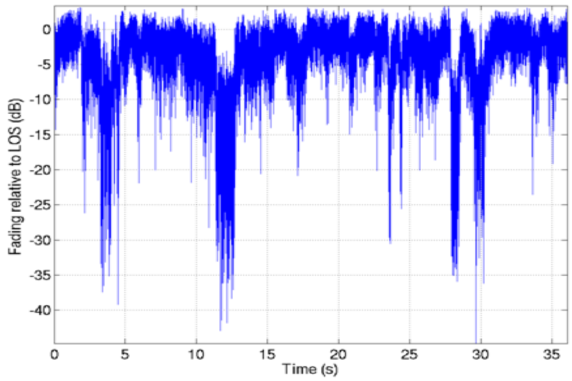

Figure 4. Excerpt from LMS channel for intermediate tree shadow environment

Then, inside each state (mid-scale), the channel fading is assumed to follow a Loo distribution (basically the distribution of a Rice process whose direct path amplitude is log-normally distributed) [6]. The input parameters for each state are the log-normal parameters of the direct path amplitude and the multipath power assumed to be constant. Another input parameter at this intermediate scale is the shadowing correlation length that influences the dynamics of the direct path amplitude change within one state.

At small scale, in our implementation, the fading dynamics are taken into account by using a Zheng-Xiao model (Classical Doppler spectrum). One should note that this model is narrow band. In other words, fading coefficients are varying only along the time axis. For simulations in this paper, Intermediate tree shadow environment is used, with vehicle moving at 50 km/h, seeing satellite with 40 degrees elevation. A channel excerpt is shown in Fig. 4.

IV. CHANNEL CAPACITY

When equiprobable assumption is made at the transmitter, the channel capacity can be assessed by computing mutual information between transmitted and received symbols, respectively X and Y, as it has been done in [8]. In addition, a computation of mutual information using LLR metrics is derived in [7]. This computation is performed via averaging measured mutual information over a sufficiently large number of samples constituting a sufficient statistic. Channel capacity C is therefore defined as:

$$C = I(X, Y) \tag{2}$$

Nowadays, BICM is adopted in most advanced telecommunication standards. Assuming bit interleaving with infinite depth, channel capacity can be written as the sum of $log_2(M)$ independent channels, provided that mutual information computation is averaged over a long period.

$$C = \sum_{i=1}^{\log_2 M} E[i(b_i; I, Q)] \tag{3}$$

E is the expectation operator, b_i is the transmitted bit, I and Q are the in phase and quadrature received symbols, i is the mutual information operator, M is the number of states of the modulation. Mutual information between bit b_i and received I and Q components is defined by

$$i(b_i; I, Q) = log_2 \frac{1}{P(b_i)} + log_2 P(b_i \mid I, Q) \tag{4}$$

taking into account that LLR general definition is given by

$$LLR(b_i) = \ln \frac{P(b_i = 1 \mid I, Q)}{P(b_i = 0 \mid I, Q)} \tag{5}$$

And that :

$$P(b_i = 0 \mid I, Q) + P(b_i = 1 \mid I, Q) = 1 \tag{6}$$

we obtain:

$$P(b_i \mid I, Q) = \frac{1}{1 + e^{(-1)^{b_i} . LLR(b_i)}} \tag{7}$$

As a result $i(b_i;I,Q)$ becomes

$$i(b_i; I, Q) = \log_2 \frac{1}{0.5} + \log_2 \frac{1}{1 + e^{(-1)^{b_i} . LLR(b_i)}} \tag{8}$$

Using (3), channel capacity C, in bits/s/Hz, is now equal to

$$C = \log_2 M * E\left[1 - \log\left(1 + e^{(-1)^{b_i} . LLR(b_i)}\right)\right] \tag{9}$$

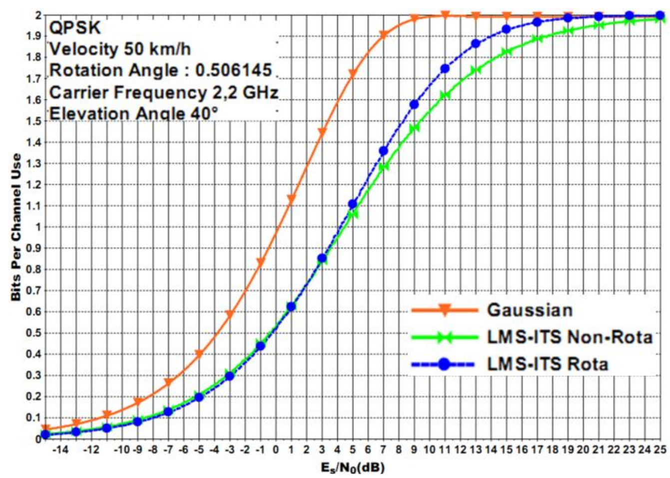

Figure 5. Channel capacity for LMS-Intermediate Tree Shadow Environment (LMS-ITS). 250 ms Time Interleaving

Results in Fig. 5 over LMS-ITS environment show mainly that for high spectral efficiencies (or high signal to noise ratios), rotation of the constellation can show a significant gain in required signal to noise ratio Es/N0, reaching in some cases more than 1.5 dB.

Interleaving depth and type does not affect obtained results despite computation via Monte Carlo averaging of measured mutual information. Indeed, averaging is performed over a large number of channel uses or transmissions far superior to interleaving depth. The expectation being between the transmitted bit and its LLR,

ISBN: 978-1-61208-348-3

the order of bit transmission does not alter the average value over the sequence.

V. CODED SIMULATIONS

A. Parameters and simulation chain

From channel capacity results, suitable working points where rotated constellations bring an important gain seem to be those with high spectral efficiencies. To verify this assertion, the DVB-T2-like transmission chain [1] shown in Fig. 6 was chosen considering ideal receiver as a first step. Error rates are computed at the output of the LDPC decoder. Indeed, the assumption made in the DVB-T2 specification that a frame error rate of 10^{-4} at the output of the LDPC decoder corresponds to a frame error rate of 10^{-7} at the output of the BCH decoder is also assumed. Simulation parameters are summarized in table II.

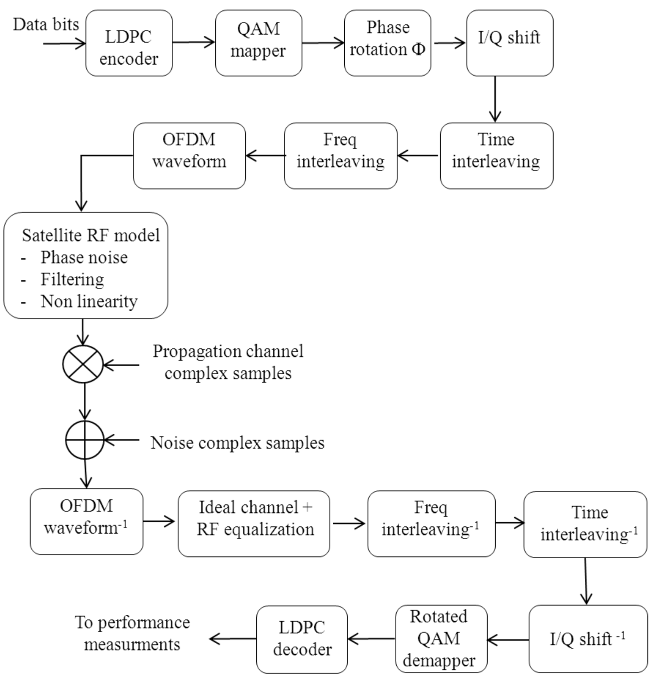

Figure 6. DVB-T2 like Transmission chain

Considered satellite radio frequency model includes frequency filtering, phase noise and amplifier non-linearity impairments. Applied phase noise and amplifier non linearity models are compliant to the definition provided in [9].

We would like to recall that in satellite microcosm technical conventions, Input Back Off (IBO) is defined as the power difference between input power giving maximum output power and current input power. Output Back Off (OBO) equals to the difference between maximum deliverable power in continuous wave signal and current output power of modulated signal.

TABLE II. MAIN PARAMETERS FOR PERFORMED SIMULATIONS

Parameter name	Value
Center frequency	2,2 GHz
Bandwidth	5 MHz
Constellation and rotation	QPSK, with Φ= 29.0 degrees rotation or without rotation
Coder	LDPC 16200 bits length. No BCH encoder
Propagation channel	LMS-ITS 3 states model, 50 km/h, 40° satellite elevation
OFDM	2K FFT size, 1/4 guard interval
Satellite RF model	with and without, variable Input Back Off for the amplifier (IBO)

TABLE III. summarizes considered IBO values and their respective OBO. These values condition obtained results and are of great importance when dimensioning a satellite link.

TABLE III. IBO VS OBO FOR CONSIDRED S-BAND AMPLIFIER

IBO (dB)	OBO (dB)
0	1.37
2	1.6
4	2.2

B. System dimensioning and optimization

From a satellite system optimization/dimensioning point of view, two metrics have usually to be considered : power loss, corresponding to OBO value, and signal quality loss, equal to the performance gap considering RF sub-block or not. Total loss metric is then defined as:

$$Total\ loss = signal\ quality\ loss + power\ loss \qquad (10)$$

A good choice would minimize Total loss value. But for different combinations giving nearly the same *Total loss* amount, preferred solution would be the minimization of signal quality loss, corresponding to a better carrier over intermodulation power ratio. In our case, total loss is around 1.85 dB obtained by the combination of 0.25 dB of signal quality loss and 1.6 dB of power loss.

C. Performance Results

Figure 7. and Figure 8. show FER simulation results at the output of the LDPC decoder for the considered DVB-T2-like chain with a code rate R = 11/15 and R = 2/3 respectively. Corresponding results confirm channel capacity predictions. Indeed at 10^{-4} of FER, rotated constellation brings a 1.3 dB gain over a LMS-ITS channel with R = 11/15 and 1.0 dB with R = 2/3 when no impairments are considered. Additional gains ranging from 0.15 to 0.5 dB are achieved when filtering, phase noise and amplifier non-linearity with 4.0 and 0.0 dB IBO are introduced. Therefore, rotated constellation seems to improve robustness to different types of impairments.

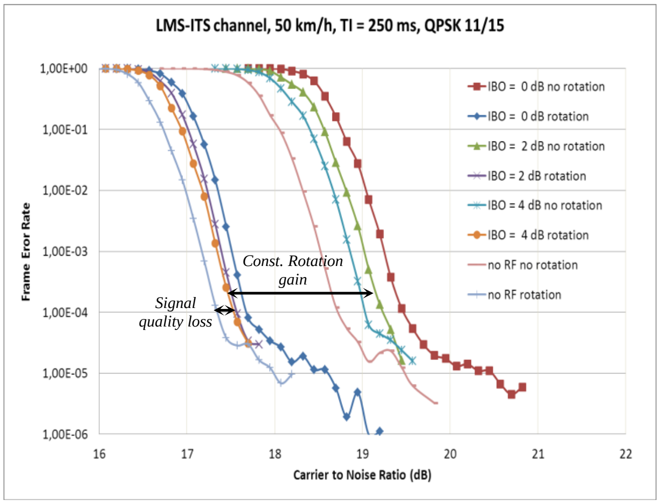

Figure 7. FER comparison results between a rotated and a classical QPSK for R=11/15 with and without impairments.

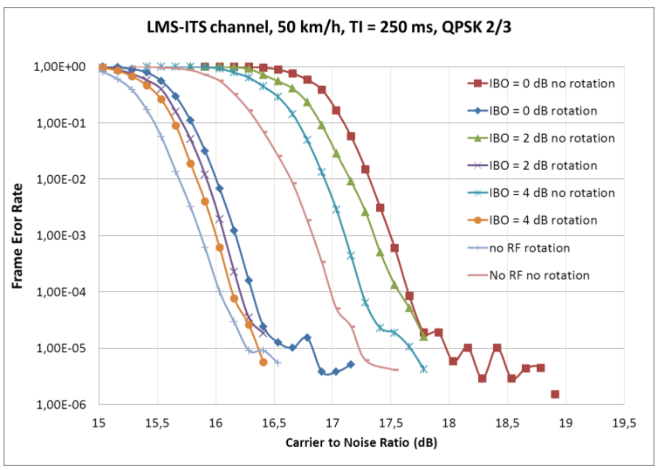

Figure 8. FER comparison results between a rotated and a classical QPSK for R=2/3 with and without impairments.

VI. CONCLUSION

In this paper, the study of rotated constellation was performed over a satellite-to-vehicle link in S-band. In addition, impairments of a satellite payload have been considered. Backed by channel capacity computations and coded simulation results, a substantial gain greater than 1.5 dB was pointed out for medium to high spectral efficiencies/coding rates. Moreover, larger gains were obtained when channel impairments were considered. Complexity overhead is negligible provided that interleaving blocks process I/Q cells as in the DVB-T2 standard. The use of this standard in a satellite context may appear in a satellite-terrestrial hybrid system, where for market considerations, there is a single chipset to receive terrestrial and satellite link. Through this paper, a way to make DVB-T2 waveform better optimized for satellite link has been shown. Lastly, whereas this paper was limited to QPSK modulation and DVB-T2 adopted rotation angle, other studies are ongoing considering interleaver design, rotation angle choice, and other QAM modulations over such satellite channels.

ACKNOWLEDGMENT

The first author thanks the Research and Technology decision board of French Space Agency allowing this kind of applicative research.

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