TURBO-EQUALIZATION OF THE REMAINING INTERFERENCE IN A PRE-DISTORTED NON-LINEAR SATELLITE CHANNEL

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ABSTRACT

In satellite broadcast and broadband communication systems, it is desirable to relax as much as possible the complexity of terminals for feeder-to-user links. Pre-distortion algorithms are therefore considered at the transmitter side to compensate for the non-linear interference induced by the channel. In case of large channel lengths and multi-level constellations, remaining interference after pre-distortion may however still be significant. In this paper, we show that the system performance can be improved by combining a pre-distortion algorithm with a low-complexity turbo-equalization structure at the receiver side. This structure relies on the observation that the interference before pre-distortion and the remaining interference after pre-distortion are correlated.

***Index Terms*—** Non-Linear Interference, Satellite Communication Channel, Pre-Distortion, Turbo-Equalization.

1. INTRODUCTION

Compensation of the non-linear interference induced by a satellite communication channel can be applied at the transmitter (pre-distortion) or at the receiver side (equalization or detection). In satellite broadcast and broadband scenarios where a star network topology is usually considered, pre-distortion can be advantageous for the forward link, since it is desirable to concentrate the computational load into the feeder station and relax as much as possible the complexity of the terminals. Data pre-distortion refers to the case where the pre-distortion of the symbols is applied prior to the pulse shaping. It allows to compensate for inter symbol interference (ISI) and it avoids out-of-band emissions. Several pre-distortion algorithms have already been proposed in the literature. In [1] and [2], the pre-distortion method is based on the minimization of the mean square error (MSE) between the transmitted and received symbols using a Volterra model as pre-distorter. A second pre-distortion algorithm is the order p inverse for non-linear systems, described for instance in [3] and specified for the satellite channel in [4]. It removes all Volterra coefficients up to the pth order from the model relating the received to the transmitted symbols. Another data pre-distortion method has been proposed in [5]. The value of each pre-distorted symbol is function of the un-pre-distorted neighboring symbols. The values of the pre-distorted symbols can be calculated offline and stored in a look-up table. These values are pre-computed in order to minimize the mean square error between the initial and the received symbols. The performance of this algorithm has been assessed for high order modulations in [6]. The number of pre-computed values depends exponentially on the channel length and the modulation order. In [7], an iterative pre-distortion algorithm minimizing the mean square error between the transmitted and received symbols has been proposed, and extended to the multi-carrier-per-channel scenario in [8]. All these pre-distortion algorithms involve a trade-off between performance and complexity, and the choice of a pre-distortion algorithm will depend on the system constraints and requirements. In all cases however, residual interference still remains, impacting the system performance.

Compensation of the interference at the receiver side has already been thoroughly studied. The non-linear satellite communication channel can be described as a trellis, so that the maximum a posteriori equalizer using the BCJR algorithm can theoretically be used. However, the number of channel states grows exponentially with the modulation order and the channel memory. Therefore, considering high order modulations and large channel lengths, the use of such an equalizer is not possible. A first alternative is to use reduced state algorithms as described in [9]. However, neglecting a too high number of channel states can lead to severe performance loss. Another solution is to use detection algorithms based on reduced Volterra models [10]. As for pre-distortion methods, both approaches are always limited by complexity issues: these equalization structures are expected to perform poorly for large channel lengths and high non-linearities. Iterative algorithms using soft interference cancellation equalizers based on turbo-equalization structures have therefore been proposed. The basic idea is the exchange of intrinsic information between a soft input soft output (SISO) equalizer and a soft decoder to approximate the performance of the optimum receiver while complexity remains tractable. Linear turbo-equalization has been described in many references, as for instance in [11]. Soft interference cancellation equalizers, first presented for the linear case in [12], allow to deal with non-linear interference. It first estimates the symbol interference from the decoder information and subtracts it from the received symbols. [13] proposes an interference cancellation algorithm assuming that all transmitted symbols have the same energy. Another interference cancellation algorithm is presented in [14], assuming a perfect knowledge of the channel. This algorithm has a linear complexity with the channel length and modulation order and is independent of any intrinsic parameter. The performance of turbo-equalizers still strongly depends on the performance achieved by the SISO equalizer only. If the information from the SISO equalizer at the first iteration is not accurate enough, the decoder will be unable to achieve any performance gain. Combination of pre-distortion and soft interference techniques can help to improve the system performance. In this paper, we consider the pre-distortion algorithm proposed in [7], as it significantly outperforms other pre-distortion algorithms for large channel lengths and high modulation orders. We will investigate how the performance of this pre-distortion method can be further improved using a soft interference cancellation equalizer.

2. SYSTEM MODEL

The block diagram of the considered system is depicted in Fig. 1. The modulation is a multi-level and linear modulation defined in the DVB-S2 standard (see [15]). The coded and interleaved bits are denoted as $c_{n,k}$ and then modulated to produce the symbols s_n. $c_{n,k}$ corresponds to the bit k of symbol n, where k belongs to $\{1, ..., log_2(M)\}$, M being the modulation order. The pre-distortion algorithm takes the symbols s_n as input and produces the output symbols x_n, which are the symbols actually transmitted to the channel. The shaping and receiver filters are square root raised cosine (SRRC) pulses. Onboard the satellite, the input multiplexer (IMUX) filter is a bandpass filter which selects the subband to be amplified. The satellite high power amplifier (HPA) can be seen as a non-linear memoryless device. The output multiplexer (OMUX) filter is also a bandpass filter, necessary to remove the out-of-band non-linearities produced by the power amplifier. The larger the signal bandwidth, the more inter-symbol interference will be induced by the IMUX and OMUX filters. Finally, the received symbols are denoted as y_n.

The relation between x_n and y_n is described by the Volterra model, which is an analytical model relating the input and the output of a non-linear system with memory:

$$y_n = \sum_{m=0}^{\infty} \sum_{n_1,\ ...,\ n_{2m+1}} H_{2m+1}(n_1,\ ...,\ n_{2m+1}) x_{(n-n_1)} ... x_{(n-n_{m+1})} x^*_{(n-n_{m+2})} ... x^*_{(n-n_{2m+1})} + w_n \qquad (1)$$

The coefficients $H_{2m+1}(n_1 ... n_{2m+1})$ are called the Volterra coefficients of the system. The term w_n is the standard additive white Gaussian noise (AWGN).

We consider here the pre-distortion algorithm described in ([7]). Blocks of N symbols are successively processed; the pre-distortion aims to minimize the square error between the initial block of symbols and the received symbols. As the algorithm complexity is linear with N, it can be applied with large block size (e.g. the size of a DVB-S2 PLFRAME, as defined in ([15])). The choice of this algorithm will be justified in the next section. The remaining interference after pre-distortion is defined as follows:

$$I_n \triangleq y_n - s_n \qquad (2)$$

At the receiver side, a posteriori probabilities $P^1_{Y|S}(y_n|s)$ are first calculated assuming that the remaining interference behaves like additional AWGN:

$$P^1_{Y|S}(y_n|s) \triangleq \frac{1}{2\pi} exp(0.5 \frac{||y_n - s||^2}{P_{noise} + P_{interf}}) \qquad (3)$$

where P_{noise} and P_{interf} respectively refer to the noise and remaining interference power. The goal of the turbo-iterative structure of the receiver, presented at Fig. 1, is to provide at each iteration an a posteriori estimation of the remaining interference, denoted as $\hat{I}_n|s$, used to improve the Gaussian detection at the next iteration. At any iteration $k > 1$, a posteriori probabilities $P^k_{Y|S}(y_n|s)$ are calculated as follows:

$$P^k_{Y|S}(y_n|s) \triangleq \frac{1}{2\pi} exp(0.5 \frac{||y_n - \hat{I}_n|s - s||^2}{P_{noise}}) \qquad (4)$$

$\hat{I}_n|s$ is obtained from the a priori symbol probabilities as follows. Firstly, log-likelihood ratios (LLR) for each coded bit, denoted as LLR^E, are calculated. The soft decoder produces new LLR, LLR^D, from LLR^E, as in classical turbo-equalization of linear channels. From LLR^D, the soft mapper updates the a priori symbol probabilities, denoted as $P^D_n(s)$, and produces the following soft symbols:

$$\hat{s}_n = \sum_s P^D_n(s) s \qquad (5)$$

If the symbols were not pre-distorted and if the channel was perfectly known at the receiver, an estimation of $\hat{I}_n|s$ could easily be obtained from $\hat{s}_n$ by simulating the channel with the soft symbols $\hat{s}_n$, as done in ([14]). Next section will detail how this can be extended when the symbols are pre-distorted.

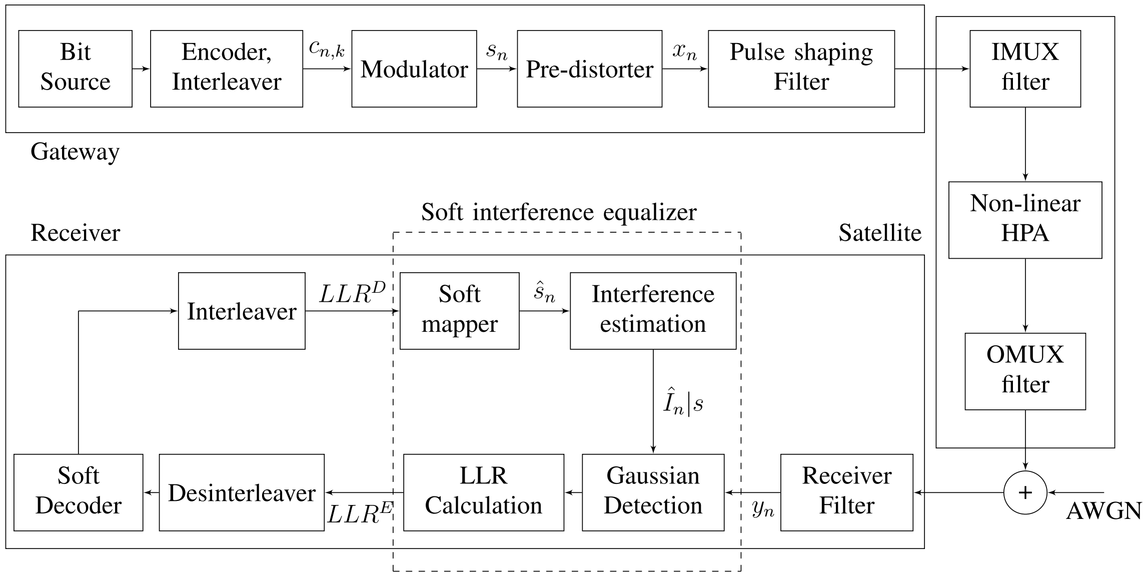

Fig. 1. Block diagram of the satellite channel

3. ESTIMATION OF THE REMAINING INTERFERENCE

To estimate $\hat{I}_n|s$ from $\hat{s}_n$, it is assumed that the channel is perfectly known at the receiver. The easiest approach would be to take hard decisions on $\hat{s}_n$ and to simulate the pre-distortion algorithm with the decided symbols as input. Hard estimates of the pre-distorted symbols are thus obtained and the remaining interference can then be estimated by simulating the channel with these estimates as input. In this approach, due to the hard decisions, the estimation of the remaining interference, $\hat{I}_n|s$, is the same for any tentative symbol s, as in ([14]). A drawback of this approach is the lost of soft information. Moreover, it increases the complexity of the receiver, since it has to emulate the pre-distortion algorithm. To avoid these drawbacks, it is assumed that each interference term I_n can be written as:

$$I_n = F(I_n^{\text{w/o pred.}}, s_n) \tag{6}$$

where $I_n^{\text{w/o pred.}}$ is the interference term affecting symbol n when no pre-distortion has been applied. F is a complex function that relates the interference without pre-distortion to the interference after pre-distortion, for a given received symbol. Assuming that the relation (6) is representative and known by the receiver, $\hat{I}_n|s$ can be directly calculated from the a posteriori interference estimate $\hat{I}_n^{\text{w/o pred.}}|s$. The term $\hat{I}_n^{\text{w/o pred.}}|s$ can be obtained using channel simulations with $\{...\hat{s}_{n-2}, \hat{s}_{n-1}, s, \hat{s}_{n+1}, \hat{s}_{n+2}...\}$ as input (note that for a given received symbol y_n, $\hat{s}_n$ is not used to estimate $\hat{I}_n^{\text{w/o pred.}}|s$).

In the following, we use the term *constructive* (resp. *destructive*) *interference* if the received symbol is more (resp. less) powerful than the reference symbol. Denoting respectively as S_{inner} and S_{upper} the subsets of symbols from the inner ring(s) and from the upper ring , we assume that the relation (6) can be explained as follows:

- The pre-distortion algorithm is able to compensate all interference for the symbols belonging to S_{inner}.
- The pre-distortion algorithm is able to compensate all interference for the symbols belonging to S_{upper} if the interference without pre-distortion was constructive. Some interference remains after pre-distortion if the interference without pre-distortion was destructive due to the limitation of the maximum available power at the output of the HPA.

For the sake of simplicity, we assume a linear relation between $I_n^{\text{w/o pred.}}$ and I_n:

$$\begin{aligned} &I_n = 0 \text{ if } s_n \in S_{\text{inner}} \\ &I_n = A I_n^{\text{w/o pred.}} + B \text{ if } s_n \in S_{\text{upper}} \end{aligned} \tag{7}$$

The choice of the pre-distortion algorithm can now be better justified. Firstly, it is shown in ([7]) that it outperforms other pre-distortion algorithms for large channel lengths and high modulation orders, so that best a posteriori statistics is obtained after the first Gaussian detection. Moreover, the assumption made in (6) may not be verified for other pre-distortion algorithms, as part of the remaining interference is also due to approximations done in the pre-distortion algorithm, such as channel shortening and simplification of

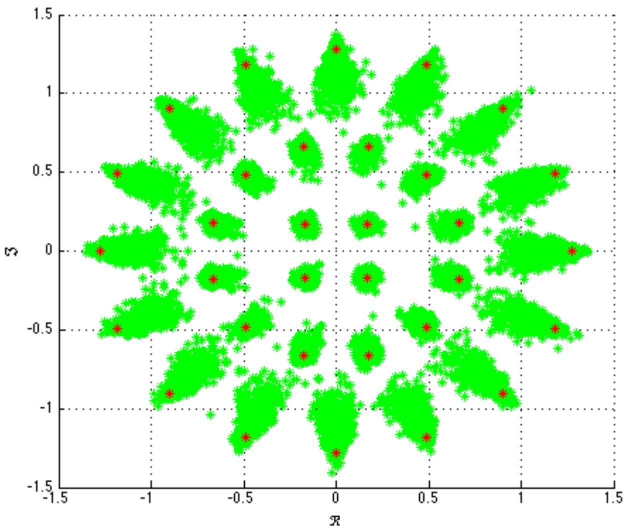

Fig. 2. Initial constellation and received symbols after pre-distortion.

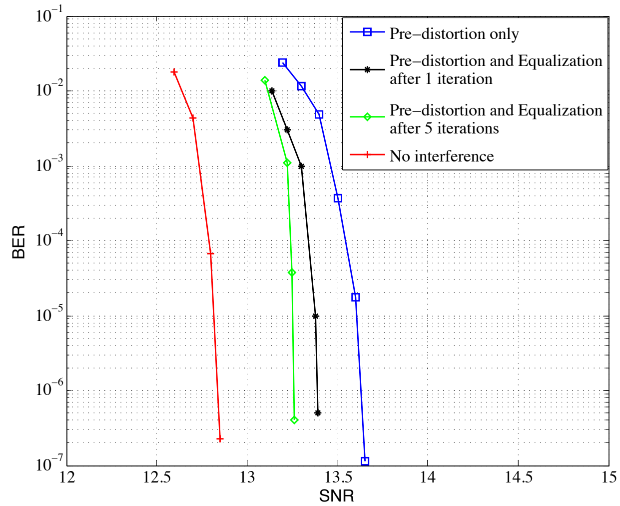

Fig. 3. BER curve for symbol rate=36Msymb/s

the Volterra model presented in (1). This interference term is unpredictable at the receiver without emulating the whole pre-distortion algorithm, which has to be avoided on a forward satellite link, as it increases the computational load in the terminal.

In conclusion, the soft symbols $\hat{s}_n$ are used to compute $\hat{I}_n^{\text{w/o pred.}}|s$ using channel simulations, from which $\hat{I}_n|s$ is calculated using (7). Considering a channel of length L_c, it can be easily shown that for a given block of symbol of size N, $M_{\text{upper}} \times L_c$ channel simulations with N inputs are necessary per iteration, where M_{upper} is the number of symbols in S_{upper}. In comparison, only one channel simulation per iteration was necessary in [14].

4. NUMERICAL RESULTS

In this section, 32-APSK symbol mapping is considered, shaped with SRRC waveform shaping and a roll-off factor equal to 0.1. The TWTA amplifier, IMUX and OMUX filters have typical characteristics similar to those provided in [15]. The amplifier input back-off is set to 3 dB. The IMUX and OMUX spectral responses have cut-off frequencies equal to 36MHz. The considered symbol rate is 36Msymb/s, so that the total bandwidth of the signal is equal to 39.6MHz (thus exceeding the theoretical channel width). The encoder is the LDPC encoder with rate 3/4 proposed in the DVB-S2 standard. The interleaver is the one defined in the DVB-S2 standard for 32-APSK modulation. Fig. 2 shows the initial (normalized) constellation and the constellation of received symbols y_n with pre-distortion . Pre-distortion is applied as described in [7]. It allows to decrease the MSE from -13 dB to almost -19 dB. The received constellation is here normalized such that $H_1(0) = 1$. Unsurprisingly, the remaining interference I_n is more significant for the symbols belonging to the upper ring. The amplifier saturation is obvious, as the remaining interference for these upper symbols is mainly destructive. It should be noticed that remaining interference also affects the other symbols to a much lower extent, since these symbols are less impacted by the limitation of the maximum available power at the output of the HPA. Fig. 3 represents the bit error rate (BER) performance considering the soft interference equalizer structure together with symbol pre-distortion. The performance improvement is about 0.2 dB at a target BER=10^{-6} considering a single iteration. Increasing the number of iterations to 5 allows a performance increase by circa 0.35 dB for BER=10^{-6}. Taking a number of iterations larger than 5 does not allow to significantly increase the performance. The proposed structure has only a performance loss of about 0.5 dB compared to a channel without interference at a target BER=10^{-6}.

5. CONCLUSION AND FUTURE WORK

In this paper, we have proposed a soft interference equalizer to mitigate the impact of remaining interference in a pre-distorted non-linear satellite communication channel. In the proposed structure, the receiver does not have to simulate the pre-distortion algorithm to estimate the remaining interference. Instead, the algorithm is based on the correlation between the interference with and without pre-distortion. Simulation results with 32APSK modulation show that a performance increase of 0.35 dB at a target BER=10^{-6} is brought by equalization with regard to a system where the channel compensation is exclusively applied at the transmitter side.

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