Comparison of signal predistortion schemes based on the contraction mapping for satellite communications with channel identification

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***Abstract*—The expected increase of data rates in future satellite communications (DVB-S2X) will require higher-order modulations and sharper roll-off, which makes the transmission more sensitive to non-linear interference due to on-board amplifiers. One solution is the predistortion of the signal that is carried out at the transmitter either on the data sequence (data-based) or on the modulated signal (signal-based). In this paper, we focus on single carrier communication and consider two signal-based predistortion techniques relying on the contraction mapping theorem, optimized from an error defined either from the data (data-optimized) or from the modulated signal (signal-optimized). We compare both schemes according to different figures of merit (normalized minimum square error, adjacent channel interference, total degradation and robustness towards channel identification). We show that, under realistic satellite transmission conditions, including satellite channel model and channel identification, the data-optimized signal predistortion scheme outperforms the signal-optimized scheme in terms of total degradation, whereas the signal-optimized scheme minimizes the adjacent channel interference due to spectral regrowth.**

***Index Terms*—Satellite communication, predistortion, contraction mapping theorem, power amplifiers, spectral regrowth.**

I. Introduction

The need for higher data rates over satellite communication links has pushed to develop an evolution of the DVB-S2 [1], the DVB-S2X [2], which introduces more spectrally-efficient constellations and sharper roll-off. However, the higher-order constellations are more sensitive to non-linear interference generated by the on-board amplifier. The compensation of the impairment resulting from the non-linearity is, then, a key point for higher satellite throughput [3].

The mitigation of non-linear interference can either be done at the transmitter with predistortion [3]–[11] or at the receiver with equalization [12]. In the literature, the predistortion techniques are separated into two categories, the data predistortion, which operates at symbol rate [10], [11], and the signal predistortion which operates at a higher sample rate after the pulse shaping filter [3]–[9].

One class of signal predistortion techniques relies on the application of the contraction mapping theorem, which aims to linearize the non-linear channel with [5]–[7] or without [8] memory. These techniques use an iterative optimization algorithm. The optimization error is defined from the desired signal at the non-linear system output. The objective is to converge towards the fixed-point of the associated contraction mapping.

In [4], we considered satellite communications and we proposed to apply the contraction mapping theorem to develop a data-optimized signal predistortion, with an optimization error defined from the data sequence. Assuming perfect channel identification, the resulting scheme, referred to as data-optimized signal predistortion in this paper, outperforms one of the best signal predistortion technique in satellite communications [3][1].

However, most of these papers assume the perfect knowledge of the non-linear system model. In practice, this model has to be identified. [7] investigates the impact of modeling errors on the linearization method by considering an arbitrary erroneous Volterra model without implementing the identification process and concludes that such techniques are robust provided the condition for convergence keeps satisfied.

In this paper, we focus on the best signal predistorsion schemes in a realistic single carrier satellite communication environment with channel model identification. We first describe the linearization method of [5]–[8] that leads to a signal-optimized signal predistortion suited for satellite communications. Then we present the data-optimized signal predistorsion scheme [4]. In order to determine whether it is better to define the optimization error from the data sequence or from the modulated signal, we compare both schemes in terms of normalized minimum mean square error (NMSE), adjacent channel interference (ACI) and total degradation (TD). To be as close as possible to the practice, we implement an identification algorithm to obtain the non-linear model with memory and our study completes the conclusion drawn by [7]. Finally, we show the robustness of the data-based signal predistorsion scheme towards identification mismatch.

[1]In [3] the author claims that his proposed scheme outperforms the well-known indirect learning architecture described in [9], [13] and simulations support this comment.

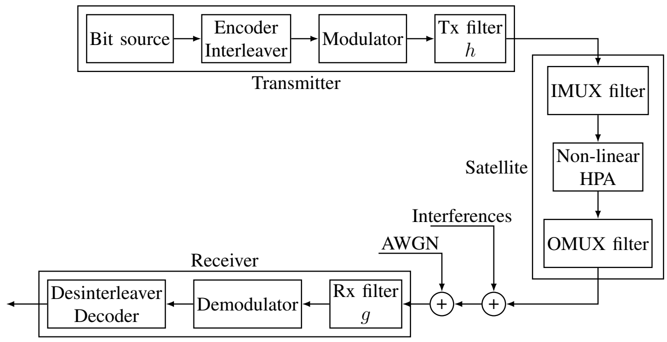

Fig. 1. Transmission model

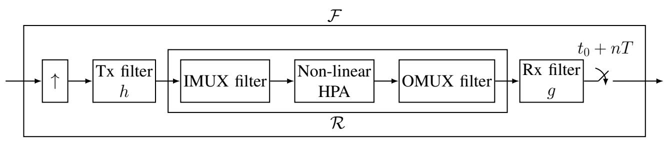

Fig. 2. Relation between the data-based and the signal-based model.

The paper is organized as follows. Section II describes the system model. The signal-optimized and the data-optimized signal-predistortion techniques are described in Section III and Section IV respectively. The comparison of both schemes in terms of NMSE, ACI, TD and robustness towards non-linear model mismatch is carried out in Section V. Finally, Section VI concludes the paper.

II. System model

The article focuses on single-carrier-per-transponder scenario of a satellite communication link. This scenario allows to improve the amplifier efficiency by operating closer to the saturation [14]. The main source of impairment is due to the satellite transponder which behaves as a non-linear channel with memory [15]. The non-linear channel with memory is the result of the cascade of the input multiplexer (IMUX), the non-linear high power amplifier (HPA) and the output multiplexer (OMUX). The IMUX selects the carrier of interest. The OMUX limits the spectral regrowth caused by the distortion and reduces the spillage over adjacent channels. We suppose that the signal-to-noise ratio (SNR) is sufficient on the uplink channel to be considered noise-free. On the other hand, on the downlink channel, we consider that the signal is corrupted by AWGN and ACI. We also assume that the overall impulse response $h * g$, where h and g are respectively the transmitter and the receiver filters, satisfies the Nyquist intersymbol interference (ISI) criterion. A block diagram of the satellite transmission model is depicted in Fig. 1.

III. Signal-optimized signal predistortion

Let us consider a non-linear system with memory modeled by the operator $\mathcal{R}\{.\}$. The desired signal at the non-linear system output is denoted by $x(t)$ and $\bar{x}(t)$ stands for the

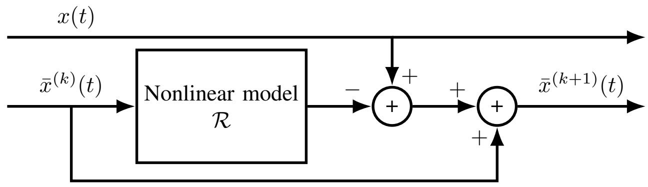

Fig. 3. k-th stage of the signal-optimized signal predistortion [5]–[8].

predistorted signal. The purpose of linearization as described in [5]–[8] is to solve the following equation:

$$\mathcal{R}\{\bar{x}(t)\} = x(t). \tag{1}$$

To express the predistortion problem as a fixed-point problem, one can either inverse the linear part of the non-linear system, as it is done in [5], [6] or add $(I - \mathcal{R})\{\bar{x}(t)\}$ on both sides of (1) as it is done in [7]. The latter solution is preferable since it avoids a computationally expensive operation of inversion and we get:

$$(I - \mathcal{R})\{\bar{x}(t)\} + x(t) = \bar{x}(t), \tag{2}$$

where I is the identity operator.

According to the contraction mapping theorem, if the operator $\mathcal{T}\{.\} = (I - \mathcal{R})\{.\} + x(t)$ is a contraction mapping, the solution is unique and can be reached iteratively by applying the operator $\mathcal{T}$, namely:

$$\bar{x}^{(k+1)}(t) = \mathcal{T}\{\bar{x}^{(k)}(t)\}, \tag{3}$$

$$= \bar{x}^{(k)}(t) + x(t) - \mathcal{R}\{\bar{x}^{(k)}(t)\}. \tag{4}$$

The condition for the operator $\mathcal{T}\{.\}$ to be a contraction mapping, when the non-linear system can be described as a Volterra model, is given in [5], [7]. The iterative structure is illustrated in Fig. 3.

Let us now consider its application to satellite communications. The non-linear operator $\mathcal{R}\{.\}$ refers to the satellite transponder, which consists of the cascade of the IMUX filter, the HPA and the OMUX filter as illustrated in Fig. 2. The desired signal is the modulated signal defined by:

$$x(t) = \sum_n d_n h(t - nT), \tag{5}$$

with h the impulse response of the transmitter filter, T the symbol duration and d_n the n-th transmitted complex symbol of the symbol sequence $\boldsymbol{d}$.

This scheme aims at minimizing the error between the non-linear transponder output and the modulated signal. It thus reduces both the non-linear interference and the spectral regrowth, and so the ACI.

If the condition of contraction given in [5], [7] is unsatisfied, few iterations might still improve the performance [7]. Otherwise, as in [8], a constant step-size can be introduced to ensure that $\mathcal{T}\{.\}$ is a contraction mapping. The convergence is validated numerically in Section V.

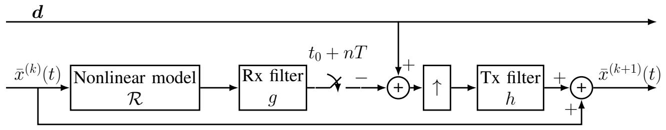

Fig. 4. k-th stage of the data-optimized signal predistortion.

IV. Data-optimized signal predistortion

This section focuses on the data-optimized signal predistortion technique proposed in [4]. In that case, the non-linear channel consists of the transmitter filter, the satellite transponder and the receiver. The non-linear operator $\mathcal{F}\{.\}$ represents the discrete-time equivalent non-linear channel (cf. Fig. 2).

The data-optimized signal predistortion scheme is obtained from a data predistortion scheme, which applied on the data sequence $\boldsymbol{d}$. Let us first describe the data predistortion technique. The purpose of the data predistortion is to solve:

$$\mathcal{F}\{\bar{\boldsymbol{d}}\} = \boldsymbol{d}, \tag{6}$$

where $\bar{\boldsymbol{d}}$ is the predistorted sequence of symbols.

From (6), we reformulate the problem as a fixed-point problem:

$$(I - \mathcal{F})\{\bar{\boldsymbol{d}}\} + \boldsymbol{d} = \bar{\boldsymbol{d}}. \tag{7}$$

This scheme minimizes the error between the discrete-time non-linear channel output and the desired data sequence. Then, here again, according to the contraction mapping theorem, if $\mathcal{P}\{.\} = (I - \mathcal{F})\{.\} + \boldsymbol{d}$ is a contraction, the solution is unique and can be reached iteratively using:

$$\bar{\boldsymbol{d}}^{(k+1)} = \mathcal{P}\{\bar{\boldsymbol{d}}^{(k)}\}. \tag{8}$$

The condition for the operator to be a contraction mapping is the same as the one defined in Section III.

Now, let us use the data predistortion scheme to define a data-optimized signal predistortion scheme as in [4]. The data-based model, denoted by $\mathcal{F}$, and the signal-based model, denoted by $\mathcal{R}$ can be linked as illustrated in Fig. 2. Denoting by g the impulse response of the low-pass receiver filter, the operator $\mathcal{F}$ depends on $\mathcal{R}$ as follows:

$$\mathcal{F}\{\boldsymbol{d}\} = \left\{[g(\tau) * \mathcal{R}\{x(\tau)\}]_{\tau=t_0+nT}\right\}, \tag{9}$$

where t_0 is the optimal sampling time instant that minimizes the distortion and $*$ denotes the convolution.

Assuming that $h * g$ satisfies the Nyquist ISI criterion and combining (5), (9) and (8), we obtain:

$$\bar{x}^{(k+1)}(t) = \bar{x}^{(k)}(t) + \sum_n (d_n - \left[g(\tau) * \mathcal{R}\{\bar{x}^{(k)}(\tau)\}\right]_{\tau=t_0+nT}) h(t - nT). \tag{10}$$

The resulting data-optimized signal predistortion scheme is illustrated in Fig. 4, where the error is computed from the data sequence and the discrete-time equivalent channel output.

Let us mention that $\mathcal{R}$ doesn't include the transmit and the receive filters contrary to $\mathcal{F}$. As a consequence, compared to the original data predistortion, and in the context of realistic channel identification, the data-optimized signal predistortion scheme exhibits two advantages: first, it reduces the number of kernels to estimate and secondly, it limits the risk of identification errors. Both signal-optimized and data-optimized signal predistortion schemes require the same non-linear system identification ($\mathcal{R}$) but differ from the update equation used in the iterative algorithm (see (4) and (10)).

V. Performance evaluation

In this section, we compare the performance of the signal-optimized and the data-optimized signal predistortion, with perfect or imperfect knowledge of the non-linear channel through Monte Carlo simulations. In case of imperfect knowledge, a realistic channel identification is carried out as described in section V-A. In both cases, the algorithms are initialized with $\bar{x}^{(0)}(t) = x(t)$.

For the simulations, the transmitter and receiver filter are square-root raised cosine (SRRC) filters with a 5% roll-off. The characteristics of the IMUX, OMUX filters, traveling-wave tube amplifier (TWTA) and the 32-APSK constellation are those defined in the DVB-S2 [1]. The symbol rate is set to 38 MBd. The interferers are delayed and time-shifted version of the output of the OMUX filter located at 40 MHz on either sides of the carrier of interest. The interference can, then, be expressed as:

$$y_{AC}(t) = \sum_{\substack{m=-M_i/2 \\ m \neq 0}}^{M_i/2} y(t + \Delta_{t,m}) \cdot e^{j2\pi m \Delta_f t}, \tag{11}$$

where $y(t)$ is the output of the OMUX filter, $\Delta_{t,m}$ is a time-delay chosen such that the interferer is not synchronized with the carrier of interest, Δ_f is the carrier spacing and M_i is the (even) number of adjacent carriers. In our case, we consider only two adjacent carriers ($M_i = 2$). An oversampling factor of 8 is used. In order to ensure the contraction condition, a real constant step-size is introduced, when needed. The step-size reduces the amplitude of the updating term in eq.(4) and eq.(10), as it is done in [8]. In the simulations, the step-size is adjusted for an input back-off (IBO) of 13dB.

A. Identification

To identify the non-linear system $\mathcal{R}$ (composed of IMUX, HPA and OMUX), we use a memory polynomial model (MP) [16], which is a reduced-complexity Volterra model [9]. It allows practical on-the-fly implementation [3]. We apply a least mean square (LMS) algorithm, as in [17], with the step parameter set to 10^{-5} and a training sequence that spans 500000 symbols. The memory polynomial is expressed as follows:

$$z(t) = \sum_{k=1}^{K} \sum_{l=-L}^{L} a_{kl} s(t - l) |s(t - l)|^{k-1}, \tag{12}$$

where $z(t)$ is the output of the model, $s(t)$ is the input, the a_{kl} are the polynomial coefficients of the non-linearity, K is the maximum order and L is the memory depth. As in [9], only

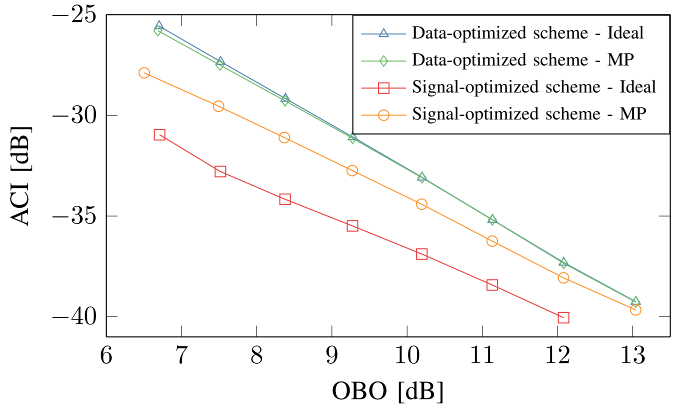

Fig. 5. ACI at the output of the matched filter versus the OBO.

odd power terms up to the fifth order ($K = 5$) are considered. The memory depth is set to 2 ($L = 2$).

B. Figures of merit

The total degradation TD is a common measure of the quality of distortion compensation and of the efficient use of the amplifier. It depends on the difference in signal-to-interference-plus-noise ratio (SINR) for a given bit error rate (BER) between the non-linear case and the AWGN channel (without ACI), plus the output back-off (OBO). The SINR in the nonlinear case and for the AWGN channel are respectively denoted by $\frac{E_b}{N_0}\Big|_{NL}$ and $\frac{E_b}{N_0}\Big|_{AWGN}$. The OBO is the difference between the maximum amplifier power output and the mean power output. The OBO is computed after the receiver filter. The TD reads:

$$TD = OBO + \frac{E_b}{N_0}\Big|_{NL} - \frac{E_b}{N_0}\Big|_{AWGN} \quad \text{[dB]}. \qquad (13)$$

The NMSE measures the in-band distortion. It is defined by:

$$NMSE = 10\log\left(E\left[\frac{\sum_n |\hat{d}_n - d_n|^2}{\sum_n |d_n|^2}\right]\right) \quad \text{[dB]}, \qquad (14)$$

where E is the mathematical expectation and $\hat{d}_n$ is the n-th gain and phase corrected sampler output *without ACI*.

The spectral regrowth generated by the non-linear amplification can lead to spillage over adjacent carriers. We measure the interference at the output of the receiver filter g by the parameter denoted by ACI and equal to:

$$ACI = 10\log\left(E\left[\frac{\int |(y_{AC} * g)(t)|^2 \mathrm{d}t}{\int |(y * g)(t)|^2 \mathrm{d}t}\right]\right) \quad \text{[dB]}. \qquad (15)$$

C. Results

The following results are obtained from to the identified non-linear channel after the training phase as described in section V-A.

The ACI performance is given in Fig. 5 for both perfect and identified non-linear system model. The signal-optimized signal predistortion scheme outperforms the data-optimized scheme up to 5.4 dB for both cases. However, whereas the data-optimized scheme exhibits similar performance in

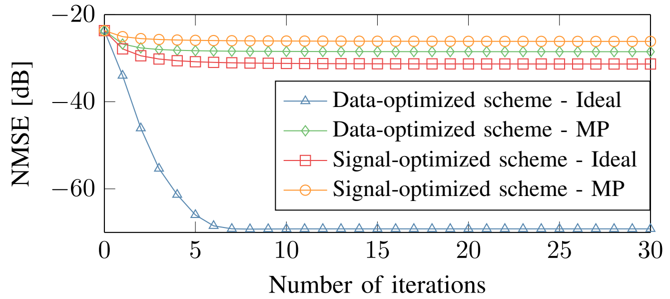

Fig. 6. NMSE at the output of the matched filter for an IBO of 14 dB versus the number of stages.

both cases, the signal-optimized scheme is more sensitive to identification mismatch (degradation of up to 3.3 dB). Improvements might be obtained by, first, the use of a full-Volterra model instead of a memory polynomial model and, then, by increasing the order used to describe the channel. However, a higher order and/or a full-Volterra model would significantly increase the complexity.

As for the NMSE, given in Fig. 6 the data-optimized scheme outperforms the signal-optimized one significantly in both cases (38 dB for the ideal case and 2.5 dB in the identified case). Both methods have converged after 10 iterations.

The total degradation TD *with ACI* is plotted in Fig. 7 as a function of OBO.We observe that, at their optimum point, the signal-optimized scheme performs slightly better (0.3 dB) than the data-optimized one when the non-linear channel is perfectly known. The trend is reversed in case of imperfect identification with MP model. The data-optimized scheme outperforms the signal-optimized scheme largely by 1.8 dB .

We conclude that the data-optimized signal predistortion scheme is more effective in practice. The complexities of both methods are nearly equivalent since they are mainly driven by the non-linear channel model and the number of stages of the iterative structure. The data-optimized scheme outperforms the signal-optimized one in terms of TD, NMSE and robustness towards identification mismatch. The remaining ACI can be dealt with at the receiver with an equalizer combined with a channel decoder.

VI. Conclusion

In this paper, we investigated a data-optimized and a signal-optimized signal predistortion schemes based on the contraction mapping theorem in the context of realistic satellite communications with channel model identification. We compared the performance in terms of NMSE, ACI, TD and robustness towards identification mismatch. The identification of the non-linear channel with memory was done with a LMS algorithm applied on a reduced-complexity Volterra model which allows practical implementation. The complexities of both methods are nearly equivalent since they are mainly driven by the non-linear model and the number of stages. With realistic channel identification, the data-optimized scheme outperforms the signal-optimized one in terms of NMSE and TD (up to 1.8 dB). The residual ACI could be dealt with at the receiver. Thus,

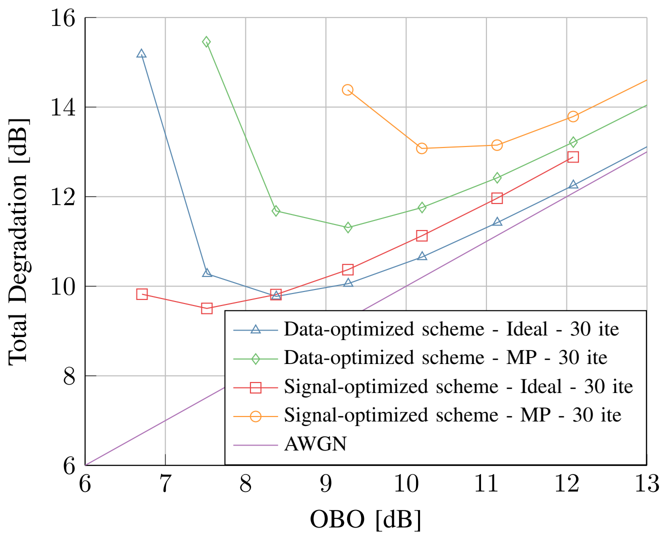

Fig. 7. Total degradation with ACI for a target BER of 10^{-4} for the data-optimized and the signal-optimized signal predistortion scheme with perfect knowledge of the channel (Ideal) or with identification (MP).

the data-optimized scheme achieves a better trade-off between performance and robustness towards identification mismatch.

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