# Real-time Iterative Pre-distortion in Commercial DVBS2X Satellite Modulator

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***Abstract*****—** In order to meet the ever-increasing demand for satellite throughput, high efficiency amplitude and phase shift keying (APSK) modulation orders have been introduced in the latest revision of the DVBS2X standard, posted in 2015, along with tighter roll-off factors of 0.05 and 0.1, leading to an increase of about 15% in achievable spectral efficiency in the AWGN channel. Nevertheless, nonlinear distortions caused by the on-board high power amplifier (HPA), especially when driven close to saturation, as well as linear distortions induced by the payload channelizing filters (IMUX, OMUX), unravel these benefits unless mitigated. In this context, our institute have developed a powerful pre-distortion technique, based on the so-called small variation algorithm (SVA). Following intensive software simulation campaigns, a proof of concept demonstration was completed using in-house FPGA-based hardware pre-distortion mock-up, confirming that achievable spectral efficiency can be increased by up to 11% thanks to the SVA mitigation technique.

***Index Terms***—SVA iterative pre-distortion, DVB-S2X, achievable spectral efficiency, model based FPGA prototyping

## I. Introduction

The latest DVB standard, known as DVB-S2X (extension to DVB-S2) has introduced a set of innovations, such as high efficient APSK modulations and low roll-off factors, to improve the overall efficiency of satellite links. However, access to the most efficient transmission schemes requires very good link budgets, which implies a low level of linear and non-linear distortions. The systematic linearization of the on-board power amplifier, as well as adequate adjustment of the amplifier operating point (Output-Back-Off, i.e. OBO), greatly reduces the impact of non-linear distortions on the transmitted signal. In addition, use of guard bands limits inter-symbols (ISI) and adjacent carriers (ACI) interferences. Despite these provisions, satellite operators very rarely use modulation schemes higher than 16APSK. The implementation of a symbol pre-distorter in the transmitter allows mitigating both non-linear distortions introduced by the on-board amplifier while reducing the output back-off (OBO), as well as linear distortions, especially those caused by the group delay variation in the payload filters. The benefit of symbols pre-distortion before spectral shaping over signal pre-distortion is to keep the transmitted signal band within the limits defined by the Nyquist emission filter. However, this method is inherently suboptimal as its effect is limited to the signal band, and thus cannot mitigate out-of-band distortions induced by the on-board amplifier (spectrum regrowth). In addition, in multi-carriers configurations, the digital pre-distorter (DPD) must have access to the symbols of all carriers. Thus, it is particularly suitable for single-carrier per transponder applications (DTH, VSAT,...).

Many algorithms for pre-distortion of symbols have been proposed in the literature. Among the most significant, we can mention the pre-distortion symbol based on Volterra's modelling [1], [2]. This method consists of applying a Volterra model to the symbols of the constellation, trying to invert the channel transfer function. In practice, the order and depth of the Volterra series memory must be truncated for the method to be implemented at a reasonable cost, which limits its accuracy. Another method is based on the use of a look-up table (LUT) [3], [4]. This table matches the symbol sequences of the constellation (A) PSK with the pre-distorted symbol sequences for the $M^L$ sequence combinations, where M represents the number of constellation states and L the length of the sequence. Here again, it is advisable to limit the depth of the memory (in practice to 4) to contain the size of the memory needed to store the table. This paper focuses on a third method, based on the small variation algorithm (SVA). Intensive simulation campaigns have shown that this method outperforms traditional methods, while maintaining the complexity at a compatible level of an FPGA implementation. This paper is organized as follows. Section II briefly describes the SVA principle and introduces the framework. Section III presents the performance study of the SVA digital pre-distorter (DPD) and the main outcomes. Section IV presents the architecture of a DPD prototype and the design method used. Finally, section V describes the experiments carried out in a laboratory environment.

## II. SVA Pre-Distortion Principle

In this section, the principle of SVA pre-distortion is briefly explained, and the optimizations considered for both software and hardware model are detailed.

### A. *General Formulation*

In [5], the authors have proposed a new iterative pre-distortion algorithm, called SVA for Small Variation

Manuscript received June 25, 2019; revised January 5, 2020.
doi:10.12720/jcm.15.2.115-121

Algorithm. This study has shown that the performance improvement brought by SVA algorithm represents several dB on the MSE and up to 1.5 dB on the link budget with 32-APSK modulation, compared to state-of-the-art pre-distorters based on memory polynomials [2] and look-up tables [4]. Basically, SVA consists in pre-distorting a block $L$ of transmitted symbols to minimize the Euclidian distance between the transmitted $\boldsymbol{s}$ and received symbols $\boldsymbol{y}$:

$$\varepsilon_{k,j} = \boldsymbol{y} - \boldsymbol{s} \tag{1}$$

The pre-distorted symbols $x_{k,j}$ are updated at each step $j$ ($j = 1 \dots L$ assuming a block of $L$ symbols) of each $k$ iteration based on a linear approximation of the channel output variation ($F_{k,j}^{Lin}$):

$$x_{k,j} = x_{k,j-1} + \Delta_{k,j}^{lin} \mid \Delta_{k,j}^{lin} = \underset{\Delta_{k,j}}{\operatorname{argmin}}\left(\left\|\varepsilon_{k,j} + F_{k,j}^{Lin}\right\|^2\right) \tag{2}$$

The major drawback of this method is the complexity induced by the number of channel simulations involved by the iterative process; basically, three channel simulations are needed to compute the small variation $\Delta_{k,j}^{lin}$ to be applied to the symbol at step $j$ of iteration $k$; one simulation to evaluate the Euclidian distance $\varepsilon_{k,j}$ and two additional simulations to assess the channel output variation function $F_{k,j}^{Lin}$. Nevertheless, parametric studies have shown that it is possible to limit the number of channel simulations at iteration $k$ without significant loss of performance by considering that the channel response to an input variation is finite. In addition, the channel model can be optimized to significantly reduce the complexity of implementation, as detailed in section II-B.

### B. *Channel Model*

The digital pre-distorter (DPD) channel model is designed to closely reproduce both linear and non-linear distortions induced by the transmission channel. In the current framework, we consider six subsystems, in line with the system model described in section III-A:

- The transmitter square raised root cosine (TX SRRC) filter,
- The payload IMUX filter,
- The payload on-board high power amplifier (HPA),
- The payload OMUX filter,
- The receiver square raised root cosine (RX SRRC) filter,
- The symbol timing phase synchronizer.

Nevertheless, we consider some simplifications to make DPD implementation on a FPGA target feasible. First, we merge TX SRRC and IMUX filters by convoluting their discrete impulse response. The resulting impulse response, $h_1(n) = h_t(n) * h_{IMUX}(n)$, is then shortened and implemented as a single polyphase interpolation FIR filter structure of four 22-tap branches : $h_{i=0\dots3}^{1}(n = 0 \dots 21)$. In this way, the filter response is accurately reproduced for an acceptable implementation complexity. We also perform the same optimization with OMUX and RX SRRC filter allowing implementing these filters in a single polyphase decimation FIR structure $h_{i=0\dots3}^{2}(n = 0 \dots 21)$ . Besides, we do not implement the symbol timing phase synchronizer. Instead, its behaviour, i.e. the average timing instant chosen by the detector, is modelled by properly resample one of the filter impulse response. Finally, the HPA amplitude and phase characteristics (AM/AM and AM/PM) are converted into a complex gain implemented as a lookup table (LUT). The resulting channel model is depicted in "Fig. 1".

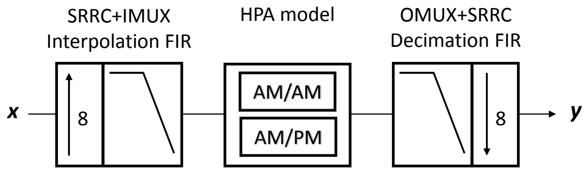



Fig. 1. SVA channel model.

It should be noted that the SVA iterative pre-distortion method applies to any non-linear memory channel, as long as it can be accurately modelled at an acceptable implementation cost.

## III. Numerical Study

Intensive simulations have been performed to evaluate the benefit of SVA DPD to improve DVB-S2(X) links efficiency for application areas that uses a single carrier per transponder configuration. This performance is measured at receiver level based on the NMSE metric, and assessed at system level by evaluating the achievable spectral efficiency based on EXIT charts computations [6], [7].

### A. *System Model*

We consider the system model depicted in "Fig. 2". The transmission subsystem (gateway) is composed of the functional blocks detailed in DVB-S2 normative documents [8], [9]. Optionally, a digital pre-distorter (DPD) can be applied on the physical frame (PL) frame according to the principle exposed in section II. The transmitter shaping filter is implemented as a polyphase interpolation FIR structure that deliver the transmitted signal in baseband, sampled at $Fs = Ns.Rs$, where $Rs$ is the simulated symbol rate and $Ns$ a tunable oversampling factor.

The channel subsystem models a transparent Ku-band satellite transponder, with 36MHz bandwidth and a frequency spacing of 40MHz, composed of an input filter (IMUX), a linearized TWTA operated at a tuneable input back off (IBO) and an output filter (OMUX). The channel main characteristics are given in "Fig. 3". The downlink noise is modelled as an Additive White Gaussian Noise (AWGN) with zero average mean and variance function of the simulated $Es/No$ ratio.

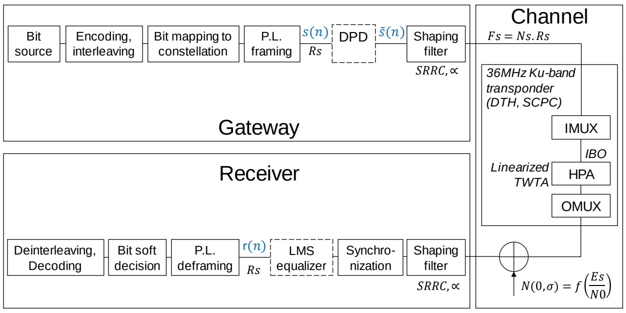
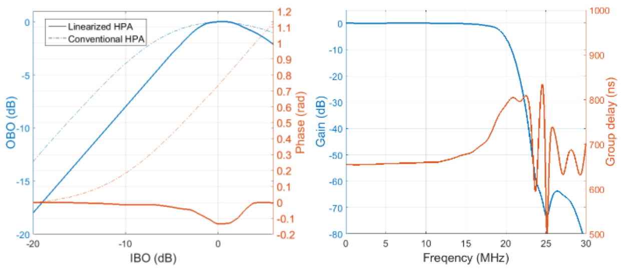



Fig. 2. System model.

At receiver input, a shaping filter, paired to the transmitter square raised root cosine filter, processes the downlink signal. This filter is implemented as a polyphase decimation FIR structure in order to keep only two samples per symbol period. The synchronization subsystem includes a symbol synchronizer that recovers the symbol-timing phase from the sample input based on a Gardner timing error detector and generates symbol output by resampling the input at the optimal timing instant. In addition, the carrier phase is recovered based on DVB-S2 guidelines [10]. Then, optionally a 16-tap LMS equalizer is applied to mitigate the linear distortions introduced by the channel. Before being applied, the equalizer is trained with dummy physical layer (PL) frames.

Further, bit soft decisions, decoding and desinterleaving are performed in order to recover the transmitted bit sequence.




(a) (b)

Fig. 3. Channel characteristics: (a) HPA AM/AM and AM/PM transfer functions (b) channel gain and group delay profile as function of the frequency offset wrt the channel center frequency.

## B. Simulation Set-up

The performance offered by SVA DPD is evaluating with regards to a typical DVB-S2 and DVB-S2X transmission scheme, based on the system model defined in the previous section. For the DVB-S2 reference scenario, we assume a transmission at a symbol rate $Rs$ of 30MBauds with rolloff $\propto$ of 0.2 resulting in a signal bandwidth of $(1{+}\propto)Rs =$ 36MHz that matches the transponder bandwidth. For the DVBS2X reference scenario, the rolloff factor is lowered to 0.1 while maintaining the same signal bandwidth, leading to increase the spectral efficiency. Also, higher order 64APSK and 128APSK constellations are considered for performance assessment. For both reference scenarios, we assume that a 16-tap LMS equalizer is applied as explained in section III-A. On the opposite, the DPD technique is investigated without equalizer. Furthermore, we consider a symbol rate of 36Mbauds with a roll-off of 0.1, leading to a signal bandwidth of 39.6MHz greater than the transponder bandwidth but still lower to the transponder carrier spacing. This allows to challenge the ability of SVA DPD technique to overcome the linear distortions that occurs when the signal band edges fall into the selective zone of IMUX and OMUX filters. Finally, the gains offered by DPD is assessed with both conventional and linearized on-board amplifiers.

## C. Performance Metrics

Normalized MSE (NMSE) is used to characterize the in-band distortion. The mean square error is computed between the received symbols after time, frame and carrier phase recovery and the related transmitted symbols.

$$MSE = \frac{1}{N}\sum_{i=0}^{N-1}(r_i - s_i)^2 \qquad (3)$$

Furthermore, in order to evaluate the asymptotic performance of DPD transmission scheme, the achievable spectral efficiency is evaluated based on EXIT charts computations [6] according to the following rational. The achievable coding rate is first evaluated using the area theorem (area under the obtained EXIT curve). Even if the area theorem is only proven for the binary erasure channel, it provides a good approximation for other types of channels. The area under EXIT curves gives the highest achievable coding rate suitable for the iterative detection. Then, the achievable spectral efficiency is deduced as a function of the SNR [7].

By convention, the spectral efficiency is assessed with respect to the transponder carrier spacing, i.e. 40MHz. Therefore a DVB-S2 transmission scheme at $Rs$=30MHz using 32APSK is de facto limited to an achievable spectral efficiency of $log_2(32) \times (30/40) = 3.75\text{bit.s}^{-1}/\text{Hz}$.

## D. Results

The achievable spectral efficiency was computed based on EXIT charts as described in Section III-C for a range of $IBO$ and $Es/No$ ratio, and then expressed as function of the $SNR$ defined as $SNR = Es/No + OBO$ (dB).

"Fig. 4" depicts the optimum achievable spectral efficiency over the range of SNR for each transmission scheme defined in section III-B. Describing the graph from bottom to top:

- The red curve exhibits the gain offered by a typical DVB-S2X transmission compared to the previous release of the standard (blue curve). Up to a SNR of about 17dB, the spectral efficiency improvement is only due to the use of a lower roll-off factor at equivalent signal bandwidth. Beyond this value, usage of high modulation schemes allows to increase this gain.

- The yellow curve demonstrates the performance of DPD when a linearized on-board amplifier is considered. SVA based DPD offers an increased achievable spectral efficiency of about 11% compared to a typical DVB-S2X transmission.
- The violet curve demonstrates the performance of DPD without on-board linearization. Compared to the previous scenario, the achievable spectral efficiency is slightly increased despite the conventional amplifier. Thus, SVA pre-distortion method can be considered as a credible alternative to on-board TWTA linearization.
- Finally, the green curve represents the link achievable spectral efficiency through an additive white Gaussian noise (AWGN) channel.

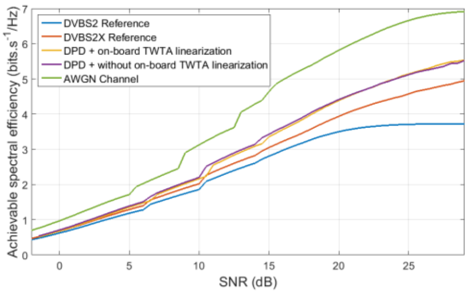



Fig. 4. Achievable spectral efficiencies.

"Fig. 5" illustrates the benefit of SVA DPD when applied on a 32-APSK constellation. The blue dots figure the reference received constellation, i.e. when no pre-distortion is applied, at an OBO target value of 2dB, without thermal noise. The reds dots allow to assess graphically the effect of SVA based DPD on the reduction of linear and nonlinear distortions while maintaining the same level of output back off. The gain that the SVA based DPD offers in terms of NMSE is therefore greater than 8dB.

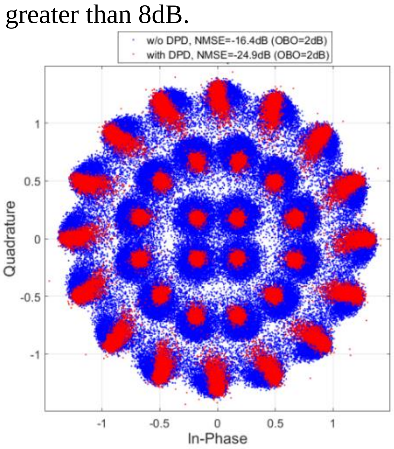



Fig. 5. Received constellation improvement thanks to SVA based DPD (@OBO=2dB).

## IV. Prototyping

Following the software simulation phase, we designed a DPD prototype based on the SVA method to demonstrate the validity of the concept in an environment more representative of real operating conditions. This section describes the architecture of this prototype and the design method used.

### *A. Hardware*

The pre-distortion function was prototyped on a XILINX VC709 board equipped with a VIRTEX7 XC7VC690T FPGA. This board is coupled to a commercial DVB-S2 modulator (TYGER model from TEAMCAST manufacturer) modified to allow the processing of complex I/Q symbols on a daughter board, before the SRRC filter. Data are exchanged via a fast serial link using the Aurora protocol. This prototype delivers a modulated signal according to the DVB-S2(X) standard in L-band in a range of $Rs$ from 0.05Mbauds to 48Mbauds when DPD is activated or up to 60Mbauds when pre-distortion function is bypassed.

### *B. Prototyping Method*

We have experienced a model-based design to implement the pre-distortion function on FPGA as depicted on "Fig. 6". The synthesizable RTL code that implements the pre-distortion function is automatically generated from a Simulink model using Mathworks HDL coder. We designed the DPD model in such a way that a new pre-distortion prototype based on an alternative channel model can easily be re-generated, if necessary. The implementation model directly derives from the reference simulation model used to establish the performance of the pre-distortion solution. Compared to the latter, it integrates all the design constraints inherent to its implementation on FPGA. In particular, we have converted the model to fixed-point, and refined some complex functions to meet area / timing constraints. All model refinement steps have been validated within an integrated test environment. In parallel, the functions for managing the interfaces of the VC709 board, generating clocks, etc. have been written directly in VHDL code. Finally, we have integrated all these source files into a Vivado® project to generate the FPGA bitstream.

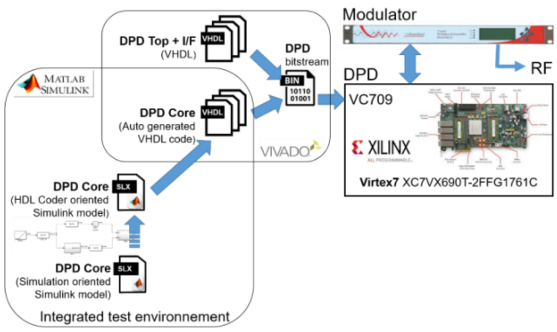



Fig. 6. DPD prototyping workflow.

The main characteristics of this design are:

- System frequency (Fsys) = 200MHz,
- Flexible useful symbol rate up to 48 MHz; the design automatically adapts to the value of the symbol rate programmed on the modulator,

- Percentage of use of FPGA resources: ~50%,
- Functional parameters configurable on the fly via Ethernet link. Therefore, the pre-distortion prototype can be evaluated with different transponder characteristics without the need to regenerate the bit stream; simply reload a new configuration file with the appropriate characteristics of the IMUX, OMUX, and power amplifier filters (transfer functions and operating point).

## V. EXPERIMENTATION

We have tested the experimental pre-distortion device in the CNES Telecom Engineering Laboratory (LIT) on a test bench representative of a satellite feeder link. This section details the experiments and presents the results of the measurements in relation to the simulated references.

### A. *System Configuration and Experiment Setup*

The experimental bench, depicted in "Fig. 7", is composed of the following subsystems:

- A DVB-S2 modulator integrating the pre-distortion device under test (DUT). The equipment is operated in test mode (PRBS) and with constant constellation (CCM mode).
- A satellite propagation channel which includes a propagation channel emulator (PCE) which implements the IMUX and OMUX filters of the satellite transponder and a flight model of a linearized Ka travelling wave tube amplifier (TWTA)
- A characterization receiver that provides the performance metrics described hereunder.

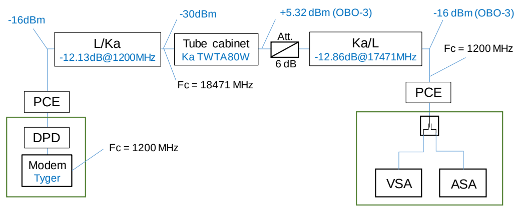



Fig. 7. DPD experiment setup.

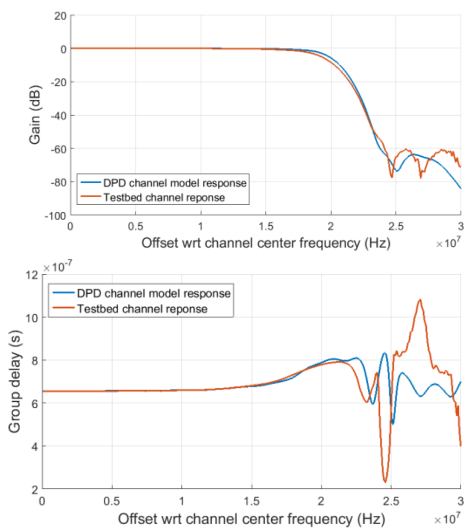



Fig. 8. Comparative DPD and testbed channel responses.

TWTA AM/AM and AM/PM nonlinear distortion characteristics have been first measured and then converted as a complex gain transfer function to feed the DPD channel model. IMUX and OMUX characteristics from [10] have been considered to configure both PCE and DPD channel model. The amplitude and phase response of the test bench was measured with a vector network analyser prior to the experimentation campaign and checked against the DPD channel model response. The slight differences observed in "Fig. 8" can be considered representative of a typical DPD setup where the response of the channel model cannot perfectly match the actual transponder response.

### B. *Performance Metrics*

We consider the error vector magnitude (EVM) and the modulation error ratio (MER) performance metrics to characterize the constellation quality. EVM is defined as the error vector in the diagram on the right. We have configured the measuring equipment to normalize this value to the mean reference power, i.e. the mean power of the reference signal at symbol instants.

The modulation error ratio (MER) is closely related to EVM:

$$MER = -20.log_{10}(EVM) \text{ dB}$$

where the EVM is normalized to the mean reference power.

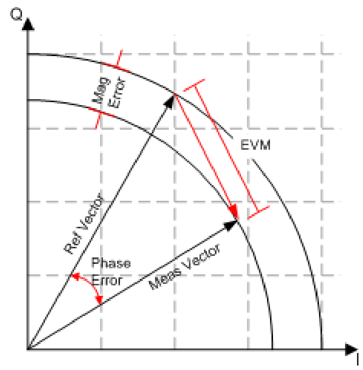



Fig. 9. EVM.

### C. *Experimentation Plan*

Two main transmission scenarios were carried out on the experimental test bench in a single carrier per transponder configuration:

- A nominal scenario for which the transmission symbol rate is matched to the transponder bandwidth (at -3dB), to reach the best trade-off between the transmission capacity and the level of signal distortion caused by the selectivity of the payload filters,
- A more aggressive transmission scenario, called ***evo***, characterized by a single carrier signal with a bandwidth greater than the bandwidth at -3dB of the satellite transponder, to maximize the transmission capacity.

The different test cases based on these scenarios are detailed in the table I.

TABLE II: EXPERIMENTATION PLAN

| Test case | ModCod | Rs (Mbauds) | $\alpha$ | DPD | OBO (dB) | ΔGD (ns) | ΔGD (%Ts) |
|---|---|---|---|---|---|---|---|
| 1 | 16APSK2/3 | 30 | 0.2 | No | 2.0 | 65.4 | 193 |
| 2 | 32APSK3/4 | | | | | | |
| 3 | 16APSK2/3 | | | Yes | | | |
| 4 | 32APSK3/4 | | | | | | |
| 5 | 16APSK2/3 | 36 | 0.1 | No | 2.0 | 128.6 | 463 |
| 6 | 32APSK3/4 | | | | | | |
| 7 | 16APSK2/3 | | | Yes | | | |
| 8 | 32APSK3/4 | | | | | | |

### D. Results

The experimental results are summarized in the table II. It presents the gain on the MER provided by the pre-distortion for the two transmission scenarios studied and for 16APSK and 32APSK modulations. This result must be put into perspective with respect to the group delay variation (ΔGD) in the signal band.

TABLE II: RESULTS

| Scenario | ModCod | Rs (Mbauds) | $\alpha$ | OBO (dB) | ΔGD (ns) | ΔGD (%Ts) | MER Gain[2] (dB) |
|---|---|---|---|---|---|---|---|
| nominal | 16APSK2/3 | 30 | 0.2 | 2.0 | 65.4 | 193 | 8.7 |
| | 32APSK3/4 | | | | | | 6.8 |
| evo | 16APSK2/3 | 36 | 0.1 | 2.0 | 128.6 | 463 | 13.6 |
| | 32APSK3/4 | | | | | | 12.4 |

Overall, the experimental results confirm the interest of the pre-distortion device to improve the quality of an SCPC transmission through a satellite transponder, even with a linearized tube. We note:

- A gain of about 7/8dB on the MER at the same target OBO (~2dB) on the nominal scenario (Rs=30Mbauds, roll-off: $\alpha$=0.2),
- A gain of 12/13dB on the MER at the same target OBO (~2dB) on the evo2 scenario (Rs=36Mbauds, roll-off: $\alpha$ =0.1).

Figures in appendices illustrate the quality of the received constellation, with and without pre-distortion and for both scenarios.

## VI. CONCLUSION

In this paper, a digital pre-distorter (DPD) based on the iterative small variation algorithm was studied in a single carrier per satellite transponder configuration. In that context, a gain of 11% on the achievable feeder link spectral efficiency compared to a DVB-S2X typical transmission was demonstrated by numerical simulation. Alternatively, when the on-board power amplifier is operated at an output back off (OBO) of 2dB, the improvement of the received constellation in term of NMSE is greater than 8dB. Following the numerical study, a FPGA DPD prototype was developed using a rapid prototyping method based on Mathworks and Vivado software suites. Experimentations carried out in the CNES Telecom Engineering Laboratory (LIT) have confirmed the numerical results in a real-time context on a test bench representative of a satellite transmission. Therefore, the SVA based DPD offers a powerful method to mitigate both linear and non-linear distortions for single carrier per transponder configurations. For a satellite operator, this solution enables higher modulation orders, thus increasing the link throughput. Further work is underway to adapt this pre-distortion solution to wideband transponders, for which memory effects and implementation constraints are more critical.

## APPENDIX A RESULTS FIGURES[3]

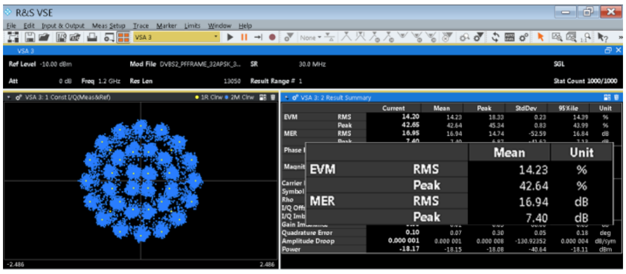



Fig. 10. Received constellation (nominal scenario, w/o pre-distortion).

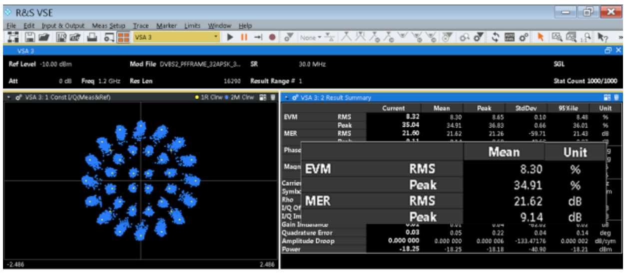



Fig. 11. Received constellation (nominal scenario, with pre-distortion).

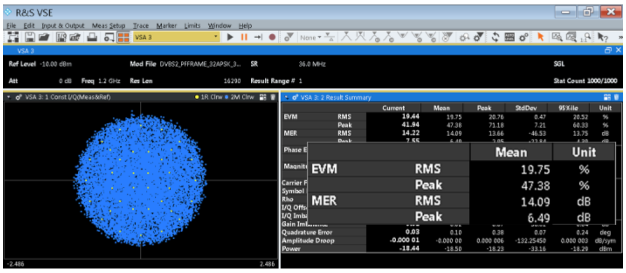



Fig. 12. Received constellation (evo scenario, w/o pre-distortion).

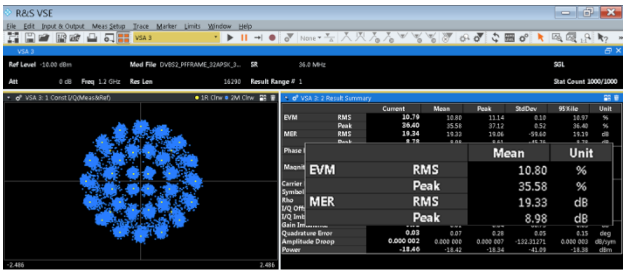



Fig. 13. Received constellation (evo scenario, without pre-distortion).

[2] The gain values presented in table II are derived from MER measurements corrected to reflect the actual improvement of the received symbols when the transmitted symbols are taken into account (DA mode: Data Aided)

[3] VSE measurements (e.g. EVM/MER) are performed without knowledge of the transmitted symbols (NDA mode: No Data-Aided).

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## AUTHOR CONTRIBUTIONS

This research work was carried out as part of the NEWCAST project at IRT Saint-Exupéry, Toulouse, France. Christophe Lavallée is the project manager. As such, he has set up the partnership with CNES to carry out the experiment. Philippe Potier conducted the research work and wrote the paper; both authors had approved the final version.

## ACKNOWLEDGMENT

The authors wish to thank the LIT laboratory staff for their valuable help in setting up the experiment.

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