Development, Modelling and Simulation of Advanced Techniques to Estimate and Improve the Performance of Satellite Telecommunications Systems in Non-Linear Channels

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Abstract. Non-linear amplifiers that are used near saturation in satellites, cause severe distortions of the transmitted signal. This dissertation proposes novel signal processing techniques that counteract these distortions to improve performance. Firstly, the fact that the non-linearities introduced by memoryless bandpass amplifiers preserve the symmetries of the M-ary Quadrature Amplitude Modulation (M-QAM) constellation is exploited, to present a Cluster-Based Sequence Equalizer (CBSE). The proposed equalizer exhibits enhanced performance compared to other techniques, including Volterra equalizers and neural network equalizers. Moreover, this gain in performance is obtained at a substantially lower computational cost. Secondly, a new constellation shaping technique, which efficiently and effectively reduces the Peak to Average Power Ratio (PAPR) of Orthogonal Frequency Division Multiplexing (OFDM) systems, is proposed. The proposed technique requires minimal implementation complexity, while it offers considerable performance gains. Closed form analytical expressions for the distribution of the PAPR and the Bit Error Rate (BER) are derived and their accuracy is verified via simulations. Finally, a detailed comparative study of two single-carrier frequency-division multiple access schemes is presented, namely localized FDMA scheme (LFDMA) and interleaved FDMA scheme (IFDMA), versus orthogonal scheme (OFDMA), for a satellite up-link based on the digital video broadcasting via satellite (DVB-S) standard. Considering two state-of-the-art high power amplifiers, operating in the K- and S-bands, the performance of synchronous and asynchronous LFDMA, IFDMA and OFDMA is evaluated in a multi-user environment including inter-block interference.

Keywords: CBSE equalization, PAPR reduction, SC-FDMA, OFDMA, satellite systems.

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1 Introduction

The role of a satellite is to receive a signal from an earth station or another satellite (uplink) and, acting as a simple repeater, to transmit it to another earth station or satellite (downlink) [1]. Fig. 1 illustrates a typical satellite communication system [1]. New generation satellites have regenerative payloads [2, 3] with on-board processing. This means that the baseband transmitted signal is available on-board, via demodulation, and hence uplink and downlink can be treated separately.

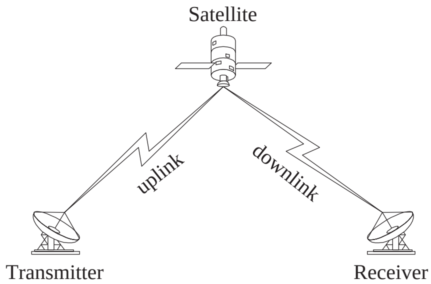

Fig. 1. Satellite communication system.

The need to maximally exploit on-board resources in a satellite communication system often imposes driving a high power amplifier (HPA), such as the travelling wave tube amplifier (TWTA), at or near its saturation point, resulting in a nonlinear distortion of the signal, and rendering the overall link nonlinear. To overcome nonlinear distortions, constant modulus constellation symbols (e.g., 4-QAM) are commonly used [2]. However, large QAM signal constellations have to be adopted whenever high bandwidth efficiency is required [4], resulting in severe nonlinear distortions. Two approaches have been proposed for solving the problem of correct reception of the transmitted signal in those cases: (a) Equalization [5–7] and (b) Predistortion or power amplifier linearization [5,8–10]. Equalization refers to processing the signal at the receiver side in order to recover the transmitted data, thus post-cancelling the link's nonlinear (amplifier) and linear (multipath) distortions. Conventional linear equalizers combat only the Inter-Symbol Interference (ISI), introduced by the propagation channel, while nonlinear equalizers aim also at equalizing the non-linear effects of the HPA. The main drawback of the equalization approach is the additional cost and the computational load it entails for each terminal. On the other hand, predistortion techniques aim at pre-cancelling the nonlinear effects via modelling the inverse of the amplifier characteristic and pre-distorting the data *prior to* the amplification stage. The overall characteristic then becomes linear. The advantage of this approach lies in the fact that only a single system is needed for cancelling the HPA nonlinearity at the satellite, compared to using an equalizer in each terminal. On the other hand, its main drawback is that the predistorter must be on-board, so it cannot be applied to the satellites already on orbit. Moreover, in case multipath is present, an equalizer at the terminal side is still needed.

The non-linearities introduced by memoryless bandpass amplifiers preserve the symmetries of the M-QAM constellation. A CBSE that takes advantage of these symmetries is presented. The proposed equalizer exhibits enhanced performance compared to other techniques, including the conventional linear transversal equalizer, Volterra equalizers and Radial Basis Function (RBF) network equalizers [5]. Moreover, this gain in performance is obtained at a substantially lower computational cost.

In recent years, the increasing commercial demand for higher data rates has led to the utilization of OFDM in several well known standards, including the 2nd generation of Digital Video Broadcasting by Satellite (DVB-S2) [11], Digital Video Broadcasting by Satellite Handheld (DVB-SH) [12] and 3rd Generation Partnership Project (3GPP) [13]. The main technical advantage for such a choice is OFDM's robustness in the presence of frequency selective fading channels commonly encountered in wireless broadband communication systems [14]. Moreover, OFDM simplifies the equalization process at the receiver's side. A major drawback of the OFDM technology is the high PAPR of the transmit signal [14]. The presence of high PAPR becomes even more critical when non-constant envelope modulation techniques, such as M-QAM, are used for transmission in order to increase the overall system capacity. Hence, the transmit power amplifiers have to operate with a large input power back-off, (IBO), from their peak power which leads to poor power efficiency [14].

In the second chapter of the dissertation, a novel, low computational complexity constellation shaping technique is presented and its performance is analysed and evaluated in order to counteract high PAPR. In the past the problem of high PAPR in OFDM has been extensively studied and various techniques have been proposed and analysed for its reduction [15]. The novelty of the proposed technique is that, in contrast to previous art, constellation shaping takes place *after* the Inverse Fast Fourier Transform (IFFT) operation instead of before, thus, directly modifying the OFDM symbol. This makes the technique independent of the modulation format, the number of subcarriers, N, or the input to the IFFT signal combination. Furthermore, handshake between transmitter and the receiver is not necessary, power increase of the transmit signal is avoided through power normalization while this procedure can be easily reversed at the receiver. Analytical closed form expressions for the PAPR distribution and the BER performance of the proposed technique are provided.

Finally, the dissertation presents a thorough and detailed comparison study of multiple access techniques for the DVB-S2. This study was done for the European Space Agency in collaboration with the European Satellite Communications Network of Excellence (SatNEx) [16]. To the best of our knowledge, similar studies for state-of-the-art satellite based systems, such as DVB-S type, are not available in the open technical literature. Orthogonal Frequency Division Multiple Access (OFDMA) is the multiple access scheme that naturally extends

OFDM to simultaneously serve multiple users. Single Carrier Frequency Division Multiple Access (SC-FDMA) schemes are employed as alternative access schemes, which offer reduced PAPR as compared to OFDMA's high PAPR [17]. Although SC-FDMA utilize single carrier modulation at the transmitter and frequency domain equalization at the receiver and typically achieve lower PAPR, they have similar transmitter structure and BER performance, as compared to an OFDMA system. The key difference in the transmitters of the two schemes is the presence of an additional discrete Fourier transform (DFT) in SC-FDMA. Among the various SC-FDMA schemes, the most popular are: (i) Localized FDMA (LFDMA); and (ii) Interleaved FDMA (IFDMA) [17]. The application of z-FDMA[1] schemes for state-of-the-art satellite multi-user systems is considered. In particular, z-FDMA access scheme performances, for a DVB-S satellite link operating in dual frequency bands (K- and S-Bands) in the presence of non-linear HPA and synchronization error are presented.

This dissertation summary has the following structure. The preservation of M-QAM symmetries by memoryless nonlinear amplifiers is demonstrated in section 2, where the new equalization algorithm is referred. In section 3 a short description of the proposed PAPR reduction technique is given while in section 4 the system model is illustrated and a summary of the comparative results is offered. Section 5 gives some concluding remarks. All the results presented here are already published [5, 18–20].

2 Cluster-Based Equalizer for Satellite Communication Channels with M-QAM Signaling

There are two technologies for the HPA on board satellites: Travelling Wave Tube Amplifiers (TWTA) and Solid State Power Amplifiers (SSPA).

- TWTA can generally be considered as memoryless. They are characterized by an AM/AM conversion and an AM/PM conversion. These are commonly modelled by a Saleh model [21].
- SSPA have intrinsically memory. It is common to model an SSPA with memory by a memoryless non-linearity (see [22] for the type of the non-linearity) followed by a linear IIR filter [8].

Here we will deal only with TWT amplifiers, due to their dominant use in satellites. According to Saleh's model [21], an input

$$x(t) = A\cos(2\pi f_c t + \theta) \tag{1}$$

into a bandpass amplifier produces an output of the form [23, 24]:

$$z(t) = g(A)\cos[2\pi f_c t + \theta + \Phi(A)] \tag{2}$$

[1] For the conciseness of the presentation, from now on and unless otherwise stated, the notation z-FDMA ($z \in \{\mathrm{L}, \mathrm{I}, \mathrm{O}\}$) will be used as a common representation of the three multiple access schemes considered in this work, i.e., LFDMA, IFDMA and OFDMA.

where the nonlinear gain function $g(A)$ is commonly referred to as the *AM/AM characteristic* and the nonlinear phase function $\Phi(A)$ is called the *AM/PM characteristic.* These are expressed as

$$g(A) = \frac{\alpha_a A}{1 + \beta_a A^2} \tag{3}$$

$$\Phi(A) = \frac{\alpha_p A^2}{1 + \beta_p A^2} \tag{4}$$

The adopted signaling scheme, namely rectangular M-ary QAM, may be viewed as a form of combined digital amplitude and digital phase modulation. In view of eqs. (1–4), the baseband complex envelope of the TWTA output is given by

$$\begin{aligned}\tilde{z}(t) &= g\big[A(t)\big]e^{j\left\{\theta(t)+\Phi\left[A(t)\right]\right\}} \\ &= \big[A(t)e^{j\theta(t)}\big]\left\{\frac{g\big[A(t)\big]}{A(t)}e^{j\Phi\left[A(t)\right]}\right\} \\ &\triangleq \tilde{x}(t)G\big(|\tilde{x}(t)|\big)\end{aligned} \tag{5}$$

where ˜ denotes complex envelope. In words, *the output of the TWTA is the product of the input signal with a factor that depends only on the input amplitude.* The result is an amplitude change and a phase rotation of the input signal constellation points. Eq. (5) implies that *the change is the same for all constellations points that share the same energy level.* The M symbols in the input constellation can be grouped in two possible ways (see Fig. 2a for the example of 16-QAM):

1. in I circles on the complex plane, where I is the number of the energy levels (for the 16-QAM case, $I = 3$), and
2. in $M/4$ squares (four points in each square), that are centered on the origin.

It is not difficult to see that *the above symmetries (1, 2) of the constellation are preserved* by the amplifier. This is a consequence of the fact that the angles between the constellation points that lie on the same energy circle remain unaltered (see Fig. 3). Thus, the resulting points continue to form squares centered on the origin, as it was the case prior to the application of the nonlinearity.

These symmetries can be efficiently exploited to reduce the total number of cluster centers to be estimated directly from the training sequence in the CBSE equalizer, thus leading to a significant gain in performance, compared to Volterra and NN-based techniques, and at a significantly lower computational cost.

The performance of the proposed equalizer is compared with two of the most widely used non-linear equalizers: a Volterra series equalizer and an RBF equalizer. The algorithms are compared in terms of the resulting BER and their computational requirements. CBSE outperforms its competitors in every case. The Bayesian equalizer performs almost equally well, however, it is far more expensive in terms of computational requirements. It is of interest to note that

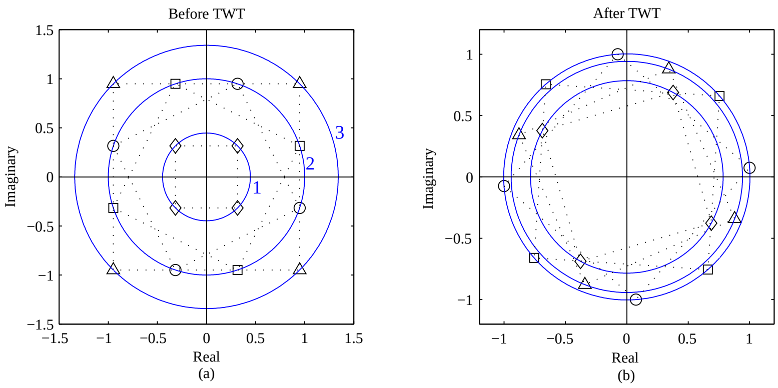

Fig. 2. 16-QAM constellation at the (a) input and (b) output of the TWTA. The 3 energy levels and the 4 squares formed by the 16 constellation points are illustrated.

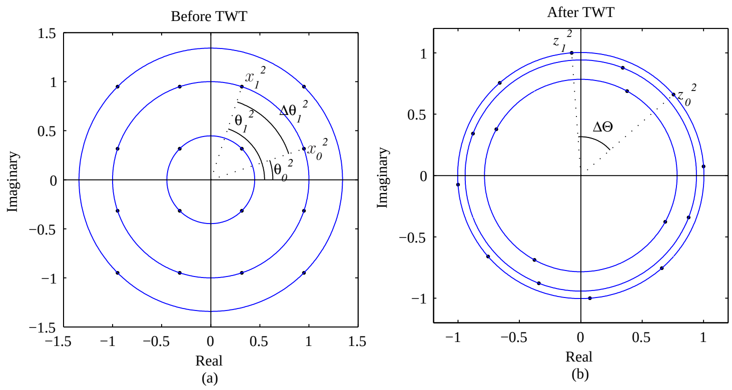

Fig. 3. 16-QAM constellation at the (a) input and (b) output of the TWTA. Angles between equal modulus symbols are shown: $\Delta\Theta = \Delta\theta_1^2$.

even in the case of 0 dB IBO (full power efficiency [1]) with 16-QAM where other methods fail [7], the proposed equalizer still offers some gain (Fig. 4).

Table 1 shows the total number of real operations required for the processing of a received block consisting of 20 training samples (per energy zone) and 500 data symbols, for a two-taps channel with the 16-QAM signaling scheme. Observe that the superior performance of the CBSE equalizer is attained at a substantially lower complexity, especially in terms of real multiplications/divisions.

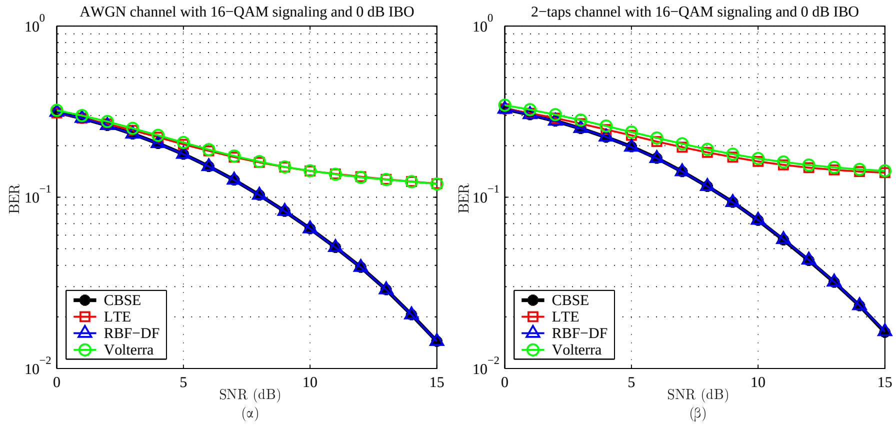

Fig. 4. BER performance for 16-QAM at 0 dB IBO. (a) AWGN and (b) 2-taps channel.

Method	**Mul/Div**		**Add/Sub**		$(\cdot)^2$		**exp(·)**
	Training	Decision	Training	Decision	Training	Decision	Decision
CBSE	32	0	356	512000	—	256000	—
RBF-DF		128000		1016000		512000	128000
LTE	1620	6000	1800	5000	360	—	—
Volterra	19080	114000	16920	77000	2520	—	—

Table 1. The total number of real operations for each equalizer, for a 2-taps channel ($L = 2$) with 16-QAM input, needed to process a packet of 60 training and 500 information samples; $L_{\text{LTE}} = 3$, $p = 3$, $L_V = 21$, $M_V = 36$.

3 The Novel PAPR Reduction Technique

To obtain a PAPR lower than that of the original time domain vector $\mathbf{x}$, a new time domain vector $\mathbf{y}$ is needed so that the following holds

$$\text{PAPR}(\mathbf{y}) < \text{PAPR}(\mathbf{x}) \Leftrightarrow \frac{P^y_{max}}{P^y_{av}} < \frac{P^x_{max}}{P^x_{av}} \tag{6}$$

where

$$P^x_{max} = \max_{0 \le n \le N-1} |x_n|^2, \tag{7}$$

$$P^x_{av} = \frac{1}{N} \sum_{n=0}^{N-1} |x_n|^2 \tag{8}$$

and similarly for P^y_{max}, P^y_{av}. It can be easily verified that if

$$P^y_{max} = P^x_{max} + P_1 \tag{9}$$

and

$$P^y_{av} = P^x_{av} + P_2 \tag{10}$$

with

$$\frac{P_1}{P_2} < \frac{P^x_{max}}{P^x_{av}} \tag{11}$$

then Eq. (6) always holds. Thus, if a new vector $\mathbf{y} = \mathbf{x} + \alpha\mathbf{u}$ is defined with α positive and $\mathbf{u} = [x_1/|x_1| \dots x_n/|x_n| \dots x_N/|x_N|]^T$ then PAPR($\mathbf{y}$) (as shown in the dissertation) is always less than or equal to the initial PAPR, independently of the vector $\mathbf{x}$. If α is known at the receiver there is no need of any side information or transmit power increase. The parameter α can be selected during the communication system design according to the desired level of BER or CCDF performance.

Analytical expressions for the achievable PAPR reduction and equivalent BER having α as the main parameter of interest are presented and verified by means of computer simulations (Fig. 5). The performance of the proposed technique in terms of PAPR reduction is superior as compared to other known similar techniques at the expense of a BER performance degradation. Performance evaluation comparisons were made with the TI technique, as a representative from the family of constellation shaping techniques, and with the AC technique, as a rival with comparable simplicity. The obtained performance evaluation results have shown that the proposed technique is an attractive alternative for PAPR reduction regardless of the number of subcarriers N and the modulation format.

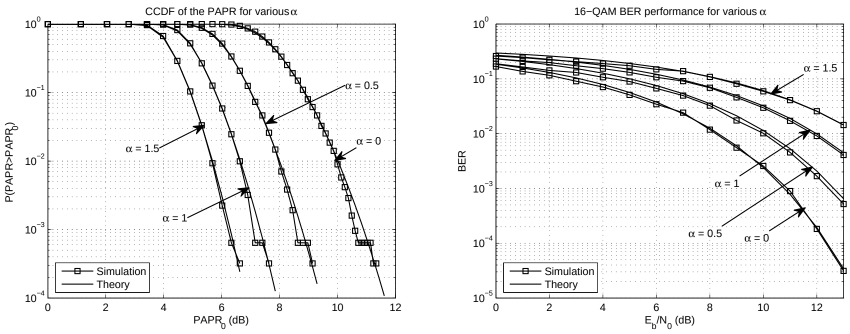

Fig. 5. CCDF and BER performances of the proposed technique for various α for 16-QAM and $N = 256$.

4 SC-FDMA vs. OFDMA in DVB-S

The block diagram of the system model under consideration, shown in Fig. 6, represents the up-link of a typical multi-user satellite communication system. Both synchronous and asynchronous signal reception has been considered for two state-of-the-art HPAs operating in the K- and S-band. Performance evaluation results have shown that, although, IFDMA outperformed the other two schemes

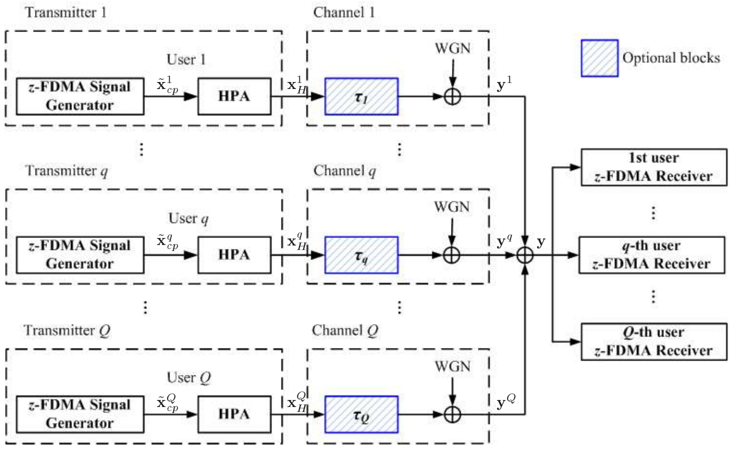

Fig. 6. Block diagram of the system under consideration.

in terms of Total Degradation for a synchronous system, for asynchronous reception it is the most sensitive to degradation. OFDMA, due to its large PAPR, has been found as the most sensitive to non-linearity. On the contrary, LFDMA had only slightly inferior performance as compared to IFDMA for synchronous reception while it outperformed the other two access schemes in the asynchronous scenario examined, i.e., in the presence of IBI and non-linearity.

Table 2. Advantages and disadvantages for each access scheme in a non-linear channel and in the presence of IBI. A (+) means advantage, a (−) means disadvantage and (≈) means almost equal to the best.

	OFDMA	LFDMA	IFDMA
Non-linearity	−	≈	+
$i = 0 \rightarrow \tau_C/T_s = \frac{1}{8}$	−	≈	+
$i = 6 \rightarrow \tau_C/T_s = \frac{11}{64}$	−	+	≈
$i = 12 \rightarrow \tau_C/T_s = \frac{7}{32}$	−	+	−
$i = 18 \rightarrow \tau_C/T_s = \frac{17}{64}$	−	+	−

5 Conclusions

This dissertation proposes novel signal processing techniques that deal efficiently with the non-linear distortions introduced by the satellite amplifiers. A CBSE for satellite channels is proposed exploiting the fact that TWT memoryless non-linearities respect the symmetries underlying the signaling scheme, thus leading to a significant gain in performance, compared to Volterra and NN-based techniques, and at a significantly lower computational cost. A simple time domain constellation shaping technique that achieves PAPR reduction in OFDM with minimal complexity is introduced. Theoretical expressions are derived for key performance measures, i.e., BER and CCDF, while simulation results verify the accuracy of the derived analytical expressions. The performance of the proposed technique in terms of PAPR reduction is superior as compared to other known similar techniques at the expense of a BER performance degradation. Finally, a thorough comparison study is presented for two SC-FDMA schemes, LFDMA and IFDMA versus OFDMA, for a satellite up-link, based on DVB-S. Both synchronous and asynchronous signal reception has been considered for two state-of-the-art HPAs operating in the K- and S-band. As a further research topic it will be interesting to investigate the total degradation performance of the proposed PAPR reduction technique in a DVB-S scenario combined with the CBSE and LFDMA.

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