Optimising DVB-S2(X) Links in Nonlinear Environments

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INTRODUCTION

Satellite communication standards such as the second-generation digital video broadcasting for satellites, i.e., DVB-S2(X), exploit phase-shift keying (PSK) and amplitude and phase-shift keying (APSK) modulation schemes as they are more robust against nonlinearity than quadrature amplitude modulations (QAMs) [1] [2]. However, the system performance of satellite communication remains profoundly influenced by the presence of the nonlinear high power amplifiers (HPA). In this contribution, we analytically and numerically study the end-to-end distortion of the APSK constellation from the digital IQ signal at the transmitter across to the nonlinear channel and back to the recovered digital IQ signal at the receiver. We demonstrate that the distortion depends not only on the input back-off (IBO) of the HPA but, critically, also on the roll-off of the matched digital root raised cosine (RRC) bandwidth-limiting filters used at transmitters and receivers. Consequently, we derive informed guidelines for the adaptive operation of satellite links. Focusing on 16 APSK (4+12 version) modulation, the main contributions of our work include;

1. We present an accurate estimation of the Gaussian spreading of the received symbols around reference constellation points. The digital pre-distortion at the transmitter is applied. It has been shown that the spreading depends on the choice of RRC roll-off factor and HPA IBO. This estimation enables us to obtain the equivalent additive Gaussian noise determined by the combined RRC and HPA characteristics. Significantly, we then proceed to demonstrate that the performance of the nonlinear channel can be approximated by a linear channel with an additional known noise source.
2. The informed estimation of the optimum IBO which can minimise the system bit error rate (BER) is obtained. Importantly we show that the optimum IBO depends on both the channel noise and the roll-off.
3. An adaptive operation of DVB-S2X link with dynamic power control is achieved, which maintains performance close to optimum by computationally efficient estimation of the combination of MODCOD, RRC roll-off and IBO operation on a given HPA.

The paper is organized as follows. In Section II, we provide some backgrounds including the satellite link descriptions, the adverse impacts from nonlinearity and inter-symbol interference (ISI). In Section III, we introduce the digital pre-distortion algorithm and obtain the equivalent linear link by ‘translating’ the ISI into equivalent Gaussian noise. Then, the optimum HPA IBO under different RRC roll-off and channel noise is achieved. In Section IV, an adaptive operation specifying the combination of MODCOD, RRC roll-off and HPA IBO is proposed, which can maximise the system spectrum efficiency while still guaranteeing the BER requirement. Conclusions are drawn in Section V.

BACKGROUND

In the following we detail the system link for the end-to-end DVBS2(X) standard. The system block diagram considered is shown in Fig. 1. The nonlinearity of HPA is simulated with the Saleh’s model of the AM/AM and AM/PM characteristics, see (1) and (2). The selected coefficient values (α_a = 2.1322, β_a = 1.0746, α_Φ= 1.7054, β_Φ = 1.5072) are taken from [1], [3].

$$A[u] = \frac{\alpha_a u}{1+\beta_a u^2} \tag{1}$$

$$\Phi[u] = \frac{\alpha_\Phi u^2}{1+\beta_\Phi u^2} \tag{2}$$

Over the nonlinear channel, the output APSK constellation after the matched RRC filter at the receiver end, is affected by two kinds of impairment. The first is the constellation centroids warping effect due to the AM/AM and AM/PM nonlinear characteristic of HPA. The second is the clustering effect due to the ISI caused by combined RRC and HPA characteristics. As shown in Fig. 2(a), the blue 'cloud' contains the detected constellation symbols after matched RRC through a nonlinear channel, red crosses indicate the centroids of the corresponding clusters, and black circles are the reference constellation. Note that no additive thermal noise is included in the simulations shown in Fig. 2.

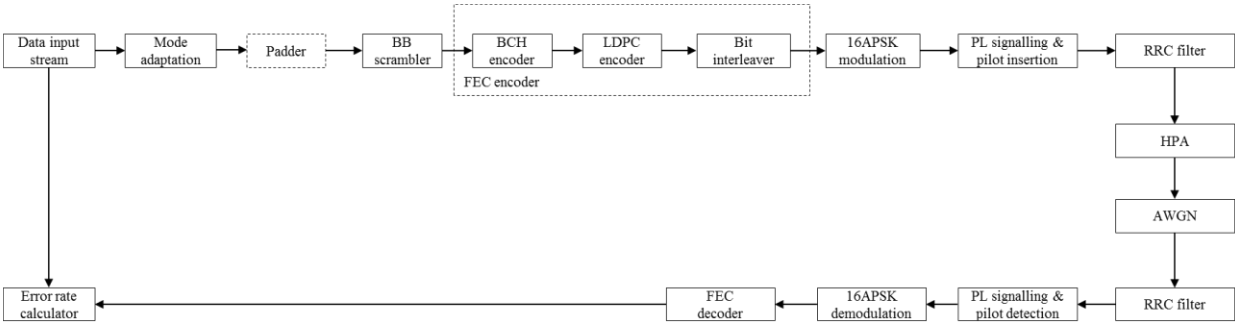
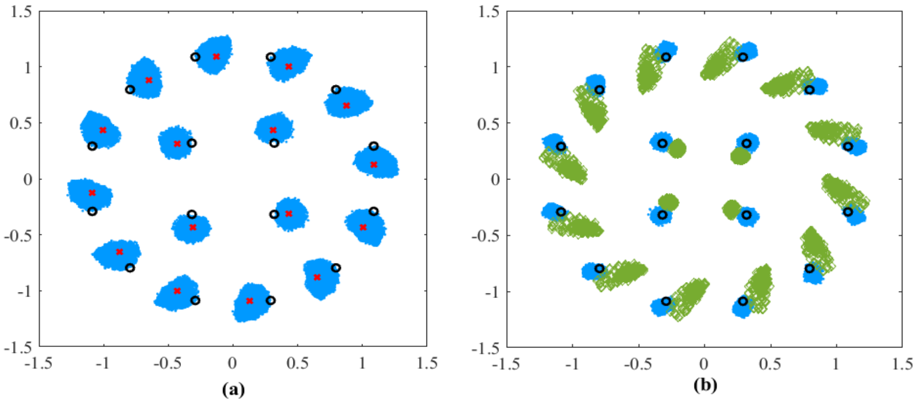


Fig. 1. DVB-S2 system block diagram



(a) **(b)**

Fig. 2. 16APSK signal constellation showing warping and clustering effects due nonlinear distortions. Roll-off=0.35, IBO=3dB. (a) Constellation after matched RRC filter without pre-distortion. Blue 'cloud': detected constellation symbols without pre-distortion. Red crosses: centroids of the corresponding clusters. Black circles: reference constellation. (b) Constellation after matched RRC filter with pre-distortion, L=3. Blue 'cloud': detected constellation symbols with pre-distortion. Green squares: mapping constellation of modulator. Black circles: reference constellation.

DIGITAL PRE-DISTORTION ALGORITHM AND OPTIMAL IBO IMPLEMENTATION

In this section we describe digital pre-distortion technique used to combat the channel nonlinearity. With pre-distortion before RRC filter at the transmitter end, the warping and clustering effects can be reduced significantly and the ISI can be approximated by an equivalent Gaussian noise.

A. Digital Pre-distortion

Given the utilisation of RRC filters, the memory of the channel should be considered when designing pre-distortion algorithms, i.e., conditioning the pre-distorted modulator constellation not only to the current transmitted symbol but also to the $(L-1)/2$ preceding and $(L-1)/2$ following symbols (L symbols in total) [4] [5]. For the current received symbol, there are M^{L-1} combinations of neighbouring symbols. In this case, the spreading of each received symbol can be regarded as being involved by M^{L-1} sub-clusters. M is the modulation order and M=16 for 16APSK modulation. The pre-distortion is preferably performed off-line in the absence of AWGN according to the following steps:

1. Generate W symbols over the nonlinear link and compute the centroids of all sub-clusters after matched RRC;
2. Calculate the error vectors between each sub-cluster and the reference constellation point.
3. Update the pre-distorted constellation points through an iterative least mean square (LMS) [5] method to minimise the errors.

The result of this procedure is a look-up table specifying the mapping constellation, as the green squares shown in Fig. 2(b). The blue points in the same plot are the output constellation after matched RRC with data pre-distortion. The modulator will read the look-up table in real-time with an address determined by the current, the (L-1)/2 preceding and (L-1)/2 following symbols.

B. Equivalent Noise of ISI after Pre-distortion

Applying the pre-distortion approach, the warping effect caused by nonlinear characteristic of HPA has been largely overcome, and the clustering effect due to the ISI has been reduced and can be approximated by equivalent Gaussian noise. The mean of the equivalent Gaussian noise is zero, and its variance σ_{ISI}^2 are summarised in Table I as functions of roll-off and IBO values. Roll-off = 0.35, 0.25 and 0.20 are inherited from DVB-S2 [1] whereas new values of 0.15, 0.10 and 0.05 have been added in DVB-S2(X) [2]. From Table I, we can see that the equivalent variance reduces as the IBO increases, but there is a limitation to this reduction. This is because the non-linearity of HPA becomes less distinct with an increasing IBO. However, owe to the imperfect RRC characteristic, i.e., the finite memory length, the ISI is still in linear system, which indicates the limitation equivalent variance. Based on the obtained equivalent noise, the BER performance of the nonlinear channel can be approximated by a linear channel with an additional known noise source which is verified by the numeric results shown in Fig. 3.

Table I. Equivalent noise variance σ_{ISI}^2 for different IBO and roll-off.

Roll-off IBO (dB)	0.05	0.10	0.15	0.20	0.25	0.35
0	0.0497	0.0368	0.0267	0.0210	0.0175	0.0113
1	0.0303	0.0191	0.0139	0.0092	0.0076	0.0038
2	0.0240	0.0143	0.0083	0.0054	0.0041	0.0019
3	0.0194	0.0110	0.0053	0.0029	0.0025	0.0014
4	0.0176	0.0086	0.0038	0.0019	0.0015	7.3598e-04
5	0.0162	0.0075	0.0026	0.0011	7.2893e-04	4.6501e-04
6	0.0155	0.0069	0.0021	5.4797e-04	4.1060e-04	2.5624e-04
7	0.0152	0.0065	0.0017	2.4809e-04	2.5297e-04	1.4992e-04
8	0.0152	0.0063	0.0016	1.3410e-04	2.0919e-04	1.1771e-04
9	0.0151	0.0063	0.0015	9.6810e-05	1.4992e-04	9.9372e-05
10	0.0152	0.0063	0.0015	6.1416e-05	1.3895e-04	9.3706e-05
11	0.0151	0.0063	0.0015	5.5189e-05	1.3120e-04	8.8208e-05
12	0.0151	0.0063	0.0015	4.9254e-05	1.2706e-04	8.7422e-05

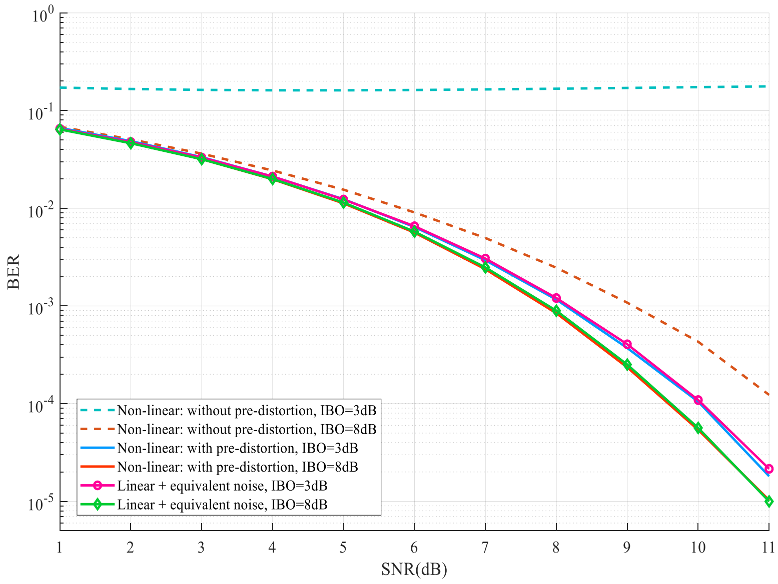


Fig. 3. BER performance comparison, roll-off = 0.35.

C. Optimal IBO Implement

The total link degradation (D_{tot}) is defined in [5] as the sum of the link degradation and the HPA output back-off (OBO), see (3). $\left[\dfrac{E_s}{N_0}\right]_{\mathrm{req}}^{\mathrm{NL}}$ and $\left[\dfrac{E_s}{N_0}\right]_{\mathrm{req}}^{\mathrm{AWGN}}$ are the average symbol energy over noise density required to achieve the target BER in the nonlinear and linear channel, respectively. By using the Gaussian approximation for the ISI, the required energy over noise density in the nonlinear channel can be calculated as in (4).

$$D_{tot}[\mathrm{dB}] = \left[\frac{E_s}{N_0}\right]_{\mathrm{req}}^{\mathrm{NL}}[\mathrm{dB}] - \left[\frac{E_s}{N_0}\right]_{\mathrm{req}}^{\mathrm{AWGN}}[\mathrm{dB}] + \mathrm{OBO}[\mathrm{dB}] \tag{3}$$

$$\left[\frac{E_s}{N_0}\right]_{\mathrm{req}}^{\mathrm{NL}} = \left[\frac{E_s}{N_0}\right]_{\mathrm{req}}^{\mathrm{AWGN}} \left(1+\frac{\sigma_{\mathrm{ISI}}^2}{N_0}\right) \tag{4}$$

Therefore, the D_{tot} can be rewrite as,

$$D_{tot} = \left(1+\frac{\sigma_{\mathrm{ISI}}^2}{N_0}\right)\mathrm{OBO}\,. \tag{5}$$

The optimum IBO for a fixed roll-off can be obtained by minimising the D_{tot}. The numeric results of the optimum IBO values with associate BER for different roll-off factors and channel AWGN power N_0 are shown in Fig. 4.

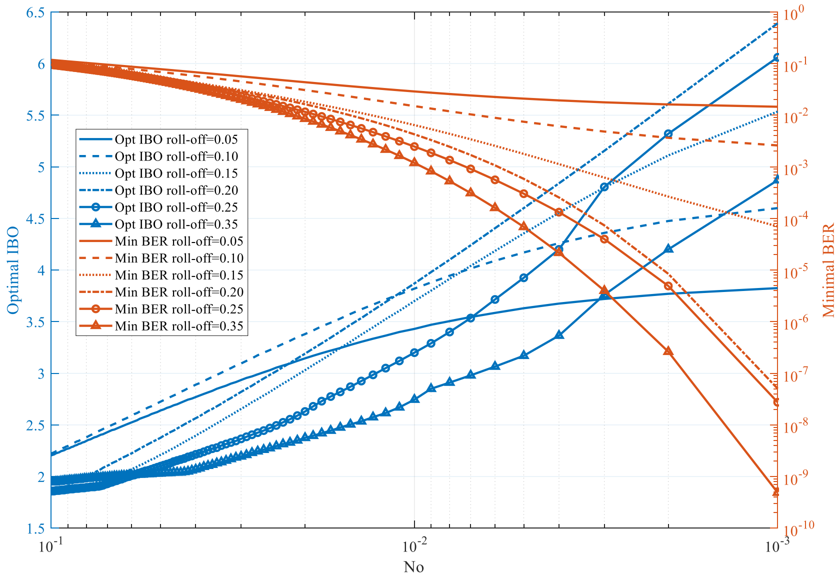


Fig. 4. Optimum IBO for different roll-off with varied AWGN power.

ADAPTIVE OPERATION OF DVB-S2X LINK

A. BER and Spectrum Efficiency of LDPC

Forward error correction (FEC) codes based on low-density parity check (LDPC) codes concatenated with Bose–Chaudhuri–Hocquenghem (BCH) codes are applied in the DVB-S2(X) system which is very powerful to improve the BER performance, as the mapping relations indicated in Fig. 5. For example, with the application of LDPC-9/10, the FEC is able to improve BER performance from 0.02 to as low as 10^{-4}. Lower code rate means better error correction performance but lower spectrum efficiency. Note, the BER performance in Fig. 5 is achieved by numeric simulations using MATLAB, and it bottoms out at around 10^{-5} due to the computational limitation of MATLAB.

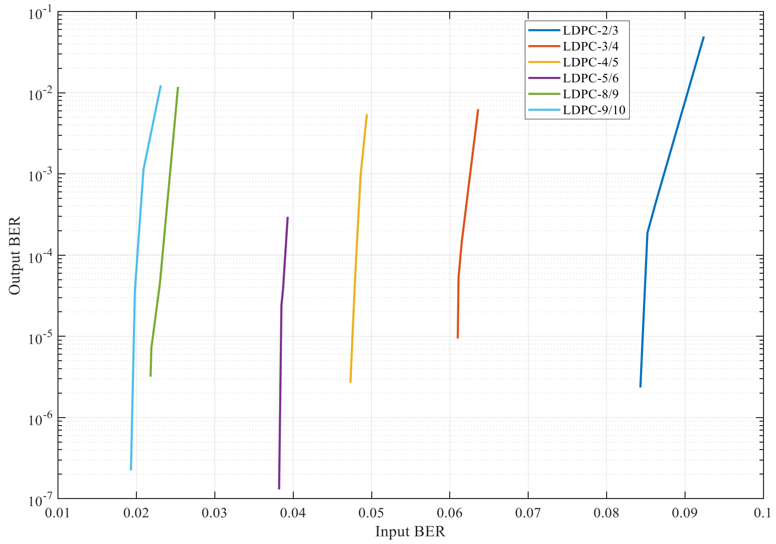


Fig. 5. BER mappings between systems without FEC and with FEC

B. Link Optimisation Realisation

The target of the link optimisation is to maximise the spectrum efficiency of satellite links while maintain required detection performance, e.g., BER. This is a multi-dimensional optimisation problem, involving four system parameters, MODCOD, RRC roll-off and IBO operation on a given HPA. This is mathematically formulated in (6),

$$\begin{aligned} &\max \ E(\alpha,\gamma) \\ &\text{s.t.} \quad B(\alpha,\gamma,\beta,N_0) \le T \end{aligned} \tag{6}$$

where E represents the spectrum efficiency determined by the ModCod scheme α and roll-off value γ. B represents the BER determined by ModCod scheme α, roll-off value γ, channel noise power N_0 and the optimal IBO β obtained . T denotes the threshold of the required detection performance.

For example, if the output BER threshold (i.e., with FEC) is set to be 10^{-5}, the input BER thresholds for different ModCod schemes can be found from curves in Fig. 5 as [{α=16APSK-2/3, T=0.085}, {α=16APSK-3/4, T=0.061}, {α=16APSK-4/5, T=0.047}, {α=16APSK-5/6, T=0.038}, {α=16APSK-8/9, T=0.022}, {α=16APSK-9/10, T=0.019}]. When the channel noise power is set to be N_0=10^{-2}, the optimum IBO and the associated minimal BER for each roll-off drawn from Fig. 4 are [{γ = 0.05, β = 3.145, B = 0.04347}, {γ = 0.10, β = 3.38, B = 0.03063}, {γ = 0.15, β = 3.03, B = 0.0182}, {γ = 0.20, β = 3.19, B = 0.01627}, {γ = 0.25, β= 2.63, B = 0.0116}, { γ = 0.35, β = 2.375, B = 0.008524}]. Then, considering roll-off γ = 0.05, only three ModCod schemes can be chosen, i.e., 16APSK-2/3, 16APSK-3/4 and 16APSK-4/5. This is because for other ModCod schemes, the BER requirement cannot be met. Finally, 16APSK-4/5 will be selected under γ=0.05 for the highest spectrum efficiency among these three ModCod schemes. Accordingly, we can achieve the optimum combinations of ModCod and IBO for each roll-off value under N_0=1e−02 as listed in Table II. Based on Table II, by comparing the maximum spectrum efficiency for each roll-off, the optimal combination of link parameters under N_0=10^{-2} is {α = 16APSK-9/10, γ = 0.15, β= 3.03}.

Table II. Spectrum efficiency for different ModCod and roll-off under N_0=10^{-2}

Roll-off	Optimum IBO	Optimum ModCod	Spectrum efficiency
0.05	3.145	16APSK-4/5	3.0149
0.10	3.38	16APSK-5/6	3.0002
0.15	3.03	16APSK-9/10	3.1020
0.20	3.19	16APSK-9/10	2.9728
0.25	2.63	16APSK-9/10	2.8539
0.35	2.375	16APSK-9/10	2.6425

In summary, Algorithm I is designed to realise the adaptive operation by adjusting the link parameters depends on the channel noise power.

Algorithm I

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o  Set the detection performance threshold based on standard requirement.
o  Calculate the input BER thresholds (without FEC) for different ModCod based on mapping relations shown in Fig. 5.
o  Get the real-time channel noise power.
o  For roll-off = {0.05, 0.10, 0.15, 0.20, 0.25, 0.35}
     •  Get the minimal BER and associate optimum IBO obtained in Fig. 4,
     •  Get the viable ModCod schemes by comparing the minimal BER with the input BER thresholds,
     •  Calculate the spectrum efficiency of each viable ModCod scheme,
     •  Select the optimum ModCod scheme which responds to the maximum spectrum efficiency for each roll-off.
o  End
o  Get the optimal combination of roll-off (respond to the optimal IBO) and ModCod scheme by comparing the spectrum efficiency achieved for each roll-off.
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CONCLUSION

This paper reported on the approximated linear link with equivalent additive noise for the DVBS2(X) nonlinear link. Optimum HPA IBOs for different roll-off factors and channel noise power were obtained to minimise the system BER. With further consideration of the effects of different LDPC code-rates to the BER performance and spectrum efficiency, as well as the effects from different roll-off factors to the spectrum efficiency, an adaptive operation algorithm to maximise the system spectrum efficiency while still guaranteeing the detection performance was formulated and validated via numerical simulations

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