Performance Analysis of Fractionally Spaced Equalization in Non-linear Multicarrier Satellite Channels

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Nomenclature

ACI	=	Adjacent Channel Interference
APSK	=	Amplitude Phase Shift Keying
BER	=	Bit Error Rate
BSS	=	Broadcast Satellite Services
DPD	=	Digital Predistortion
EQ	=	Equalization
FSS	=	Fixed Satellite Services
HPA	=	High Power Amplifier
IBO	=	Input Back-Off
IMD	=	Inter Modulation Distortions
IMUX	=	Input MUX
ISI	=	Inter-Symbol Interference
L-TWTA	=	Linearized Travelling Wave Tube Amplifier
OBO	=	Output Back-Off
OMUX	=	Output MUX
TD	=	Total Degradation
TWTA	=	Travelling Wave Tube Amplifier

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Joint amplification of multiple carriers with a single wideband high power amplifier (HPA) has been considered towards reusing the satellite resources among multiple links to reduce the mission cost. The non-linear characteristic of the HPA, especially near saturation, coupled with the on-board IMUX/ OMUX filters result in non-linear adjacent carrier interference (ACI) and inter-symbol interference (ISI) during multicarrier power amplification. To benefit from the advantages of multicarrier transmissions, on-ground techniques to mitigate the non-linear distortions need to be devised. These techniques include predistortion

at the transmitter and equalization at the receiver. Several works have considered the use of multicarrier predistortion along with single carrier equalization. A symbol synchronous equalizer, while being simple to implement, may not necessarily provide for the optimum linear filter. Towards improving the performance, fractionally spaced equalizers (FSE) have been considered. Such receivers are shown to provide enhanced performance by effectively compensating for the group delay distortions. The objective of this work is to consider the use of FSE in the context of multicarrier transmissions over non-linear channels and illustrate their performance enhancements

I. Introduction

On-board power amplification is required to achieve the required SNR at the receiving ground user terminal (UT). However, the high power amplifier (HPA) operation is inherently non-linear and can generate severe interference that limits the SNR and hence the achievable throughput. As the amplifier is operated in its high efficiency region, the non-linear distortion effects increase requiring a natural trade-off between power and spectral efficiencies. Non-linear distortions become significant when multilevel modulation schemes are employed or when inter-modulation products (IMD) are excited in the multicarrier operation mode[1]. In fact, the application of multi-level modulation schemes or multicarrier signalling increases the signal peak to average power ration (PAPR) to which the performance of HPA is very sensitive. On the other hand, joint amplification of multiple carriers by a single on-board HPA reduces weight as well as the cost providing flexibility to the on-ground up-link gateway (GW).

Mitigation techniques for optimizing power and spectral efficiency in such a scenario include gateway digital predistortion (DPD) and UT equalization. Multicarrier data predistortion was first introduced in Ref. 1 showing significant performance improvement[2]. Recently, more traditional signal predistortion techniques are shown to also improve the performance while respecting the limited uplink bandwidth[3]. Concerning the UT equalization, symbol synchronous equalization[1] is a favoured approach since it is simpler to implement. However, it may not necessarily provide for the optimum linear filter[5]. Towards improving the system performance, receivers working at a rate higher than the symbol rate have been considered. Such architecture, referred to as the Fractionally Spaced Equalizer (FSE)[5], is shown to provide improved performance by compensating effectively for the group delay distortions[5]. In particular, when having sufficient taps, an FSE can be considered as implementing an analogue filter that is insensitive to timing offsets. Thus FSEs make the system robust to receiver sampling phase and their application in terrestrial networks has been widespread.

The use of FSE in satellites was initially considered in[6] for use on transmit and receive links. The FSE structure was linear and it was shown to reduce the effect of group delay on both the links. Linear FSE was also proposed for the cancellation of multiple access interference in the integrated satellite and cellular systems promoted by the COST 227 Integrated Space/ Terrestrial Mobile Networks[7]. In Ref 8, the use of FSE in non-linear satellite channel with a single carrier has been considered. In particular, Ref. 8 proposed an architecture comprising a FSE followed by a non-linear Volterra equalizer. Adaptation of FSE and Volterra equalizers were provided. Such a receiver was shown to perform better than symbol spaced equalizers because of its ability to emulate the optimal receiver filter-bank. Further in Ref. 9, the use of FSE for satellite UMTS (S-UMTS) is considered and its desirable properties highlighted and its performance gains illustrated.

In this work we consider the system architecture of Ref. 1 where multicarrier data predistortion is applied at the gateway for compensating for the non-linear distortions while the UT supports advanced FSE equalization. Further, we provide a method to optimize the receiver decoding for compensating the residual non-linear effects by improving demapping of the symbols.

II. Multiple Carrier Satellite Transmissions

A. Scenario

Figure 1 illustrates the addressed satellite system scenario, which refers to a multicarrier satellite channel where independent channels are uplinked to a transparent satellite. A gateway transmits a broadcast or broadband forward link carrier, typically a DVB-S2 signal, to a number of receivers. The considered frequency bands are mainly Ka-band and Ku-band frequencies for broadcast or broadband fixed satellite services (BSS/FSS) applications.

On board the satellite, joint filtering and amplification takes place before the signals are downlinked to ground receivers. As described in Ref. 1, joint on board filtering and amplification of the stream of carriers allows for a significant saving in hardware complexity and weight.

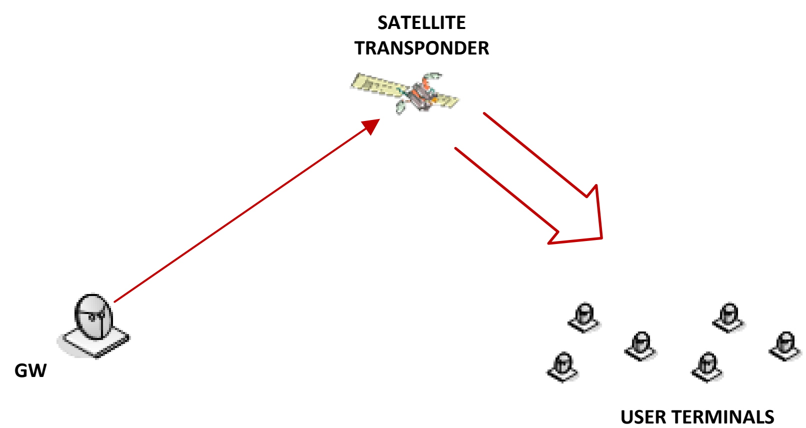

Figure 1: Considered Satellite Communication System Scenario

B. Multicarrier Non-linear Satellite Channel Characteristic

The channel model is shown in Figure 2. M carriers are uplinked from a single gateway to a satellite transponder for channelization power amplification. IMUX and OMUX filter responses are depicted in Figure 3 for the case of a standard 36 MHz transponder bandwidth.

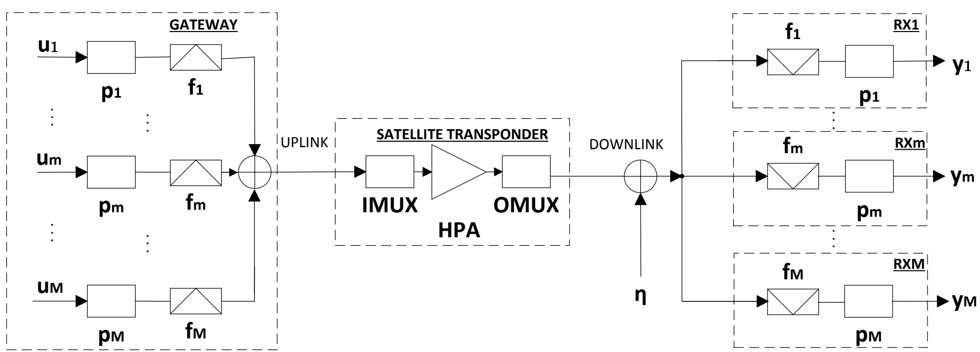

Figure 2: Channel Model for the considered scenario where f_m is the m*th* carrier center frequency and p_m is the pulse shaping function

On-board HPAs are implemented with TWTAs that are intrinsically non-linear, especially when operated in their high efficiency region. However, partial linearization of the TWTA amplifier can be achieved on-board by means of specific RF technology resulting in the Linearized-TWTA (L-TWTA). Further, the TWTAs used in Ku-band can be assumed to have a transfer characteristic largely independent of the frequency. Such memoryless amplifier functions are characterized by the AM/AM and AM/ PM curves. These curves are depicted in Figure 4 for a representative TWTA and L-TWTA considered in the exercise.

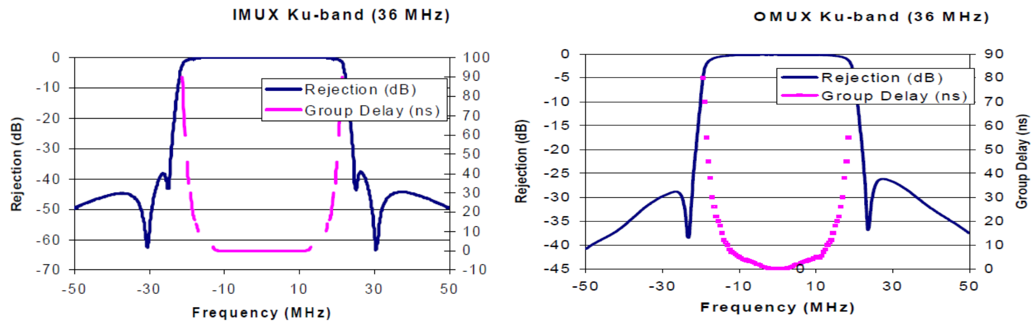

Figure 3: Typical IMUX and OMUX filter characteristics

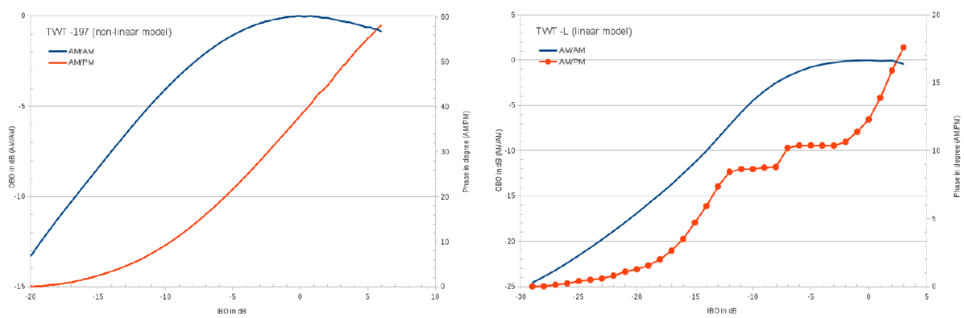

Figure 4: LUT based AM/AM and AM/PM characteristics TWT 197 (left) and LTWTA

Since the channel is non-linear and has memory, we not only have constellation warping effects but significant ISI and ACI. Inter-symbol Interference is generated by the inherent memory combined with the non-linear characteristic of the amplifier. However, in our scenario, the dominant interference effects are the non-linear ACI excited by the intermodulation products generated by the multicarrier joint amplification: these effects are analysed[9] and their manifestations illustrated[1].

C. Baseline On-ground Mitigation Techniques

On ground mitigation techniques can be put in place to increase power and spectral efficiency of the transmission[1,2]. Multicarrier data predistortion is considered at the transmitting gateway in combination with single carrier symbol rate equalization at the receiving user terminals[1].

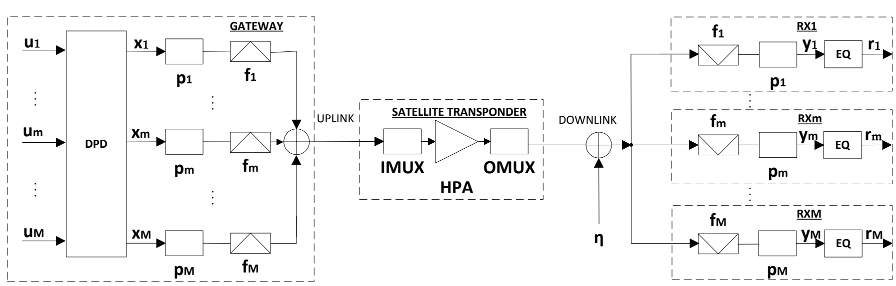

Figure 5: Block diagram of the system implemented in Ref 1

Figure 5 depicts the overall baseline system model where both predistortion and equalization are applied in accordance to Ref. 1. The data predistortion function takes the form of a multicarrier memory polynomial where each carrier is predistorted by a polynomial function with memory,

$$x_m(n) = \sum_p \sum_{k_1} h^{(1)}_{m,p}(k_1) u_p(n-k_1) + \sum_{p_1 p_2 p_3} \sum_{k_3} h^{(3)}_{m,p_1,p_2,p_3}(k_3)\ u_{p_1}(n-k_3) u_{p_2}(n-k_3)[u_{p_3}(n-k_3)]^* \quad (1)$$

where $u_p(n-k_p)$ is the $n-k$ th symbol of the pth carrier and $\{h^{(d)}_m(k)\}$ are the coefficients relative to the polynomial degree d. Parameters estimation is based on sporadic feedback provide by some dedicated receiver to the transmitting gateway[1].

Single carrier symbol rate equalization is implemented at the UT applying MMSE linear of linear symbol rate filtering[1],

$$r_m(n) = \sum_{k_1} g_m(k_1) y_m(n-k_1) \quad (2)$$

where $y_p(n-k)$ is the $n-k$ th symbol of the mth carrier and $\{g_m\}$ are the linear coefficients. Notice that eq.2 includes the case of linear filtering. Estimation of the equalizer parameters is performed using the pilots already included in DVB-S2 standard[1].

III. Fractionally Spaced Equalization

Given the baseline scenario described in Section II.C, we investigate the case wherein the symbol rate equalization at UT is substituted with FSE equalization. We further provide an advanced non-linear technique for optimized decoding of symbols in a non-linear channel. These aspects are described in the sequel.

A. FSE in multicarrier scenario

The primary goal of this work is to investigate the use of FSE in a multicarrier scenario with the aim of reducing the performance degradations caused by

1. Non-constant group delay of the on-board filters
2. Residual non-linear distortions that are present after the use of DPD

Further, the FSE is implemented on a per carrier basis with the requirement of a low receiver complexity. In view of this, we consider a FSE working at an oversampling factor of 2 and not any higher. This receiver is based on the assumption that the group delay distortions are significant and that the DPD has well compensated for the non-linear distortions. In addition, it is also seen from earlier works that the gains in performance due to higher oversampling do not offset the increase in receiver complexity and training overhead. Hence the oversampling factor of 2 is considered henceforth.

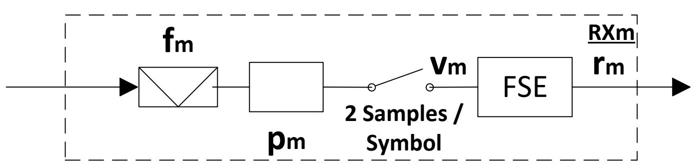

Figure 6 : FSE receiver block diagram

Given the restriction to an oversampling of 2 and referring to Figure 5, we consider a general equalization function with the expression,

$$r_m(n) = \sum_{k_1} b_m(k_1)\ v_m(n-k_1) \quad (3)$$

where $v_m(n-k)$ is the $n-k$ *th* received symbol of the *mth* carrier in upsampled domain and b_m are the linear coefficients. Notice that in Figure 6, we consider as matched filter a standard square root raised cosine function as per DVB-S2 standard. The output of the FSE is sampled at the symbol rate. It is important to note that the bandwidth of the signal used in processing is $(1+\alpha)/T_s$ where α is the roll-off factor and corresponds to the bandwidth of the matched filter and T_s to the symbol time. Let $y_m(n)$ be the output of FSE when $v_m(n)$ is the stream input to the FSE. Assuming that the training consists of N pilots denoted by $u_m(n)$, the coefficients of the FSE are designed to minimize the error $\sum_{n=1}^{N} E[\,r_m(n) - u_m(n)]^2$ where $r_m(n)$ is the response of the FSE to $v_m(n)$. Further $v_m(n)$ is the stream obtained when $u_m(n)$ is transmitted. The minimization is a Linear Least Squares problem (both for linear filters and kernel of non-linear filters) and can be solved using standard techniques[1,2]. Note that the design is similar to the training pursued in Ref 1.

B. Optimized Demapping

Demapping in the traditional sense involves generating Euclidean distance between a received (and processed) point and those in the constellation. However, since the non-linearites and memory effects are not completely compensated, a bias is, in general, added to the constellation points at the receiver. In other words, the centroids obtained from the scatter plot do not coincide with the reference constellation points. To overcome this mismatch, the decoder is tuned to compute Euclidean distance to the centroids and not the constellation points *per-se*. Let $\mathcal{F}_k$ be the cluster of points obtained corresponding to the constellation points $\{a_k\}$. Let c_k denotes the centroid of $\mathcal{F}_k$ obtained as,

$$c_k = arg\min_{c} \sum_{x \in \mathcal{F}_k} |x - c|^2 , \ k \in [1, M] \tag{4}$$

Instead of finding the Euclidean distance between any received point and $\{a_k\}$, we consider demapping to $\{c_k\}$. The proposed scheme differs from the "average constellation demapping" (ACD) where the demapping is performed to $\{\beta a_k\}$ where β is obtained as,

$$\beta = arg\min_{c} \frac{\sum_{k=1}^{M} \sum_{x \in \mathcal{F}_k} |x - c|^2}{\sum_{k=1}^{M} |a_k|^2} \tag{5}$$

On the other hand, the centroid based demapping (CBD) uses M variables instead of one in the average constellation demapping. Figure 7 show the residual bias between the estimated centroids and the standard reference constellation points.

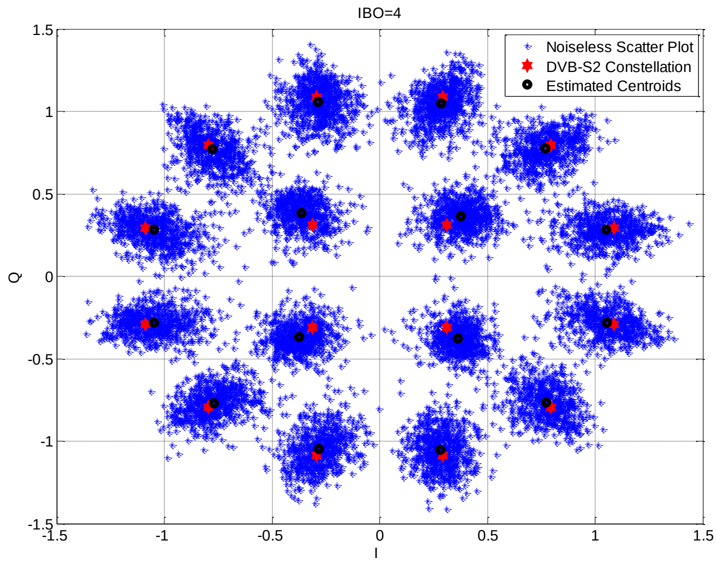

Figure 7: Noiseless Receiver Scatter Plot with Centroids for a Three Carriers Satellite Channel with Multicarrier DPD applied at the GW. Scatter plot relative to the Inner Carrier with 16APSK modulation scheme.

The centroids are obtained apriori using the same training used for the estimation of the equalizer coefficients. Once the centroids are obtained, implementing the centroid based decoding is trivial. Note that a serial processing paradigm is used: equalizer coefficients are derived first based on constellation points and then the centroids are found using the equalizer output (after equalization is applied). This method is straightforward (if not optimal) and allows for a simpler decoder implementation.

IV. Simualtion Results

The performance and sensitivity of the key channel parameters is investigated with respect to the total degradation defined as:

$$\mathrm{TD} = \left.\frac{\mathrm{E_b}}{\mathrm{N_0}}\right|_{\mathrm{NL}} - \left.\frac{\mathrm{E_b}}{\mathrm{N_0}}\right|_{\mathrm{Ideal}} + \mathrm{OBO}.$$

The term $\left.\frac{\mathrm{E_b}}{\mathrm{N_0}}\right|_{\mathrm{NL}} - \left.\frac{\mathrm{E_b}}{\mathrm{N_0}}\right|_{\mathrm{Ideal}}$ reflects the loss in SNR of a practical HPA compared to ideal HPA for achieving the same BER at an identical OBO level. This term is penalized by output back off (OBO), defined as $\frac{P_{out}}{P_{sat}}$ [dB], to reflect on the loss in power efficiency with higher OBO. As OBO increases, the practical HPA is pushed more and more into the linear region and $\left.\frac{\mathrm{E_b}}{\mathrm{N_0}}\right|_{\mathrm{NL}} - \left.\frac{\mathrm{E_b}}{\mathrm{N_0}}\right|_{\mathrm{Ideal}}$ reduces. Thus one could see a trade-off between the two components and an optimum OBO minimizing the TD is usually seen.

A. Results for Single Carrier

The first scenario investigated is a 30 Mbaud single carrier signal fully occupying the transponder bandwidth of 36 MHz. The resulting TD is depicted in Figure 8: yellow curve illustrating the performance for the standard equalization[1], blue depicting the performance of FSE with averaged constellation demapping and the red curve corresponds to FSE with centroid based demapping. Notice that for the single carrier scenario, no predistortion is applied at the transmitting GW. The TD is reduced by applying FSE of about 0.1 dB and centroid based demapping provides an additional gain   about 0.15 dB.

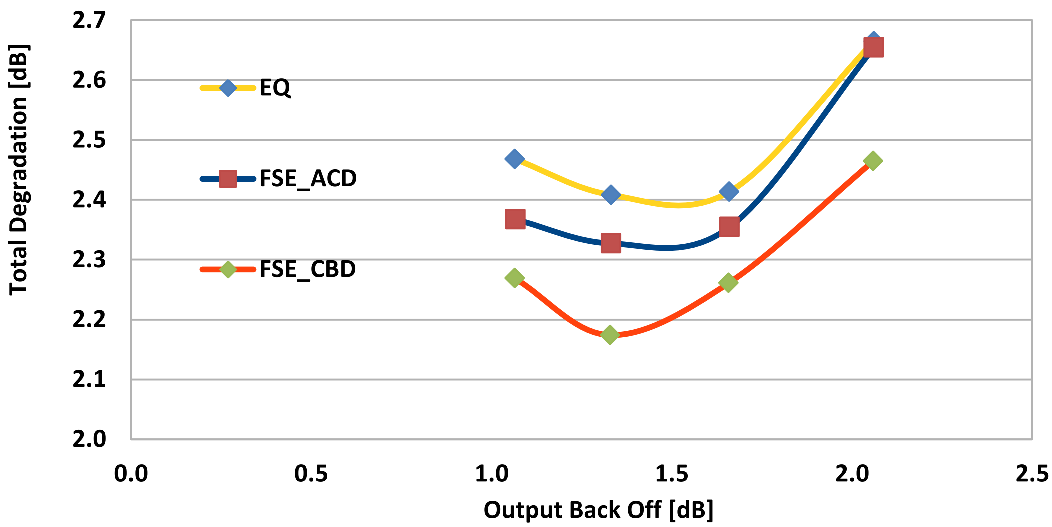

Figure 8 : TD performance of different equalizers for Single Carrier per HPA, 30 Mbaud, 16 APSK, Roll-off=0.2, LDPC with Code Rate=3/4

B. Results for Dual Carrier

Figure 9 and Figure 10 show the TD results for a dual carrier scenario where multicarrier data predistortion is applied at the TX to counteract the distortion generated by the IMD. Only the performance of one carrier is shown due to symmetry. In the first case, we have each carrier with 16.36 MBaud while in the second one we use 18 MBaud carriers. In both cases we consider 16 APSK modulation with code rate ¾. The results for 16.36 Mbaud given in Figure 9 shows that FSE with average constellation demapping provides about 0.2 dB over standard equalization while centroid demapping provides further 0.2 dB of TD gain.

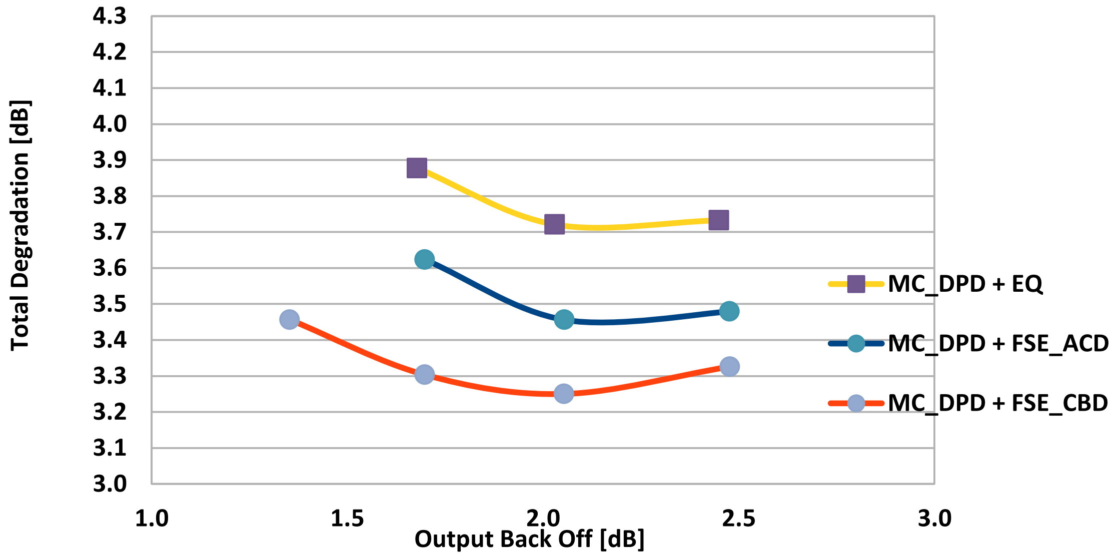

Figure 9 : TD performance of different equalizers for two carriers per HPA, 16.36 Mbaud, 16 APSK, Roll-off=0.2, LDPC with Code Rate=3/4

Results for 18 Mbaud depicted in Figure 10 show prominent degradation due to the increase bandwidth usage. Also in this case, FSE equalization provides about 0.2 dB of gain over the standard symbol spaced equalization. FSE combined with centroid demapping shows a TD minimum slightly moved to the left, toward higher power efficiency region, and provides additional 0.25 dB of TD gain.

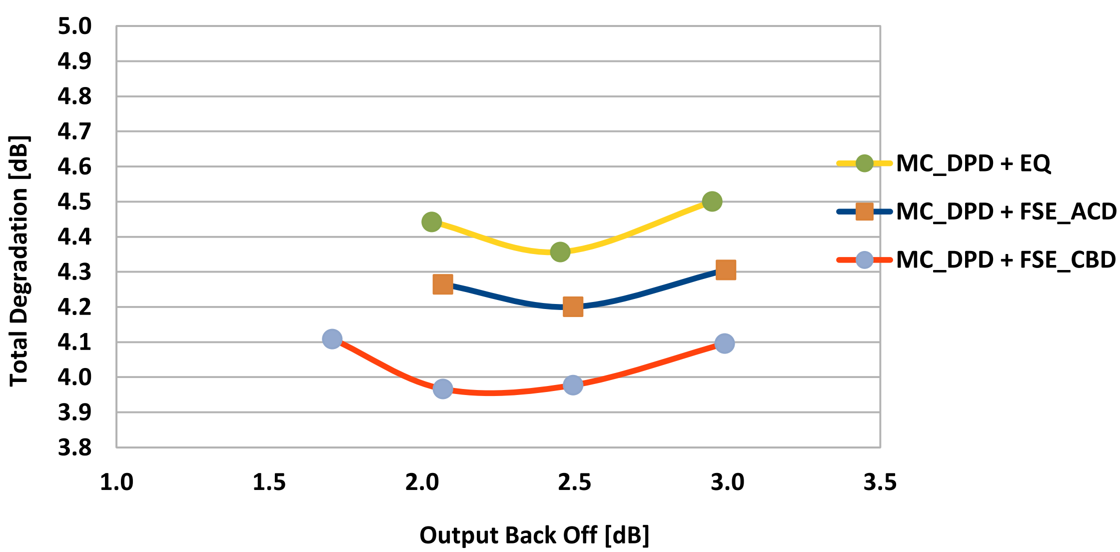

Figure 10 : TD performance of different equalizers for two carriers per HPA, 18 Mbaud, 16 APSK, Roll-off=0.2, LDPC with Code Rate=3/4

C. Triple Carrier

We consider three equally spaced carriers, each with a rate of 10 Mbaud and roll-off of 0.2 filling up the available 36 MHz transponder bandwidth. Figure 11 shows the results for the case of 16APSK with code rate ¾ and Figure 12 for the case of 32 APSK with code rate 4/5. In both cases we show results for the internal carrier and for one of the external carriers because of the system symmetry.

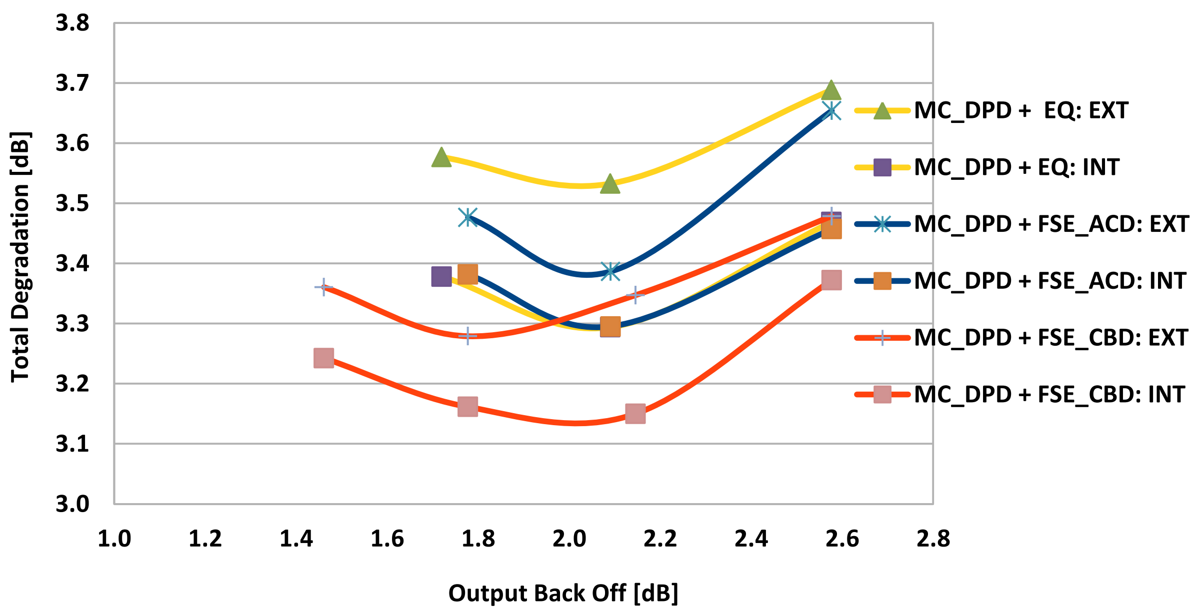

Figure 11 : TD performance of different equalizers for three carriers per HPA, 10 Mbaud, 16 APSK, Roll-off=0.2, LDPC with Code Rate=3/4

In Figure 11 it can be observed for each carrier, (both external and internal), a relative gain about or less 0.1 dB is achieved by the application of FSE. On the other hand, a further 0.15~0.2 dB of TD reduction is provided by the application of centroid based demapping.

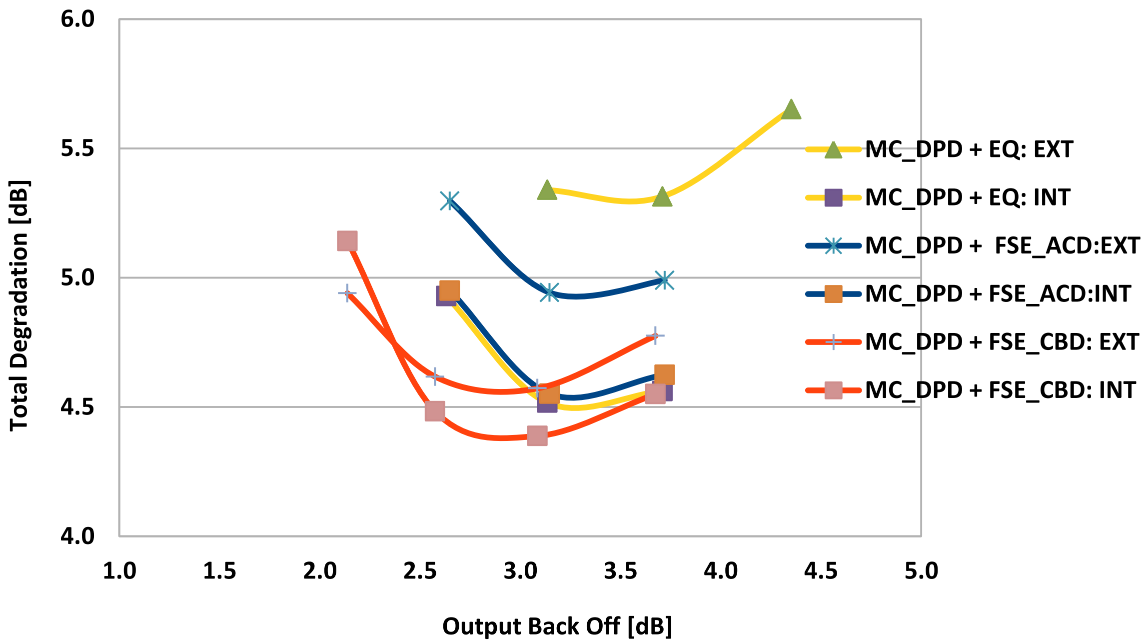

Figure 12 : TD performance of different equalizers for three carriers per HPA 10 Mbaud, 32 APSK, Roll-off=0.2, LDPC with Code Rate=4/5

Moving from 16 APSK to 32 APSK increases the spectral efficiency but generates a generalized performance degradation (kindly refer to Figure 12 in comparison to Figure 11). Depending on the observed carrier, FSE can provide TD reduction from 0.05 to 0.25 dB with respect to the standard symbol rate equalization. The combination of centroid demapping and FSE equalization has a synergic effect providing additional 0.5 dB of gain and reducing the position of the OBO minimum of about 0.6 dB.

D. Robustness to Sampling Error

In this section, we assess the sensitivity of FSE and standard equalization with respect to receiver sampling error. The sensitivity is investigated by computing the system bit error rate when the receiver sampling is intentionally moved from the ideal sampling instant. The bit error rate results for the inner channel in a three carriers scenario is depicted in Figure 13 for different sampling errors. FSE equalization can substantially compensate for the receiver sampling error even when considering very large error. On the other hand, symbol rate equalization is very sensitive to sampling error and can generate severe performance degradation.

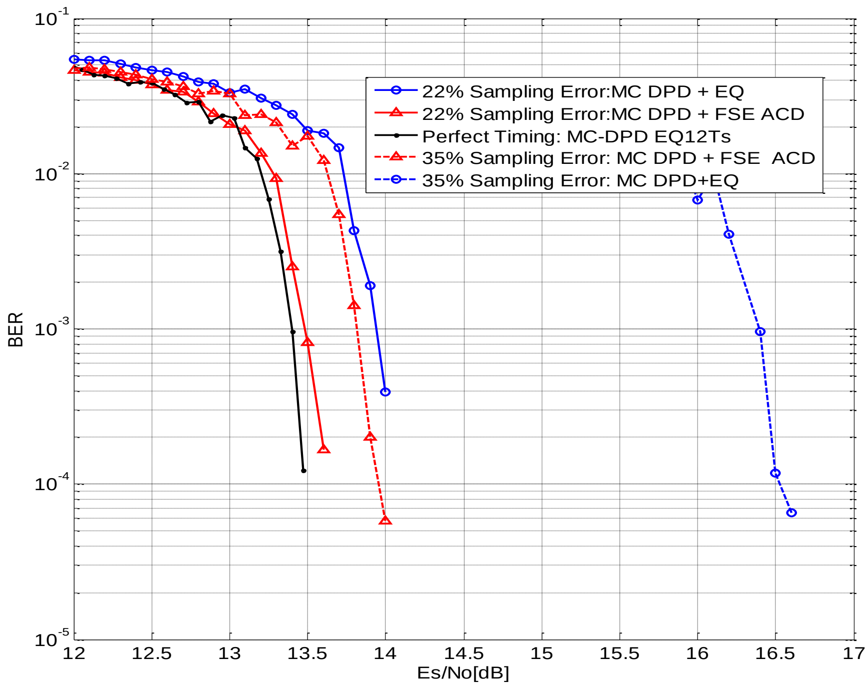

Figure 13 : Sensitivity of equalization schemes to timing error, central carrier of a three carrier per HPA channel, 16 APSK, Roll Off=0.2, IBO=4 dB, LDPC with Code Rate=3/4

V. Conclusion

The paper studied the use of FSE techniques for multiple carrier non-linear satellite channels. Multicarrier data predistortion is considered as baseline at the uplink GW while FSE equalization techniques are evaluated at the UTs for different scenarios. Towards improving decoding performance, optimized symbols demapping is implemented after FSE to compensate for the residual distortion bias. FSE is shown to provide $0.1 - 0.2$ dB of TD gain. The combination of FSE with the optimized symbols demapping method provides an addition $0.1-0.3$ dB of TD reduction. Further, also in this specific scenario, it is shown that FSE is very robust to the receiver sampling error. In conclusion FSE is shown to provide improved performance and robustness with very low complexity impact in the UT architecture motivating its use in future satellite systems.

VI. Acknowledgments

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