A more accurate gain metric to assess predistortion techniques

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Communication systems have multiple performance metrics, such as flexibility, scalability and efficiency. The latter is however one of the oldest concerns of communication technology and still very relevant, for example in satellite communications. An efficiency improvement directly translates to the significant improvement in operational expenditures while sometimes also allowing capital expenditure gains. While efficiency or throughput gain within a given frequency bandwidth is typically the ultimate purpose of new signal processing techniques such as predistortion techniques, publications mostly focus on the signal-to-noise ratio (SNR) gain, as this is easier to measure and does not depend on the granularity of the applicable modulation and coding technology. Furthermore, it is commonly assumed that this SNR gain must be significantly large, e.g. larger than 1 dB, to yield a measurable guaranteed throughput gain. This motivates a revisit of using SNR gains as the benchmark for predistortion techniques. We explain that considering SNR gains assumes that the same signaling is used in the baseline and the improved system. However, we show by means of an example that systems with predistortion may achieve higher throughputs using non-orthogonal signaling which can exhibit higher symbol rates in the same occupied bandwidth. We therefore conclude that achieved average throughput over a range of SNRs in a given occupied bandwidth is the most comprehensive metric to assess predistortion techniques and we explain how to compute it, enabling the relevant players in the satellite ecosystem to take informed decisions, as the presented technologies are no long theoretic but ready for sale.

I. Introduction

Predistortion improves the error rate performance over non-linear channels, such as forward links (from hub to terminal) in satellite communications, given high SNR in the uplink (from hub to satellite). An overview of recent predistortion technologies is given in [11]. Typically, the predistortion *gain* is expressed as *total degradation gain* achieved over a given non-linear channel [15, 4, 7]. Total degradation accounts for the non-linear distortion as well as the power penalty induced by back-off given at the input of the on-board traveling wave tube amplifier (TWTA). For any Frame Error rate (FER) greater than zero, total degradation (TD) is defined in dB as,

$$\mathrm{TD}|_{\mathrm{FER}} = \frac{E_s}{N_0}|_{\mathrm{NL}} - \frac{E_s}{N_0}|_{\mathrm{AWGN}} + \mathrm{GOBO}, \tag{1}$$

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where, $\frac{E_s}{N_0}|_{\text{NL}} - \frac{E_s}{N_0}|_{\text{AWGN}}$ represents, for the same downlink noise density, the additional required useful signal power to achieve a given FER over a non-linear channel compared to the AWGN channel[a]. The global output back-off (GOBO) is defined as the difference between the TWTA output power when it is driven at saturation with a pure carrier signal and the TWTA output power when it is fed with the useful signal at a given global input back-off (GIBO) [12]. Operating the amplifier at lower backoff (i.e. higher input power) leads to larger non-linear distortion; hence, $\frac{E_s}{N_0}|_{\text{NL}}$ needs to be increased to achieve said given FER. However, in a linear operation region, $\frac{E_s}{N_0}|_{\text{NL}}$ mirrors $\frac{E_s}{N_0}|_{\text{AWGN}}$, while the TD is dominated by the large GOBO value.

Alternatively, Eq. (1) can also be expressed as,

$$\text{TD}|_{\text{FER}} = \frac{C_{\text{sat}}}{N}|_{\text{NL}} - \frac{E_s}{N_0}|_{\text{AWGN}}, \tag{2}$$

where $N = N_0 * R$, where R is the symbol rate of the considered carrier, and where $\frac{C_{\text{sat}}}{N}|_{\text{NL}} = \frac{E_s}{N_0}|_{\text{NL}} + \text{GOBO}$. Note that sometimes $\frac{C_{\text{sat}}}{N_{\text{ref}}}|_{\text{NL}}$ is considered instead of $\frac{C_{\text{sat}}}{N}|_{\text{NL}}$, where $N_{\text{ref}} = N_0 * \text{BW}$ (BW is the occupied bandwidth). As we compare schemes with the same occupied bandwidth, which is standard in satellite communications, $\frac{C_{\text{sat}}}{N_{\text{ref}}}|_{\text{NL}}$ and $\frac{C_{\text{sat}}}{N}|_{\text{NL}}$ are the same up to a constant.

Summarizing, the total degradation gain is an improvement of the link budget, expressed as a *dB-gain*.

In this paper, we show that predistortion is also capable of significantly improving the spectral efficiency by using non-orthogonal signaling such as Faster than Nyquist [17] or frequency overlapping of carriers. As a consequence, predistortion techniques should be assessed on their average throughput gain instead of only TD gain.

The bulk of the prior art [15, 1, 13, 16, 3], as well as the industry [3, 19], uses TD gain[b] (the well known *dB-gain*) to assess predistortion techniques. Even though the prior art is valuable in assessing the capability of predistortion to compensate for the non-linear channel effects, we are blind regarding their capability to compensate for interference due to non-orthogonal signaling. In this paper, we show that only looking at TD gain leads to false conclusions and a more comprehensive metric to assess predistortion technology is *average throughput gain.*

II. Total degradation does not consider suboptimality of orthogonal signaling for non-linear channels

A. Optimality of orthogonal signaling for frequency-flat AWGN channels in the presence of infinite resources

We first recapitulate the reason for using orthogonal signaling [5, 22, 24]. We start with considering Nyquist filtering (SRRC pulse shaping and matched filtering) for single carrier transmission. For frequency non-selective or frequency-flat[c] additive white Gaussian noise (AWGN) channels, Nyquist filtering guarantees intersymbol-interference (ISI) free transmission, i.e., the discrete-time symbol level channel is a simple single-tap filter. In other words, it guarantees orthogonal signaling in the time domain. While it allows the use

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[a] E_s is the useful energy per symbol, or equivalently, the useful signal power spectral density. N_0 is the noise power spectral density. Both values are those required to achieve a given FER, either over a non-linear channel ($\frac{E_s}{N_0}|_{\text{NL}}$) or over an AWGN channel $\frac{E_s}{N_0}|_{\text{AWGN}}$.

[b] In [20], TD gain was used to compare different predistortion techniques. In [9, 20], thanks to reduced regrowth, the carrier rate in the return link could be extended, but orthogonal signaling was kept as a baseline.

[c] A frequency-flat channel means that it can be represented by a single tap in a tapped-delay line representation. This is achieved under several conditions, e.g. the symbol-time is much larger than the maximum difference between channel path delays (or equivalently, the signal bandwidth is much smaller than the inverse of the maximum difference between channel path delays) and the symbol time is much smaller than the coherence time of the channel (or equivalently, the signal bandwidth is much larger than the Doppler frequency).

of a low complex symbol-by-symbol detector at the receiver, it has also been shown in several ways that Nyquist filtering is optimal for frequency-flat channels. Allowing an infinite resource complexity and using capacity achieving mappings and error-correcting codes (e.g. Gaussian codebooks), the Shannon capacity can be achieved using Nyquist filtering with 0% roll-off. In practice, a roll-off stricly larger than 0% has to be used which results in limited degradation w.r.t. the Shannon capacity. For a given signal bandwidth, Nyquist filtering can be shown to maximize the SNR [22].

In the case multiple carriers are used, the orthogonal signaling in time is extended in frequency by transmitting the multiple carriers in non-overlapping frequency bands.

B. Suboptimality of Nyquist filtering in many realistic scenarios

As explained above, Nyquist signalling provides for a orthogonal paradigm to reduce ISI. However, constrained by finite resources, higher roll-offs are sometimes adopted which significantly degrade the spectral efficiency of the system. It is known [9] that time-frequency packing (e.g. Faster-than-Nyquist signaling[d] and carriers overlapping in frequency[e]) can improve the spectral efficiency. If the system is able to cope with the interference due to non-orthogonal signaling, the efficiency of the communication system can be increased.

More fundamentally, for many other channels, e.g. channels with memory (such as the non-linear satellite channel) the optimality of orthogonal signaling has not been shown. In fact, the high peak-to-average power ratio is a disadvantage of Nyquist filtering with low roll-off schemes when transmitting over non-linear channels. Note that the literature proposed linear modulations in combination with Nyquist filtering to improve transmission over such non-linear channels; these include the Offset and Differential modulations and APSK constellations. However, it is shown in [6] that the Offset and Differential modulations method are not adequate in countering non-linear effects and the problem of spectral regrowth persists. Alternatively, different receiver architectures in combination with Nyquist filtering have been proposed to counter the non-linearities [9, 4]. While receiver techniques are always in disadvantage w.r.t. transmitter techniques (as the received signal is impaired by noise and other channel effects), many of these receiver architectures are also infeasible, either due to complexity or due to the architecture of the user terminals (inability to process very large bandwidths for example).

Next to time-frequency packing, other solutions have been proposed as an alternative to Nyquist filtering, such as continuous phase modulations or partial response filtering [23].

C. Perfect match of predistortion and non-orthogonal signaling

Regardless of the disadvantages mentioned above, Nyquist filtering is still the mostly used signaling technique today for spectral efficient sensitive use cases in satellite communications, e.g. see the DVB-S2(X) standards [10]. To the best of authors' knowledge, no significant improvement upon Nyquist filtering itself has been found when employing linear modulations over non-linear channels in the absence of predistortion. Waveforms based on FTN and TF-packing have been considered during the study phase leading to the DVB-S2X [14]. However, it has been reported in [14] that FTN provides negligible improvement compared to the case where the DVB-S2 and DVB-S2X symbol-rates are optimized to achieve the higher spectral efficiency

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[d] The orthogonal requirement was first relaxed [17] in where the transmit pulses were placed closer than the Nyquist rate leading to Faster than Nyquist (FTN) signalling. The optimal pulse spacing was asymptotically shown to enhance the efficiency of the system without losing on performance. FTN has been proposed to improve the spectral efficiency of DVB in [18].

[e] On the other hand, a different approach to Time-Frequency (TF) packing was introduced for AWGN channels in [2]. It extends the non-orthogonality in time to the frequency domain by also partly overlapping the carriers in frequency. A study involving TF packing of a single carrier per transponder has been considered in [21].

and an enhanced receiver including an adaptive equalizer is adopted. Note that this study did not consider successive interference cancellation or advanced predistortion (i.e., also able to compensate for distortions from non-orthogonal signaling), which significantly changes the picture as we show below.

On the other hand, predistortion is perfectly suited to cope with the interference due to non-orthogonal signaling. We show below that the predistortion technique can improve the spectral efficiency by not only anticipating the non-linear distortions introduced on-board the satellite, but also by anticipating the distortions introduced by using non-orthogonal signaling.

Expressing the gain of predistortion in terms of total degradation (the *dB-gain*) assumes that the transmitter and receiver use the same signaling in the cases with and without predistortion. However, while Nyquist filtering and orthogonal frequency multiplexing is close to optimal without predistortion (as argued above and concluded in [14]), it is not when using predistortion.

Therefore we claim that the more accurate metric to compare predistortion technologies for non-linear channels is achieved throughput within a given occupied bandwidth (which can be compared with the Shannon capacity within that bandwidth) instead of total degradation.

D. Contribution of this paper - insisting on a paradigm shift from total degradation to throughput

In this paper, we will present the total degradation gain achieved by a particular predistortion technique [11] and its corresponding throughput gain when adopting only orthogonal signaling. We then show that this throughput gain can be significantly increased when considering non-orthogonal signaling. We will elaborate on how to correctly compute the *average throughput gain*. This example should make clear that a paradigm shift is needed from total degradation to throughput.

Finally, we put forward a teaser, where we suggest that symbol-level predistortion (or a combination of symbol-level predistortion and sample-level predistortion) performs better than sample-level predistortion as it can better deal with non-orthogonal signaling.

III. Considered system model - academic ACM system over linearized channel

To illustrate the differences of the gain metrics, we consider a specific channel model. We consider a typical non-linear channel with the following AM/AM and AM/PM characteristic (see Fig. 1)

Such TWTA characteristic is considered linearized, as its small signal gain is only 2.8 dB and it has almost no phase rotations before saturation. Hence, not many non-linear distortions are caused by the amplification in the region before saturation. Still, there is a significant non-linearity at saturation. Furthermore, the considered AM/AM characteristic is very challenging as it falls back heavily beyond saturation, which prevents adopting small GIBOs. Besides the TWTA, standard IMUX and OMUX filters are present as well with a bandwidth extending over all carriers for a single beam transponder.

The adopted signaling consists of transmitting 4 equally large carriers of 7.5 Mbaud and 20% roll-off, yielding an occupied bandwidth of 36 MHz. In an adaptive coding and modulation (ACM) system, only a finite amount of modulation and codes (modcods) are available. Depending on the link budget, a specific modcod can be used. Here, we consider an academic example of modcods spaced by 1 dB in SNR threshold. We simulated only 1 threshold, for a 32-APSK 5/6 modcod of the DVB-S2(X) standard, which is our reference modcod with a reference spectral efficiency. The remaining thresholds follow from the academic assumption of 1 dB spacing. Assuming well designed modcods[f], the efficiency increase of a modcod with a threshold

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[f] In a local SNR region, the SNR degradation w.r.t. the Shannon capacity remains constant (e.g. it is 2 dB for spectral

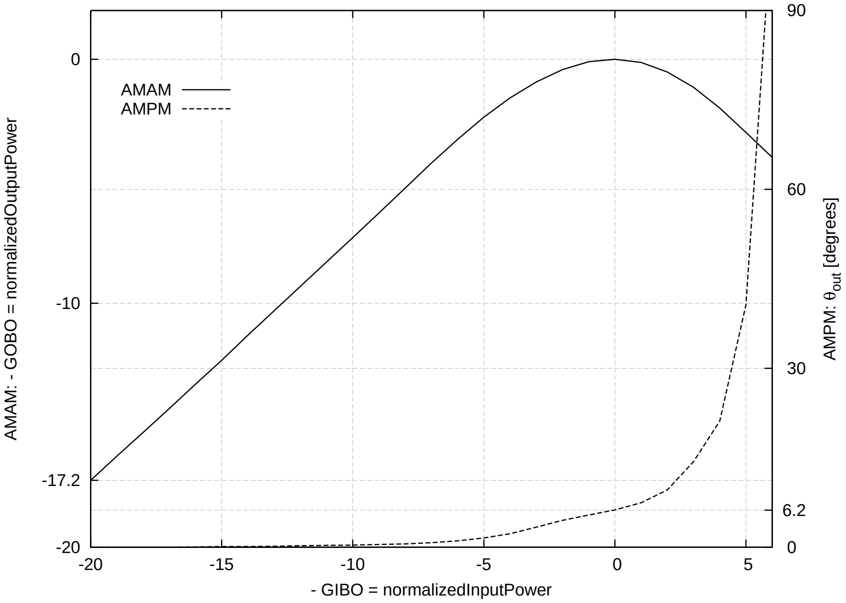

Figure 1. The considered *linearized* transponder (AM/AM and AM/PM characteristic) for the simulations reported in this paper.

that is 1 dB higher is conjectured to be the same as the efficiency increase achieved by Shannon for 1 dB SNR increase from the initial reference spectral efficiency.

In Fig. 2, we show the reference ACM performance (commonly referred to as a staircase diagram) without predistortion and with and without orthogonal signaling over the considered channel. The x-axis is

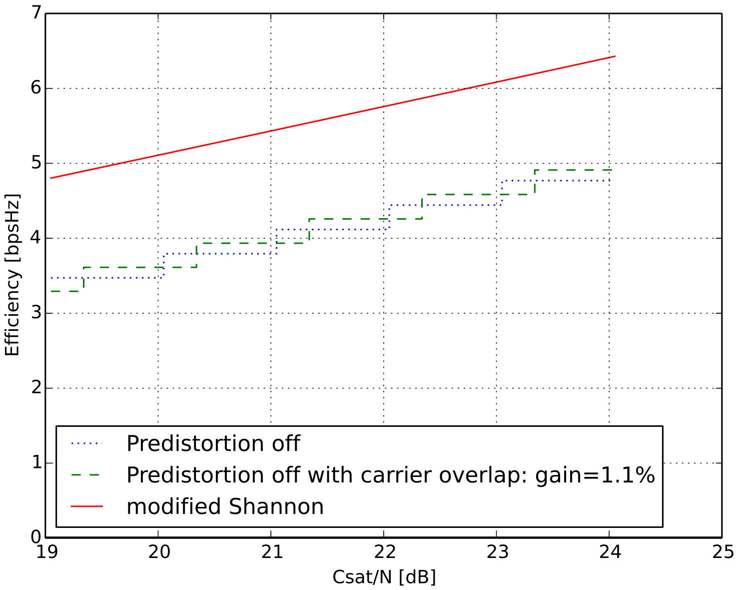

Figure 2. The ACM performance without predistortion and with (dotted) and without (dashed) orthogonal signaling over the considered channel.

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efficiencies between 3 and 4 bpsHz), which can be justified by looking at the DVB-S2X performance [8, 25]. The consequence is that the efficiency versus SNR graphs of the ACM system and Shannon run parallel.

$\frac{C_{\text{sat}}}{N}$ defined in the introduction, $\frac{C_{\text{sat}}}{N}|_{\text{NL}} = \frac{E_s}{N_0}|_{\text{NL}} + \text{GOBO}$. The y-axis is the spectral efficiency.

The dotted curve is the normal ACM performance with orthogonal signaling. As this is an academic example, we assume a zero dB ACM margin, meaning that a better modcod can be achieved at its threshold (while in reality some margin is required above its threshold to take into account link jittering and other phenomena). However, it can be easily shown that any adopted ACM margin leads to the same average throughput gain. The x-coordinate of the left point of the dotted curve is the simulated $\frac{C_{\text{sat}}}{N} = 19.05$ dB threshold for 32 APSK 5/6 with 20% roll-off. Its spectral efficiency is roughly 3.47 = 5 * 5 / 6 / 1.2, neglecting synchronization overhead.

The full line is an upperbound of the performance, referred to as the modified Shannon bound. For a given $\frac{C_{\text{sat}}}{N}$, it represents the Shannon efficiency at an SNR of $\frac{C_{\text{sat}}}{N} - \text{TD}|_{\text{FER}}$, thus at the linear threshold $\frac{E_s}{N_0}|_{\text{AWGN}}$ of the considered modcod, here 14.3 dB. The y-coordinate of the left point is thus $\log_2(1 + \text{SNR}_{\text{lin}})$, where $\text{SNR}_{\text{lin}} = 10.0^{\frac{14.3}{10}})$. The loss with respect to Shannon is here thus caused by roll-off and non-capacity achieving modcod.

The dashed curve is the ACM performance with non-orthogonal signaling, which is in this case limited to an overlap of carriers. By means of simulations, it was found that it was optimal to increase the symbol rate by 4% for a simulated $\frac{C_{\text{sat}}}{N} = 19.34$ dB threshold. The non-orthogonal signaling yields an *average throughput gain* of 1.1%, which can be computed from Fig. 2 as explained in Sec. IV. So even without predistortion, non-orthogonal signaling is optimal (for the considered use case with 20% roll-off), even though the gains are rather small.

The next section elaborates how the *average throughput gain* is computed from these (and in general, any) two simulated ACM performance curves.

IV. Computation of average system throughput gain within a given bandwidth

We now present how to compute the throughput gain of one system versus another based on the ACM performances, as shown in Fig. 2. The throughput for a given $\frac{C_{\text{sat}}}{N}$ is simply the efficiency times the occupied bandwidth. As the latter is equal for both cases, we can limit ourselves to considering the efficiency. It is immediately clear that the throughput *gain* of carrier overlapping depends on the $\frac{C_{\text{sat}}}{N}$. In fact, the realized efficiency is sometimes higher and someitmes lower. Therefore, the *average* system throughput gain is more insightful.

Here, we consider a set of links consisting of a range of terminals in a given beam and a range of beams in a given application. The SNR seen by the terminals varies over this set. As the clear-sky SNR is by far the largest contributer in the total link throughput, we consider the SNR range from 19 to 24 dB and assume that the SNR has a uniform distribution[g] between 19 and 24 dB when considering the set of all terminals. Therefore, the area below the staircase curve is proportional to the average link throughput. As a consequence, the throughput gain of predistortion is the ratio of the areas below the corresponding staircase curves. Computing this ratio yields the average gain of 1.1% referred to in the legend of Fig. 2.

The average system performance is of high importance as it is directly proportional to the throughput capacity of the system. It is therefore an essential business metric of the system capacity and efficiency of the overall system. Especially the forward link performance is the main contributor to the overall efficiency and performance of satellite access networks.

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[g] If the actual distribution would not be uniform, this would not impact the analysis or results significantly. A uniform distribution of SNRs in a limited range is justified by data from satellite operators.

V. Average system throughput gain by exploiting faster than Nyquist or frequency packing through with predistortion

Optimizing the frequency overlap by means of simulation yields the following ACM performance, see Fig. 3. Using the method presented in Sec. IV, we computed a throughput gain of 9.6% of the predistortion with frequency packing w.r.t. no predistortion.

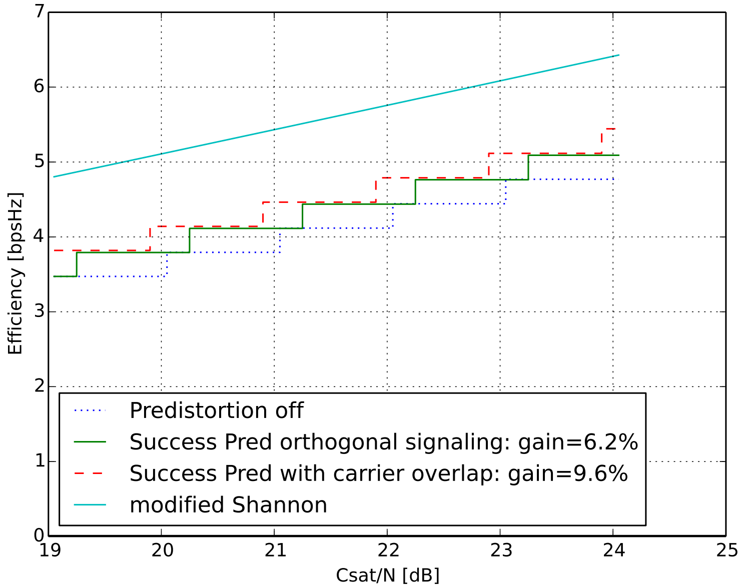

Figure 3. The ACM performances with successive predistortion and with (dashed) and without (lowest full line) orthogonal signaling over the considered channel, compared to the ACM performances without predistortion and orthogonal signaling (dotted) and the modified Shannon bound.

Note that the throughput gain corresponding to the total degradation is 6.2%. However, this gain is increased to 9.6% by using non-orthogonal signaling. Taking into account that without predistortion non-orthogonal signaling also yields a gain of 1.1%, the gain of predistortion is 8.5% allowing non-orthogonal signaling.

It is clear that not all predistortion technique exhibiting a given total degradation gain can further exploit the time-frequency domain to extend this total degradation gain in the same way. For example, sample-level predistortion, after the pulse-shaping filter, will not be able to anticipate on the frequency overlap of carriers. It is thus clear that total degradation gain is not a representative metric to assess predistortion techniques.

VI. Conclusion

The best predistortion techniques not only allow to compensate for channel distortions, but also for distortions from non-orthogonal signaling, such as Faster than Nyquist or frequency overlapping of carriers. The typical gain metric, total degradation gain, does not capture this capability as it requires the spectral efficiency to be the same with and without predistortion. However, the advantage of non-orthogonal signaling is that the spectral efficiency can increase within the same occupied bandwidth. Therefore, we propose to adopt average throughput gain over a range of SNRs as the metric to assess predistortion techniques and we show how to compute it. We provide an example where an average throughput gain close to 10% is achieved for a linearized transponder with large fallback beyond saturation.

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