Advantages of Using Dynamic Predistortion with the CDM-760

June 2016

Introduction

Space segment costs are typically the most significant operating expense for any satellite-based service, having a direct impact on the viability and profitability of the service. When a single-carrier utilizes an entire satellite transponder, e.g. 36-MHz or 72-MHz bandwidth, there is an opportunity to capture additional link efficiency not available in a multi-carrier setting. This is done by operating the transponder, specifically the traveling-wave-tube amplifier (TWTA) diagrammed in Figure 1, in the nonlinear saturation region.

However, when operating in this regime, amplifiers suffer from nonlinear distortion, commonly characterized by *amplitude-to-amplitude* modulation (AM-AM) conversion as well as *amplitude-to-phase* modulation (AM-PM). In addition, amplifiers incorporate short-term memory arising from physical device phenomena that adds a filtering-like effect to the transponder. Additionally, input and output multiplexing filters (IMUX and OMUX) add linear distortion as signal bandwidths approach the limit of the transponder.

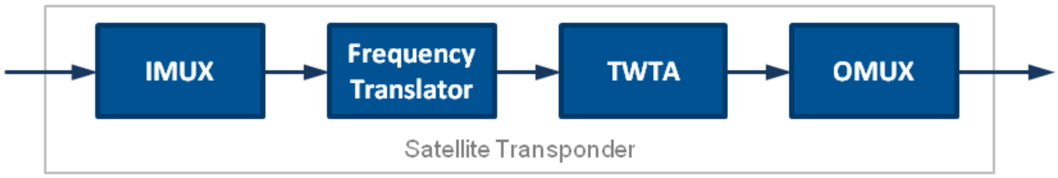


Figure 1: Satellite transponder, with input IMUX and OMUX filters, TWTA, and frequency translator

The in-band distortion produces degradation in bit error rates relative to that of an ideal transponder. The traditional approach to mitigating these effects is to reduce the transponder output power, i.e. increase output backoff. However, a reduction in the transponder output power typically forces a lower modulation and coding order in the modem, decreasing the space segment efficiency and further increases costs.

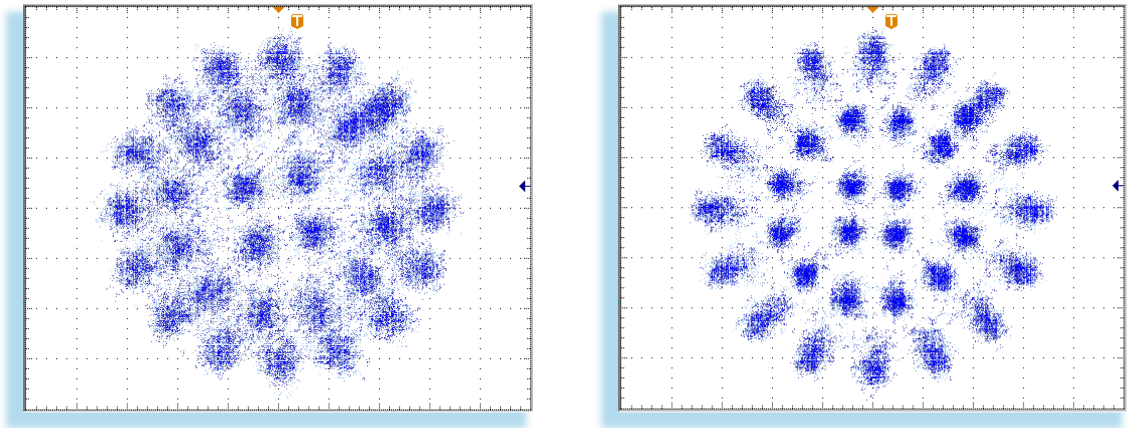
Comtech EF Data has added a new approach to continuously optimize satellite communication efficiency – *Dynamic Predistortion (DPD)* on the CDM-760. Working in tandem with DPD, a new *crest factor reduction (CFR)* technique is dynamically applied as well to further enhance performance. These innovative technologies, collectively labeled and referred to as DPD, create high signal integrity while operating the satellite transponder in the higher efficiency nonlinear region. They provide a significant increase in link margin, by as much as 2 dB, and/or in spectral efficiency, by as much as 6%. These improvements can translate to

- Reducing OPEX
- Reducing CAPEX
- Increasing throughput without using additional transponder resources
- Increasing link availability (margin) without using additional transponder resources
- Or a combination of these to meet business objectives.

As an alternative to simply backing off a power amplifier, predistortion employs an approximate inverse nonlinearity ahead of the power amplifier, at a low power level to a digital baseband signal, such that the cascade operation is closer to ideal. Additionally, when DPD is enabled, *crest factor reduction* precedes the predistorter to reduce the signal's magnitude range. Working together, both preempt the degrading effects of the satellite transponder when attempting to operate a link with highest spectrally efficiency.

Figure 2: Cascade of crest factor reduction, predistorter and satellite transponder, baseband diagram

Example results illustrate the benefit of DPD when applied to a 32-APSK constellation as shown in Figure 3. All distortion pictured is induced by driving the TWTA into its nonlinear region, i.e. additive noise is not included in the plots. While maintaining the same output backoff a significant proportion of the distortion is removed when DPD is applied. Here, the modulation error ratio (MER), a common measure of constellation quality, significantly improves from 18.5 dB to 22.5 dB.



(a) Without DPD, MER=18.5 dB (b) With DPD, MER=22.5 dB

Figure 3: Constellation 32-APSK improvement at the receiver from predistortion (without added noise) with 2dB output backoff on a TWTA.

Predistortion

Predistortion preemptively compensates the uplink waveform by expanding the signal peaks that will be compressed by the satellite amplifier. Note that a nonlinear satellite channel is not a fully invertible system so residual distortion will still be present even when the predistorter is applied. In addition, the linear filtering effects of the link are compensated by DPD. But, again the effects cannot be fully removed due to inherent limits in computational capacity.

Since the best predistorter for a particular satellite transponder is unknown, one must be identified through a training process. The CDM-760 can train the predistorter according to either of the following two approaches diagrammed in Figure 4:

(1) *Local*, DPD training involves a single modem and ground-station
(2) *Remote*, DPD training involves two modems and ground stations

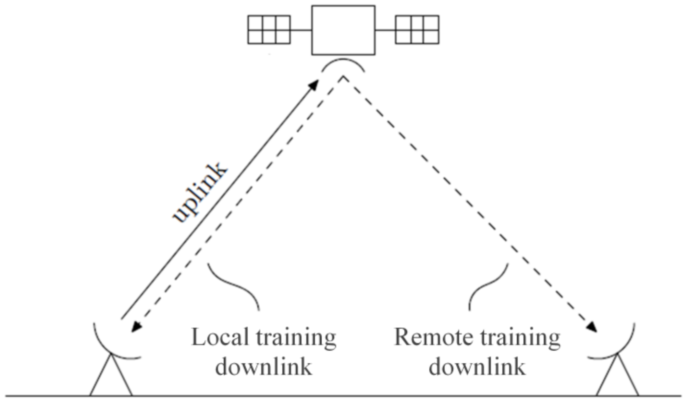


Figure 4: Satellite link illustration

The local training case requires the CDM-760 modem to "listen" to its own outbound undergoing distortion imparted primarily by the non-linearity, along with the input/output multiplexing filters, on the satellite. The remote case does not require the full signal loop-back. Instead additional processing at the remote end is required. Using the same messaging approach as adaptive modulation and coding (ACM) control, a return link is required to the original transmit modem to pass trained coefficients.

Under both approaches the predistorter is trained according to the 'indirect learning' architecture. Figures 5 and 6 illustrate the training procedure for local and remote training respectively.

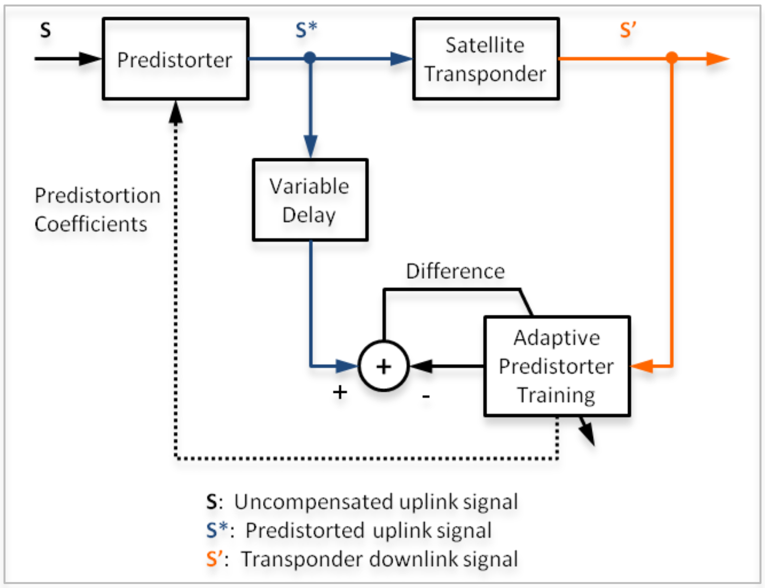


Figure 5: Indirect learning architecture using the *local* training approach

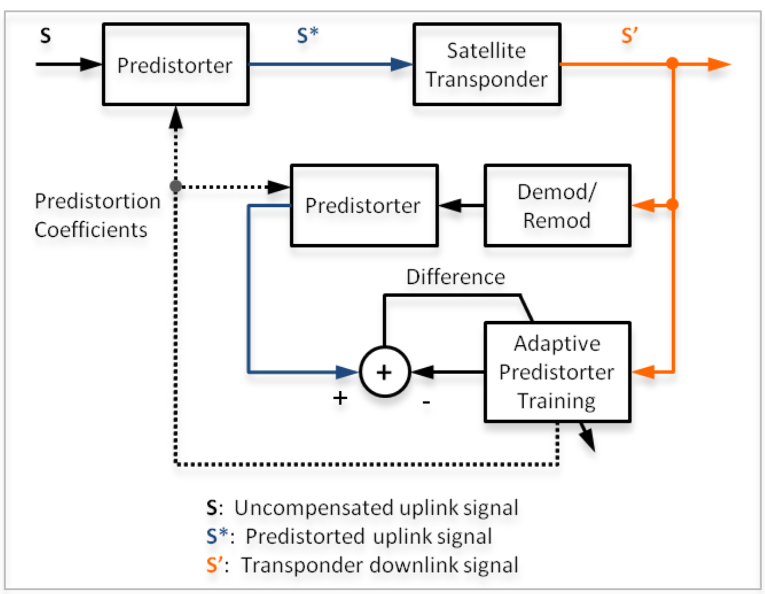


Figure 6: Indirect learning architecture using the *remote* training approach

In both approaches, the training procedure is essentially the same. The training procedure starts by initializing the predistorter to be a pass-through system, i.e. signal **S*** equals signal **S**. Then, the downlink signal **S'** is time-aligned with the uplink signal such that the difference, created by the satellite channel, can be monitored. Next, based on minimizing the difference signal an adaptive inverse nonlinear system is trained by adapting complex-valued predistorter coefficients. The predistorter in training is positioned following the satellite channel, forming a so call 'post-inverse' system. Finally, the trained coefficients are relayed internally to the predistorter.

The predistorter alters the uplink signal particularly in terms of the signal's magnitude distribution. Due to this, the new 'best' inverse system identified on the next iteration will differ slightly. After several iterations (typically 5-10), the complex coefficients converge for the current conditions. The trained coefficients are relayed to the predistorter on a regular interval of every 0.5 seconds. In addition to providing initial convergence, the dynamic nature of the predistorter continues the optimization process in the midst of varying link conditions or user-applied transmit configuration changes. Furthermore, the constantly updating approach automatically optimizes for physical changes over the life cycle of the satellite transponder.

When adjusting for the best transponder output backoff power, as detailed in a later section, the predistorter adaptively determines the best predistorter for the particular backoff. Additionally, the best predistorter is identified and stored for the 15 most recent modcods employed. This is particularly valuable with ACM, where switching between modcods can occur frame by frame. Many of these tradeoffs are challenging or impossible to fully optimize with a stagnant predistorter.

Crest Factor Reduction

The objective of crest factor reduction (CFR) is to preemptively act upon the uplink waveform so that the downlink received signal has less distortion. Though the objective is similar, how CFR achieves this is conceptually quite different from predistortion.

CFR reduces the magnitude peaks of the uplink waveform by applying a scaled, opposing compensation pulse to the signal's largest magnitude peaks. Since this process includes the possibility of creating new magnitude peaks when cancelling others, the technique is re-applied in successive stages. Additionally, the compensation pulses are shaped so the frequency spectrum of the uplink signal is unchanged from that of the normal square-root raised-cosine shape.

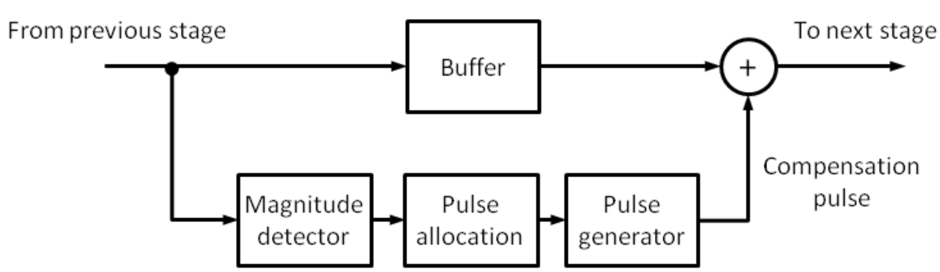


Figure 7: Peak cancellation block diagram

Similar to predistortion, this process intentionally introduces distortion to the uplink signal. Also comparable to predistortion, the level of CFR applied is determined dynamically depending on the amount of non-linear compression in the satellite link. But, different from predistortion, the added distortion from CFR is not intended to invert the effects of the transponder. Instead, the aim is essentially to avoid the most distorting effects of the transponder that would have been applied to the largest magnitude peaks. Though limited distortion is intentionally applied, on balance there is less overall less distortion on the downlink signal than if the technique were not applied. Compounding the benefit, with CFR the predistorter concentrates resources on reducing distortion over a narrower range of signal magnitudes, further improving performance.

Specifications

Symbol Rate Range	Minimum of 20 Msps up to a maximum symbol rate dependent on constellation size and training approach, as follows: **Local:** QPSK: 72 Msps 8PSK: 72 Msps 16-points, e.g. 16-APSK: 72 Msps 32-points, e.g. 32-APSK: 72 Msps 64-points, e.g. 64-APSK: 54 Msps **Remote:** QPSK: 75 Msps 8PSK: 60 Msps 16-points, e.g. 16-APSK: 45 Msps 32-points, e.g. 32-APSK: 36 Msps 64-points, e.g. 64-APSK: 27 Msps
Coefficient Update Rate	Every 0.5 seconds
Coefficient Database Storage	15 sets, immediately loaded with modulation and coding change
Satellite Round Trip Delay Range	0 – 300 milliseconds
Monitor Functions	Round trip delay, in microseconds (Local only) Frequency offset (between transmitted outbound and received outbound): 100 Hz resolution (Local only) DPD compensation, in tenths of a dB (ratio of peak-to-average power ratios, predistorter output to input)

Operational Requirements

Typically predistortion and crest factor reduction are applied in a digital system collocated with the nonlinear amplifier. However, in this application these techniques must be applied remotely from a ground-based modem to compensate for the nonlinearity of the orbiting satellite transponder. Due to the removed nature of this implementation some operational requirements must be met.

In the *local* implementation, as shown in Figure 8, the transmitting modem must receive its own outbound, **S'**, for the previously described predistortion training.

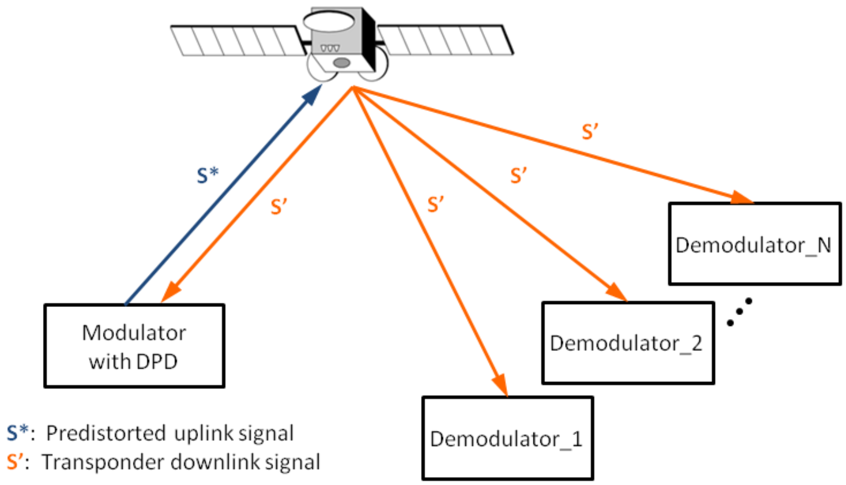


Figure 8: Satellite links for local DPD

As such, local DPD can only be employed under the following conditions:

- The link must include a "loop-back" circuit (i.e. the transmitting station must be able to receive its own outbound).
- Local DPD requires the use of the modem's receive signal chain. Consequently, the CDM-760 will operate in Transmit Only mode when local DPD is enabled. ACM cannot be employed as a result.

In the *remote* implementation, as show in Figure 9, there must be a full-duplex circuit so the trained coefficients can be returned to the predistorter.

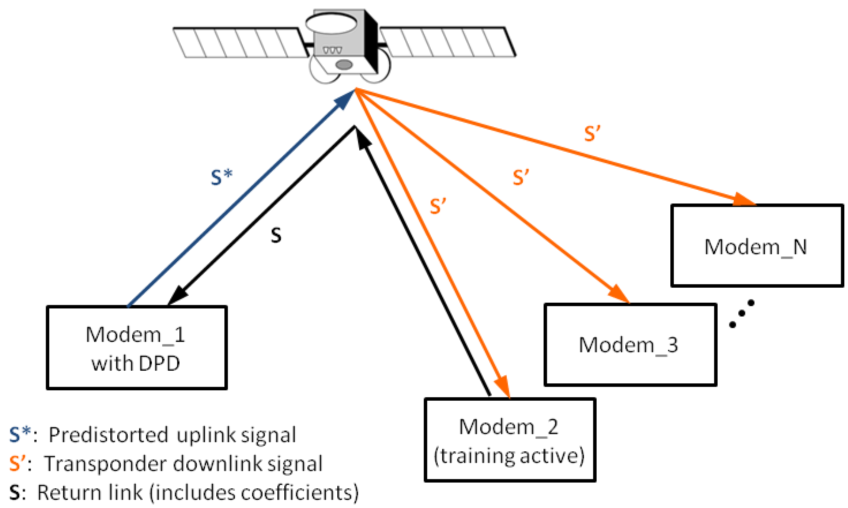


Figure 9: Satellite links for remote DPD

As such, remote DPD can only be employed under the following condition:

- There must be a full-duplex circuit to return trained coefficients. Note sending the coefficients adds a very low overhead burden and are automatically passed much the same as ACM messaging.

For both local and remote DPD, if the satellite transponder were processing other carriers or other processing was applied, the nonlinear transponder's operation on the carrier of interest would become unpredictable. Therefore, additional operational restrictions applicable to both local and remote DPD are:

- The link must be over a single-channel-per-transponder configuration. That is, multiple carriers, even in a CnC configuration, cannot be operated on the transponder to which DPD will be applied.
- The satellite must be a "non-processing" satellite (i.e. does not demodulate/ remodulate the signal).

Operational Recommendations

The DPD function has not been shown to provide significant benefit with smaller constellations of QPSK or 8-PSK since these are not affected as much by nonlinear distortion. The technique does not harm these links but doesn't provide significant benefit either. Nonetheless, DPD is strongly recommended for use with larger constellations.

In addition, to minimize "False" feedback acquisition.

- Keep the search delay range as narrow as possible
    - Once the modem has reported the search delay, narrow the search delay range to the nominal reported value +/- 5 ms, e.g. if the modem reported delay is 245 ms, narrow the search range to say 240 –250 ms

Use external data source (e.g. Fireberd) or internal BER tester when testing DPD performance.

Link Design

DPD link design involves finding the FEC, modulation combination, and transmit power level that provides optimal bandwidth utilization. Just like conventional link design, it is an iterative process that involves trying different FEC, modulation, and transmit power combinations with DPD until an optimal combination is found. This process is described in the next section.

Commissioning and Deployment

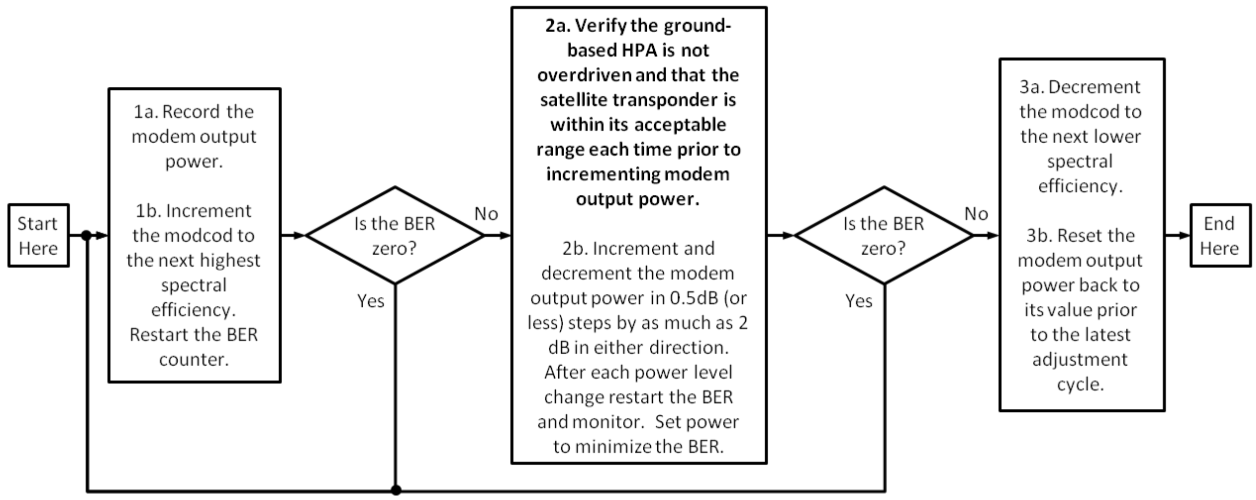
The following procedure is recommended for ***local*** DPD commissioning. Though a loop-back is created in this procedure, this does not create a loop in the user network since the received data is intentionally prevented from leaving the modem when in local DPD mode.

(1) Setup the transmit configuration.
  a. Use a modulation and coding (modcod) scheme with slightly lower spectral efficiency than expected to close the link.
  b. Leave the DPD function OFF.

(2) Turn ON the carrier. Leave the DPD function OFF.
  a. Setup the receiver configuration to receive the looped-back signal.
  b. Verify that the demodulator is locked.
  c. Verify that the received signal level is within specifications.
  d. Measure/record the Es/No.

(3) Turn the DPD function to LOCAL.
  a. After the demodulator has relocked, wait 30 seconds to allow the predistorter to fully converge to the current transponder conditions.
  b. Measure/record the DPD compensation.
  c. Measure/record the Es/No and compare to previous result without DPD. If the DPD compensation level is low <1.0 dB, then the Es/No improvement may be small since the transponder is not driven deep into compression yet.
  d. Enable the BER test mode.

(4) Follow the flow chart to maximize spectral efficiency and optimize the uplink power.



(5) Basic performance validation
   a. Measure/record the DPD compensation.
   b. Measure/record the Es/No.
   c. Turn DPD function OFF and compare the measured Es/No and BER, assuming the demodulator is able to achieve lock.

(6) Initiate service
   a. Turn DPD back to LOCAL.
   b. Disable BER test mode.

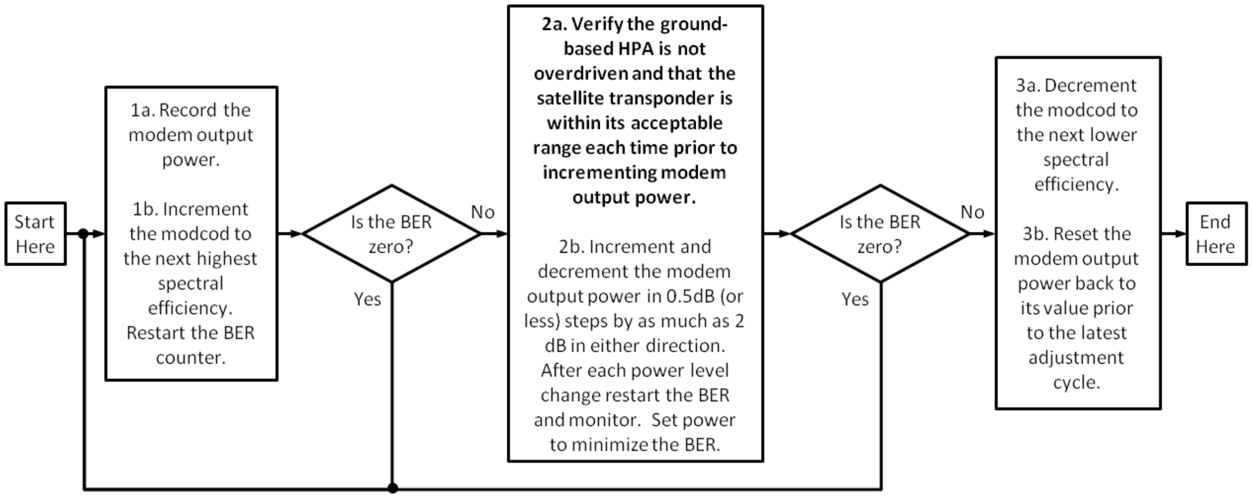
The following procedure is recommended for ***remote*** DPD commissioning. In the procedure DPD will be applied to the link originating from Site A. DPD training will be conducted at Site B. Since the bandwidth of the link originating from Site B is expected to be below 20Msps, DPD will not be applied to this carrier even though DPD will be ‘enabled’ at this site in the following.

(1) Setup the transmit configuration at both sites.
   a. Site A should use a modulation and coding (modcod) scheme with slightly lower spectral efficiency than expected to close the link.
   b. Leave the DPD function OFF at both sites.

(2) Turn ON the carrier at both sites. Leave the DPD function OFF at both sites.
   a. Setup the receiver configuration at both sites.
   b. Verify that the demodulators are locked at both sites.
   c. Verify that the received signal level at both sites are within specifications.
   d. Measure/record the Es/No at Site B.

(3) Turn the DPD function to REMOTE at both sites.
   a. After the demodulators have locked, wait 30 seconds to allow the predistorter to fully converge to the current transponder conditions.
   b. Measure/record the DPD compensation at Site A.
   c. Measure/record the Es/No and compare to previous result without DPD. If the DPD compensation level is low <1.0 dB, then the Es/No improvement may be small since the transponder is not driven deep into compression yet.
   d. Enable the BER test mode.

(4) Follow the flow chart to maximize spectral efficiency and optimize the uplink power at Site A only.



(5) Basic performance validation
   a. Measure/record the DPD compensation at Site A.
   b. Measure/record the Es/No at Site B.
   c. Turn DPD function OFF at both sites and compare the measured Es/No and BER, assuming the demodulator is able to achieve lock.

(6) Initiate service
   a. Turn DPD back to REMOTE mode at both sites. If the demodulator cannot re-lock this procedure will need to be repeated starting from step (1) without returning to step (5).
   b. Disable BER test mode.

Example Results

As previously mentioned, DPD can provide a significant link margin increase. The increase comes in the form of two separate link budget categories. First, the link margin required to accommodate transponder nonlinear effects may be reduced. Second, the transponder output back off (OBO) may be reduced.

Example results for a C-band, 36 MHz transponder are described in the following. Note the performance improvement will vary from transponder to transponder and link to link depending on the exact characteristics.

Figures 10 and 11 display the total degradation reduction provided by digital predistortion for 16-APSK and 32-APSK respectively with DVB-S2 EB1. The tests used a 5% square-root raised cosine rolloff factor and 34.28 Msps. Additionally, the OBO was optimized for each configuration, which varied between 1.2 dB and 3.2 dB. The balance between the reduced margin for nonlinear distortion versus the reduction in the OBO is shown by the stacked bar graph format.

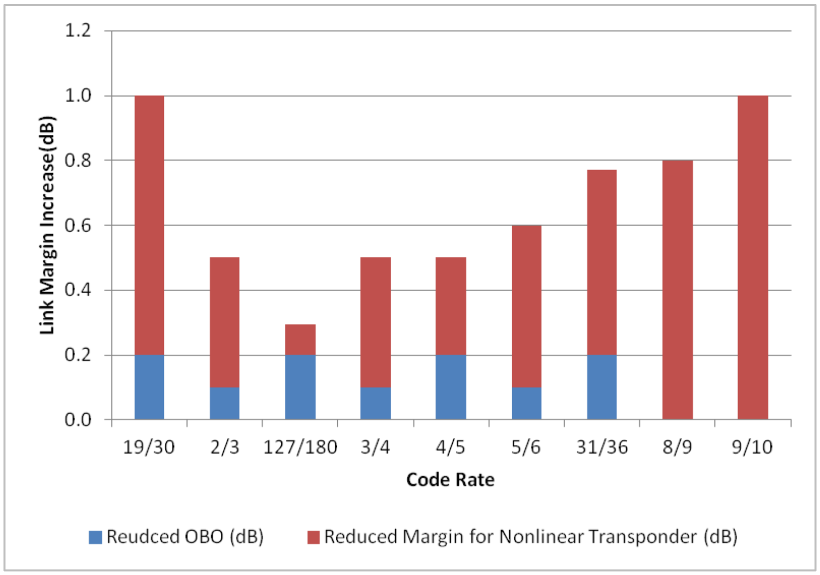


Figure 10: Link Margin Increase for 16-APSK DVB-S2 EB-1 Modcods, C-band, 36MHz Transponder

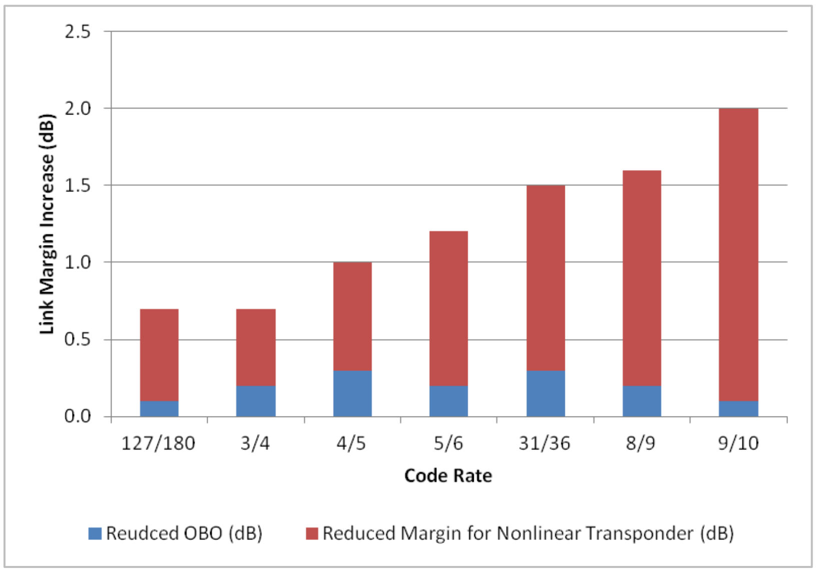


Figure 11: Link Margin Increase for 32-APSK DVB-S2 EB-1 Modcods, C-band, 36MHz Transponder

The overall link margin improvement varied from 0.3 up to 1.0 dB for 16-APSK and from 0.7 to 2.0 dB for 32-APSK. While the optimum output backoff was reduced (or equal) with predistoriton, the reduced margin for the nonlinear transponder was the dominant source of link margin increase for this transponder.

DPD and DoubleTalk® Carrier-in-Carrier®

DPD cannot be used with DoubleTalk Carrier-in-Carrier since this would involve transmitting two carriers simultaneously over the same transponder. DPD can only compensate for the nonlinear transponder in a single-carrier-per-transponder scenario.

DPD and Adaptive Coding and Modulation (ACM)

Local DPD can only operate in constant coding and modulation (CCM) mode because the modem’s receive port is used to receive predistortion feedback. Thus, since the distant-end modem cannot signal

Es/No readings back to the transmit modem, the ACM system does not have the information it needs to select the best modulation and coding combination.

Remote DPD is fully compatible with both ACM and CCM.

DPD and Automatic Uplink Power Control (AUPC)
DPD is fully compatible with AUPC.

DPD Latency
DPD has no measureable effect on signal latency.

Summary
Comtech EF Data's DPD can provide significant savings in operational expenses and/or enhanced performance.

The following should be considered when evaluating DPD:
- DPD can only be used in single-channel-per-transponder links.
- DPD can be trained in two different approaches, local or remote, for which each has unique specifications and operational restrictions.
- The maximum savings is generally achieved when the output backoff of the transponder is optimized when DPD is engaged.

For additional information, please contact us.

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