New Forward Error Correction and Modulation Technologies

Low Density Parity Check (LDPC) Coding and 8-QAM Modulation in the CDM-600 Satellite Modem

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Revision 4 – January 25, 2005

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Introduction

In the past few years there has been an unprecedented resurgence in interest in Forward Error Correction (FEC) technology. The start of this new interest has its origins in the work done by Claude Berrou *et al*, and the landmark paper in 1993 - *Near Shannon Limit Error Correcting Coding and Decoding - Turbo Codes*. FEC is considered an essential component in all wireless and satellite communications in order to reduce the power and bandwidth requirements for reliable data transmission.

Claude Shannon, considered by many to be the father of modern communications theory, first established, in his 1948 paper *A Mathematical Theory of Communication*, the concept of Channel Capacity. This places an absolute limit on how fast it is possible to transmit error-free data within a channel of a given bandwidth, and with given noise conditions within that channel. He concluded that it would only be possible to approach this limit through the use of source encoding - what is familiar today as Forward Error Correction. He postulated that if it were possible to store every possible message in the receiver, finding the stored message that most closely matched the incoming message would yield an optimum decoding method. However, for all but the shortest bit sequences, the memory required for this, and the time taken to perform the comparisons, makes this approach impractical. For all practical purposes, the memory requirement and the decoding latency become infinite.

For many years there were few advances in the quest to approach the Shannon Limit. The Viterbi algorithm heralded a major step forward, followed in the early 1990s by the concatenation of a Viterbi decoder with Reed-Solomon hard-decision block codes. However, it remained clear that the Shannon Limit was still an elusive target. Berrou's work on Turbo Codes showed, through the use of an ingeniously simple approach (multiple, or *iterative* decoding passes) that it is possible to achieve performance close to the Shannon Limit. Berrou's early work dealt exclusively with iteratively-decoded convolutional codes (Turbo Convolutional Coding, or TCC), but in time the iterative approach was applied to a particular class of block codes called Product Codes - hence Turbo Product Coding (TPC). TPC exhibits inherently low decoding latency compared with TCC, and so is considered much more desirable for 2-way, interactive satellite communications applications.

In August 1999, Comtech became the first company in the world to offer, on a commercial basis, satellite modems that incorporate TPC. Since its inception, Comtech has continued to develop and refine its implementation of TPC in its products, and now offers a comprehensive range of code rates (from Rate 5/16 to Rate 0.95) and modulations (from BPSK to 16-QAM). However, in the past few years, as part of the general interest in Turbo coding, a third class of Turbo coding has emerged, namely Low Density Parity Check Codes (LDPC). It is more like TPC than TCC, in that it is an iteratively-decoded block code. Gallager first suggested this in 1962, but at the time, the implementation complexity was considered to be too great, and for decades it remained of purely academic interest. Now, however, with silicon gates being cheap, plentiful and fast, an LDPC decoder can easily be accommodated in a large Field Programmable Gate Array (FPGA) device. Further interest in LDPC was stimulated in 2003, when the Digital Video Broadcasting (DVB) committee adopted LDPC codes (proposed by Hughes Network Systems) as the basis for the new DVB-S2 standard.

The LDPC method on its own produces an undesirable 'flaring' in the Bit Error Rate (BER) *vs.* Eb/No characteristic, and for this reason it is desirable to concatenate a short BCH code with LDPC. This concatenation produces almost vertical BER *vs.* Eb/No curves, as can be seen in the performance graphs that are presented later.

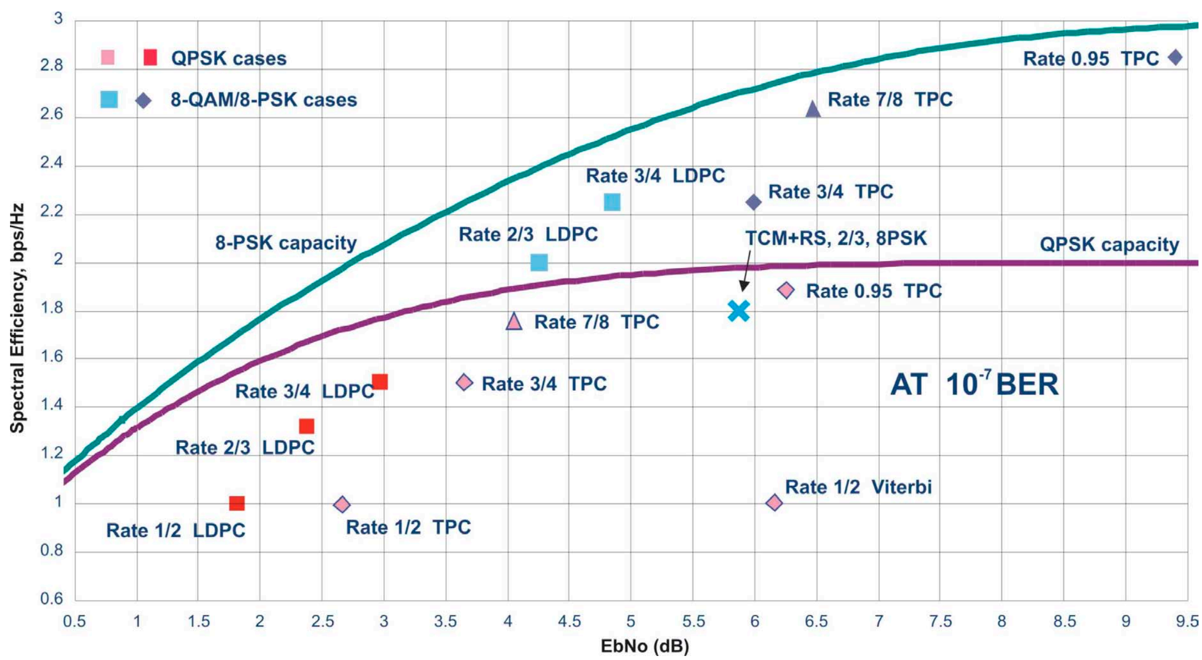
In order to take full advantage of the coding gain increase that LDPC provides, it became necessary to find an alternative to 8-PSK. Comtech EF Data has therefore developed an 8-QAM approach that permits acquisition and tracking at much lower values of Eb/No than 8-PSK. A discussion of this approach follows the presentation of the performance results for LDPC.

Comtech EF Data has chosen the CDM-600 platform as the first satellite modem in which to implement both LDPC and 8-QAM.

LDPC versus TPC

So, is LDPC better than TPC? The answer must be 'sometimes, but not always', and there are issues, such as latency, that must be taken into consideration. The graph shown below illustrates the performance of various TPC and LDPC modes relative to the Shannon Limit - the Channel Capacity is shown for both QPSK and 8-PSK. Error free transmission is not possible for values of spectral efficiency (capacity) *vs*. Eb/No above these limit curves. The horizontal distance to the limit provides a metric of overall performance.

It can be seen from this graph that for Code Rates above 3/4, Comtech's TPCs are very close (1 - 1.5 dB) from the Shannon Limit. However, at 3/4 and below, LDPCs are performing 0.7 - 1.2 dB better than TPCs.



It is clear that in order to provide the best possible performance over the range of code rates from 1/2 to 0.95, both an LDPC and a TPC codec need to be offered.

In order to meet this requirement, Comtech EF Data has developed a combination LDPC/TPC Codec module that can be added to the CDM-600 Modem, and which provides the following operating modes:

TPC Modes - completely compatible with the 2nd generation (High Rate) modes:
Rate 5/16, 21/44 BPSK
Rate 1/2, 3/4, 7/8, 0.95 QPSK/OQPSK
Rate 3/4, 7/8, 0.95 8-PSK
Rate 3/4, 7/8 16-QAM

LDPC Modes:
Rate 1/2 BPSK
Rate 1/2, 2/3, 3/4 QPSK/OQPSK
Rate 2/3, 3/4 8-PSK
Rate 2/3, 3/4 8-QAM
Rate 3/4 16-QAM

This new LDPC/TPC codec module may be installed in any existing CDM-600, as a simple field upgrade, or already installed in new modems ordered from the factory. It requires Firmware Version 1.6.1 (or higher) to be installed.

Please contact the Sales Department at Comtech EF Data for pricing and delivery information.

The table that follows compares all TPC and LDPC modes available in Comtech EF Data's CDM-600, and shows Eb/No performance and spectral efficiency (occupied bandwidth) for each case. This information will be of particular interest to satellite operators wishing to simultaneously balance transponder power and bandwidth. The large number of modes offered will permit, in the majority of cases, significant power and/or bandwidth savings when compared with existing schemes such as concatenated Viterbi/Reed-Solomon, or the popular 8-PSK/Trellis/Reed-Solomon (Intelsat IESS-310).

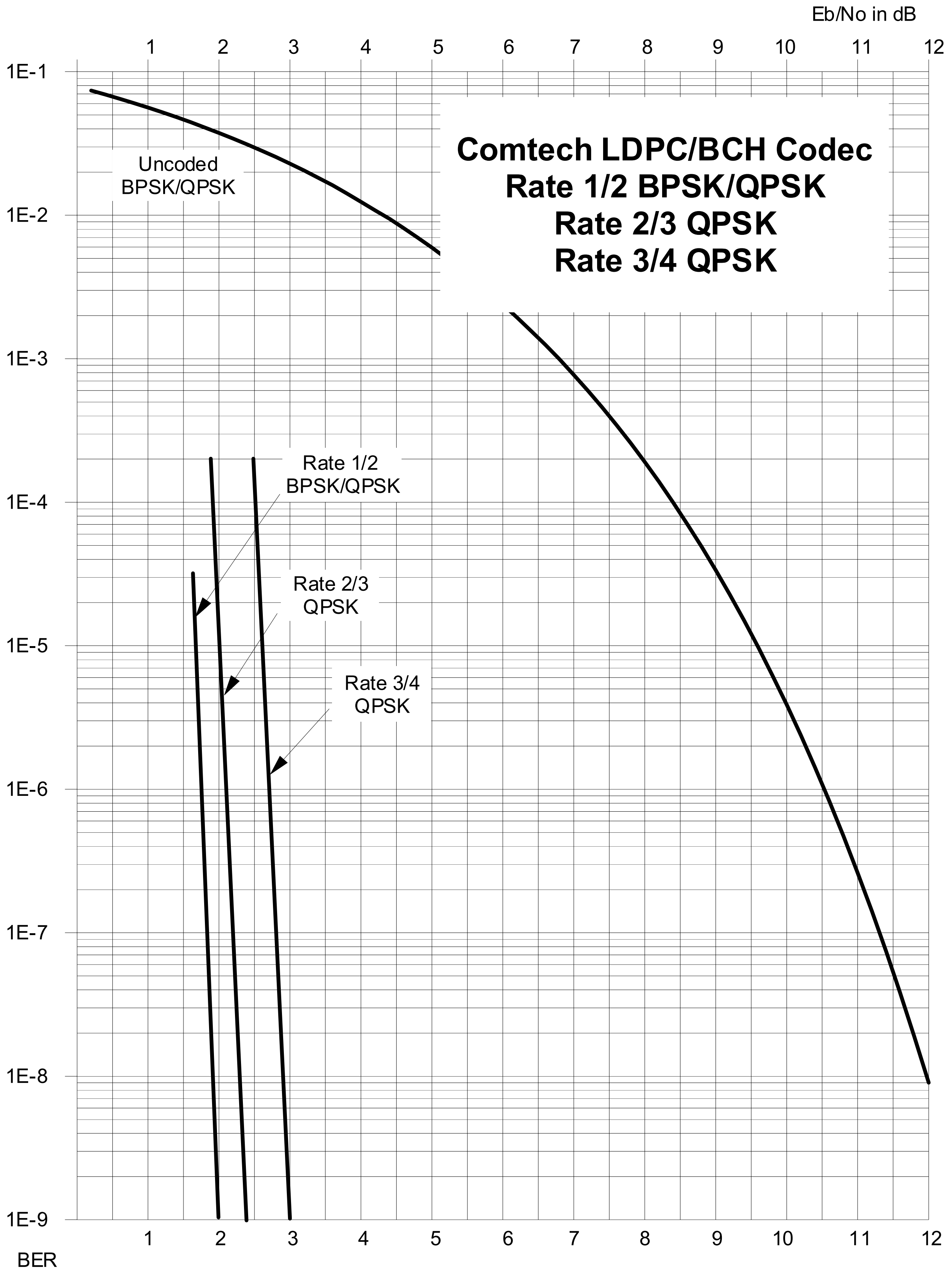
Following the Table, BER *vs.* Eb/No curves are shown for the new LDPC cases.

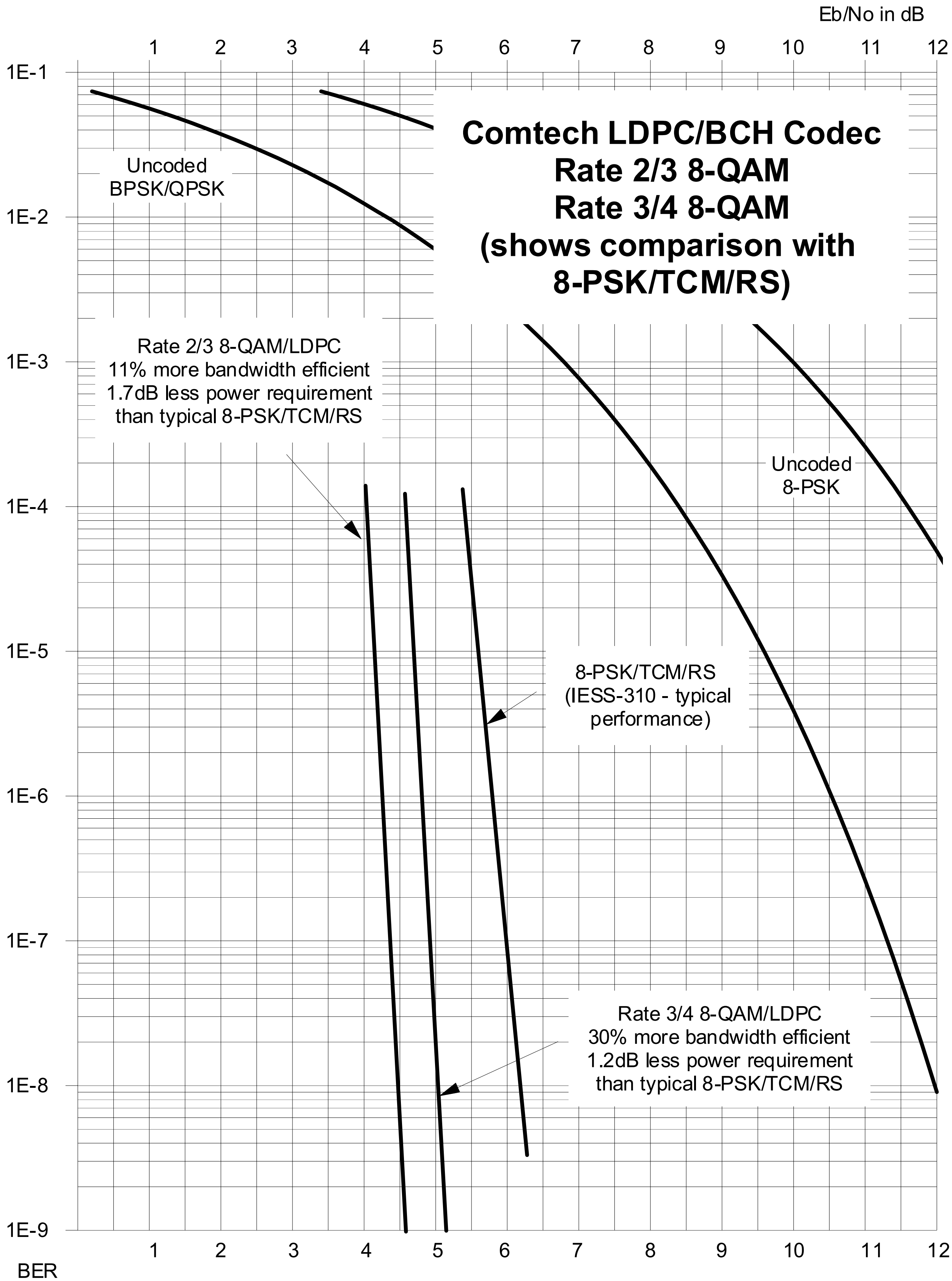
Comparison of all Comtech EF Data TPC and LDPC Modes
(CDM-600 with LDPC/TPC Codec and Firmware Version 1.6.1)

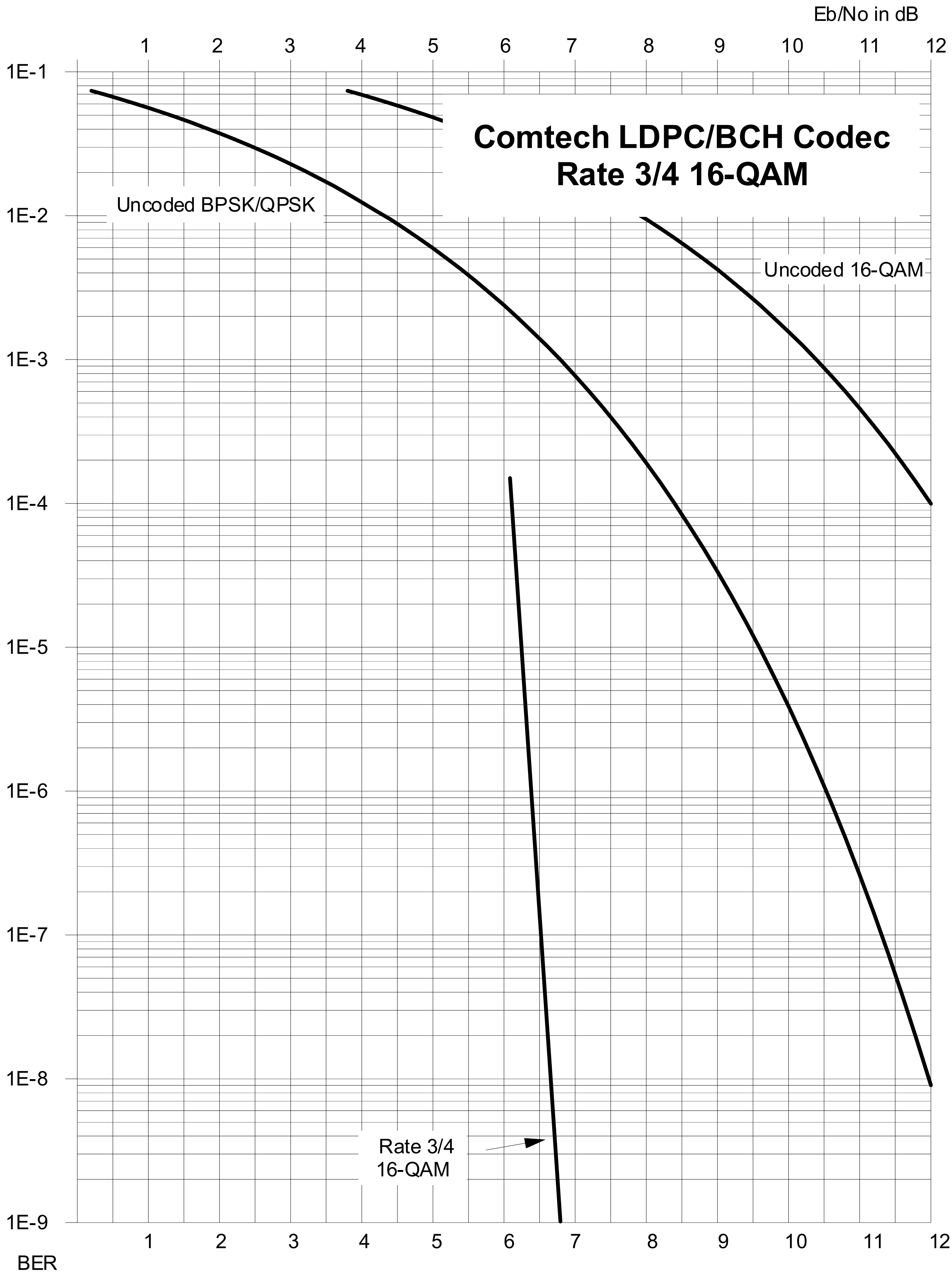
Mode	Eb/No at BER = 10^{-6} (typical)	Eb/No at BER = 10^{-8} (typical)	Spectral Efficiency (bps per Hertz)	Symbol Rate	Occupied * Bandwidth for 1 Mbps Carrier
*QPSK Rate 1/2 Viterbi **	5.5 dB	6.8 dB	1.00 bps/Hz	1.0 x bit rate	1190 kHz
BPSK Rate 1/2 LDPC	1.7 dB	1.9 dB	0.50 bps/Hz	2.0 x bit rate	2380 kHz
BPSK Rate 21/44 TPC	2.6 dB	2.9 dB	0.48 bps/Hz	2.1 x bit rate	2493 kHz
BPSK Rate 5/16 TPC	2.1 dB	2.4 dB	0.31 bps/Hz	3.2 x bit rate	3808 kHz
QPSK/OQPSK Rate 1/2 LDPC	1.7 dB	1.9 dB	1.00 bps/Hz	1.0 x bit rate	1190 kHz
QPSK/OQPSK Rate 1/2 TPC	2.6 dB	2.8 dB	0.96 bps/Hz	1.05 x bit rate	1246 kHz
QPSK/OQPSK Rate 2/3 LDPC	2.1 dB	2.3 dB	1.33 bps/Hz	0.75 x bit rate	892 kHz
QPSK/OQPSK Rate 3/4 LDPC	2.7 dB	2.9 dB	1.50 bps/Hz	0.67 x bit rate	793 kHz
QPSK/OQPSK Rate 3/4 TPC	3.3 dB	4.0 dB	1.50 bps/Hz	0.67 x bit rate	793 kHz
QPSK/OQSK Rate 7/8 TPC	4.0 dB	4.2 dB	1.75 bps/Hz	0.57 x bit rate	678 kHz
QPSK/OQPSK Rate 0.95 TPC	6.0 dB	6.5 dB	1.90 bps/Hz	0.53 x bit rate	626 kHz
*8-PSK Rate 2/3 TCM ** and RS (IESS-310)*	5.6 dB	6.2 dB	1.82 bps/Hz	0.56 x bit rate	666 kHz
8-QAM Rate 2/3 LDPC	4.3 dB	4.5 dB	2.00 bps/Hz	0.50 x bit rate	595 kHz
8-QAM Rate 3/4 LDPC	4.7 dB	5.0 dB	2.25 bps/Hz	0.44 x bit rate	529 kHz
8-PSK Rate 3/4 TPC	5.7 dB	6.3 dB	2.25 bps/Hz	0.44 x bit rate	529 kHz
8-PSK Rate 7/8 TPC	6.6 dB	6.8 dB	2.62 bps/Hz	0.38 x bit rate	453 kHz
8-PSK Rate 0.95 TPC	8.9 dB	9.9 dB	2.85 bps/Hz	0.35 x bit rate	377 kHz
16-QAM Rate 3/4 LDPC	6.4 dB	6.6 dB	3.00 bps/Hz	0.33 x bit rate	396 kHz
16-QAM Rate 3/4 TPC	7.0 dB	7.7 dB	3.00 bps/Hz	0.33 x bit rate	396 kHz
16-QAM Rate 7/8 TPC	7.7 dB	7.9 dB	3.50 bps/Hz	0.28 x bit rate	340 kHz
*16-QAM Rate 3/4 ** Viterbi/Reed-Solomon*	7.5 dB	8.0 dB	2.73 bps/Hz	0.37 x bit rate	435 kHz
*16-QAM Rate 7/8 ** Viterbi/Reed-Solomon*	9.0 dB	9.5 dB	3.18 bps/Hz	0.31 x bit rate	374 kHz

* The occupied bandwidth is defined at the width of the transmitted spectrum taken at the –10 dB points on the plot of power spectral density. This equates to 1.19 x symbol rate for the CDM-600 transmit filtering.

** Included for comparative purposes


Eb/No in dB
1
2
3
4
5
6
7
8
9
10
11
12
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
BER
Comtech LDPC/BCH Codec
Rate 1/2 BPSK/QPSK
Rate 2/3 QPSK
Rate 3/4 QPSK
Uncoded
BPSK/QPSK
Rate 1/2
BPSK/QPSK
Rate 2/3
QPSK
Rate 3/4
QPSK


Eb/No in dB
1 2 3 4 5 6 7 8 9 10 11 12
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
BER
Comtech LDPC/BCH Codec
Rate 2/3 8-QAM
Rate 3/4 8-QAM
(shows comparison with
8-PSK/TCM/RS)
Uncoded
BPSK/QPSK
Rate 2/3 8-QAM/LDPC
11% more bandwidth efficient
1.7dB less power requirement
than typical 8-PSK/TCM/RS
Uncoded
8-PSK
8-PSK/TCM/RS
(IESS-310 - typical
performance)
Rate 3/4 8-QAM/LDPC
30% more bandwidth efficient
1.2dB less power requirement
than typical 8-PSK/TCM/RS


Eb/No in dB
Comtech LDPC/BCH Codec
Rate 3/4 16-QAM
Uncoded BPSK/QPSK
Uncoded 16-QAM
Rate 3/4
16-QAM
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1 2 3 4 5 6 7 8 9 10 11 12
BER

End-to-End Processing Delay

It is an unfortunate fact, but FEC methods that provide increased coding gain inevitably do so at the expense of increased processing delay (latency). The closer to the Shannon Limit that a code approaches, the higher the decoding delay. In many applications, IP transport being a prime example, latency is a significant issue.

As with TPC, the coding gain achievable with LDPC is a direct function of the block size used for the encoding process. In all the TPC modes employed in the CDM-600, a 4 kbit block size is used, with the exception of the Rate 7/8 case, which uses a 16 kbit block. This leads to an end-to-end latency of approximately 120 ms at a data rate of 128 kbps.

All of the LDPC modes also use a 16 kbit block size, and as a consequence, end-to-end latency will be broadly comparable to the Rate 7/8 TPC case. Comtech EF Data is continuing to investigate methods for reducing latency to the theoretical minimum possible.

The new challenges of LDPC

It can be seen from the performance graphs that LDPC is capable of producing quasi-error-free performance at exceptionally low values of Eb/No. This now starts to push the limits of demodulator performance - in order to take advantage of the improved coding gain of LDPCs, the demodulator must now acquire and track signals in noise conditions that are extremely challenging for the modem designer. While it is possible to produce acceptable demodulator performance for BPSK, QPSK and 16-QAM, the 8-PSK case provides a particularly difficult challenge. When the DVB committee addressed the DVB-S2 specification, they recognized that, at the values of Eb/No that are dictated by LDPC performance, the gain of an 8-PSK phase detector is becoming vanishingly small, and hence a conventional approach becomes impractical. To overcome this, they included so-called *pilot symbols* to aid in the acquisition and tracking process. However, this complicates both the modulator and the demodulator design, and as a result, Comtech EF Data looked for an alternative approach. 8-QAM provided the answer.

8-QAM

What is 8-QAM, and why is it important? Unlike 8-PSK, which comprises 8 equally-spaced constellation points around a unit-circle, 8-QAM is comprised of exactly half of a 16-QAM signal. Fortuitously, the 8-QAM constellation possesses some unique properties that can be exploited to permit acquisition and tracking of signals at noise levels 2 - 3 dB worse than is possible with 8-PSK. This is, then, a perfect match for the expected Eb/No values that LDPC demands. Naturally, it has exactly the same spectral efficiency as 8-PSK.

While the 8-QAM constellation itself is not new, Comtech has performed much original work related to the choice of optimum mapping and soft decision decoding, and, of course, on the techniques for acquiring and tracking 8-QAM signals. This work is the subject of a pending patent application filed by Comtech EF Data.

The basic performance of uncoded 8-QAM is inherently better than uncoded 8-PSK (by a few tenths of a dB), but has a slightly higher peak-to-average power ratio than 8-PSK. In most linear transponders, this should not be considered a problem.

Our practical experience of combining 8-QAM with LDPC has shown exceptionally robust performance - the demodulator threshold is comfortably below the level where the LDPC codec performance fails. For many years, the 8-PSK/Trellis/Reed-Solomon approach has been considered the standard to beat. Now, for the first time, performance is possible that is superior in both power and bandwidth utilization.

Conclusion

The attached table and graphs of Eb/No *vs.* BER indicate the extraordinary level of performance that is possible with both TPC and LDPC. With the wide choice of codes, modulation formats and code rates available, Comtech EF Data believes that it is now possible, using a single modem platform, to choose a modulation/code/code rate combination that will simultaneously optimize power and bandwidth for any given transponder. This powerful technology will afford satellite operators the opportunity to maximize both throughput and revenues.

Comtech EF Data has carried out a large number of link budget analyses to determine the cost savings of TPC, LDPC and 8-QAM. Compared with the already powerful Rate 7/8 TPC case, there are LDPC modes that offer 10% total cost savings in transponder costs. However, more impressively, when compared with 8-PSK/Trellis/Reed-Solomon, the cost savings achievable are around 18%. For more details on the link budget analyses that have yielded these extraordinary figures, please contact:

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