The Case for Turbo Product Coding in Satellite Communications

(Including performance results from Comtech EF Data's commercial Satellite Modems)

September 3, 2002 – ***updated and revised to reflect improved performance obtained with CDM-600 Firmware Version 1.1.5***

Introduction

In August 1999, Comtech became the first company in the world to offer, on a commercial basis, a satellite modem that incorporates Turbo Product Coding (TPC) for Forward Error Correction. This modem, the CDM-550T, and the newer, more capable CDM-600, represents an installed base of over 4,500 units in service on satellite links across the globe.

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). In September 2002, following work to optimize both demodulator performance and the soft-decision decoding algorithms used, Comtech EF Data is pleased to announce further performance improvements in most TPC modes, ranging from 0.3 to 0.8 dB.

TPC has shown itself to be both powerful and flexible, providing real benefits to satellite operators. On the one hand, its enhanced coding gain and bandwidth efficiency can reduce transponder costs significantly, or the technology can be applied to solve other problems, such as flux-density reduction from very small antennas. The latest TPC ‘engine’ used in Comtech EF Data’s TPC implementation permits data rate operation up to 20 Mbps in the present hardware, although rates up to 155 Mbps are now possible. Comtech EF Data now considers this to be a very mature technology, and after nearly three years of successful field experience, believes that a common standard for TPC would benefit the entire user community. It is our earnest belief that Turbo Coding will rapidly obsolete every other method of FEC in use today.

Background

Turbo Coding is an FEC technique developed within the last few years, which delivers significant performance improvements compared to more traditional techniques. For the first time since Forward Error Correction was first conceived it is now possible to approach the Shannon bound – the Holy Grail of communications engineering. Unlike the popular method of concatenating a Reed Solomon codec with a primary FEC codec, Turbo Coding is an entirely stand-alone method. Depending on the exact type of Turbo Coding employed, the complex interleaving/de-interleaving of the RS approach may be avoided, and consequently, decoding delays may be significantly reduced.

Two general classes of Turbo Codes have been developed, Turbo Convolutional Codes (TCC), and Turbo Product Codes (TPC, a block coding technique). TCCs were first proposed in the early 90’s by Claude Berrou, working at France Telecom. The term ‘Turbo’ was coined by the French, and has given many the impression that it is merely a marketing term. ‘Turbo’ refers to a general class of decoding algorithms that employ multiple (iterative) decoding passes to achieve the best possible error correction performance.

A Turbo Product Code is a 2 or 3 dimensional array of small block codes (which can be Hamming codes, parity codes, or a mixture). For increased performance, an additional ‘hyper-axis’ may be added to produce an *enhanced TPC* (eTPC). Encoding is relatively straightforward, but decoding is a very complex process requiring multiple iterations of processing for maximum performance to be achieved. TCC has potentially better coding gain (0.5 - 1 dB) than Turbo Product Coding (TPC) but suffers from an ‘irreducible error floor' It may produce output errors even with error-free data into the decoder. TCC's use of an interleaver/de-interleaver also increases delay significantly. There are, at present, no stand-alone ASIC solutions for TCC, and there are licensing issues with France Telecom.

TPC does not have the 'error floor' problem, and silicon TPC 'engines' are commercially available. Comtech uses two devices made by **Comtech AHA** (Pullman, Washington), the AHA4501 and the newer AHA4540 Astro. (For the past decade Comtech AHA Reed-Solomon devices have been employed in the vast majority of Open Network modems sold throughout the world.)

'Soft knee' characteristic of Turbo Product Coding

The traditional concatenated RS schemes exhibit a very pronounced threshold effect – a small reduction in Eb/No can result in total loss of demod and decoder synchronization. Comtech's TPC modes do not suffer from this problem – the demod and decoder remain synchronized down to the point where the output error rate becomes unusable. This is considered to be a particularly advantageous characteristic in a fading environment. Typically, the demod and decoder can remain synchronized *2 – 3 dB below* the Viterbi/Reed-Solomon or TCM cases.

End-to-End Processing Delay

In many cases, FEC methods that provide increased coding gain do so at the expense of increased processing delay. However, with Rate 3/4 and Rate 0.95 TPC, this increase in delay is very modest. Rate 7/8 TPC, due to the longer block size used, exhibits higher latency. The table below shows the processing delays for the major FEC types, including the TPC modes:

FEC Mode (64 kbps data rate)	End-to-end delay, ms
Viterbi, Rate 1/2	12
Sequential, Rate 1/2	74
Viterbi Rate 1/2 + Reed Solomon (interleaver depth = 4)	266
Sequential Rate 1/2 + Reed Solomon (interleaver depth = 8)	522
Turbo Product Coding, Rate 3/4 QPSK, OQPSK, 8-PSK, 16-QAM	48
Turbo Product Coding, Rate 0.95 QPSK, OQPSK, 8-PSK	69
Turbo Product Coding, Rate 7/8 QPSK, OQPSK, 8-PSK, 16-QAM	245
Turbo Product Coding, Rate 21/44, BPSK	42
Turbo Product Coding, Rate 5/16, BPSK	70

Note: To a first approximation the delay is inversely proportional to data rate. So, for example, at 128 kbps, the delay values would be half of those shown above.

Comparison of all Comtech EF Data TPC Modes
(CDM-600 with High Rate Turbo and Firmware Version 1.1.5)

Mode	Eb/No at BER = 10^{-6} Guaranteed (Typical in parentheses)	Eb/No at BER = 10^{-8} Guaranteed (Typical in parentheses)	Spectral Efficiency (bits per second per Hertz)	Symbol Rate	Occupied * Bandwidth for 1 Mbps Carrier
*QPSK Rate 1/2 Viterbi **	6.0 dB (5.5 dB)	7.3 dB (6.8 dB)	1.00 bps/Hz	1.0 x bit rate	1190 kHz
BPSK Rate 21/44 Turbo	2.9 dB (2.6 dB)	3.3 dB (2.9 dB)	0.48 bps/Hz	2.1 x bit rate	2493 kHz
BPSK Rate 5/16 Turbo	2.4 dB (2.1 dB)	2.7 dB (2.4 dB)	0.31 bps/Hz	3.2 x bit rate	3808 kHz
QPSK/OQPSK Rate 1/2 Turbo	2.9 dB (2.6 dB)	3.2 dB (2.8 dB)	0.96 bps/Hz	1.05 x bit rate	1246 kHz
QPSK/OQPSK Rate 3/4 Turbo	3.8 dB (3.3 dB)	4.4 dB (4.0 dB)	1.50 bps/Hz	0.67 x bit rate	793 kHz
QPSK/OQSK Rate 7/8 Turbo	4.3 dB (4.0 dB)	4.5 dB (4.2 dB)	1.75 bps/Hz	0.57 x bit rate	678 kHz
QPSK/OQPSK Rate 0.95 Turbo	6.4 dB (6.0 dB)	6.9 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)*	6.5 dB (5.6 dB)	6.9 dB (6.0 dB)	1.82 bps/Hz	0.56 x bit rate	666 kHz
8-PSK Rate 3/4 Turbo	6.2 dB (5.7 dB)	6.8 dB (6.3 dB)	2.25 bps/Hz	0.44 x bit rate	529 kHz
8-PSK Rate 7/8 Turbo	7.0 dB (6.6 dB)	7.2 dB (6.8 dB)	2.62 bps/Hz	0.38 x bit rate	453 kHz
8-PSK Rate 0.95 Turbo	9.3 dB (8.9 dB)	10.3 dB (9.9 dB)	2.85 bps/Hz	0.35 x bit rate	377 kHz
16-QAM Rate 3/4 Turbo	7.4 dB (7.0 dB)	8.2 dB (7.7 dB)	3.00 bps/Hz	0.33 x bit rate	396 kHz
16-QAM Rate 7/8 Turbo	8.1 dB (7.7 dB)	8.3 dB (7.9 dB)	3.50 bps/Hz	0.28 x bit rate	340 kHz
*16-QAM Rate 3/4 ** Viterbi/Reed-Solomon*	8.1 dB (7.5 dB)	8.6 dB (8.0 dB)	2.73 bps/Hz	0.37 x bit rate	435 kHz
*16-QAM Rate 7/8 ** Viterbi/Reed-Solomon*	9.5 dB (9.0 dB)	10.1 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

Rate 3/4 Modes
The CDM-550T was first introduced in August 1999 with Rate 3/4 QPSK as the only option. Offset QPSK was added in July 2001. In November 2001 the CDM-600 was upgraded to include 16-QAM, and at that time, both 8-PSK and 16-QAM Rate 3/4 TPC modes were added.

Of particular interest is the 8-PSK Rate 3/4 TPC case. In terms of BER versus Eb/No performance it compares directly with the Intelsat IESS-310 case (8-PSK Rate 2/3 TCM with concatenated Reed-Solomon), but does so *using 20% less bandwidth*. The lack of a pronounced threshold effect and the much lower latency make it an even more attractive alternative to the IESS-310 mode.

(Rate 3/4 8-PSK TPC performance improved by approximately 0.6 dB, and Rate 3/4 16-QAM TPC performance improved by approximately 0.3 dB in September 2002 – requires Firmware Version 1.1.5 or higher)

Rate 7/8 modes
These modes were added to the CDM-600 in April 2002, and cover QPSK, OQPSK, 8-PSK and 16-QAM. This became possible with the introduction of Advanced Hardware Architectures' AHA4540 Astro chip, which provides much more flexibility in choice of code rates, and permits data rates as high as 155 Mbps. As can be seen from the tables and graphs, its performance is very close to that of the Rate 3/4 case. This remarkable coding gain performance is achieved, however, through the use of a larger coding block. This results in higher latency, but for many higher data rate applications this will not be considered an issue.

(Rate 7/8 8-PSK and 16-QAM TPC performance improved by approximately 0.3 dB in September 2002 – requires Firmware Version 1.1.5 or higher)

Rate 0.95 modes
As in the case of the Rate 7/8 modes these were added to the CDM-600 in April 2002, and cover QPSK, OQPSK and 8-PSK. This rate uses the *enhanced* TPC (**eTPC**) mode. The new Rate 0.95 mode is remarkable because it adds only 5% FEC overhead, but has coding gain equal to Rate 1/2 Viterbi (at a BER of 1×10^{-7}). Unlike the Rate 7/8 case, short block sizes are used, so there is no additional delay penalty.

When comparing TPC with 8-PSK/TCM/RS, the reader's attention is directed to the case of Rate 0.95 QPSK. It can be seen that the spectral efficiency of Rate 0.95 QPSK is slightly better (1.9 bps/Hz, versus 1.82 bps/Hz), with essentially the same BER vs. Eb/No performance. Given that QPSK is inherently far more robust than 8-PSK, the Rate 0.95 QPSK TPC mode is evidently a far better choice than 8-PSK/TCM/RS.

(Rate 0.95 QPSK TPC performance improved by approximately 0.4 dB, and Rate 0.95 8-PSK TPC performance improved by approximately 0.8 dB in September 2002 – requires Firmware Version 1.1.5 or higher)

BPSK Rate 21/44 and Rate 5/16 *(Flux density reduction modes)*
Two further code rates - Rate 21/44 BPSK (very close to Rate 1/2) and Rate 5/16 BPSK (very close to Rate 1/3) were then added for a military customer and delivered in June 2000. These two rates were developed to address an entirely different case, namely that of transmission from very small antennas, with limited transmitter power. For a dish

antenna, the gain is directly proportional to its area, and the lower the gain, the less directional the antenna becomes. Thus, in satellite transmission, even though the dish may be perfectly pointed at the desired satellite, if the beamwidth is wide enough, adjacent satellites will also be illuminated. This is a potential source of interference, and for this reason the ITU (International Telecommunications Union) place strict limits on the power spectral density (also referred to as flux density) of signals arriving at adjacent satellites.

One obvious method to reduce the level is to spread the transmitted signal over as wide a bandwidth as possible. In the past, this has sometimes been achieved using Spread Spectrum modulation, but at the expense of demodulator complexity. However, by using BPSK modulation, and low FEC code rates (down to Rate 1/3, for example) the power spectral density may be reduced. Taking Rate 1/2 QPSK as a baseline, moving to Rate 5/16 BPSK Turbo Product Coding gives a reduction in power spectral density of 5 dB.

Furthermore, the increased coding gain of this FEC method allows a further reduction in transmitter power. Using Rate 1/2 Viterbi with concatenated Reed-Solomon as a baseline example, Rate 5/16 provides 1.5 - 2.0 dB improvement in coding gain. Putting these two factors together yields an overall reduction in power spectral density of approximately 7 dB. This simultaneously permits a smaller antenna, and reduced transmitter power. The disadvantage is the increased spectral occupancy of the carrier, and it will depend on the particular satellite operator to determine if this poses a severe economic problem.

There are significant technical challenges with this approach. When operating at these higher code rates (21/44 and 5/16), the demodulator is forced to operate in a region where the Ebt/No (also referred to as Es/No) is negative - in other words, there is more noise than signal. The demodulator must acquire and track in this environment, and the TPC decoder (which is block based) must acquire and track the frame unique word in the *uncorrected* error rate, which in the Rate 5/16 case can be as bad as 2×10^{-1}.

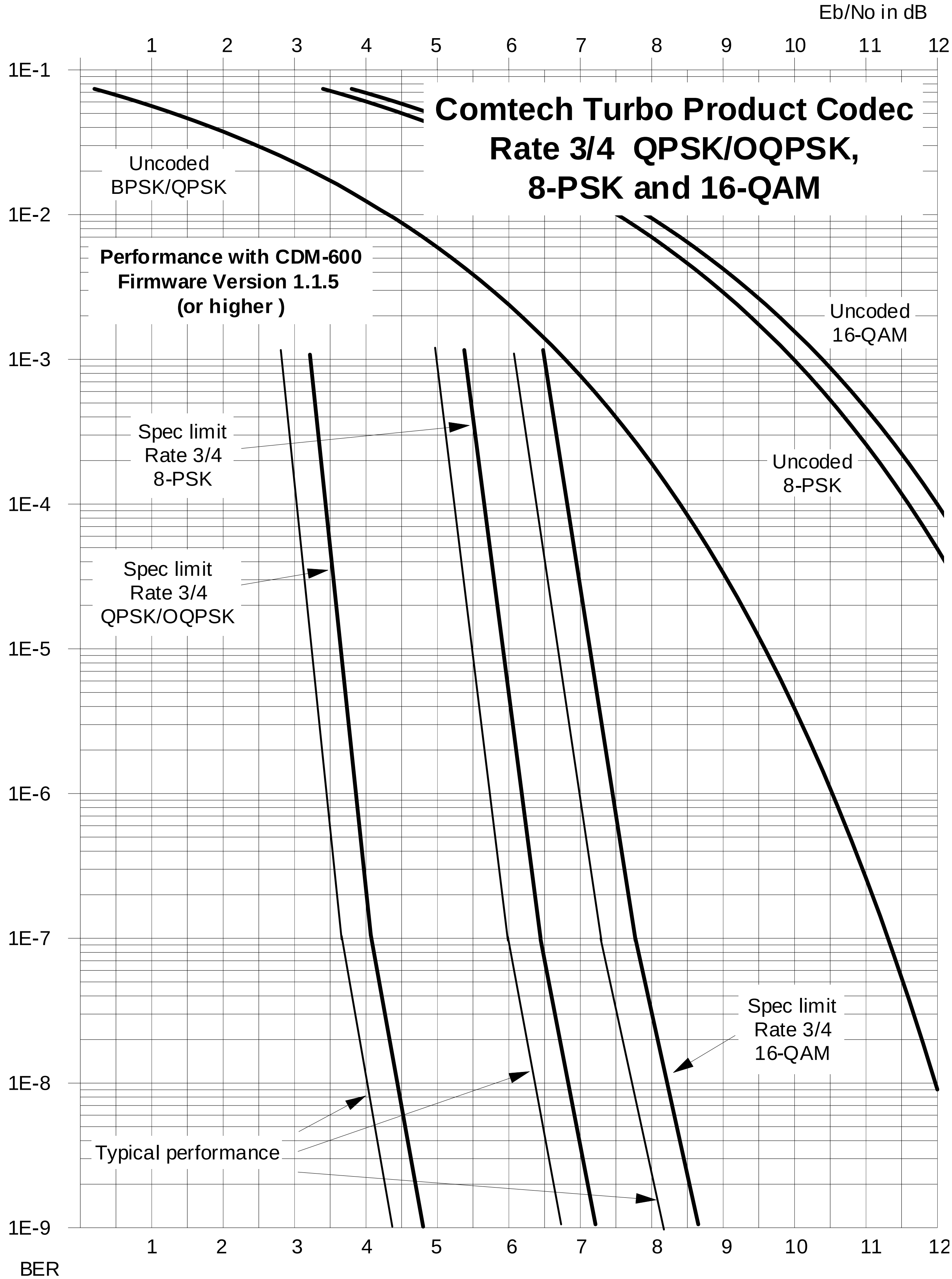
Rate 1/2 QPSK/OQPSK mode

This mode was added at the request of a Comtech customer, although we have misgivings about it usefulness. The increase in coding gain compared to either the Rate 3/4 or Rate 7/8 case is marginal, and at the expense of needless bandwidth expansion. A major disadvantage is that for a given Eb/No, this code rate reduces the Es/No (compared with Rate 3/4 or higher code rates). In QPSK mode, the demodulator is then required to operate correspondingly nearer its synchronization threshold, reducing its robustness in a fading environment.

(Rate 1/2 QPSK/OQPSK TPC performance improved by approximately 0.5 dB in September 2002 – requires Firmware Version 1.1.5 or higher)

Conclusion

The attached graphs of Eb/No versus BER indicate the extraordinary level of performance that is possible with TPC. With the wide choice of 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 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.


Eb/No in dB
1
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9
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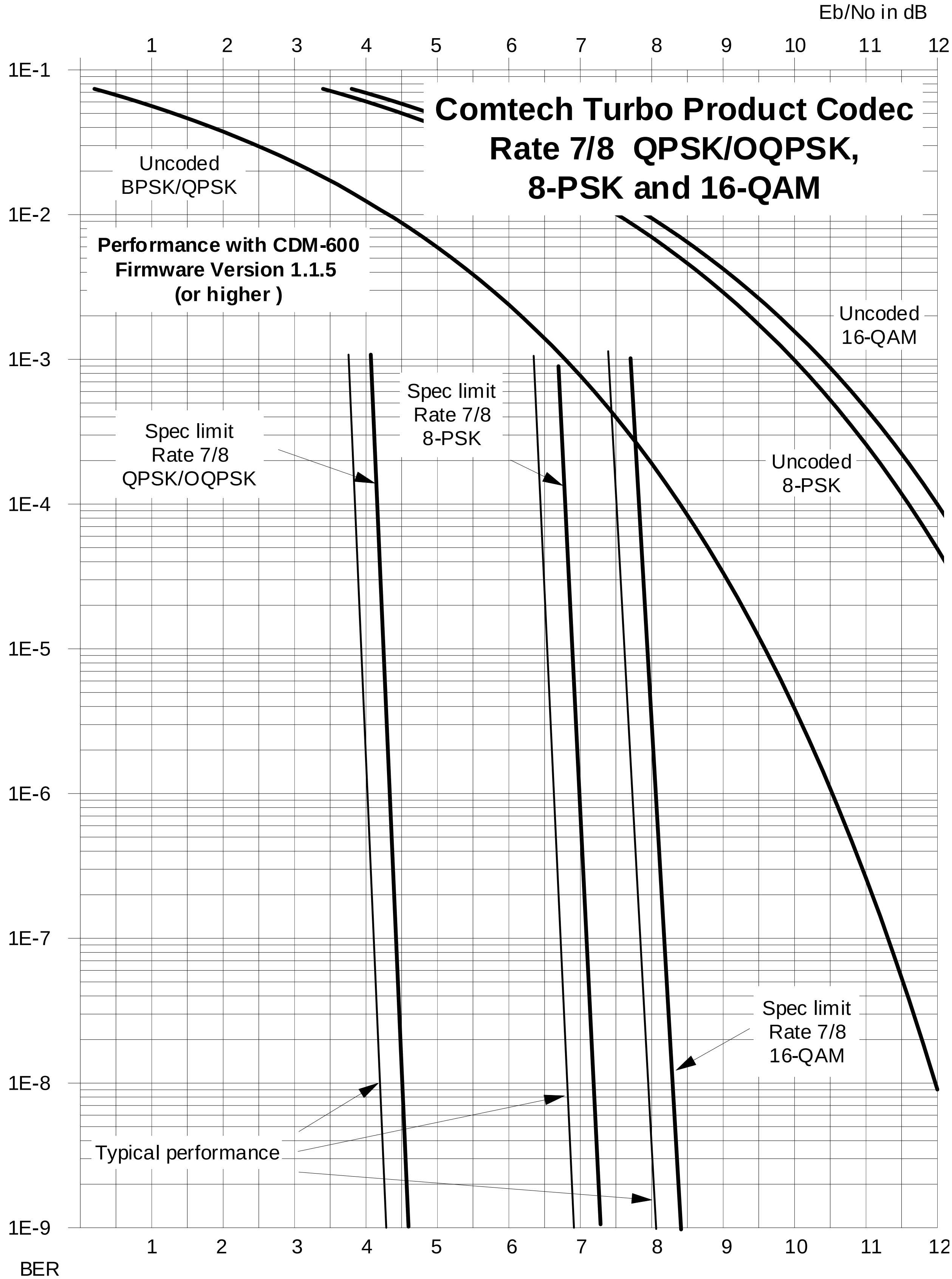
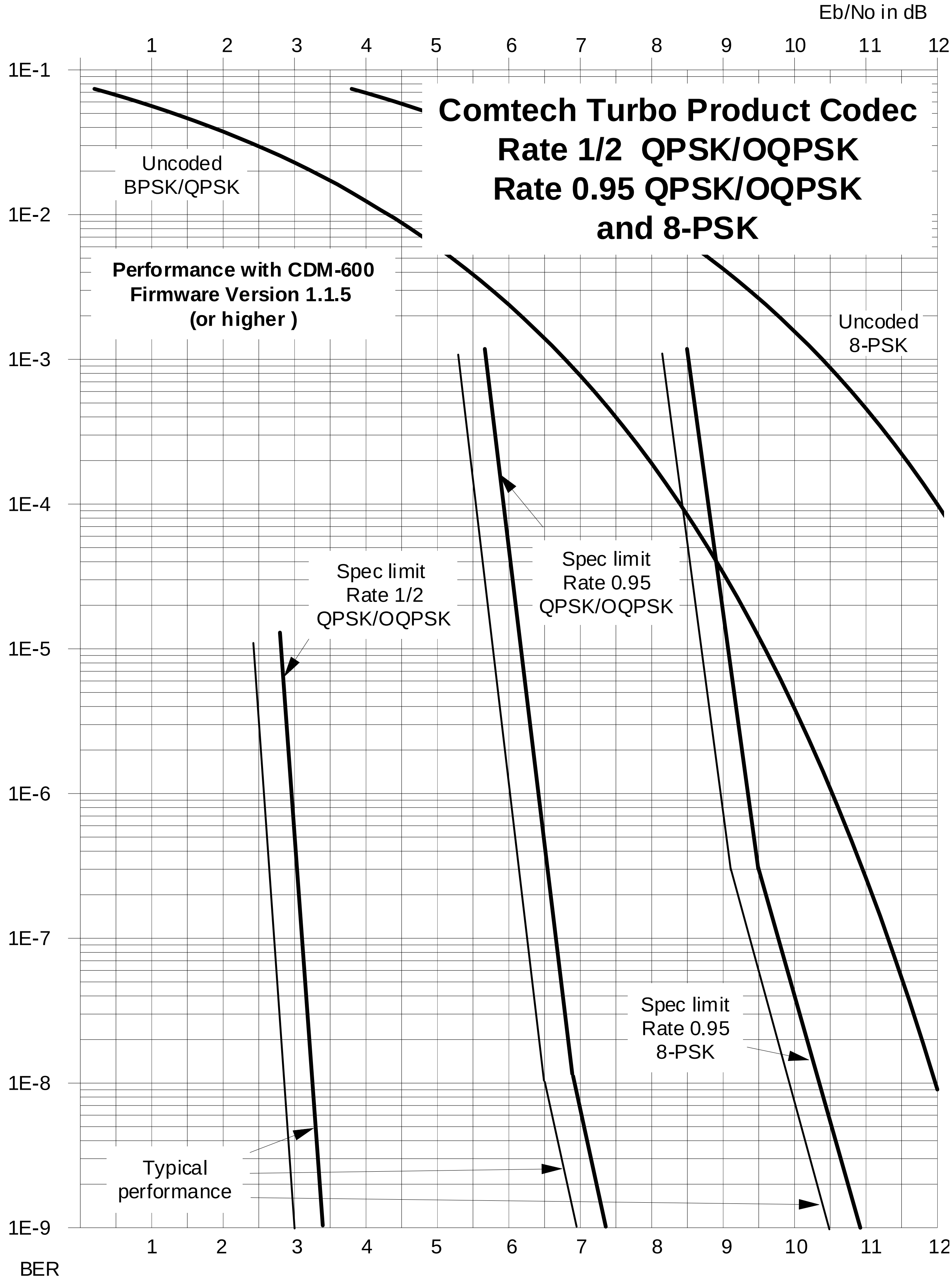
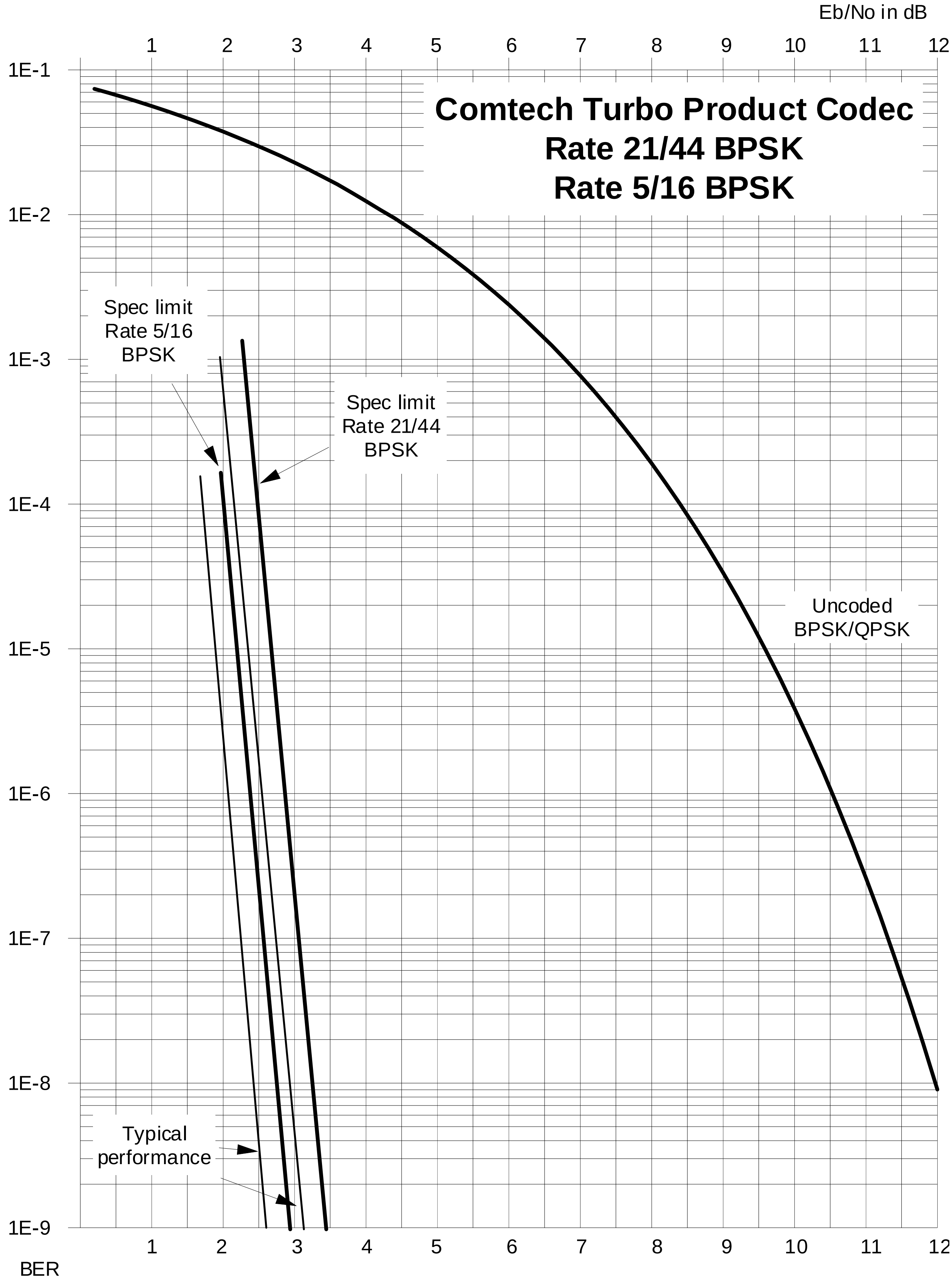
11
12
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
Comtech Turbo Product Codec
Rate 3/4 QPSK/OQPSK,
8-PSK and 16-QAM
Uncoded
BPSK/QPSK
Performance with CDM-600
Firmware Version 1.1.5
(or higher)
Uncoded
16-QAM
Uncoded
8-PSK
Spec limit
Rate 3/4
8-PSK
Spec limit
Rate 3/4
QPSK/OQPSK
Spec limit
Rate 3/4
16-QAM
Typical performance
BER


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 Turbo Product Codec
Rate 7/8 QPSK/OQPSK,
8-PSK and 16-QAM
Uncoded
BPSK/QPSK
Performance with CDM-600
Firmware Version 1.1.5
(or higher)
Uncoded
16-QAM
Spec limit
Rate 7/8
8-PSK
Spec limit
Rate 7/8
QPSK/OQPSK
Uncoded
8-PSK
Spec limit
Rate 7/8
16-QAM
Typical performance


Eb/No in dB
Comtech Turbo Product Codec
Rate 1/2 QPSK/OQPSK
Rate 0.95 QPSK/OQPSK
and 8-PSK
Performance with CDM-600
Firmware Version 1.1.5
(or higher)
Uncoded
BPSK/QPSK
Uncoded
8-PSK
Spec limit
Rate 1/2
QPSK/OQPSK
Spec limit
Rate 0.95
QPSK/OQPSK
Spec limit
Rate 0.95
8-PSK
Typical
performance
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


Eb/No in dB
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1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
Comtech Turbo Product Codec
Rate 21/44 BPSK
Rate 5/16 BPSK
Spec limit
Rate 5/16
BPSK
Spec limit
Rate 21/44
BPSK
Uncoded
BPSK/QPSK
Typical
performance
BER