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Re:	Call for Evaluations and Improvements, IEEE 802.16.1, Session #7.	
Abstract	This document tries to highlight some relevant performance issues of FEC schemes for both proposals.	
Purpose	To better evaluate proposals and amendments.	
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FEC alternatives for BWA Burst Communications

1. Introduction

This paper examines the performance of several concatenated channel coding schemes relevant for BWA applications specifically packet (burst) transmission. The following codes are considered:

(a) The inner code is a parity check code and the outer code is a Reed-Solomon (RS) code over $GF(2^8)$

(b) The inner code is punctured and unpunctured constraint length 7 convolutional code, which is the de-facto industry standard code; and the outer code is a Reed-Solomon (RS) code over $GF(2^8)$

(c) The inner code is a block code and the outer code is a Reed-Solomon (RS) code over $GF(2^8)$

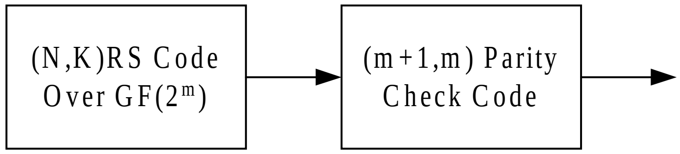
We examine (b) and (c) with and without the presence of an interleaver (option (a) does not require an interleaver). It is pointed out that while option (b) has very good performance with sufficient interleaving, option (c) has better performance for high rate coding with no interleaving.

Additionally, we briefly examine the use of Block Turbo Codes and point out their true practical performance, which indicates that they are not a highly attractive candidate for BWA.

In this paper we present coding gain results based on normalized coding rate. This means that we do not allow a code to benefit from a gain that results due to direct rate reduction. For example a rate 0.5 code which shows a C/N gain of 10 dB actually has only 7 dB coding gain due to the rate loss. It is very important to compare codes on the same basis for a fair comparison.

2. Performance of the Parity check + Reed Solomon

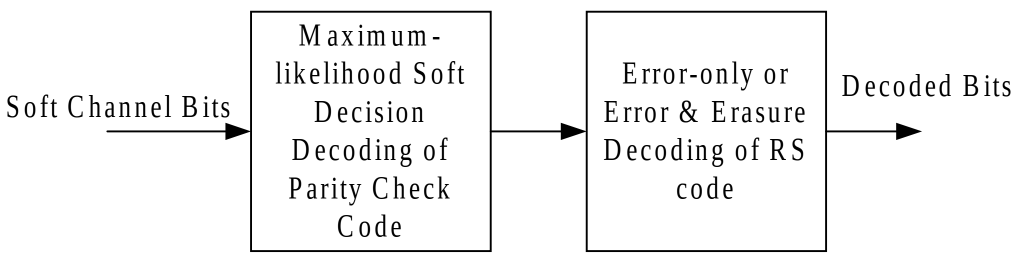
The block diagram for the encoder of this scheme is shown:



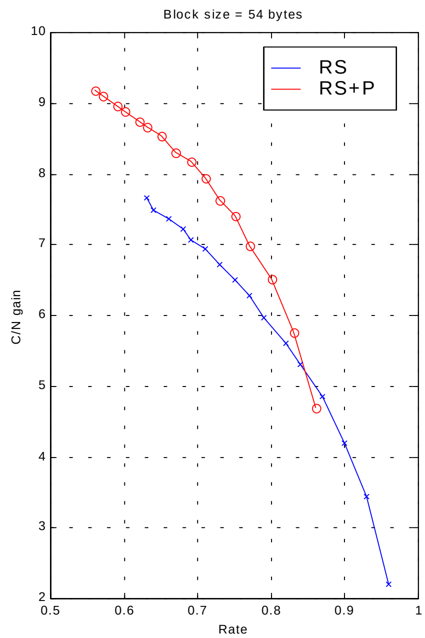
The outer code is (N, K) Reed-Solomon code over GF(2^m). The inner code is a (m+1,m) parity-check code. The minimum Hamming distance d_{min} of the inner code is 2. The overall code rate r is given by

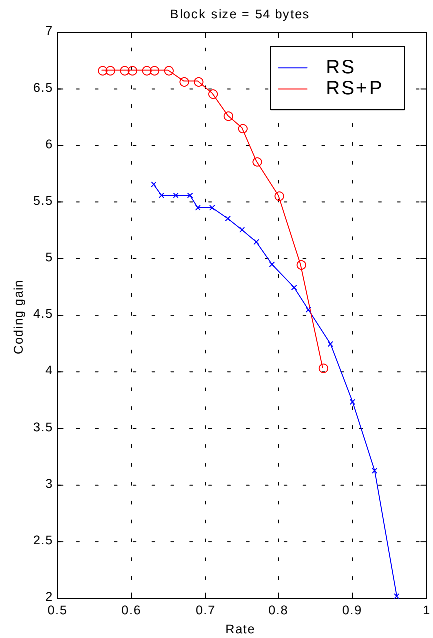
$$r = \frac{Km}{N(m+1)} = \frac{Km}{(K+R)(m+1)}$$

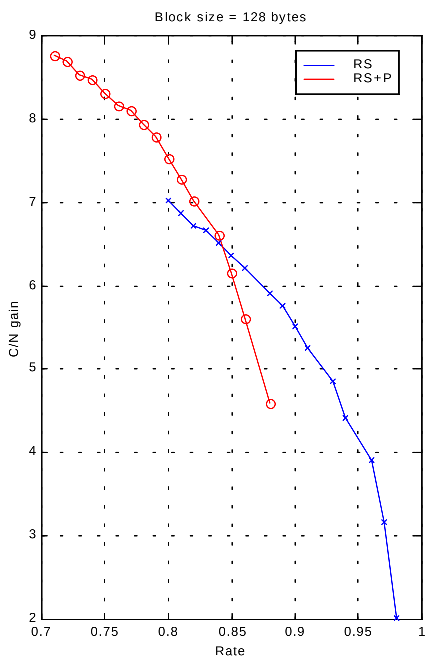
where R is the redundancy of the RS code. The following figure shows the decoder for this concatenated code.

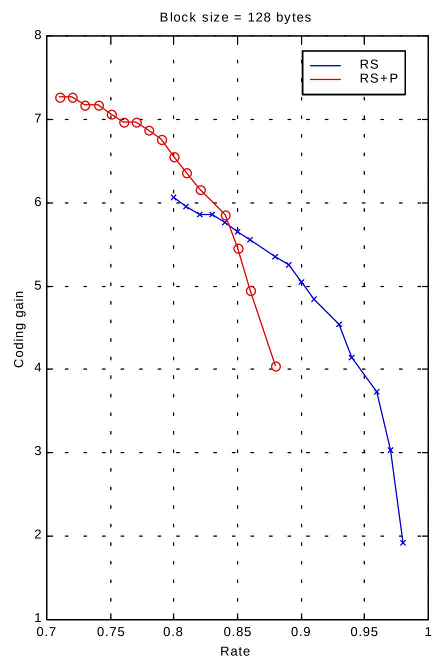


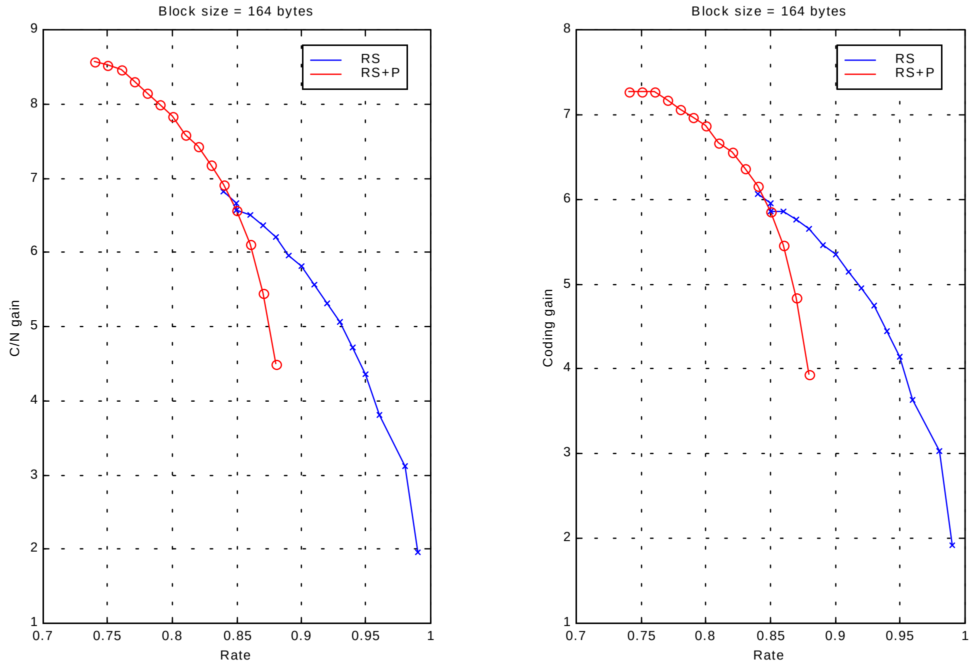
We consider the case where m=8. We examine the code performance compared to RS alone for various block lengths.


Block size = 54 bytes
RS
RS+P
C/N gain
Rate


Block size = 54 bytes
RS
RS+P
Coding gain
Rate


Block size = 128 bytes
RS
RS+P
C/N gain
Rate


Block size = 128 bytes
RS
RS+P
Coding gain
Rate



We provided results for both coding gain (rate normalized) and C/N gain (no normalization). The RS+Parity is applicable when the coding rate is chosen below 8/9 (the limit set by the parity code) and then it would usually perform better than RS alone. The advantage is more apparent for smaller blocks. For larger blocks the logic complexity of increasing the correction capabilities of the RS beyond t=16 is far greater than adding the parity soft decoding capability.

3. Performance of Concatenated Coding Scheme with Constraint Length 7 Inner Code

In order to compute the BER performance at the output of RS decoder with ideal interleaving, we need estimates of bit error rate and byte error rate at the output of the Viterbi decoder. These two numbers can easily be obtained from the simulation in reasonable amount of time. Let P_b and P_{byte} denote the bit and byte error probabilities at the output of Viterbi decoder. The RS decoder either corrects t or less number of byte errors or passes the code word unchanged when it contains more than t errors. The probability of misdecoding is quite small for reasonably high t (for example 8) and hence it can be ignored. Thus we can say that the bit error rate to the byte error rate ratio at the input and output of RS decoder is the same. Then the BER at the output of t-error correcting RS decoder for a message block length of M bytes with ideal interleaving are given by the following expression

$$(P_e)_{RS} = \frac{P_b}{P_{byte}} \frac{1}{N} \sum_{i=t+1}^{N} i \binom{N}{i} (P_{byte})^i (1 - P_{byte})^{N-i}$$

where N = M + 2t is the code word length.

The bit error rate P_b for a rate k/n convolutional code with soft decision Viterbi decoding is given by the following upper bound

$$P_b < \frac{1}{k} \sum_{d=d_{free}}^{\infty} \beta_d Q(\sqrt{2RdE_b / N_0})$$

where d_{free} is the free distance of the code, β_d is the total number of non-zero information bits on all weight d paths. These numbers are called distance spectrum of the code and can be obtained from the transfer function of the convolutional code. The distance spectrum of the constraint length 7 codes for various rates are tabulated in the literature [2]. The BER performance using the first five terms in the above summation is computed and plotted in figure 1. The BER from the simulation is also plotted. It is obvious that the simulation closely match the above bounds for all the rates.

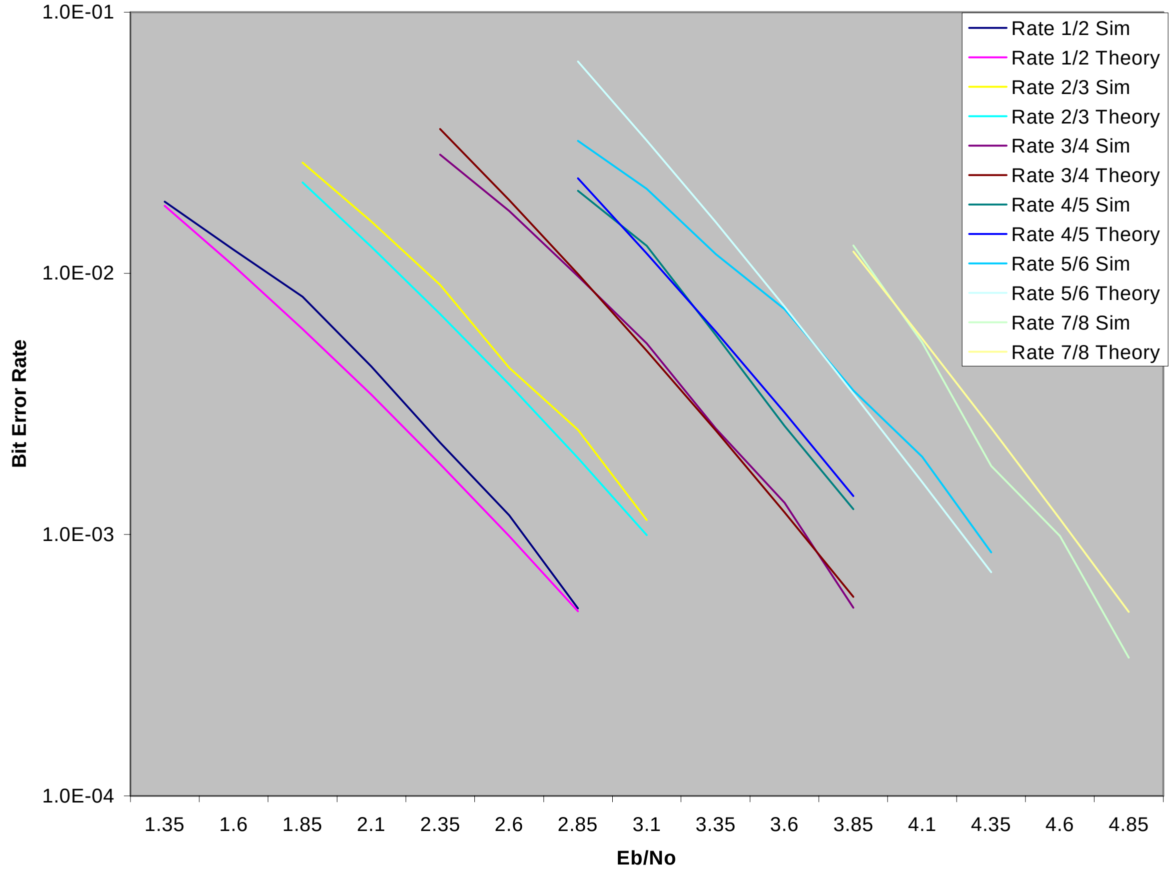


Figure 01. The BER Performance of Various Rates Constraint Length 7 Code

Next we obtain the performance of the concatenated code using different rate constraint length 7 convolutional codes as inner codes for a packet size of 53 bytes and t = 8 with and without interleaving. The BER curves are plotted in figure 2. Symbol “II” stands for ideal interleaving and symbol “NI” stands for No interleaving.

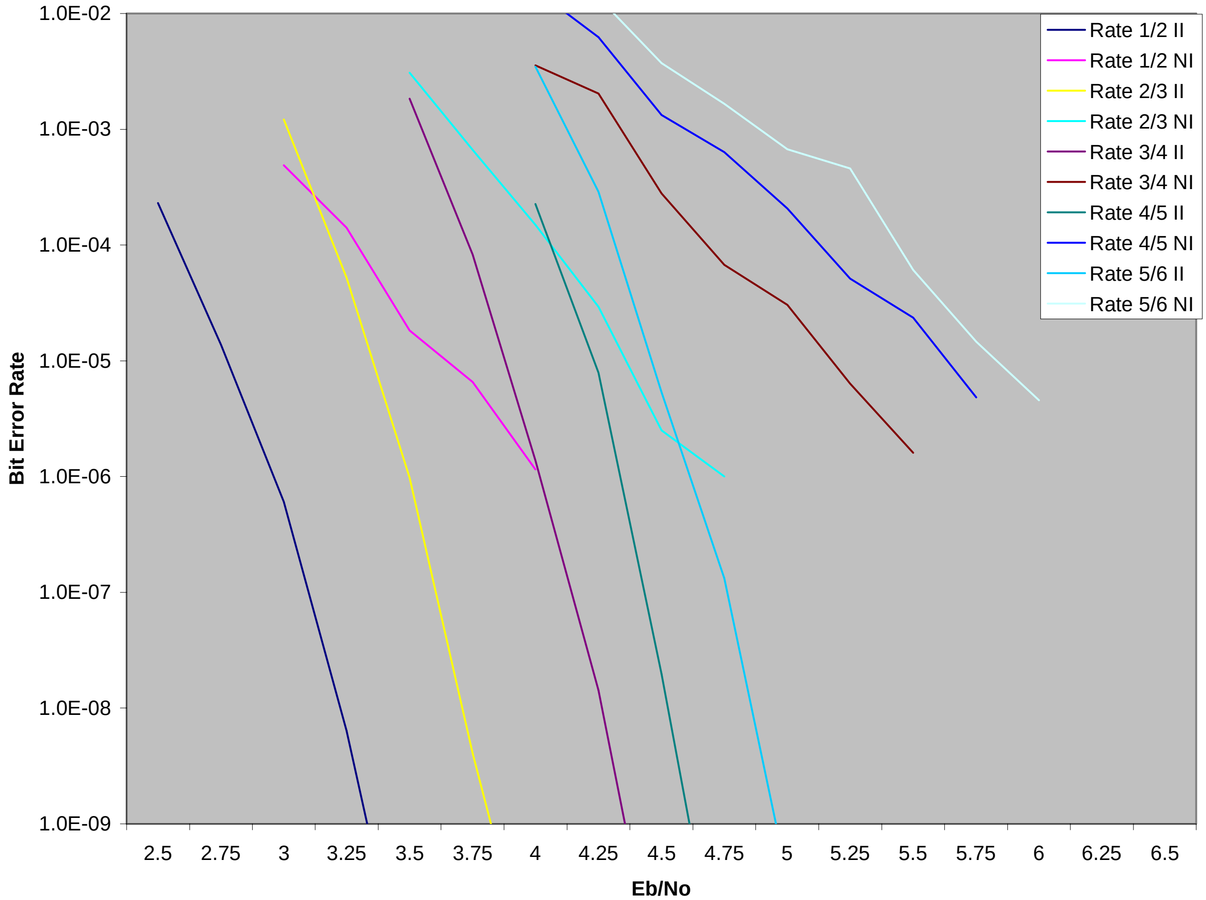


Figure 02. The Performance of Constraint Length 7 Convolutional/RS Concatenated Codes With and Without Interleaving

By extrapolating the curves obtained from the simulation, it can easily be concluded that the loss without interleaving is about 1.5 to 2.5 dB. Also note that higher is the code rate, bigger is the loss. Thus, the constraint length 7 code is quite powerful to be used as inner code, given the proper interleaving is used. Unfortunately, we cannot make the same claims if interleaving cannot be used. *For example, even a simple (9,8) parity code as an inner code outperforms the rate 5/6 code without interleaving in coding gain, coding efficiency, drastically reduced implementation complexity and decoding delay. The coding gain from rate 5/6 inner code without interleaving at output BER of* 10^{-9} *is only 5.75 dB, whereas the (9,8) parity code provides about 6.25 dB of coding gain. Even the rate 4/5 code performance is not as good as the parity code, since its coding gain at output BER of* 10^{-9} *is 6.10 dB.*

4. Another Concatenated Coding Scheme

We present a concatenated coding scheme which offers the same coding rate flexibility as the above code, has similar or better coding gain as the above code without interleaving, but offers following major advantages. The idea is to choose an inner code, which is a block code with a simple soft decoder and has the flexibility of rate choice. Such a code could be constructed for example from a weak convolutional code.

(a) This inner code has drastically reduced implementation complexity than the constraint length 7 code. In fact, the decoder for the inner code can be only slightly more complicated than the parity check decoder.

(b) The new inner code has much smaller decoding delay than the constraint length 7 code, making it ideal for packet data transmission.

(c) The same code can be used for both uplink and downlink channel without interleaving, thus providing same coding gain in both direction.

This scheme does not require interleaving yet up to 1 dB additional coding gain could be achived even with “weak” interleaving.

For the proposed concatenated coding scheme, the inner code message block is selected to be 32 bits. We will present the performance of this new concatenated scheme for various inner code rates and with 8 and 16-errors correcting RS codes over GF(2^8) as outer code. The performance of the new coding scheme is presented in figures 3 to 14, for inner codes (64,32), (48,32) and (40,32), M = 56 byte and M = 212 bytes packet sizes and t = 8 and 16. In all figures NI means No interleaving and II means Interleaving with depth 4.

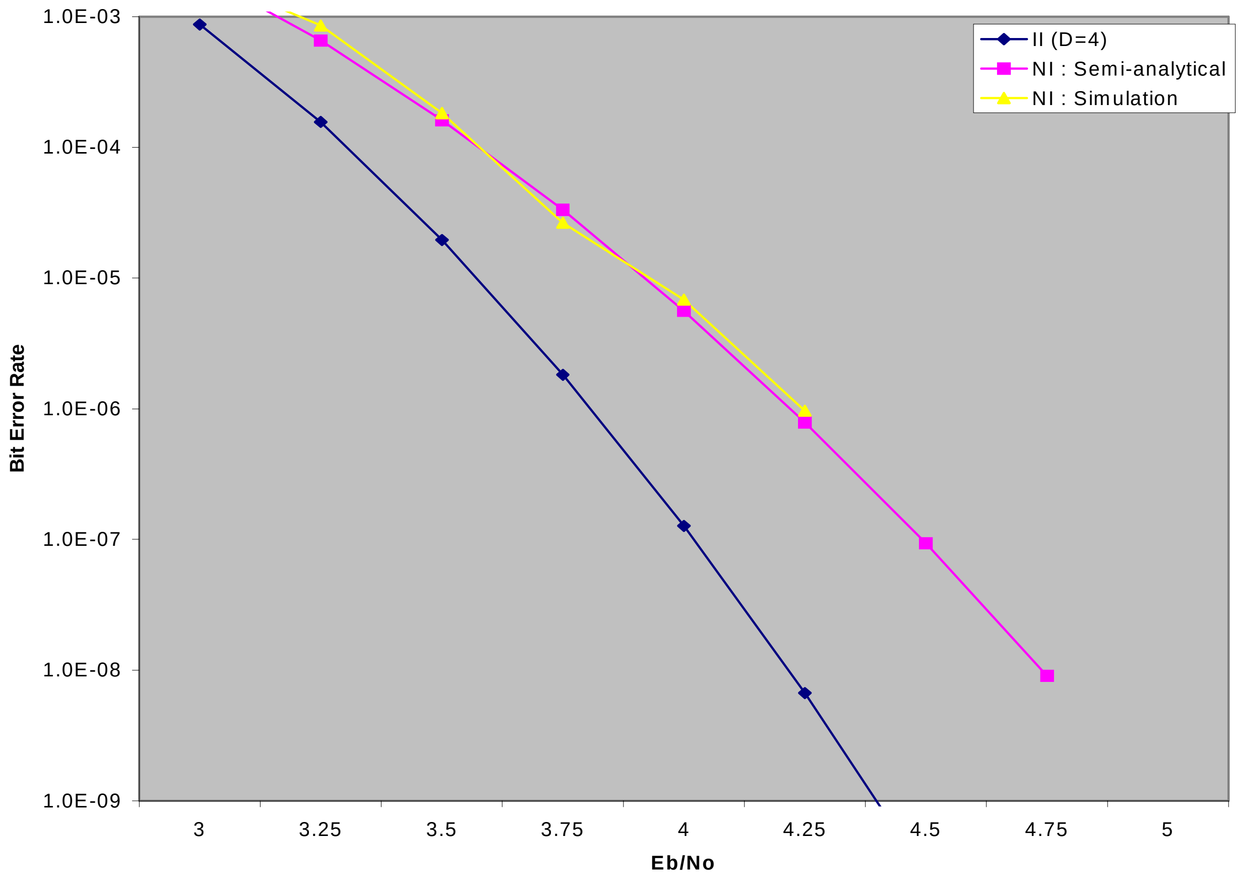


Figure 03. BER Performance : (64,32) with RS t = 8, M = 56

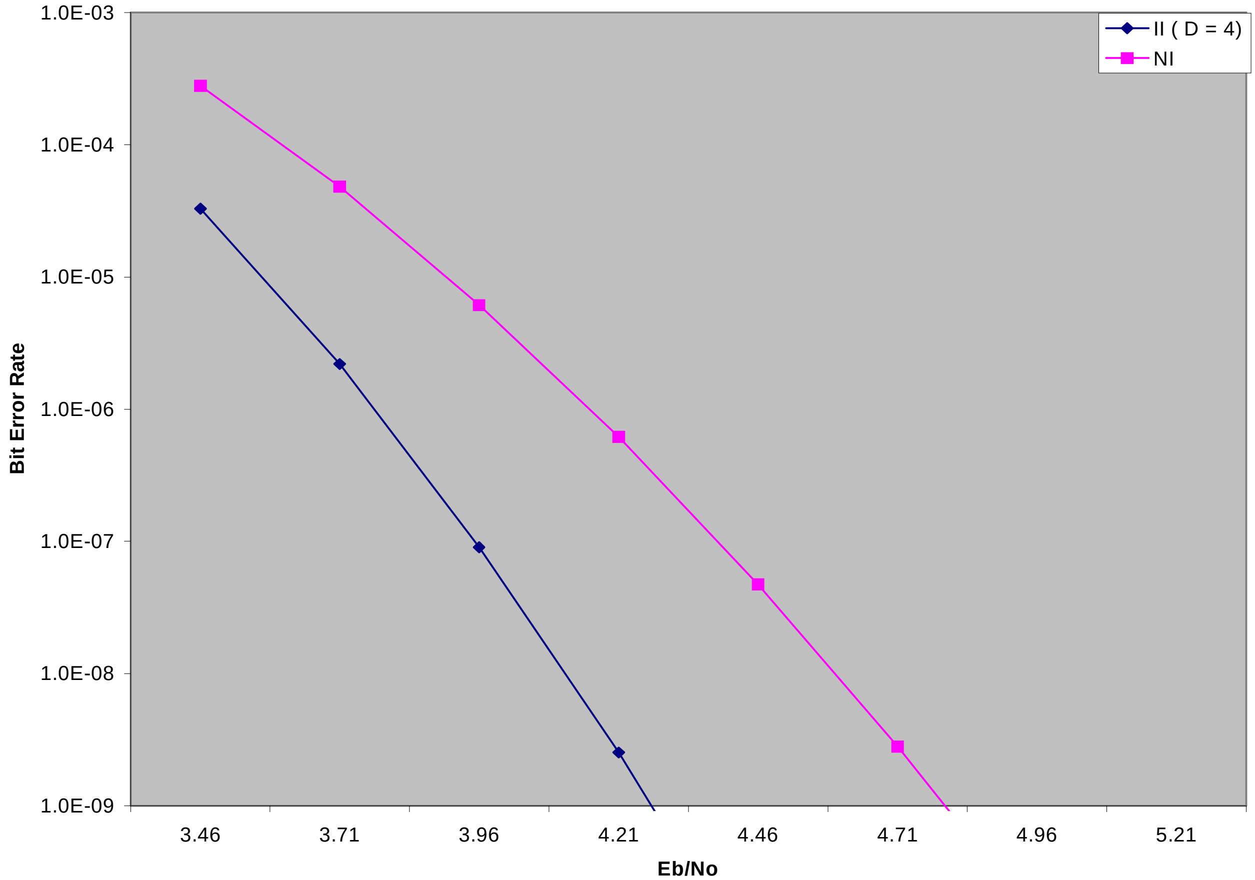


Figure 04. BER Performance : (64,32) with RS t = 16, M = 56

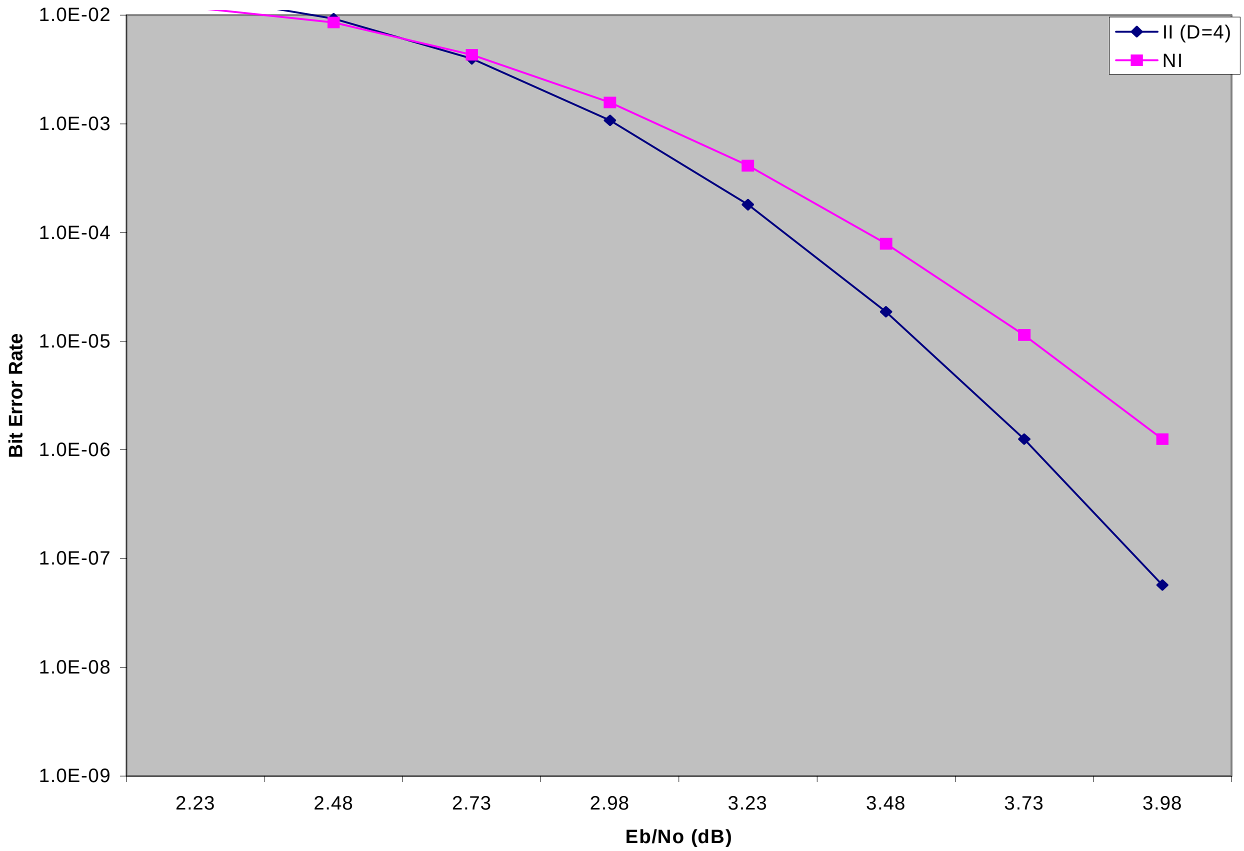


Figure 05. BER Performance : (64,32) with t = 8, M = 212

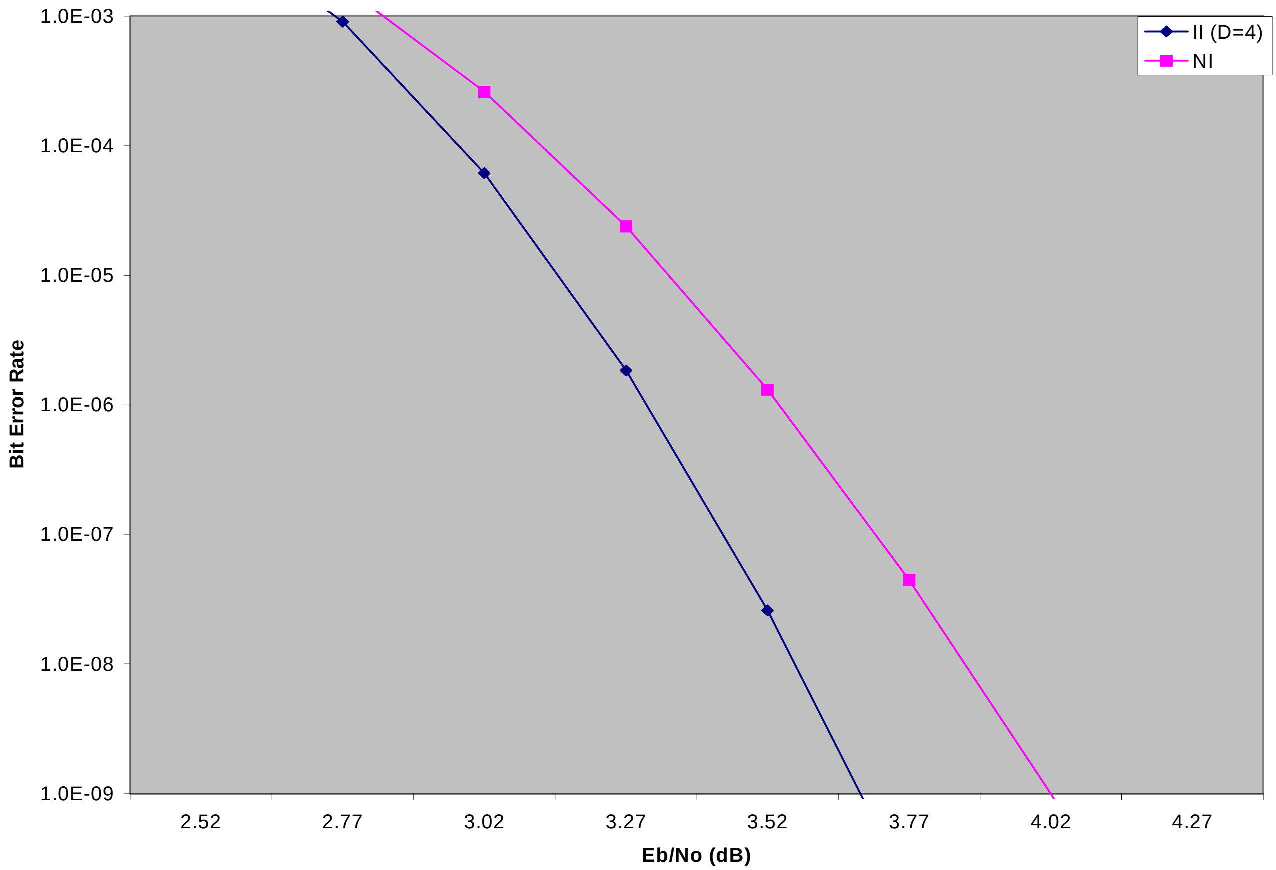


Figure 06. BER Performance : (64,32) with RS t = 16, M = 212

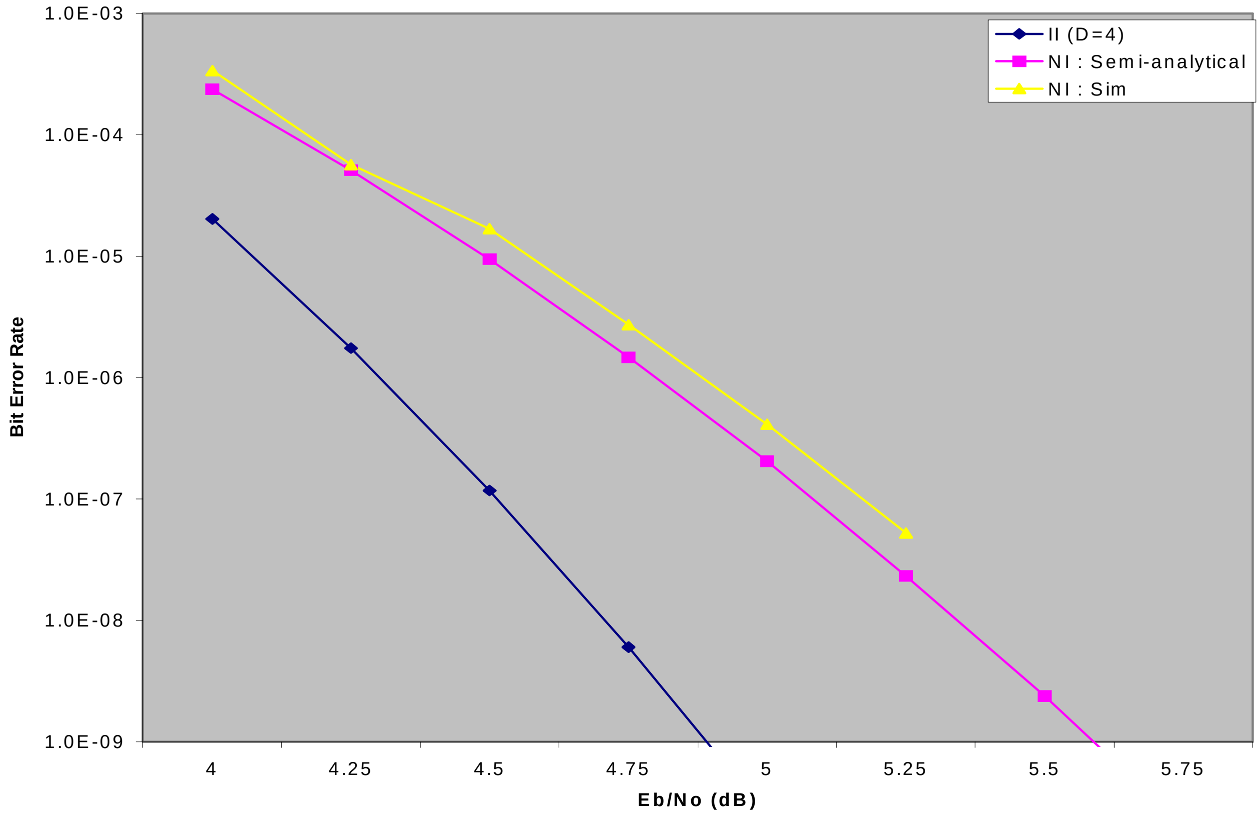


Figure 07. BER Performance : (48,32) with RS t = 8, M = 56

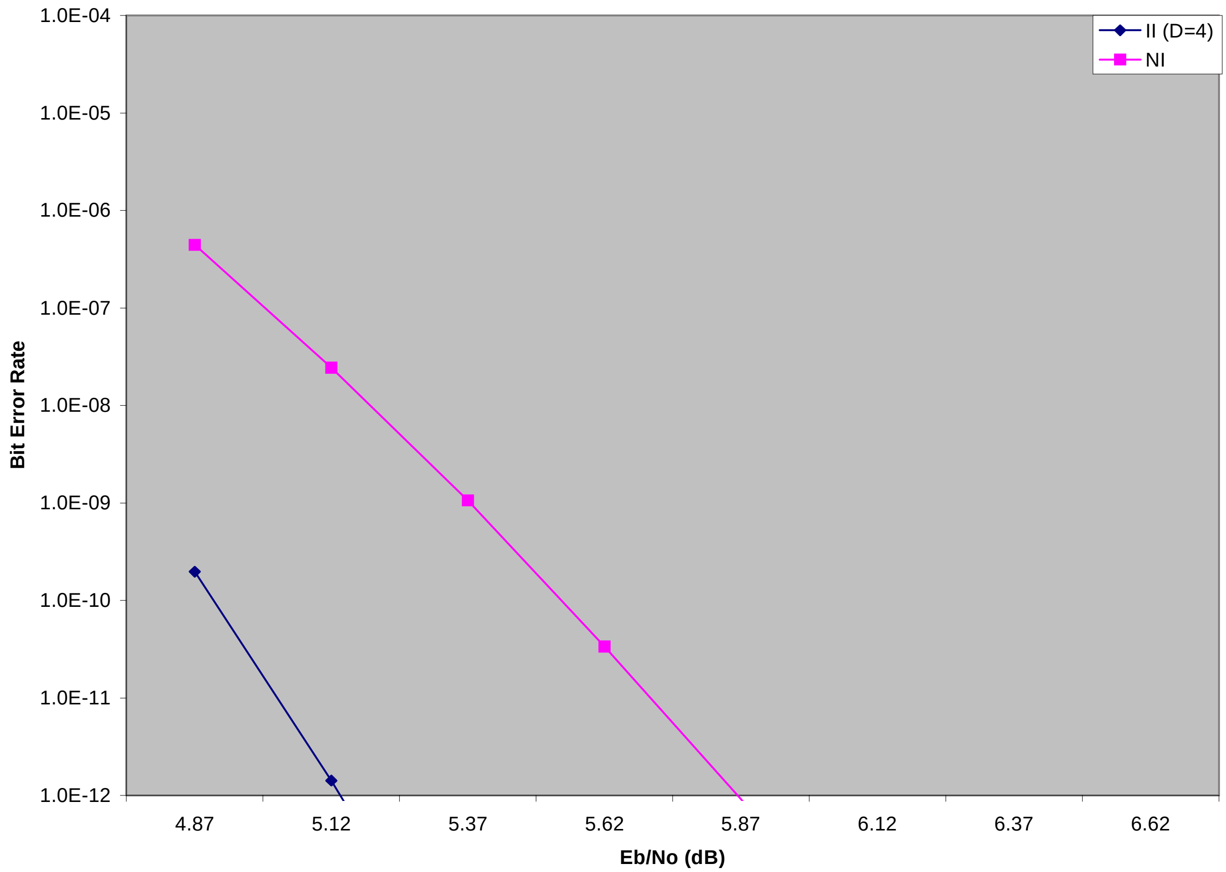


Figure 08. BER Performance : (48,32) with RS t = 16, M = 56

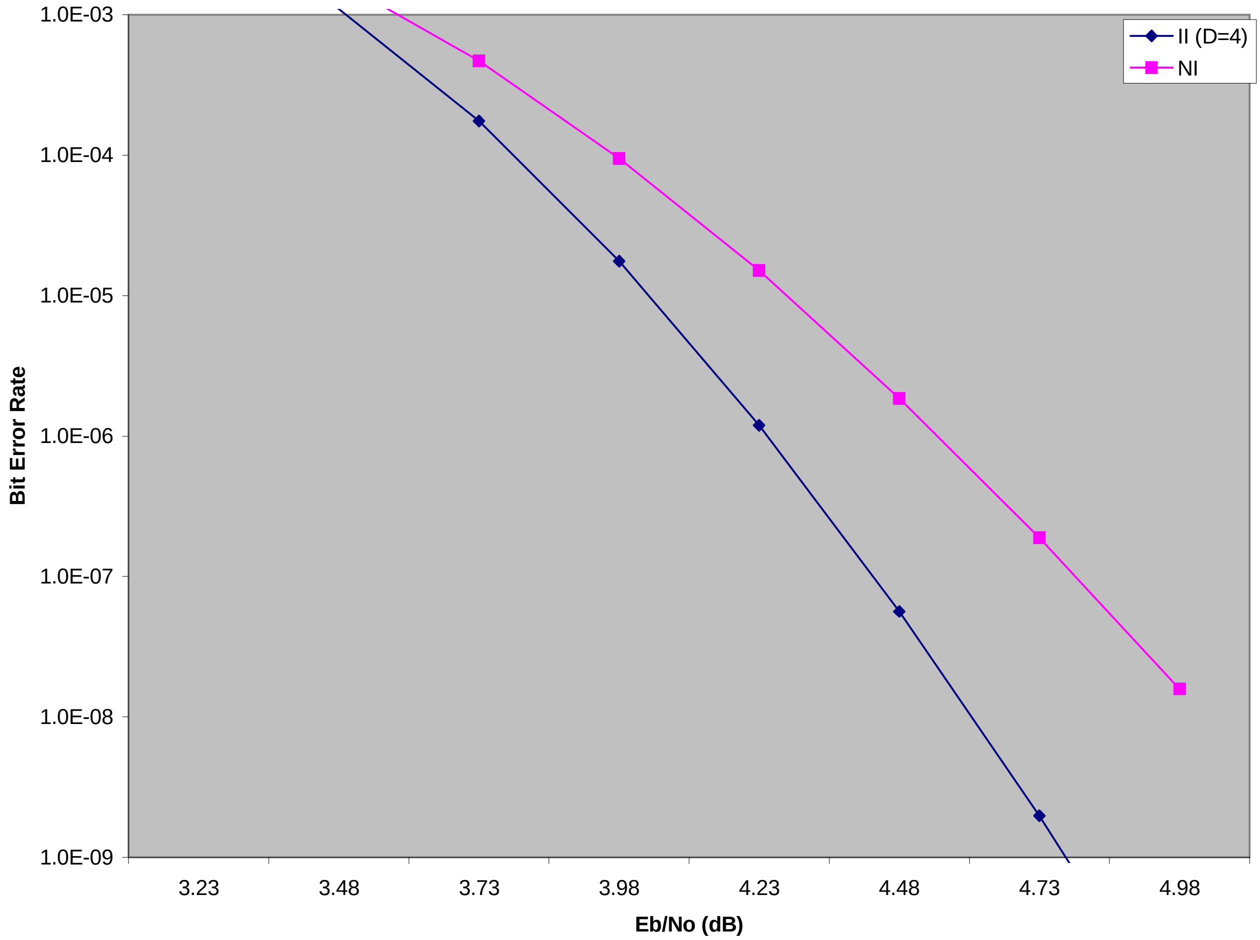


Figure 09. BER Performance : (48,32) with RS t = 8, M = 212

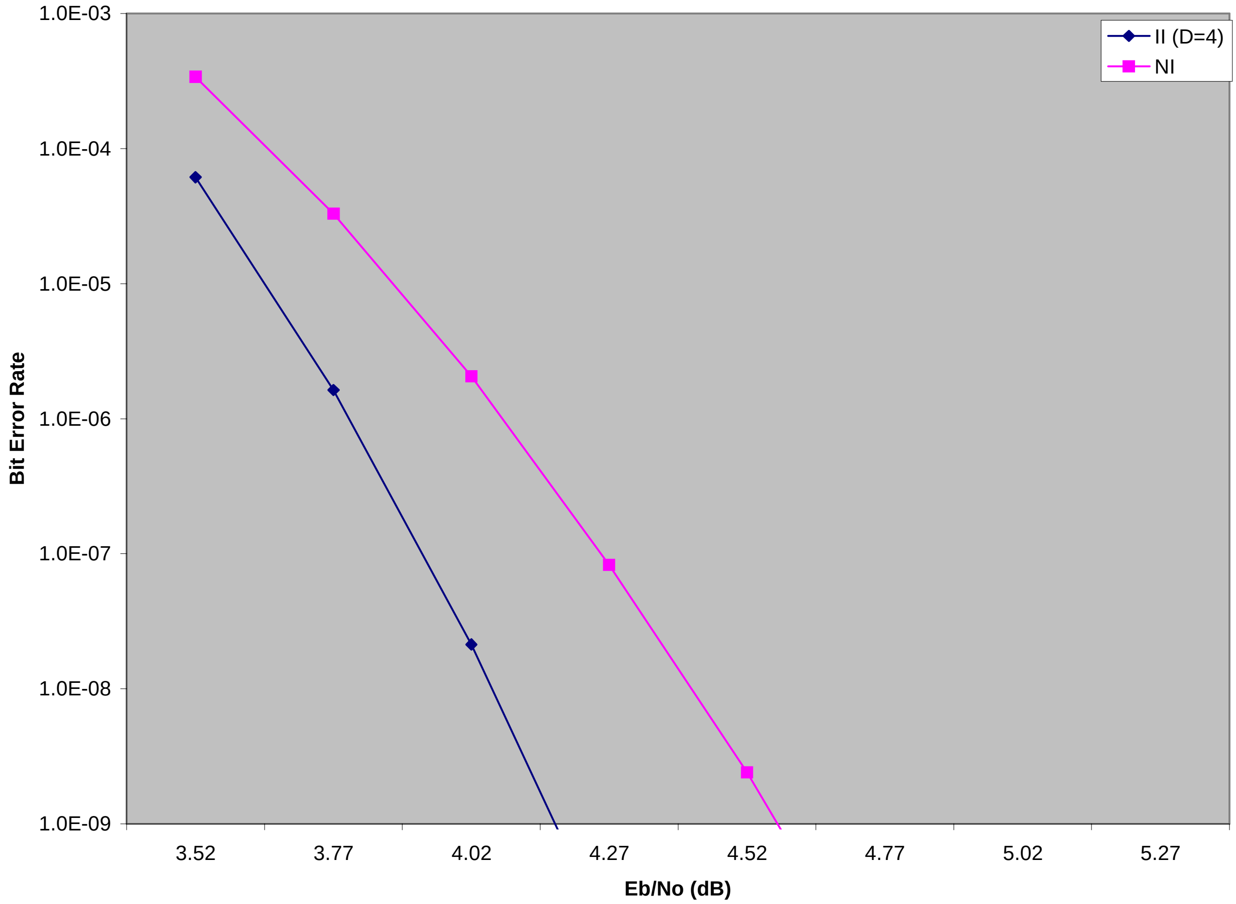


Figure 10. BER Performance : (48,32) with RS t = 16, M = 212

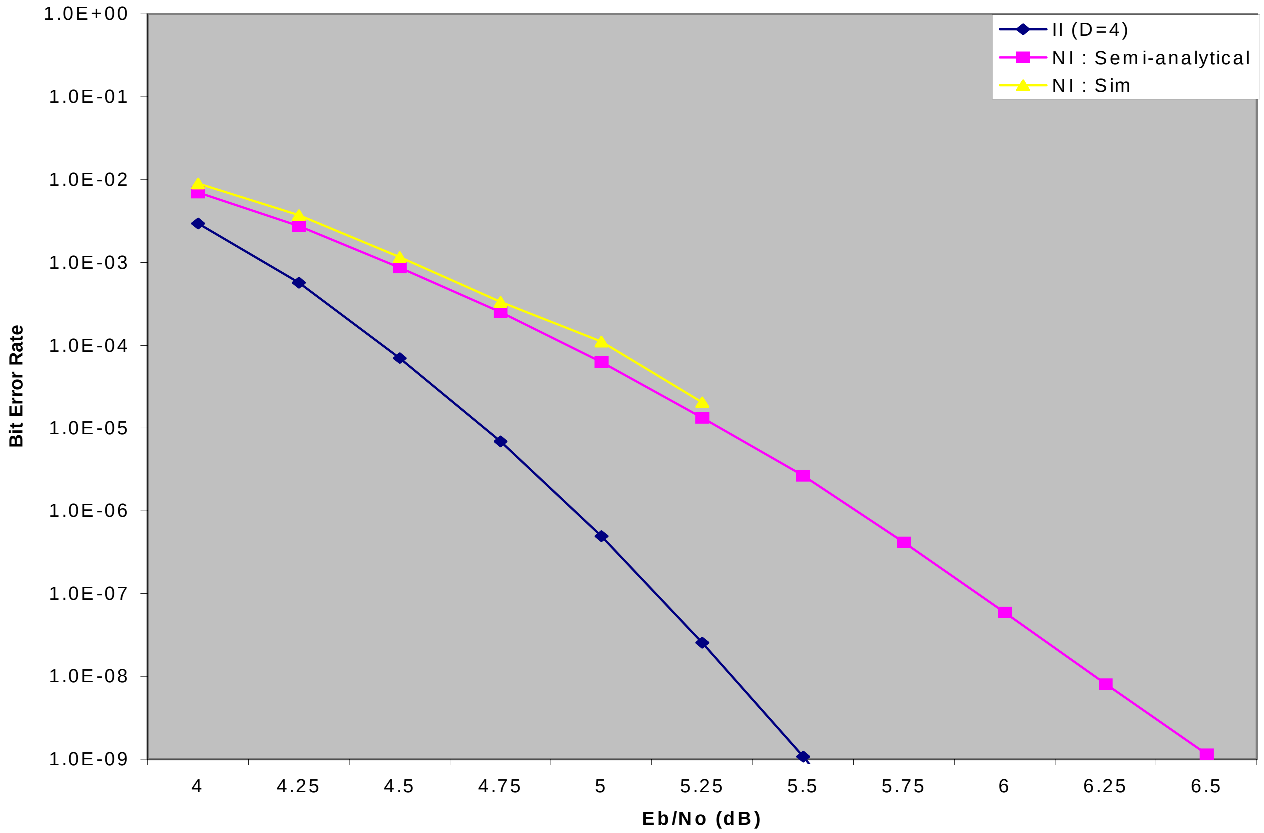


Figure 11. BER Performance : (40,32) with RS t = 8, M = 56

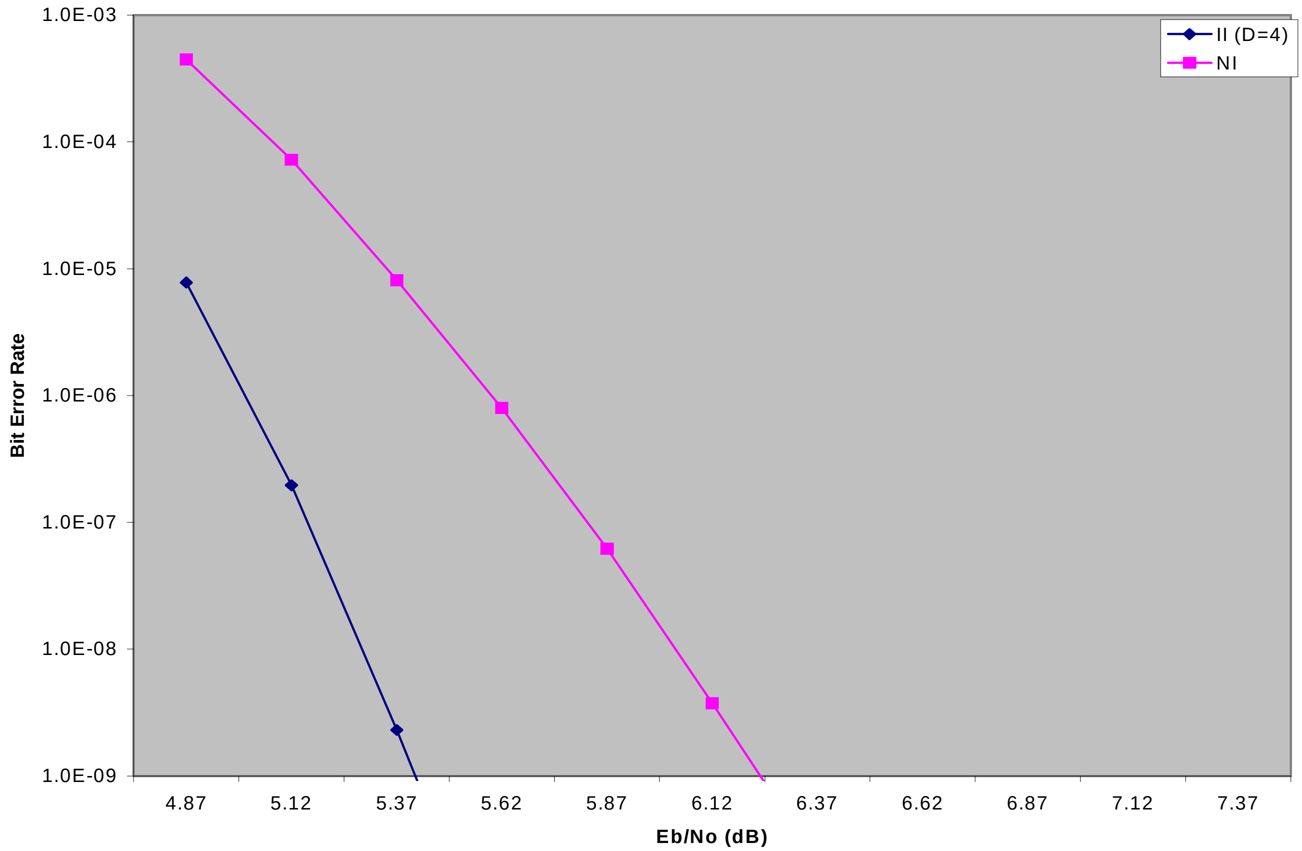


Figure 12. BER Performance : Rate 4/5, t = 16, M = 56

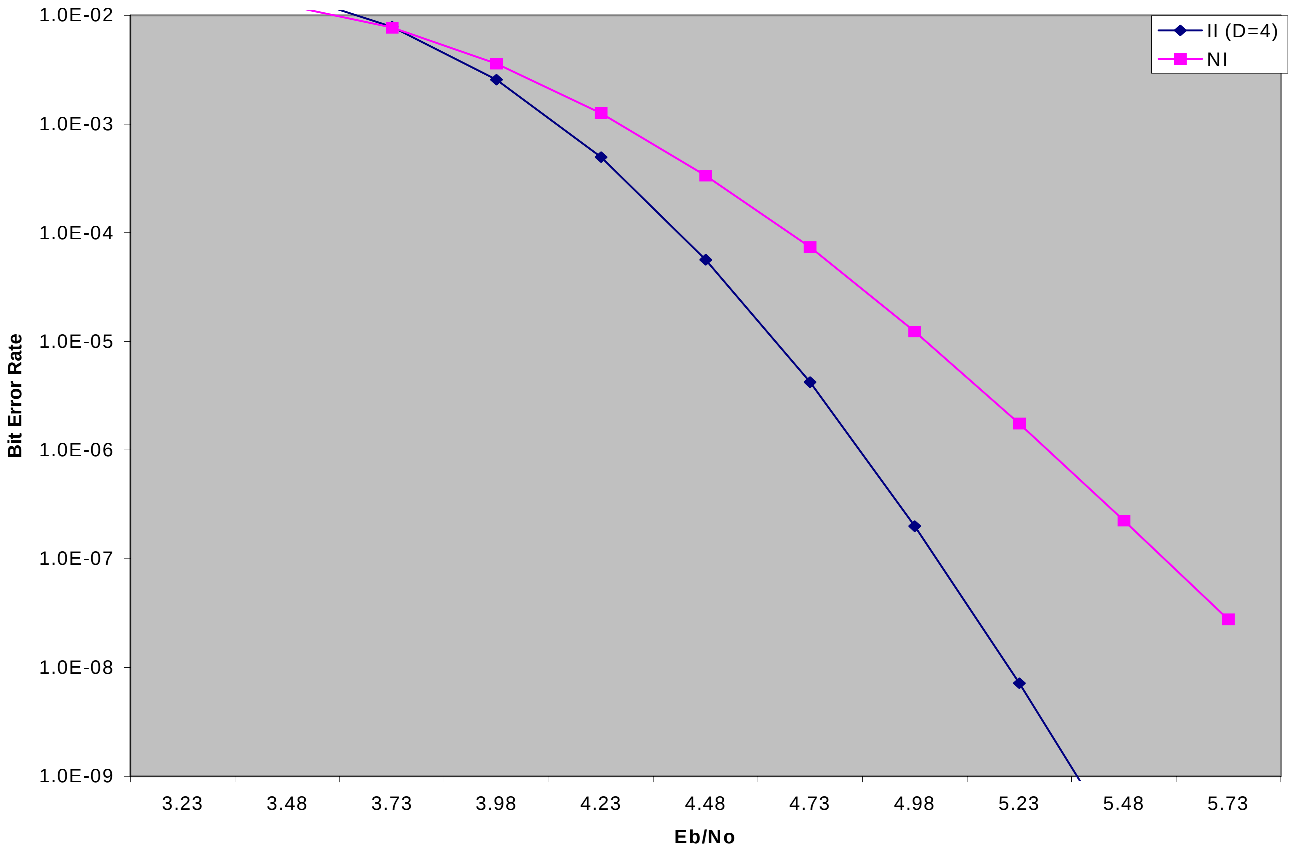


Figure 13. BER Performance : (40,32) with RS t = 8, M = 212

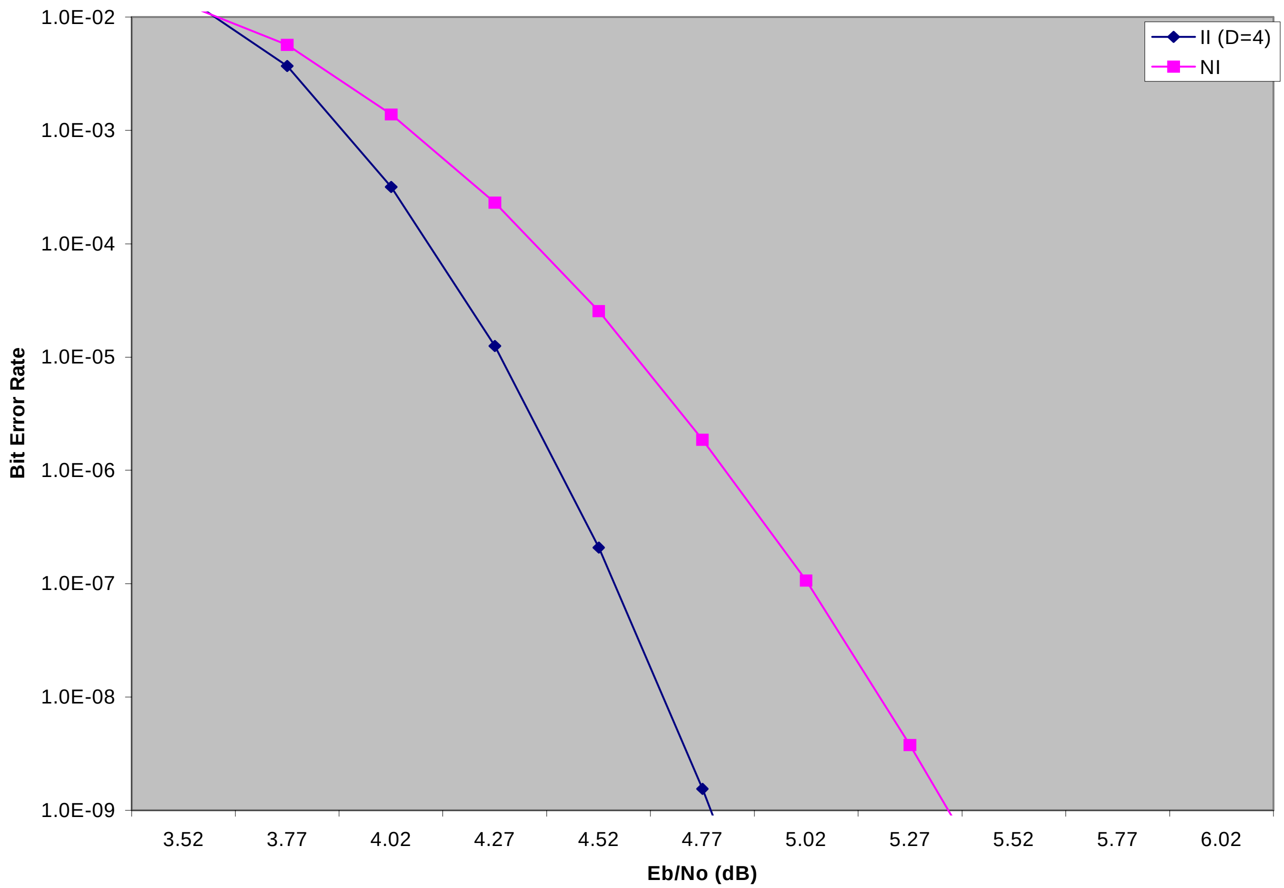


Figure 14. BER Performance : (40,32) with RS t = 16, M = 212

The performance difference with and without interleaving is about 0.5 to 1 dB. The table 02 summarizes the above results.

Table 02. Performance Summary

Block Size	Inner Code	t	Code Rate	Coding Gain (In dB) at BER 10^{-9}
56	(64,32)	8	0.38	7.50
56	(48,32)	8	0.51	6.90
212	(64,32)	8	0.46	8.00
212	(64,32)	16	0.43	8.50
212	(48,32)	8	0.62	7.25
212	(48,32)	16	0.58	7.95
212	(40,32)	16	0.70	7.10

5. Block Turbo Codes

Turbo codes are an attractive scheme as they promise higher coding gain than traditional coding schemes for the same coding rate. Turbo Product Codes (TPC) or Block turbo codes (BTC) seem to be a good candidate for BWA as they do not tend to have an "error floor" as other turbo code schemes. However as the basic soft input/soft output decoder engine for TPC is complex and sub-optimal the practical implementation is highly complex and speed limited (<40 Mbps). Furthermore some noticeable degradation compared to theory is experienced. Although the code operates on a block and does not require interleaving, it does require iterative decoding (8 to 16 iterations if maximum performance is required) which introduces latency. Therefore, BTC if at all is more suitable for continuous transmissions (TDM) and not for bursts.

The following plot is based on an IEEE paper presented in RAWCON by AHA (http://www.aha.com). In the plot a concatenated RS (208,192) +Conv. Code (rate 4/5) was compared with a BTC based on a extended Hamming code (64,57) (coding rate about 0.7). The paper did an unfair comparison by assuming no interleaving for the first scheme while allowing 16 iterations for their own code. We plotted in addition to their results of the concatenated scheme with interleaving and also the code presented in sections 4,5 in this paper.

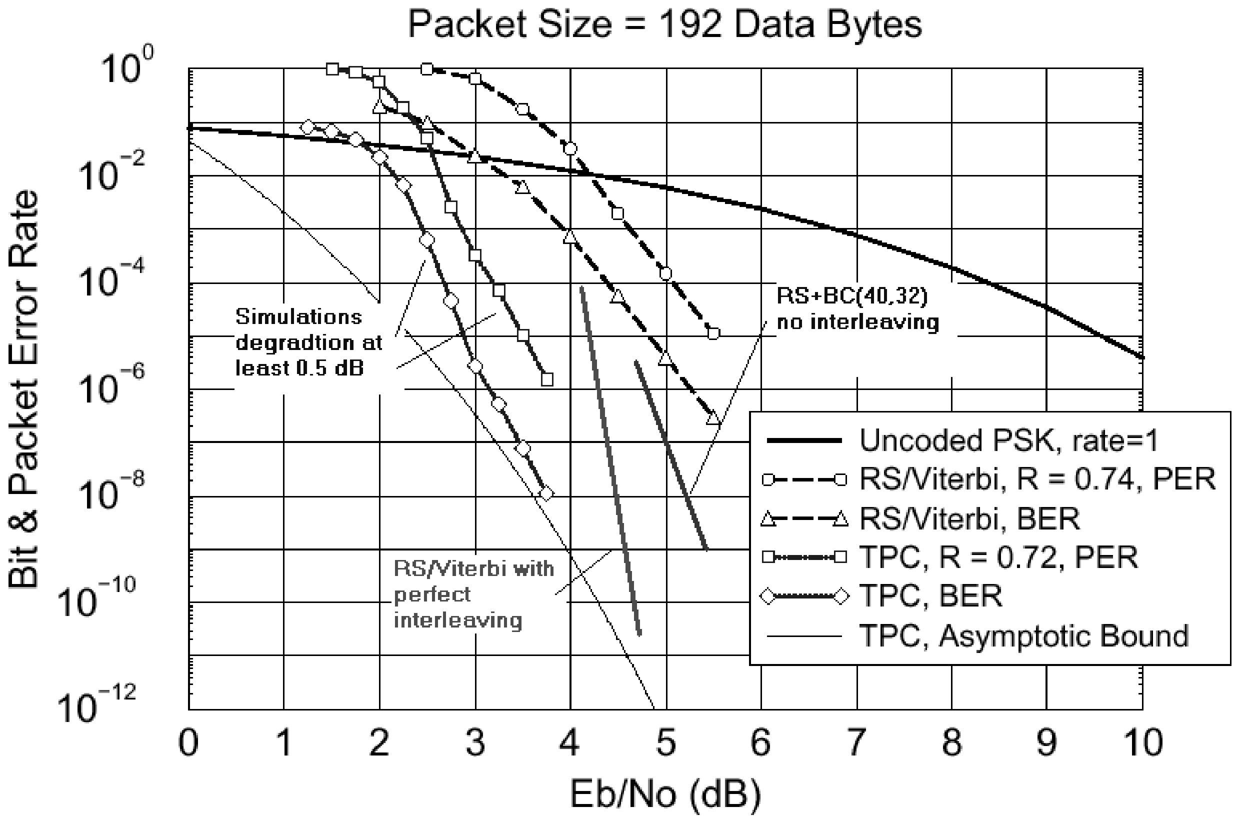


Figure 15 – TPC performance

One should pay attention to the theoretical bound for the TPC code as its sets a limit on the performance (can be used to compare previous declared results). The RS+Conv. Code with perfect interleaving is only 0.5 to 1 dB worse than the TPC. The TPC results are simulations and as mentioned earlier at least 0.5 dB degradation should be expected. We also plot the case where a (40,32) code was used with RS with no interleaving, achieving practically the same coding rate with approximately the same block size. This code is practically only 1-1.5 dB worse than the TPC yet has no "burden" on hardware complexity as the TPC does.

6. Conclusions

For burst communications we recommend the use of a concatenated scheme based on Reed Solomon and a parity check. If coding rate flexibility is required then the parity check could be replaced by a block code which can be soft decoded, gaining up to 2 dB more coding gain. For very high coding rates (>88%) Reed Solomon alone (shutting off the parity check code) would be the best choice. All of these options have no implementation risk. Block Turbo codes are not suitable for BWA burst communications as they fail to deliver their theoretical performance for a reasonable “price” and impose processing speed limitations. Even when compared to the traditional concatenated coding for continuous transmissions a performance advantage of 1 dB is not attractive enough.

References :

[1] Ted Berman, J. Freedman and Ted Kaplan, “An Analytic Analysis of a Concatenated RS/Viterbi Coding System both with and without RS Interleaving”, IPCCC ’92.

[2] “Convolutional Coding Fundamentals And Applications”, L. H. Charles Lee, Artech House Publications