A LOW-COMPLEXITY AND HIGH-PERFORMANCE CONCATENATED CODING SCHEME FOR HIGH-SPEED SATELLITE COMMUNICATIONS

Technical Report

to

NASA

Goddard Space Flight Center
Greenbelt, Maryland 20771

Grant Number NAG 5-931
Report Number 93-001

Shu Lin

Department of Electrical Engineering
University of Hawaii at Manoa
Honolulu, Hawaii 96822

February 1, 1993

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I. Introduction

This report presents a low-complexity and high performance concatenated coding scheme for high-speed satellite communications. In this proposed scheme, the **NASA Standard** (255, 223) **Reed-Solomon(RS)** code over GF(2^8) is used as the outer code and the (32, 16) second-order **Reed-Muller(RM)** code of Hamming distance 8 is used as the inner code as shown in Figure 1. The **RM** inner code has a **very simple** trellis structure and is decoded with the soft-decision Viterbi decoding algorithm. It is shown that the proposed concatenated coding scheme achieves an error performance which is comparable to that of the **NASA TDRS** concatenated coding scheme in which the **NASA Standard** rate-1/2 convolutional code of constraint length 7 and $d_{free} = 10$ is used as the inner code. However, the proposed **RM** inner code has much smaller decoding complexity, less decoding delay, and much higher decoding speed. Consequently, the proposed concatenated coding scheme is suitable for reliable high-speed satellite communications, and it may be considered as an alternate coding scheme for the **NASA TDRS** system.

II. Reed-Muller Inner Code

The (32, 16) **RM** inner code of Hamming distance 8 in non-systematic form[1] is generated by a 16 × 32 generator matrix as shown in Figure 2. This code has a 64-state and 4-section trellis diagram[2]. Recently, we have shown that this trellis diagram consists of 8 **parallel** and **structurally identical**(or **isomorphic**) 8-state sub-trellis diagrams **without cross-connections** between them as shown in Figure 3[3]. This parallel trellis structure allows us to design eight identical **small** 8-state Viterbi decoders to process the code trellis in **parallel**. This not only reduces the decoding complexity drastically but also speeds up the decoding process greatly.

The **NASA Standard** rate-1/2 convolutional inner code of constraint length 7 for the **TDRS System** has a densely connected 64-state trellis diagram with no parallel structure. Hence a single 64-state Viterbi decoder must be built to process the code trellis. Parallel processing requires additional complexity. It is clear that this densely connected 64-state Viterbi decoder is more complex than eight identical small 8-state Viterbi decoders for the (32, 16) **RM** code.

In decoding the **RM** inner code, each 8-state Viterbi decoder produces a survivor at the end of the decoding process. From the 8 survivors, the one with the **largest** path metric is then chosen as the decoded word and 16 information bits are extracted from it. We see that each decoding results in 16 information bits unlike the **NASA Standard** rate-1/2 convolutional inner code for which each decoding results only in one information bit.

The bit-error performance of the proposed **RM** inner code is shown in Figure 4. The code achieves 10^{-6} bit-error-rate (BER) at the SNR $E_b/N_o = 6.065$ dB and a 4.425 dB coding gain over the uncoded BPSK. The **NASA Standard** rate-1/2 convolutional inner code of constraint length 7 achieves 10^{-6} BER at SNR $E_b/N_o = 4.90$ dB. We see that using (32, 16) **RM** inner code, there is a 1.165 dB loss in coding gain against the **NASA standard** rate-1/2 convolutional inner code of constraint length 7. In fact, we will show in Section IV that the loss of coding gain of the overall proposed concatenated scheme is only 0.40 dB against the **NASA TDRS** concatenated system. This loss is compensated by less decoding complexity and higher decoding speed for the **RM** inner code.

III. Overall Encoding and Decoding

In the proposed concatenated coding scheme, the **RS** outer code is interleaved with a depth of 2. The encoding is accomplished in two stages. Each 223 $\times$ 8-bit message is regarded as a message of 223 8-bit bytes, each 8-bit byte is regarded as a symbol in $GF(2^8)$. At the first stage of encoding, a 223-byte message is encoded into a 255-byte codeword in the **RS** outer code. Two **RS** codewords are stored as a 16×255 array in an interleaver buffer as shown in Figure 5. Each column of the array consists of two bytes (16 bits), one from each RS codeword. At the second stage of encoding, each 16-bit column of the array in the interleaver buffer is encoded into a 32-bit codeword in the (32, 16) **RM** inner code which is transmitted using BPSK.

The decoding also consists of 2 stages, the inner and outer decodings. At the first stage of decoding, a sequence of 32 received signals is decoded into a codeword in the **RM** inner code with the soft-decision Viterbi decoding algorithm. Then 16 information bits are extracted from the decoded word and are stored in the de-interleaver buffer. After 255 inner code decodings, the de-interleaver buffer contains a 16×255 array which consists of two 8×255 sub-arrays. Each of the two 8×255 sub-arrays is regarded as a received **RS** codeword from the outer **RS** code and is decoded by the outer code decoder.

IV. Error Performance of the Overall Scheme

The proposed concatenated coding scheme is simulated and its error performance is shown in Figure 6. The scheme achieves 10^{-6} BER at the SNR $E_b/N_o = 2.93$ dB and a 7.60 dB coding gain over the uncode BPSK. The **NASA**'s **TDRS** concatenated coding scheme using the **NASA Standard** rate-1/2 convolutional inner code of constraint length 7 achieves 10^{-6} BER at the SNR $E_b/N_o = 2.53$ dB[4]. The proposed concatenated coding scheme loses 0.40 dB coding gain against the **NASA's TDRS** concatenated coding scheme. This small loss in coding gain of the proposed scheme is more than compensated by its gains in decoding complexity and decoding speed. We propose that the proposed scheme be considered as an alternate coding scheme for the **TDRS** system.

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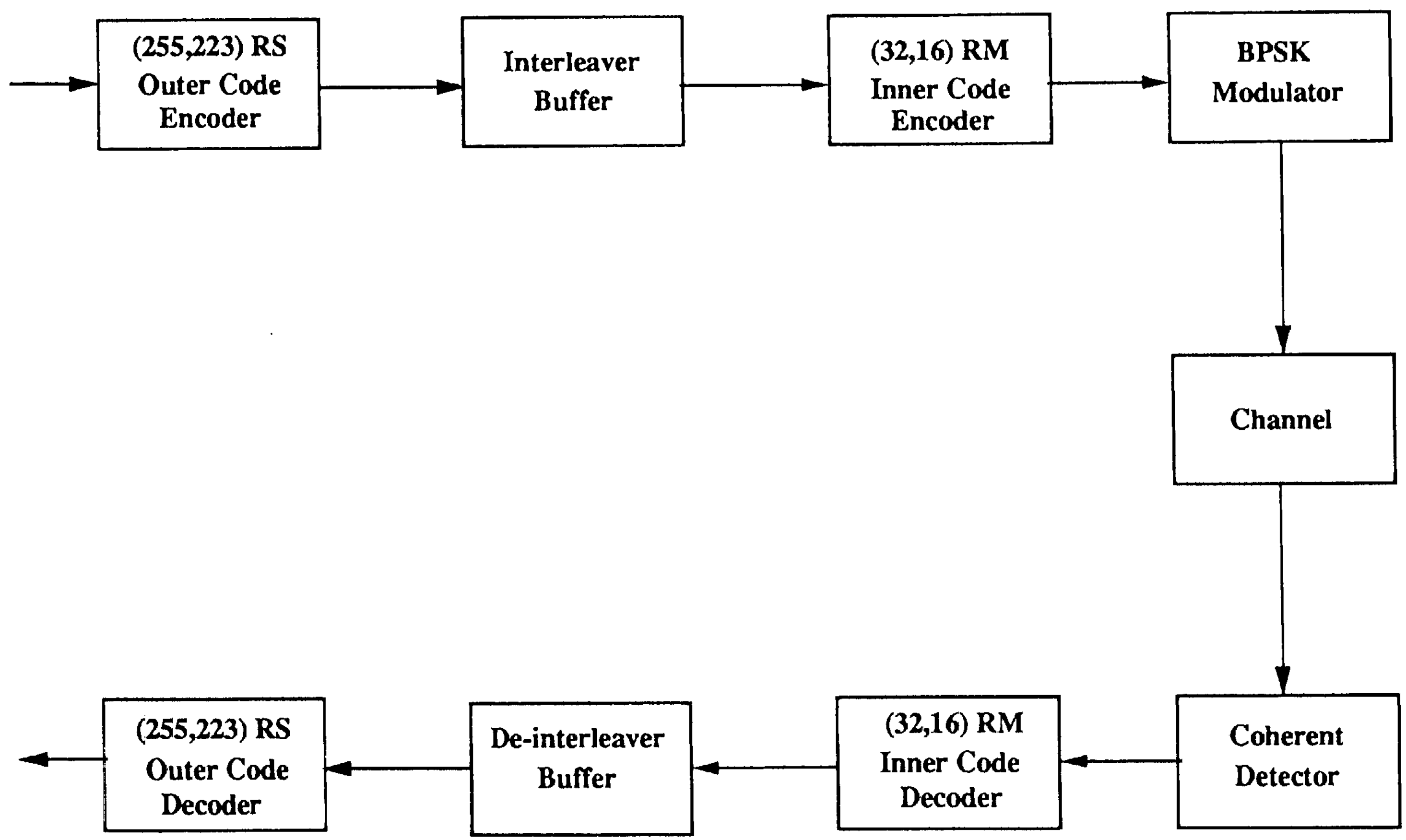

Figure 1 A concatenated coding scheme

$$
G = \begin{bmatrix}
11111111111111111111111111111111 \\
00000000000000001111111111111111 \\
00000000111111110000000011111111 \\
00001111000011110000111100001111 \\
00110011001100110011001100110011 \\
01010101010101010101010101010101 \\
00000000000000000000000011111111 \\
00000000000000000000111100001111 \\
00000000000000000011001100110011 \\
00000000000000000101010101010101 \\
00000000000011110000000000001111 \\
00000000001100110000000000110011 \\
00000000010101010000000001010101 \\
00000011000000110000001100000011 \\
00000101000001010000010100000101 \\
00010001000100010001000100010001
\end{bmatrix}
$$

Figure 2 Generator matrix for the (32,16) RM inner code

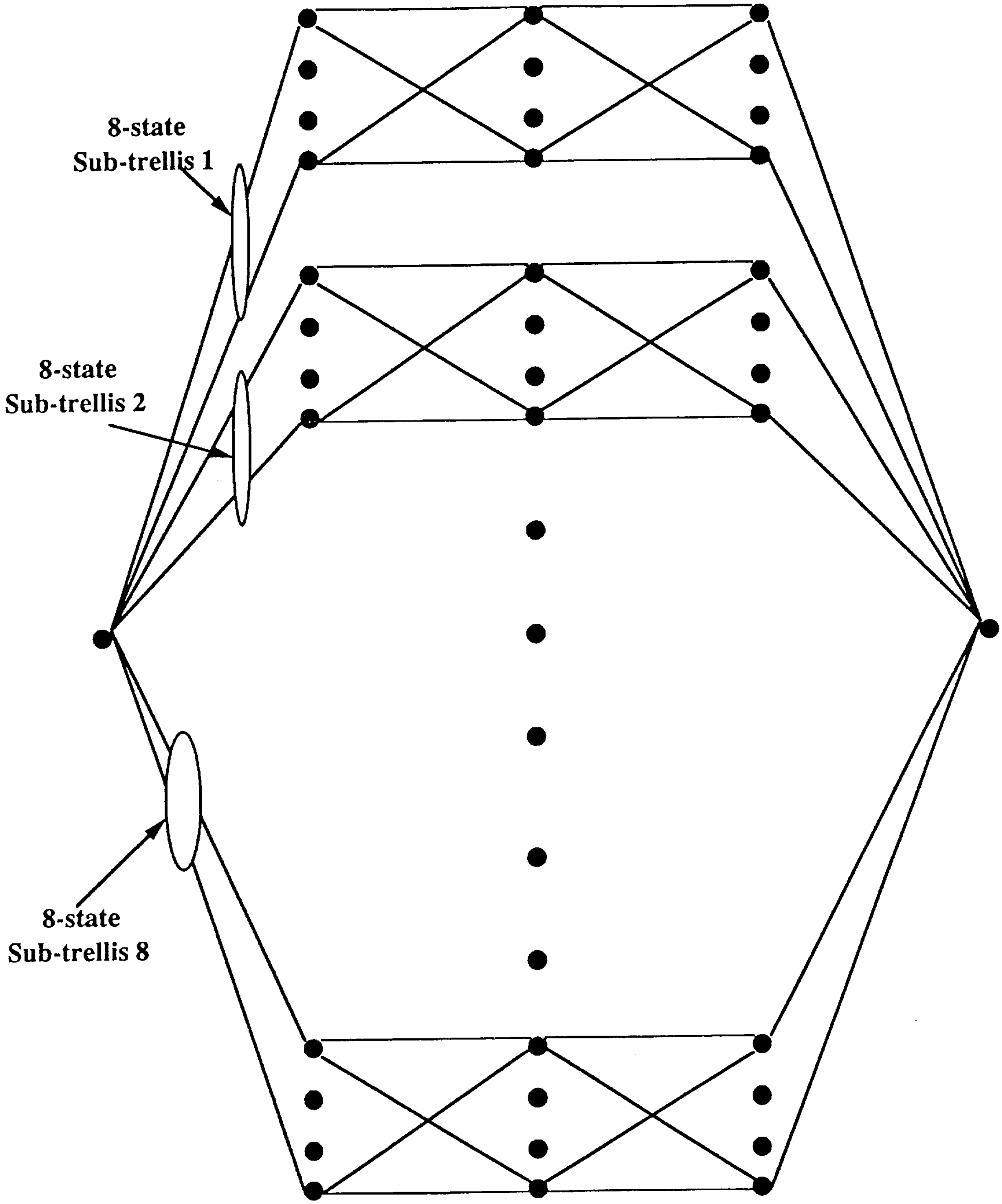

Figure 3 Trellis structure of the (32,16) RM inner code

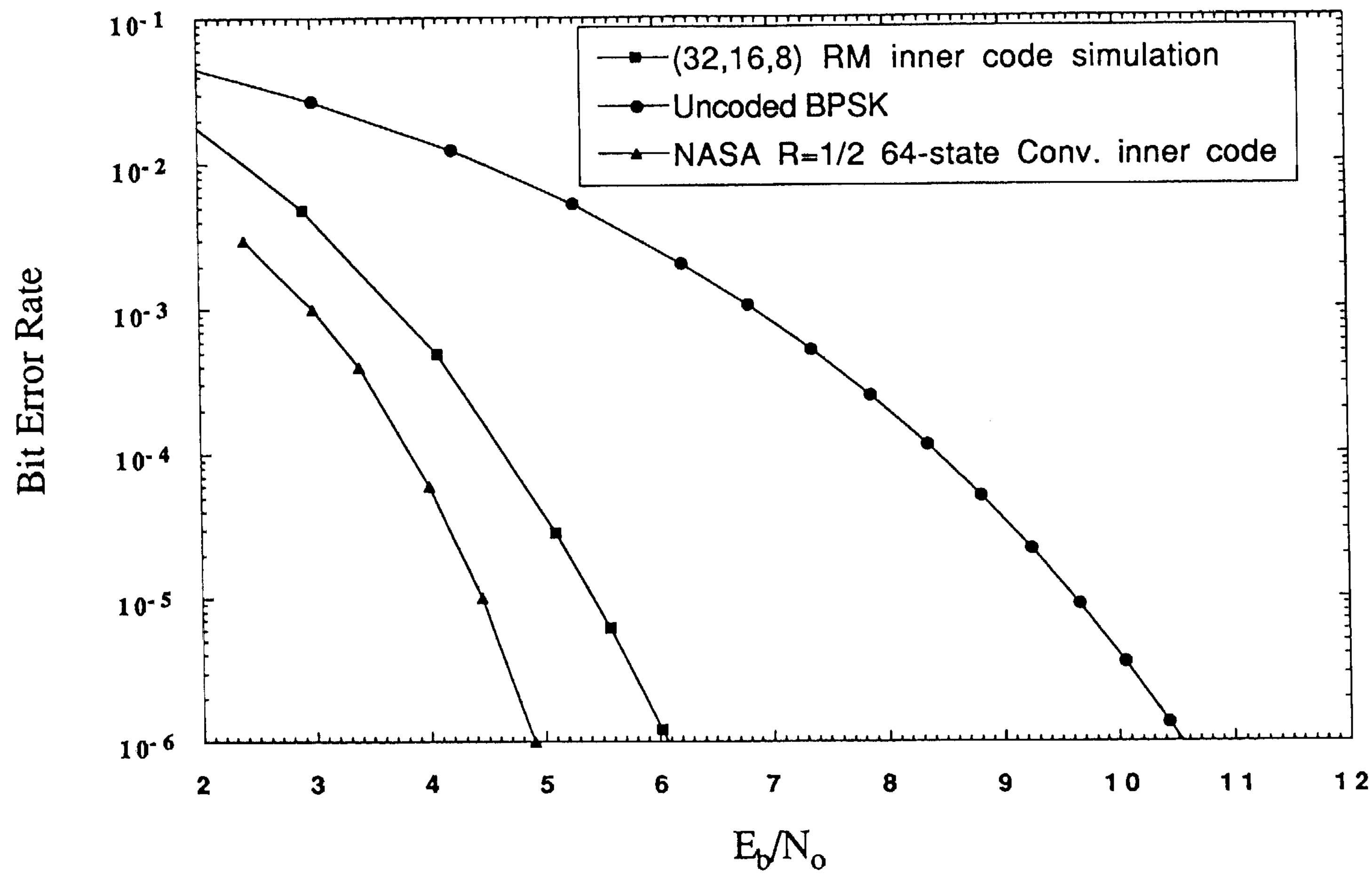

Figure 4 One-stage MLD decoding of (32,16,8) Reed-Muller inner code.

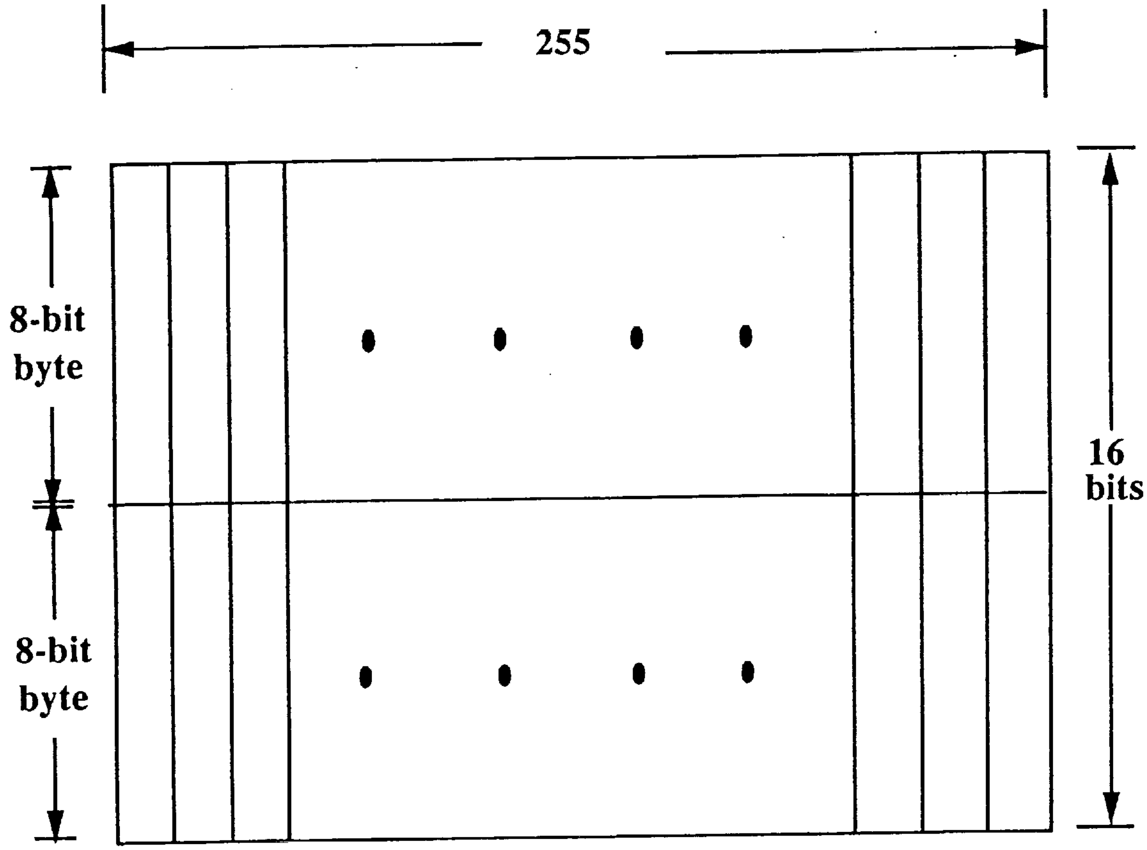

Figure 5 A RS code array with two RS codewords

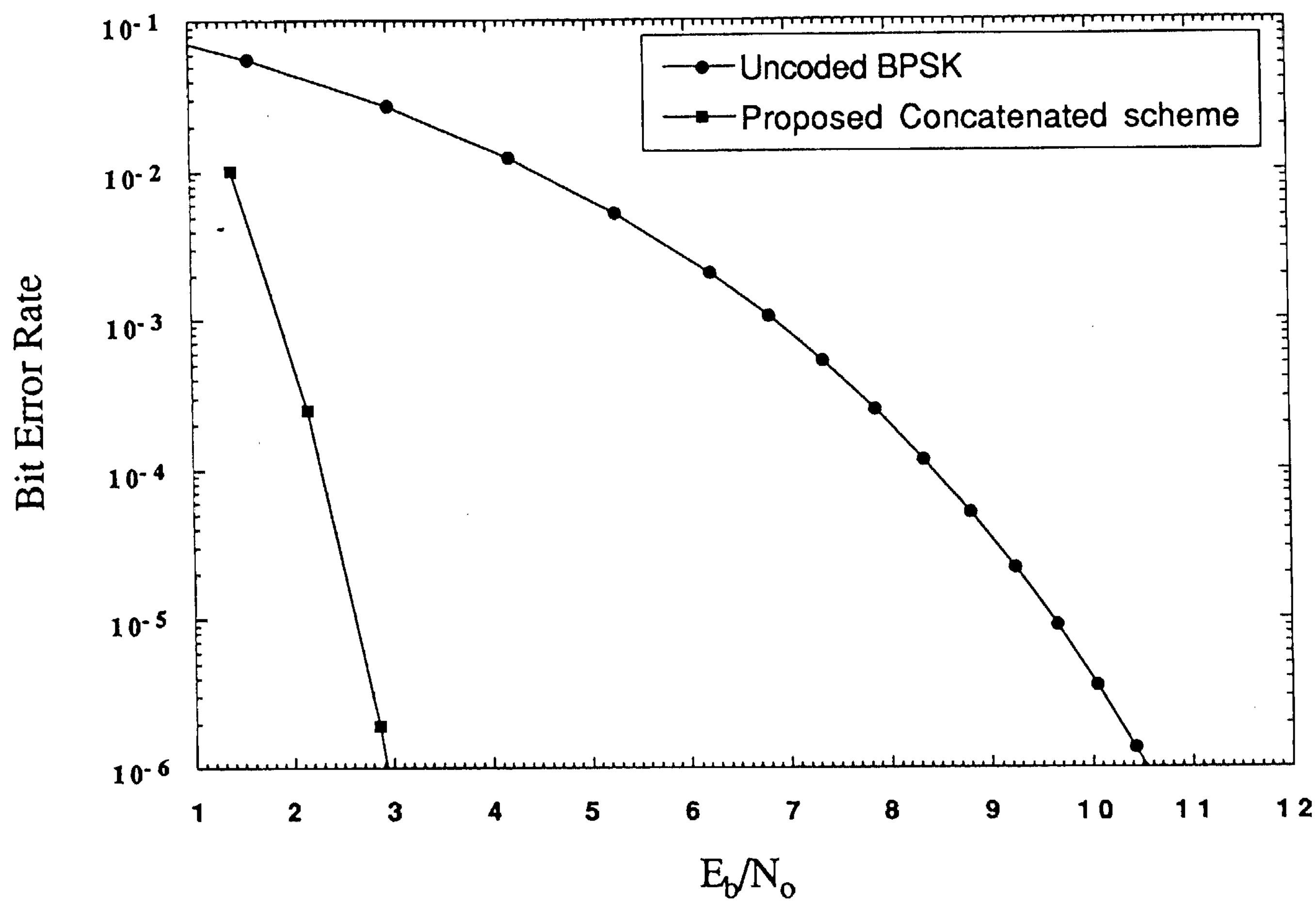

Figure 6 Bit error performance of the concatenated code with (255,223) RS code as outer code and (32,16) Reed-Muller code as inner code