BLOCK MULTIDIMENSIONAL MPSK MODULATION CODES WITH UNEQUAL ERROR PROTECTION[1]

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Resumo: O artigo descreve a construção de códigos de bloco de modulação M-PSK multidimensional com proteção desigual de erros. Um perfil de proteção desigual para o canal com desvanecimento de Rayleigh é obtido através da partição de constelações 4-dimensionais que são o produto Cartesiano de modulações 8-PSK não-uniformes ou são o produto de modulações uniformes. Códigos novos são construídos através da técnica de codificação multinível utilizando códigos componentes binários extremamente simples. Os códigos construídos são adequados para o codificador de voz VSELP descrito no sistema móvel IS-54. Um dos códigos construídos possui quatro níveis de proteção e proporciona um ganho de codificação de 16,0 dB (para uma SEGSNR de 2,0 dB) quando comparado a um sistema que utiliza modulação 4-PSK não codificada.

***Abstract*:** The construction of block multidimensional M-PSK modulation codes with unequal error protection (UEP) is considered. An UEP profile for the Rayleigh fading channel is obtained by partitioning four-dimensional constellations that are Cartesian products of non-uniform 8-PSK modulations or are subsets of a product of uniform modulations. New codes are constructed by using the multilevel coding technique with very simple binary component codes. These codes are matched to the vector-sum excited linear predictive (VSELP) codec described in the IS-54 mobile system. One of the constructed codes has four levels of protection and achieves a coding gain of 16.0 dB (at a SEGSNR of 2.0 dB) in comparison with a system that employs uncoded 4-PSK modulation.

Keywords: Multidimensional M-PSK modulation, multilevel codes, unequal error protection

1.INTRODUCTION

The combination of channel coding and modulation (coded modulation) is essential for the design of power and bandwidth efficient digital transmission schemes. On Gaussian channels, the minimum squared Euclidean distance of the code is the parameter that plays the central role as a design criterion. On fading channels, not only the minimum squared Euclidean distance, but also the minimum Hamming distance and the minimum product distance of the code should be considered in the design of the codes[1].

Nowadays in cellular mobile radio systems, the speech coders have coded bits with different sensibilities to channel errors. Therefore, it is necessary to have channel coding with unequal error protection capabilities to make the best use of channel redundancy.

A desirable feature of a technique for constructing unequal error protection codes is the possibility to control the data rates, the fraction of data that is deemed to be more important and the unequal error probability profile. Although the use of multilevel constructions with two-dimensional modulations the above mentioned parameters can be controlled in a flexible manner [2], the use of multidimensional modulations offers more advantages. It not only guarantees flexibility on controlling those parameters but also opens many possibilities of applying multistage decoding algorithms [3].

In this paper we propose new block multidimensional M-PSK modulation codes with UEP for the Rayleigh fading channel. The news codes are constructed using the multilevel coding technique with simple binary component codes and uniform and non-uniform multidimensional M-PSK modulations.We are looking for codes matched to the 7.95 kbit/s VSELP codec described in the IS-54 mobile system [9]. The VSELP codec has a frame of 159 bits. The error sensitivity of each bit was obtained by the method described in [4].

The paper is organised as follows. In section 2 the bit error sensitivity analysis of the VSELP codec is presented. In Section 3 the channel model is described and some considerations about the performance parameters are done. In Section 4 the construction of multidimensional modulation based on uniform and non-uniform 2-dimensional constellations is described. Section 5 shows

some new codes and Section 6 their performance. Finally, in Section 7 some conclusions are drawn.

2. VSELP BIT ERROR SENSITIVITY ANALYSIS

Let the original speech signal, $x(t)$, be divided into J non-overlapping segments of duration T_B. Let $q(t)$ be the reconstructed signal when no errors have occurred. Let $q_i(t)$ be the reconstructed signal when a single bit error has occurred in position i of every segment. The segmental signal-to-noise ratio (SEGSNR) can be approximated as [4]:

$$EGSSNR = -(1/J)\sum_{j=1}^{J} 10\log\left[Q^j + \sum_{i=1}^{159} P_i A_i^j \right],$$

where P_i is the bit error probability in position i,

$$Q^j = \int_{(j-1)T_B}^{jT_B} [x(t)-q(t)]^2 \, dt \bigg/ \int_{(j-1)T_B}^{jT_B} [x(t)]^2 \, dt$$

is the quantization noise normalised with the speech signal power, and

$$A_i^j = \int_{(j-1)T_B}^{jT_B} [x(t)-q_i(t)]^2 \, dt \bigg/ \int_{(j-1)T_B}^{jT_B} [x(t)]^2 \, dt.$$

By setting Q^j to zero (for all j), $P_i = 1$ and $P_l = 0$, $l \neq i$, the SEGSNR is then reduced to $-(1/J)\sum_{j=1}^{J} 10\log A_i^j$. This expression was defined in [4] as the sensitivity of the bit in position i (the average normalised noise power caused by an error in position i). Figure 1 shows the values of this sensitivity for each of the 159 bits. It can be seen that two levels of protection implies an amount of 50% of important data.

3. CHANNEL MODEL

The Rayleigh fading channel can be described as

$$r_k = \rho . x_k + n_k$$

where x_k is the kth 2-dimensional symbol transmitted, r_k is the kth symbol received and n_k is the white Gaussian noise with zero mean and variance $N_0/2$. The fading amplitude ρ has Rayleigh density given by

$$p(\rho) = \begin{cases} 2\rho\exp\{-\rho^2\}; & \rho \geq 0 \\ 0; & \rho < 0 \end{cases} \qquad (1)$$

where the average energy per received symbol is $E\{\rho^2 E_m\} = E_m$. Therefore, the signal to noise ratio (E_b / N_0) is given by $E_b / N_0 = E_m / (R.N_0)$, where E_b is the average energy per information bit and R is the bits per symbol rate. For our constructions we assumed a memoryless channel, achieved through a perfect interleaving, perfect channel state information (CSI), ideal coherent detection and a Gaussian decoding metric.

From these assumptions, it can be seen that the pairwise error probability between sequences X and $\hat{X}$ can be approximated by

$$P(X \rightarrow \hat{X}) \cong \frac{1}{d_p(X,\hat{X})} \left(\frac{4}{E_m/N_0} \right)^{d_H(x,\hat{x})} \qquad (2)$$

where E_m is average energy per transmitted symbol, $d_H(X,\hat{X})$ is the Hamming distance between the sequences X e $\hat{X}$, and $d_p(X,\hat{x})$ is the product distance defined as

$$d_p(X,\hat{X}) = \prod_{n\in\eta} |x_n - \hat{x}_n|^2 \qquad (3)$$

where η is the set of all n that $x_n \neq \hat{x}_n$.

In equation (2) we can notice that the Hamming distance $d_H(X,\hat{X})$ and the product distance $d_p(X,\hat{X})$ are important for the code performance. It is worthy of mention that similar results can be obtained for other channel models (no CSI, M-DPSK signals, Ricean channels), if the values of channel SNR are sufficiently high [1,5].
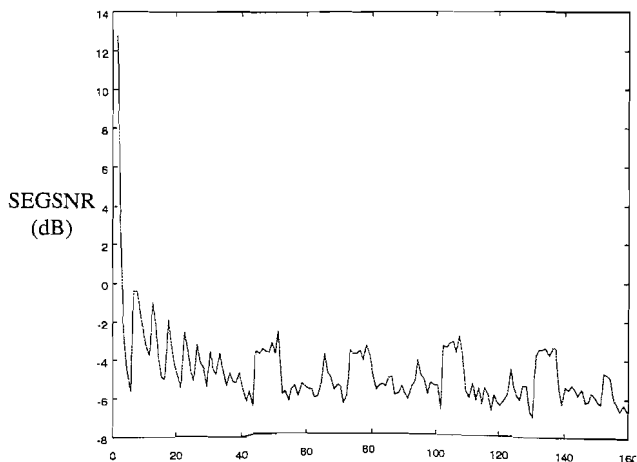

Fig. 1 - Bit error sensitivity of VSELP coded bits.

4. MULTILEVEL CONSTRUCTIONS AND MULTIDIMENSIONAL CONSTELLATIONS

Consider an initial constellation S with 2^L signals. We will define a sequence of L binary partitions. Each subset of the $(l-1)$-th partition contains two subsets of the l-th partition and has $2^{(L-l+1)}$ signals. We will label with the numbers 0 and 1 the two subsets at level 1 corresponding to the subsets at level (1-1). Therefore, the binary vector with L positions $(c_1, c_2, ..., c_L)$ can be associated to a specific signal s from S, $s = f(c_1, c_2, ..., c_L)$ [5].

We will be considering multidimensional constellations S which are the Cartesian product of 2-dimensional M-PSK modulations. Thus, a signal s of S is a sequence of n PSK signals. We will define the minimum Hamming distance, δ_H^l, as the shortest distance among the minimum distances of the subsets at level 1 of the partition. And associate to each level a minimum product distance, δ_P^l, which is the shortest distance (between) the signals that have minimum Hamming distance δ_H^l.

Figure 2 describes a multilevel construction. Initially , we have L encoders corresponding to the binary codes $C_1, C_2, ... C_L$, where $C_l = (N, K^l, d_H^l)$ is a code with length N, K^l information bits and minimum Hamming distance d_H^l.

Constructing the LxN matrix,

$$V = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1N} \\ c_{21} & c_{22} & \cdots & c_{2N} \\ \vdots & \vdots & & \vdots \\ c_{L1} & c_{L2} & \cdots & c_{LN} \end{bmatrix}$$

where the lth row of V is a codeword from C_l, and replacing each column from V by a signal from S defined by the partitions

$$s_k = f(c_{1k}, c_{2k}, ... c_{Lk})$$

we obtain a sequence $(s_1, s_2, ... s_N)$ from the multilevel code.
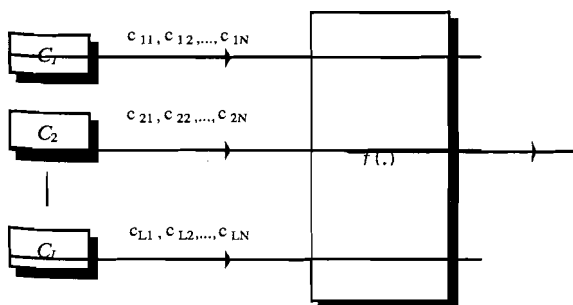
The multilevel code rate in information bits per PSK symbol is then

$$R = \sum_{l=1}^{L} K_l \bigg/ n.N \qquad (4)$$

The minimum Hamming distance of the resultant code at each level, $(d_H^l)_{res}$, is bounded by the product of the component code minimum Hamming distance and the minimum Hamming distance of that partition level, $(d_H^l)_{res} \geq \delta_H^l . d_H^l$. And the resultant code product distance for the lth, d_P^l is given by $d_P^l \geq (\delta_P^l)^{d_H^l}$ [6].

In this paper we use multidimensional constellations as initial constellation, the Cartesian products of 2-dimensional 8-PSK modulations, that is, $n = 2$. We have 2-dimensional non-uniform constellations, S_1 e S_2 as shown in Figure 3. The third one S_3 is a uniform constellation, but the total set of signals of the multidimensional constellation was reduced for only 32 signals (8 x 8) - PSK to achieve UEP properties as in the case of non-uniform constellations.

Usually in multilevel constructions, the minimum squared Euclidean distance between two signals increases successively in each level of the partitions. In this case, however, as we need to have unequal error protection, and we will make multistage decoding, it is interesting to have great distances in the first levels whenever possible. To illustrate this fact we will show the first levels of the partition made in the constellation $(S_3)^2$, with the distances δ_P^l e δ_H^l in each level. We initially have a set with 32 signals.

$$\Omega = \begin{bmatrix} 17 & 27 & 31 & 41 & 57 & 67 & 71 & 01 \\ 10 & 20 & 32 & 42 & 50 & 60 & 72 & 02 \\ 13 & 23 & 35 & 45 & 53 & 63 & 75 & 05 \\ 14 & 24 & 36 & 46 & 54 & 64 & 76 & 06 \end{bmatrix}$$

In the first level, the minimum Hamming distance δ_H^1 is equal to 1, and the minimum product distance δ_P^1 is 3,41. The two subsets are shown below.

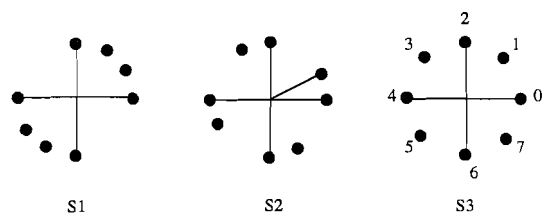Fig.2-Scheme of a multilevel coding system

Fig. 3 - Signal constellations S_1, S_2, S_3.

$$\Omega_0 = \begin{bmatrix} 17 & 27 & 31 & 41 \\ 10 & 20 & 32 & 42 \\ 13 & 23 & 35 & 45 \\ 14 & 24 & 36 & 46 \end{bmatrix}$$

$$\Omega_1 = \begin{bmatrix} 57 & 67 & 71 & 01 \\ 50 & 60 & 72 & 02 \\ 53 & 63 & 75 & 05 \\ 54 & 64 & 76 & 06 \end{bmatrix}$$

In the second level the minimum Hamming distance between the signals is equal to 1 again, and the minimum product distance 3,41. The four subsets are shown below respectively.

$$\Omega_{00} = \begin{bmatrix} 17 & 27 & 31 & 41 \\ 10 & 20 & 32 & 42 \end{bmatrix}$$

$$\Omega_{01} = \begin{bmatrix} 13 & 23 & 35 & 45 \\ 14 & 24 & 36 & 46 \end{bmatrix}$$

$$\Omega_{10} = \begin{bmatrix} 57 & 67 & 71 & 01 \\ 50 & 60 & 72 & 02 \end{bmatrix}$$

$$\Omega_{11} = \begin{bmatrix} 53 & 63 & 75 & 05 \\ 54 & 64 & 76 & 06 \end{bmatrix}$$

In the next three levels we will have respectively the Hamming distances 2,1 and 2. And the product distances 2, (0,58) and $(0,58^2)$.

The partitions of constellations $(S_1)^2$ and $(S_2)^2$ can be described by using Cartesian products of subsets of S_1 and S_2, respectively. In the following, we show these products for levels 1, 2 and 3 of the partition.

Partition of $(S_1)^2$

Level

1 $\Omega_0 = \{0,1,2,3\} \times \{0,1,...,7\}$, $\Omega_1 = \{4,5,6,7\} \times \{0,1,...,7\}$

2 $\Omega_{00} = \{0,1,2,3\} \times \{0,1,2,3\}$, $\Omega_{01} = \{0,1,2,3\} \times \{4,5,6,7\}$

$\Omega_{10} = \{4,5,6,7\} \times \{0,1,2,3\}$, $\Omega_{11} = \{4,5,6,7\} \times \{4,5,6,7\}$

3 $\Omega_{000} = \{0,2\} \times \{0,1,2,3\}$, $\Omega_{001} = \{1,3\} \times \{0,1,2,3\}$

$\Omega_{010} = \{0,2\} \times \{4,5,6,7\}$, $\Omega_{011} = \{1,3\} \times \{4,5,6,7\}$

$\Omega_{100} = \{4,6\} \times \{0,1,2,3\}$, $\Omega_{101} = \{5,7\} \times \{0,1,2,3\}$

$\Omega_{110} = \{4,6\} \times \{4,5,6,7\}$, $\Omega_{111} = \{5,7\} \times \{4,5,6,7\}$

Partition of $(S_2)^2$

Level

1 $\Omega_0 = \{0,1,4,5\} \times \{0,1,...,7\}$, $\Omega_1 = \{2,3,6,7\} \times \{0,1,...,7\}$

2 $\Omega_{00} = \{0,1,4,5\} \times \{0,1,4,5\}$, $\Omega_{01} = \{0,1,4,5\} \times \{2,3,6,7\}$

$\Omega_{10} = \{2,3,6,7\} \times \{0,1,4,5\}$, $\Omega_{11} = \{2,3,6,7\} \times \{2,3,6,7\}$

3 $\Omega_{000} = \{0,4\} \times \{0,1,4,5\}$, $\Omega_{001} = \{1,5\} \times \{0,1,4,5\}$

$\Omega_{010} = \{0,4\} \times \{2,3,6,7\}$, $\Omega_{011} = \{1,5\} \times \{2,3,6,7\}$

$\Omega_{100} = \{2,6\} \times \{0,1,4,5\}$, $\Omega_{101} = \{3,7\} \times \{0,1,4,5\}$

$\Omega_{110} = \{2,6\} \times \{2,3,6,7\}$, $\Omega_{111} = \{3,7\} \times \{2,3,6,7\}$

The multistage decoding method used is a sub optimum method, which has an excellent trade off between error probability and implementation complexity [7,1]. The idea of multistage decoding is to decode the received word $\vec{R} = (\vec{r}_1, \vec{r}_2, \cdots, \vec{r}_N)$ in L stages passing the codeword of code C_i estimated in the i-th stage, i=1,2,...,L -1, to the subsequent stages. At the first stage, for each received vector $\vec{r}_k$, k=1,2, ... , N, the decoder obtains the nearest multidimensional M-PSK signals in subsets Ω_0, Ω_1 and their squared Euclidean distances $d^2(\vec{r}_k, s(\Omega_0))$, $d^2(\vec{r}_k, s(\Omega_1))$. Based on this information, the decoder of C_1 chooses the codeword $\vec{c}_1 = (c_{11}, c_{12}, ..., c_{1N})$ which minimizes $\sum_{k=1}^{N} d^2(\vec{r}_k, s(\Omega_{c_{1k}}))$. This codeword is passed to the subsequent decoders. At the second stage, for each received vector $\vec{r}_k$, k=1,2, ... , N, the decoder of C_2 obtains the nearest multidimensional M-PSK signals in subsets $\Omega_{c_{1k},0}, \Omega_{c_{1k},1}$ and their squared Euclidean distances $d^2(\vec{r}_k, s(\Omega_{c_{1k},0}))$, $d^2(\vec{r}_k, s(\Omega_{c_{1k},1}))$. Based on this information, the decoder of C_2 chooses the codeword $\vec{c}_2 = (c_{21}, c_{22}, ..., c_{2N})$ which minimizes $\sum_{k=1}^{N} d^2(\vec{r}_k, s(\Omega_{c_{1k},c_{2k}}))$. This codeword is passed to the subsequent decoders. This process is repeated in all subsequent stages always using the estimates of previous stages until the codeword $\vec{c}_L = (c_{L1}, c_{L2}, ..., c_{LN})$ is estimated and the multistage decoding is complete.

The above described partitions of constellations $(S_1)^2$ and $(S_2)^2$ simplify the multistage decoding. The nearest multidimensional M-PSK signals in subsets Ω_0, Ω_1 and their squared Euclidean distances $d^2(\vec{r}_k, s(\Omega_0))$, $d^2(\vec{r}_k, s(\Omega_1))$ can be calculated based solely on the nearest M-PSK signals and their distances in the two-dimensional subsets $\{0,1,2,3\}, \{4,5,6,7\}, \{0,1,...,7\}$ for $(S_1)^2$ and $\{0,1,4,5\}, \{2,3,6,7\}, \{0,1,...,7\}$ for $(S_2)^2$. A similar

Level	B_1		B_2		B_3	
l	$(d^l_H)_{res}$	d^l_p	$(d^l_H)_{res}$	d^l_p	$(d^l_H)_{res}$	d^l_p
1	2	4	4	1	4	3.41^4
2	2	4	4	1	4	3.41^4
3	1	0.26	4	3.73^4	2x1	2
4	1	0.26	4	3.73^4	1	0.58
5	1	1	1	0.26	2x1	0.58^2
6	1	1	1	0.26	-	-

Table 1.

procedure can be applied to compute the nearest signals and their squared distances for the second stage. At the third stage and subsequent stages we need additionally the nearest M-PSK signals and their distances in the two-dimensional subsets $\{0,2\},\{1,3\},\{4,6\},\{5,7\}$ for $(S_1)^2$ and $\{0,4\},\{1,5\},\{2,6\},\{3,7\}$ for $(S_2)^2$.

5.EXAMPLES

We present some examples of construction.

Example1: We consider a binary partition of the 4-dimensional signal constellation $(S_1)^2$. The first and the second levels of the partition are encoded by the code $C_1=C_2=(16,15,2)$. We left the other levels uncoded, i.e. $C_3= C_4= C_5= C_6= (16,16,1)$. The rate of the multilevel code B_1 is then 2.94 bits/symbol. The distance profile of B_1 is given in Table 1. From the table we expect three different levels of protection: the information bits of C_1 and C_2 should have lower error probability than those of C_5 and C_6. C_3 and C_4 should have worse performance than C_5 and C_6. The information bits of C_1 and C_2 represent an amount of 30% of important data.

Example 2: We consider a binary partition of the 4-dimensional signal constellation $(S_2)^2$. The first and the second levels of the partition are encoded by the code $C_1= C_2 = C_3 = C_4= (8,4,4)$. We left the others levels uncoded. The rate of the multilevel code B_2 is then 2.0 bits/symbol. The distance profile of B_2 is given in Table 1. From the table we expect three different levels of protection: the information bits of C_3 and C_4 should have a slightly lower error probability than those of C_1 e C_2 and much lower than the uncoded bits of the levels 5 and 6.

The information bits of C_3, C_4, C_1 and C_2 represent an amount of 50% of important data.

Example 3: In this example we consider a binary partition of a subset of the 4-dimensional signal constellation $(S_3)^2$ with only 32 signals. The first and the second levels of the partition are encoded by the code $C_1=C_2=(8,4,4)$. We left the others levels uncoded. The rate of multilevel code B_3 is then 2.0 bits/symbol. The distance profile of B_3 is given in Table 1. The information bits of C_3, C_1 and C_2 represent an amount of 50% of important data.

6. SIMULATION RESULTS

We have simulated the transmission of blocks of 159 information bits using encoders for the multilevel codes B_2 and B_3 at the transmitter and standard multistage decoding at the receiver. For code B_1, blocks of 94 information bits were used. The coding gains are considered over uncoded 4-PSK and to a bit error probability of 10^{-3}.

Figure 4 shows simulations results for code B_1. The figure shows the expected three levels of protection. The coding gains are about 9dB, -4dB and -6dB for the first, the second and the third level, respectively.

Figure 5 shows simulations results for code B_2. The figure shows the expected three levels of protection. The coding gains are about 16dB, 15dB and -8dB for the first, the second and the third level, respectively.

Figure 6 shows simulation results for code B_3. The figure shows four levels of protection: the information bits of the binary component codes C_1, C_2 form the first level, the information bits of C_3 the second level, of C_5 the third level and of C_4 the fourth level. The coding gains are about 19dB, 12dB, -4dB e -8dB for the first, the second, the third and the fourth level, respectively.

It is possible to modify the codes of the above examples to obtain some gain for the less important data while sacrificing the data rate of the multilevel code or some of the gain of the most important data.

The overall performances of the coded systems has been evaluated by using the speech SEGSNR (defined in Section 2) as an objective quality measure [4,8]. Figure 7 shows the SEGSNR (as a function of E_b/N_0) for three different systems. Curves CS_3, CS_2 and CS_1 show the behaviour of the VSELP codec together with code B_3, code B_2 and uncoded 4-PSK modulation, respectively. At a speech SEGSNR of 2.0 dB the coding gain of system CS_2 over CS_3 is about 14.0 dB. System CS_1 achieves an additional gain of about 2.0 dB.
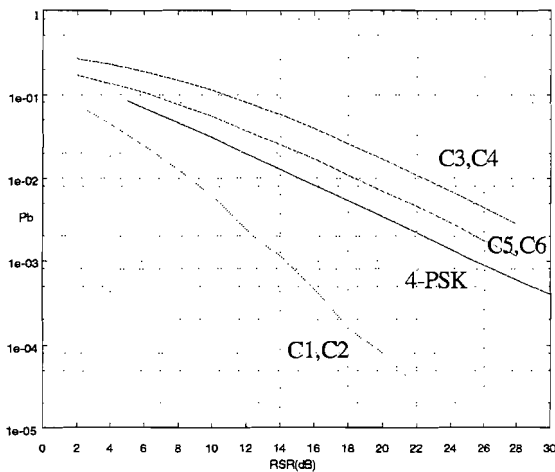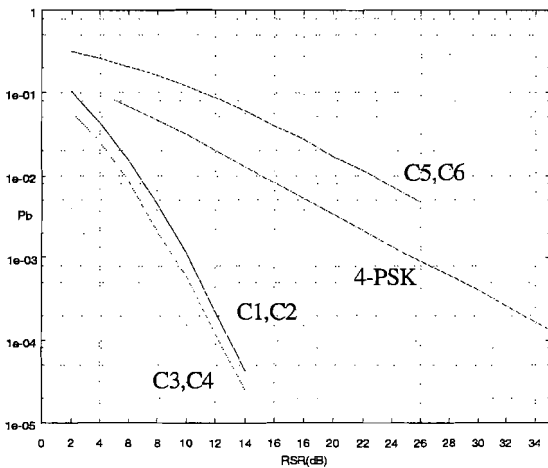
coding gain of 16.0 dB (at a SEGSNR of 2.0 dB) in comparison with a system that employs uncoded 4-PSK modulation. It is important to notice that this gain is obtained although the less important data is under the effect of a bit error probability worse than that of uncoded transmission.

Acknowledgments

Fig.4 - Performance of code B_1

Fig.5 - Performance of code B_2

Fig.6 - Performance of code B_3

Fig. 7 - Speech SEGSNR versus Channel SNR

7. CONCLUSIONS

We have described the construction of new multilevel block codes with UEP based on uniform and non-uniform 4-dimentional 8-PSK modulations.   One of the constructed codes (code B_3) has four levels of UEP and when used together with a VSELP codec achieves a
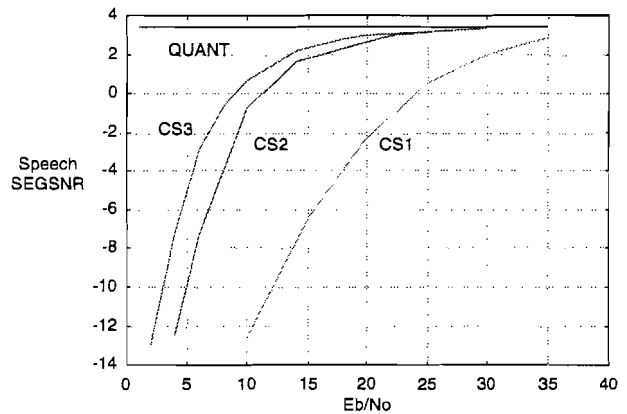
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