LETTER Special Section on Multi-dimensional Mobile Information Networks

Performance Bounds in Convolutional Coded Parallel Combinatorial SS Systems

Ken-ichi TAKIZAWA[†a)], ***Student Member***, **Shigenobu SASAKI**[†],
Shogo MURAMATSU[†], ***Regular Members***, **Jie ZHOU**[†], ***Student Member***,
and **Hisakazu KIKUCHI**[†], ***Regular Member***

SUMMARY Upper bounds on the bit error rate (BER) for maximum likelihood (ML) decoding are derived in convolutional coded parallel combinatorial spread spectrum (PC/SS) systems over additive white Gaussian noise (AWGN) channels. PC/SS systems can achieve higher data transmission than conventional multicode SS systems. To make the derivation tractable, we put a uniform interleaver between a convolutional encoder and a PC/SS transmitter. Since the PC/SS transmitter is employed as the "inner encoder," the bounds are obtained in a similar manner of the derivation in serially concatenated codes through a uniform interleaver. Two different error patterns in the PC/SS system are considered in the performance analysis. Numerical results show that the derived BER bounds are sufficiently accurate. It is found that the coded PC/SS systems outperform coded all-code-parallel DS/SS systems under the same data rate conditions if the number of pre-assigned PN codes increases.
key words: *multicode SS, convolutional codes, iterative demodulation and decoding*

1. Introduction

Because of their many useful properties for wireless communications such as anti-interference and multipath mitigation property, direct sequence spread spectrum (DS/SS) systems have been applied to various wireless radio applications including wireless local area network (LAN) [1], third generation mobile communication systems by code division multiple access (CDMA) air interfaces [2], [3], and so on. Future wireless data transmission systems require higher data rate to support various multimedia data. Potential candidates in high-rate data transmission scheme are multicode SS systems [4] and multicarrier SS systems [5] in CDMA applications. In this paper, we focus on multicode SS systems. Parallel combinatorial spread spectrum (PC/SS) systems [6] have been proposed as one of multicode SS systems with a capability of high-speed data transmission. PC/SS systems have higher-rate data transmission capability than conventional multicode DS/SS systems by transmitting plural orthogonal spreading codes out of pre-assigned orthogonal spreading codes and by the phase modulation to the transmitting PN codes.

In general, higher-rate data transmission costs larger signal power or higher signal-to-noise ratio (SNR) to maintain required error rate performance. We have investigated various error-correcting codes (ECC) to the PC/SS systems, and Reed-Solomon (RS) code is a suitable coding scheme for PC/SS systems. Error-and-erasure decoding strategy with a simple erasure decision rule has been also investigated for performance improvements in the RS-coded PC/SS systems [7], [8]. Recently, iterative decoding using soft information has been recognized as an attractive solution to achieve large coding gain in parallel and serially concatenated codes [9], [10]. Iterative demodulation/decoding that is an application of iterative decoding has been also paid much attention [11], [12]. We have proposed iterative demodulation/decoding strategy [13] as a decoding method for channel coded PC/SS systems, and a significant improvement in the error rate performance has been demonstrated through computer simulation results. Since the error rate evaluation by using computer simulations requires huge computation, the derivation of error rate bounds in a simple form is highly desirable.

In this paper, upper bounds on the bit error rate (BER) performance are derived in convolutional coded PC/SS systems through a uniform interleaver with maximum likelihood (ML) decoding over additive white Gaussian noise (AWGN) channels. To make the analysis tractable, we put a uniform interleaver between a convolutional encoder and a PC/SS transmitter. The derivation of the upper bound is based on that in serially concatenated codes through a uniform interleaver [10], because the PC/SS transmitter plays the role of inner encoder in this system. In PC/SS systems, input data is transformed to a combination of transmitting PN codes with polarity. We use squared Euclidean distance instead of Hamming distance to analyze the number of codewords for the coded PC/SS systems through a uniform interleaver. The derived bounds are compared with simulation results and the BER bounds in convolutional-coded multicode SS systems under the same data rate conditions.

This paper is organized as follows. The system model of convolutional coded PC/SS systems through

Manuscript received October 26, 2001.
Manuscript revised February 6, 2002.
Final manuscript received March 20, 2002.
[†]The authors are with the Department of Electrical and Electronic Engineering, Niigata University, Niigata-shi, 950-2181 Japan.
a) E-mail: takizawa@telecom0.eng.niigata-u.ac.jp

a uniform random interleaver is described in Sect. 2. Upper bounds on the BER performance are derived in Sect. 3. Numerical results and discussions are presented in Sect. 4. Finally, we present some conclusions in Sect. 5.

2. System Model of Convolutional Coded PC/SS Systems

2.1 PC/SS System Configuration

In PC/SS systems, a set of M orthogonal pseudo-noise (PN) codes is assigned for an individual user. Information data is conveyed by transmitting r orthogonal PN codes out of the pre-assigned M orthogonal PN codes. We denote such PC/SS system as (M, r)-PC/SS system. Additional information data is conveyed by a binary phase shift keying (BPSK) modulation for the transmitting codes. The total amount of information data per PN period is given by

$$K = r + \left\lfloor \log_2 \binom{M}{r} \right\rfloor \text{ [bits]} \tag{1}$$

where $\lfloor x \rfloor$ denotes the maximum integer that is less than x. The first term stands for the phase data of each transmitting PN codes, and the second term stands for the combination data of transmitting PN codes.

The $K-r$ bit-combination data is converted into a constant weight code (CWC) codeword whose length is M and Hamming weight is r. In this paper, we employ the Shalkwijk's CWC [14], because this CWC meets the second term in (1) conceptually. The elements of the CWC codeword represent the on-off sign of the pre-assigned orthogonal PN codes. The r corresponding PN codes to the non-zero elements are transmitted. The transmitting PN codes are modulated by the r bit-phase data. Then, the PC/SS transmitter transmits a summation of the r modulated PN codes.

PC/SS systems have potential capability of higher speed data transmission than conventional multicode SS systems. The maximum bit rate K/M in PC/SS systems is shown in Fig. 1. The maximum bit rates in conventional multicode SS systems are also displayed. All-code-parallel DS/SS systems [15] and M-ary DS/SS systems [16] are considered as conventional multicode SS systems. In fact, all-code-parallel DS/SS system is the particular case of the PC/SS system with $r = M$. The maximum bit rate in the PC/SS systems can be higher than that in the conventional multicode SS systems by suitable selection of r.

The PC/SS systems are modeled as Fig. 2. Now we define a modulated CWC codeword $\mathbf{x}$ as

$$\mathbf{x} = \{x_1, \ldots, x_j, \ldots, x_M\}, x_j \in \{-1, 0, +1\} \tag{2}$$

which is the CWC codeword whose non-zero elements are modulated by phase data. A set of the pre-assigned orthogonal PN codes with length l is represented as

$$\mathbf{H} = \begin{pmatrix} h_{1,1} & \ldots & h_{1,l} \\ \vdots & \ddots & \vdots \\ h_{M,1} & \ldots & h_{M,l} \end{pmatrix} \tag{3}$$

Each row of the matrix $\mathbf{H}$ is one of the pre-assigned orthogonal PN codes. The transmitting signal is then expressed by

$$\mathbf{s} = \mathbf{x} \cdot \mathbf{H} \tag{4}$$

$$\mathbf{s} = \{s_1, s_2, \ldots, x_l\} \tag{5}$$

At the receiver, coherent detection is assumed, and the received signal $\mathbf{r}$ is given by

$$\mathbf{r} = \mathbf{s} + \mathbf{n} \tag{6}$$

$$\mathbf{r} = \{r_1, r_2, \ldots, r_l\} \tag{7}$$

where $\mathbf{n}$ is an AWGN vector with $N_0/2$ double-sided power spectral density.

$$\mathbf{n} = \{n_1, n_2, \ldots, n_l\} \tag{8}$$

The received signal $\mathbf{r}$ is fed to a correlator bank (CB) that consists of M correlators corresponding to the pre-assigned orthogonal PN codes, individually. The set of correlator outputs is given by

$$\mathbf{z} = (\mathbf{r} \cdot \mathbf{H}^t)/M \tag{9}$$

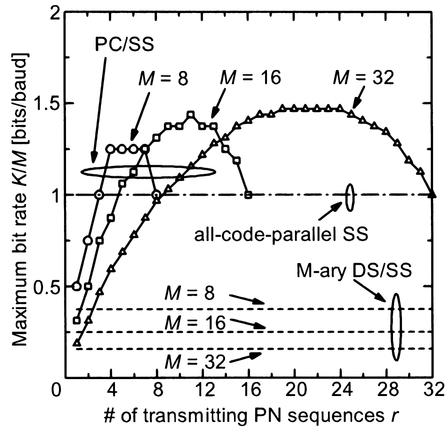


Fig. 1 Comparison of the maximum bit rate in the PC/SS systems, all-code-parallel multicode DS/SS systems, and M-ary DS/SS systems (M = 8, 16 and 32).

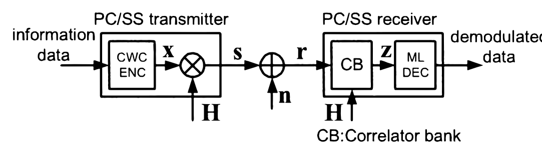


Fig. 2 PC/SS sytem model.

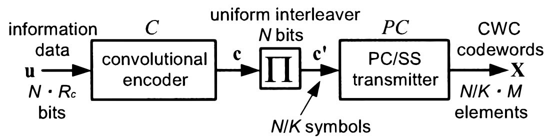


Fig. 3 Transmitter system model for a channel coded PC/SS system through a uniform interleaver.

$$\mathbf{z} = \{z_1, \ldots, z_j, \ldots, z_M\} \tag{10}$$

where $\mathbf{H}^t$ denotes a transpose matrix of $\mathbf{H}$. The correlator output $\mathbf{z}$ is the received codeword for a transmitted codeword $\mathbf{x}$.

The ML decoder computes the conditional probability $P(\mathbf{z}|\mathbf{x})$ for each codeword $\mathbf{x}$ and selects the codeword with the largest conditional probability as the estimate of the actually transmitted codeword. The conditional probability $P(\mathbf{z}|\mathbf{x})$ is given by

$$P(\mathbf{z}|\mathbf{x}) = \prod_{j=1}^{M} \frac{1}{\sqrt{2\pi}\sigma_c} \exp\left\{ - \frac{(z_j - x_j)^2}{2\sigma_c^2} \right\} \tag{11}$$

where the variance σ_c^2 is given by

$$\sigma_c^2 = \left(\frac{2KE_b}{rN_0} \right)^{-1} \tag{12}$$

In (12), E_b/N_0 denotes the signal-to-noise ratio (SNR) per bit.

2.2 Convolutional Coded PC/SS System through a Uniform Interleaver

The system model at the transmitter side of convolutional coded PC/SS systems through a uniform interleaver is shown in Fig. 3. The $N \cdot R_c$ bit-binary information stream $\mathbf{u}$ is encoded by a convolutional encoder C. A feed-forward non-systematic convolutional encoder is considered in this paper. R_c denotes the coding rate of the employed convolutional code. The codeword $\mathbf{c}$ is permuted by a uniform interleaver whose length is N bits. A uniform interleaver is employed to make the analysis tractable, which is a probabilistic device that maps a given input word into all distinct permutations with same probability. The permuted codeword $\mathbf{c}'$ is divided into each block of K bits. Not that N/K should be an integer. A PC/SS transmitter, denoted as PC, conveys the N bit-permuted codeword by a set of N/K modulated CWC codewords

$$\mathbf{X} = \{\mathbf{x}_1, \ldots, \mathbf{x}_i, \ldots, \mathbf{x}_{N/K}\}, \qquad \mathbf{x}_i = \{x_{i,1}, \ldots, x_{i,j}, \ldots, x_{i,M}\} \tag{13}$$

where the number of the total elements in $\mathbf{X}$ is $N/K \cdot M$.

At the receiver side, a set of correlator outputs $\mathbf{Z}$ is obtained, which is represented as

$$\begin{aligned} \mathbf{Z} &= \{\mathbf{z}_1, \ldots, \mathbf{z}_i, \ldots, \mathbf{z}_{N/K}\} \\ &= \{\mathbf{x}_1 + \mathbf{n}_1, \ldots, \mathbf{x}_i + \mathbf{n}_i, \ldots, \mathbf{x}_{N/K} + \mathbf{n}_{N/K}\} \\ \mathbf{z_i} &= \{z_{i,1}, \ldots, z_{i,j}, \ldots, z_{i,M}\}, \\ \mathbf{n_i} &= \{n_{i,1}, \ldots, n_{i,j}, \ldots, n_{i,M}\} \end{aligned} \tag{14}$$

where $n_{i,j}$ is a zero mean Gaussian noise sample with variance σ_c^2.

The ML decoder selects an information data as the estimate of the actually transmitted information data from the set of correlator outputs $\mathbf{Z}$.

3. Upper Bounds on the BER Performance

3.1 Pairwise Error Probability in Coded PC/SS Systems

An error event occurs in the ML decoder whenever the received codeword $\mathbf{Z}$ is closer to an erroneous codeword $\hat{\mathbf{X}}$ than the correct codeword $\mathbf{X}$ in the squared Euclidean distance. The pairwise error probability, denoted by $P_{d_E^2}$, is given by

$$\begin{aligned} &P_{d_E^2} \\ &= \Pr\left\{ \sum_{i=1}^{N/K} \sum_{j=1}^{M} |z_{i,j} - x_{i,j}|^2 \geq \sum_{i=1}^{N/K} \sum_{j=1}^{M} |z_{i,j} - \hat{x}_{i,j}|^2 \right\} \\ &= \Pr\left\{ 2 \sum_{i=1}^{N/K} \sum_{j=1}^{M} n_{i,j}(\hat{x}_{i,j} - x_{i,j}) \geq d_E^2 \right\} \end{aligned} \tag{15}$$

where d_E^2 is the squared Euclidean distance between $\mathbf{X}$ and $\hat{\mathbf{X}}$, that is

$$d_E^2 \equiv \sum_{i=1}^{N/K} \sum_{j=1}^{M} |x_{i,j} - \hat{x}_{i,j}|^2 \tag{16}$$

In this analysis, we will introduce a random variable

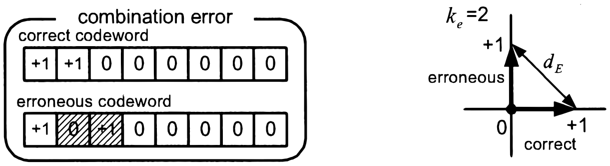
$$A = 2 \sum_{i=1}^{N/K} \sum_{j=1}^{M} n_{i,j}(\hat{x}_{i,j} - xi,j) \tag{17}$$

Since $n_{i,j}$ is a zero mean Gaussian noise sample with variance σ_c^2, the random variable A is a Gaussian variable with zero mean and variance $\sigma_A^2 = 4d_E^2\sigma_c^2$. Thus, the $P_{d_E^2}$ can be expressed as

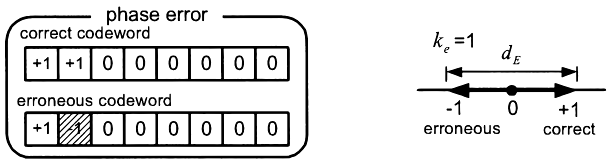
$$\begin{aligned} P_{d_E^2} &= \frac{1}{\sqrt{2\pi}\sigma_A} \int_{d_E^2}^{\infty} \exp\left(-\frac{a^2}{2\sigma_A^2} \right) da \\ &= \frac{1}{2} erfc\left(\sqrt{\frac{d_E^2 R_c K E_b}{4rN_0}} \right) \end{aligned} \tag{18}$$

where $erfc(x)$ is the complementary error function defined by

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_{x}^{\infty} \exp\left(-t^2\right) dt \tag{19}$$



(a) Combination error.



(b) Phase error.

Fig. 4 A phase error and a combination error pattern that give a minimum distance in terms of the squared Euclidean distance in (8, 2)-PC/SS system. The minimum distance computation for individual error patterns on the k_e-dimensional Euclidean subspace is also shown.

The distance d_E^2 is defined as the squared Euclidean distance between a correct codeword and an erroneous one. In general, a correct codeword will be transformed into an erroneous codeword with a smaller distance more frequently. The squared Euclidean distance can be computed in the M-dimensional Euclidean space. However, the distance is obtained easily by the computation in the sub space that is constructed by only different symbol dimensions between a correct and an erroneous codeword. If the number of different codeword elements between a correct and an erroneous codeword is k_e, the squared Euclidean distance is computed in k_e-dimensional Euclidean space.

In PC/SS systems, there are two types of the error event. The first is a combination error, and the other is a phase error. An error codeword for each error type is shown in Fig. 4. A combination error comes from the erroneous estimation of the transmitted orthogonal PN codes. A phase error comes from the erroneous estimation of the phase in the correlator output with respect to the estimated PN code that has been transmitted. If the number of phase errors and the number of combination errors is given by n_{es} and n_{ec}, respectively, the squared Euclidean distance d_E^2 is

$$d_E^2 = n_{ec} + 4n_{es} \tag{20}$$

and

$$n_{ec} + n_{es} = k_e \tag{21}$$

The minimum distance of combination error events is observed when only one transmitted PN code is wrongly estimated as displayed in Fig. 4(a), where n_{ec} is two, nes is zero, and k_e is two. The minimum squared Euclidean distance becomes two. On the other hand, The minimum distance in phase error events is observed when all transmitted PN codes are correctly estimated, but the phase of one transmitted PN code is wrongly estimated as shown in Fig. 4(b), where n_{ec} is zero, n_{es} is one, and k_e is one. The minimum distance in phase error events is four, which is twice of the minimum distance in combination error events. From these results, it is found that combination error events are the dominant factor to calculate the error rate performance in PC/SS systems.

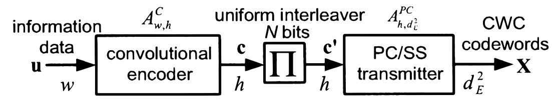


Fig. 5 Transmitter model of convolutional coded PC/SS systems through an N-bit uniform interleaver. w, h and d_E^2 denotes the squared Euclidean distance of information data, codeword and CWC codewords from a correct codeword, respectively.

3.2 The Number of the Codewords for the Coded PC/SS Systems through a Uniform Interleaver

It is key issue to obtain the average distance distribution of an overall convolutional coded PC/SS system in deriving the error rate bounds. The transmitter part in the coded PC/SS system is shown again in Fig. 5. In this figure, w, h and ${d_E}^2$ denotes the squared Euclidean distance of information data $\mathbf{u}$, permuted codeword $\mathbf{c}'$ and CWC codeword set $\mathbf{X}$, from a correct codeword, respectively.

Let A^{C-PC}_{w,d_E^2} denote the average number of the CWC codewords $\mathbf{X}$ of squared Euclidean distance d_E^2 generated by input information of distance w from a correct codeword. This A^{C-PC}_{w,d_E^2} is obtained approximately by the use of a uniform interleaver [10], [17], which is given by

$$A^{C-PC}_{w,d_E^2} = \sum_{h=0}^{N} \frac{A^C_{w,h} \times A^{PC}_{h,d_E^2}}{\binom{N}{h}} \tag{22}$$

where $A^C_{w,h}$ denotes the number of codewords $\mathbf{c}$ of distance h generated by information data $\mathbf{u}$ of distance w, and A^{PC}_{h,d_E^2} denotes the average number of codewords $\mathbf{X}$ of distance d_E^2 generated by permuted codeword $\mathbf{c}'$ of distance h, form a correct codeword. This A^{PC}_{h,d_E^2} has to be averaged over the all CWC codewords because the CWC codewords $\mathbf{X}$ is a non-linear code.

3.3 Upper Bounds on the BER Performance

The BER performance for ML decoding in convolutional coded PC/SS systems is upper-bounded by

$$P_b \leq \sum_{w=1}^{NR_c} \sum_{d_E^2=1}^{d_{max}^2} A_{w,d_E^2}^{C-PC} P_{d_E^2}$$
$$= \frac{1}{2} \sum_{w=1}^{NR_c} \sum_{d_E^2=1}^{d_{max}^2} A_{w,d_E^2}^{C-PC} erfc\left(\sqrt{\frac{d_E^2 R_c K E_b}{4rN_0}}\right) \tag{23}$$

where d_{max}^2 denotes the maximum distance in the distance d_E^2. Not that the derived bound is an average bound for a given interleaver size.

4. Numerical Results and Discussions

Figure 6 displays the bounds for convolutional coded (8, 2)-PC/SS system. A half-rate non-systematic convolutional code is applied, whose generation polynomial is [7, 5] in an octal form. The interleaver size N is set to 120 and 240 bits, because it is difficult to compute the $A_{w,d_E^2}^{C-PC}$ with a large interleaver size entirely in terms of the computation load. Simulation results are also plotted in this figure, which are obtained by iterative demodulation and decoding [7] between the PC/SS decoder and the channel decoder. In the simulation, the MAP algorithm is used in our iterative decoder. To assure the convergence, 15 iterations are used. It is found that the derived upper bounds become loose below a certain threshold value in the E_b/N_0, but sufficiently accurate above the threshold.

Figures 7 and 8 show the BER bounds of the coded (16, 5)- and (8, 3)-PC/SS systems. Convolutional code with generation polynomial [7, 5] is employed. The coding rate R_c is 1/2. The interleaver size N is set to 128 and 256 bits. The length of the PN codes l is set to M in this paper. Therefore, the bit rate per PN code period is unity in uncoded (16, 5)- and (8, 3)-PC/SS systems. The total bit rate including the ECC becomes 0.5 [bits/baud].

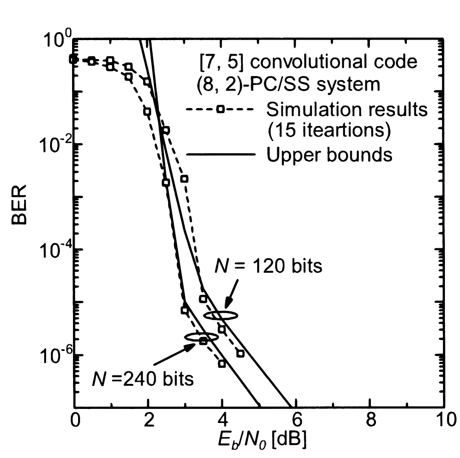


Fig. 6 Comparison the derived upper bound with simulation results in (8, 2)-PC/SS system with a uniform interleaver with length N.

BER bounds of coded all-code-parallel DS/SS systems through a uniform interleaver [18] with ML decoding have been also plotted in these figures. Generation polynomial of convolutional code, the number of pre-assigned PN codes M and the total bit rate is identical to the individual coded PC/SS systems. A rate-one encoder is assumed for inner encoder in coded all-code-parallel DS/SS systems to make a comparison under the same interleaver size condition.

In the case of M is equal to 8, the both systems are similar in the BER performance. If M is set to 16, the coded PC/SS systems have about 1 dB advantage in the required E_b/N_0 to maintain the 10^{-8} BER. This advantage of the (16, 5)-PC/SS system partly comes from the gain in the signal power energy per transmitted PN code that is determined by K/r. In the (16, 5)-PC/SS system, the K/r is 16/5. On the other hand,

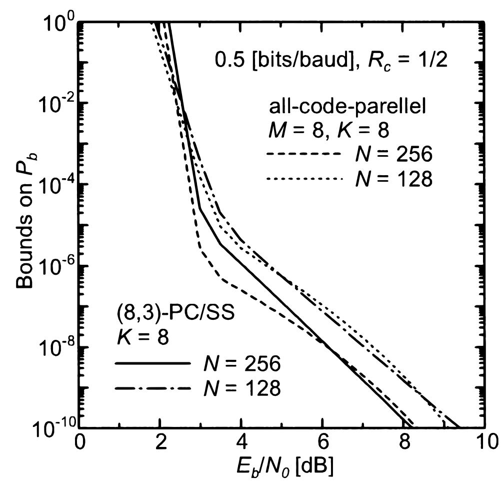


Fig. 7 BER bounds in the coded PC/SS systems with interleaver size N=128 and 256 bits. The number of PN codes M is 8.

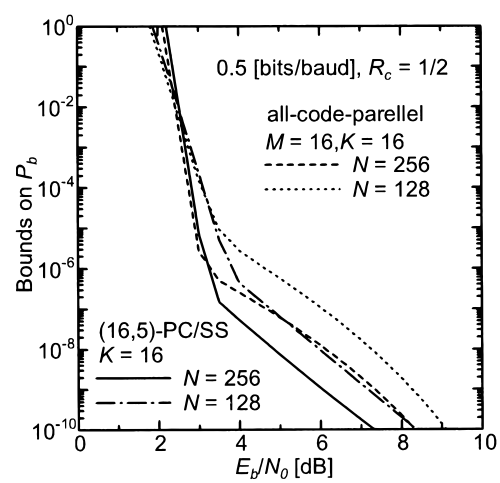


Fig. 8 BER bounds in the coded PC/SS systems with interleaver size N=128 and 256 bits. The number of PN codes M is 16.

in the (8, 3)-PC/SS system, that is 8/3. This difference leads to 0.79 dB advantage on the required E_b/N_0 for (16, 5)-PC/SS system. In the all-code-parallel DS/SS systems, the advantage is not achieved because the K/r is always unity.

5. Conclusions

Upper bounds on the BER performance has been derived in convolutional coded PC/SS systems through a uniform interleaver. The bounds have been obtained in the similar manner as the bound derivation in the SCC through a uniform interleaver except that the two different error patterns were considered in PC/SS systems. The derived BER bounds were sufficiently accurate above a certain threshold value in the E_b/N_0. It has been found that the coded PC/SS systems outperform the coded all-code-parallel DS/SS systems, if the number of pre-assigned PN codes M is set to16.

References

[1] R. van Nee, G. Awater, M. Morikura, H. Takanashi, M. Webster, and K.W. Halford, "New high-rate wireless LAN standards," IEEE Commun. Mag., pp.82–88, Dec. 1999.
[2] F. Swarts, P. van Rooyen, I. Oppermann, and M.P. Lötter, CDMA techniques for third generation mobile systems, Kluwer Academic Publishers, 1999.
[3] W. Mohr and S. Onoe, "The 3GPP proposal for IMT-2000," IEEE Commun. Mag., pp.72–81, Dec. 1999.
[4] F. Adachi, K. Ohno, A. Higashi, and Y. Okumura, "Coherent multicode DS-CDMA mobile radio access," IEICE Trans. Commun., vol.E79-B, no.9, pp.1316–1325, Sept. 1996.
[5] S. Hara and R. Prasad, "An overview of multicarrier CDMA," IEEE Commun. Mag., vol.1, pp.126–133, Dec. 1997.
[6] S. Sasaki, J. Zhu, and G. Marubayashi, "Performance of parallel combinatory spread spectrum communication systems," Proc. IEEE PIMRC'91, pp.204–208, London, UK, Sept. 1991.
[7] K. Takizawa, S. Sasaki, H. Kikuchi, and G. Marubayashi, "Use of erasure information in parallel combinatorial spread spectrum systems," Proc. IEEE VTC'00-Spring, pp.2280–2284, Tokyo, May 2000.
[8] S. Sasaki, K. Takizawa, S. Muramatsu, and H. Kikuchi, "Separate FEC coding for parallel combinatorial spread spectrum communication systems," Proc. IEEE PIMRC'01, pp.F1.1–F1.5, San Diego, CA, Sept. 2001.
[9] C. Berrou, A. Glavieux, and P. Thitimajshima, "Near Shannon limit error correcting coding and decoding: Turbo-codes," Proc. IEEE ICC'93, pp.1064–1070, May 1993.
[10] S. Benedetto, D. Divsalar, G. Montorsi, and F. Pollara, "Serial concatenation of interleaved codes: Performance analysis, design, and iterative decoding," IEEE Trans. Inf. Theory, vol.44, no.3, pp.909–926, May 1998.
[11] K.R. Narayanan and L. Stüber, "Performance of trellis-coded CPM with iterative demodulation and decoding," IEEE Trans. Commun., vol.49, no.4, pp.676–687, April 2001.
[12] P. Hoeher and J. Lodge, "Turbo DPSK: Iterative differential PSK demodulation and channel decoding," IEEE Trans. Commun., vol.47, no.6, pp.837–843, June 1999.
[13] K. Takizawa, S. Sasaki, S. Muramatsu, and H. Kikuchi, "Iterative demodulation and decoding for parallel combinatorial SS systems," IEICE Trans. Fundamentals, vol.E84-A, no.12, Dec. 2001.
[14] J.P.M. Shalkwijk, "An algorithm for source coding," IEEE Trans. Inf. Theory, vol.18, no.3, pp.395–399, May 1972.
[15] N. Guo and L. Milstein, "On rate-variable multidimensional DS/SSMA with sequence sharing," IEEE J. Sel. Areas Commun., vol.17, no.5, May 1999.
[16] S. Tachikawa, "Modulation in spread spectrum communication systems," IEICE Trans. Commun., vol.E75-B, no.6, June 1992.
[17] B. Vucetic and J. Yuan, Turbo codes principles and applications, Kluwer Academic Publishers, 2000.
[18] S. ten Brink, "Iterative decoding for multicode CDMA," Proc. IEEE VTC'99-Spring, pp.1876–1880, May 1999.