

다중경로 페이딩 환경에서의 바이너리 CDMA 시스템 성능 분석

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Performance Analysis of Binary CDMA systems in Multi-Path Fading Channel

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요약

바이너리 CDMA(B-CDMA) 기술은 CDMA 신호의 크기를 일정하게 유지시키는 새로운 변조 기법이다. 다중 코드CDMA 신호를 일정한 레벨의 신호로 양자화한 후 변조함으로써 B-CDMA 기술은 CDMA 신호가 가지는 장점들을 유지하는 동시에 최대전력 대 평균전력의 비율을 감소시킨다. 본 논문에서는 확산인자가 현저히 작지 않은 가정 하에 B-CDMA시스템의 성능을 다중 경로 페이딩 환경에서 분석한다. 수학적 분석 결과는 컴퓨터 모의실험을 통하여 검증된다.

Key Words : Binary CDMA, constant envelope modulation, quantization, multi-path channel

ABSTRACT

Binary CDMA(B-CDMA) is a new modulation scheme that employs a constant envelope modulation scheme. By quantizing the envelope of multi-codes CDMA signal into a small number of levels, the B-CDMA can reduce the peak-to-average power ratio, while preserving the advantages of CDMA signaling such as the soft capacity and robustness to interference. In this paper, we analyze the performance of B-CDMA systems in multi-path channel assuming that the spreading factor is not too small. Finally, the analytic results are verified by computer simulation.

I. Introduction

In CDMA systems, multiple codes are used for data transmission of multiple users or multiple parallel data transmission of a user. However the sum of multiple codes causes a large peak-to-average power ratio(PAPR), requiring the use of linear power amplifiers with a large back-off. Binary CDMA(B-CDMA) is a new modulation

method that quantizes multi-code CDMA signal into a small number of levels for constant envelope modulation^[1]. Thus, the B-CDMA scheme can reduce the power amplifier burden, while preserving the advantages of CDMA signaling such as the soft capacity and robustness to interference. The B-CDMA system is quite suitable for wireless transmission systems that require low cost and/or low power consumption. For example, it

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can effectively be applied to wireless home net-
working and satellite communications.

The B-CDMA signal can be generated by vari-
ous methods, such as the pulse width (PW), mul-
ti-phase (MP) and code selection (CS) methods^[1].
The PW B-CDMA signal can be obtained by
transforming the magnitude of multi-level signal
into a finite number of pulse widths. The MP
B-CDMA is generated by transforming the magni-
tude of multi-level signal into a finite number of
phases. The CS B-CDMA is generated by first
selecting the spreading code according to the data
bits. Then, the selected code is modulated using
an MP B-CDMA scheme. In the PW B-CDMA
system, the transmission bandwidth increases as
the quantization level increases^[1]. In practice, the
signal can be quantized into two levels to accom-
modate the transmission bandwidth^[1]. Note that
the two-level PW B-CDMA is a special case of
the MP B-CDMA.

Nonlinear quantization in the B-CDMA signal-
ing makes it difficult to analytically evaluate the
performance. Therefore most of previous results
were obtained by computer simulation^[2,3,4]. For
example, the performance of PW B-CDMA sys-
tem was evaluated under a special condition when
the magnitude of the signal after the despreading
is constant^[3]. The performance of MP B-CDMA
system was analyzed by calculating the error
probability considering all possible combinations
of the signal^[4]. However since there are too many
combinations of the signal, this method may not
be applicable requiring extremely high computa-
tional complexity when the spreading gain is large.
Moreover most of the previous results was eval-
uated in additive white Gaussian noise (AWGN)
channel^[2,3,4].

In this paper, we analyze the performance of
MP B-CDMA system in multi-path fading channel
assuming that the spreading factor and the number
of user are not too small. Since the CS B-CDMA
is the same as the MP B-CDMA except the code
selection block^[5], the analytic results can also be
applied to the analysis of CS B-CDMA system.

II. System model

In the MP B-CDMA system, the sum of multi-
ple codes is quantized into a finite number of
levels and then modulated using a PSK modu-
lation scheme. Fig. 1 depicts the transceiver struc-
ture of a baseband-equivalent MP B-CDMA sys-
tem, where b_j denote the j -th data bit and
 $\mathbf{d} = [d_1 d_2 \dots d_N]^T$ denotes the sum of multiple
codes, given by

$$d_i = \sum_{j=1}^{N_c} b_j c_i^j \quad (1)$$

where N_c is the number of used multiple co-
des and c_i^j is the i -th chip of spreading
code $\mathbf{c}^j = [c_1^j c_2^j \dots c_N^j]^T$ for the j -th data bit
with unit power (i.e., $|c_i^j|^2 = 1$). Here, N
is the spreading factor of the spreading code.

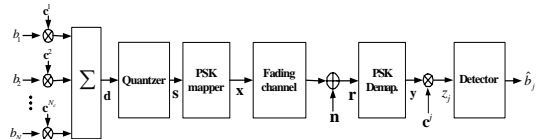


Fig. 1. MP B-CDMA transceiver structure

The sum of multiple codes is quantized as

$$s_i = f_Q(d_i) \quad (2)$$

where s_i is the i -th chip of quantized signal
 $\mathbf{s} = [s_1 s_2 \dots s_N]^T$ and $f_Q(x)$ denotes the quan-
tization function that maps the signal x in
quantization region Φ_v (i.e., $x \in \Phi_v$) onto signal
point m_v . We define quantization level ' L ' as
the number of quantization signal points. The
quantized signal s_i can be represented as

$$s_i = d_i + q_i \quad (3)$$

where q_i denotes the quantization noise. As
 L increases, the quantization noise decreases.
The quantized signal s_i is PSK-modulated at
the chip level as

$$x_i = f_{map}(s_i) \quad (4)$$

where x_i is the i -th chip of PSK modulated signal $\mathbf{x}=[x_1 \ x_2 \ \dots \ x_N]^T$ and $f_{map}(s)$ denotes the mapping function that maps the quantized signal point $s = m_v$ onto a PSK constellation μ_v as shown in Fig. 2. Note that the guard phase is required in the MP B-CDMA to reduce fatal errors between the signal points with the largest distance, such as μ_1 and μ_L [6].

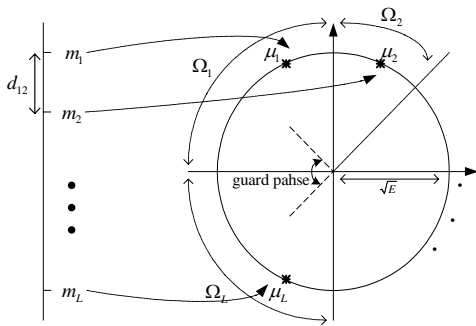


Fig. 2. PSK modulation

Since the B-CDMA is mainly intended for low cost and low power applications in mild channel environment, we consider the transmission of B-CDMA signal over a wireless channel with a line-of-sight(LOS). By assuming that the signal energy is concentrated on LOS path, the B-CDMA signal can be detected without using a rake receiver, reducing the implementation complexity. In this case the LOS path term is used for data detection and non-LOS path terms behave as the interference. Since the performance depends only on total amount of interference power, we can replace multiple non-LOS paths as a single one with the same interference power. Thus, we assume a two multi-path channel with LOS path gain h_L and effective non-LOS path gain h_N represented as

$$h_L = A + d_I + jd_Q = g_L e^{j\theta} \quad (5)$$

$$h_N = u_I + ju_Q = g_N e^{j\varphi} \quad (6)$$

where d_I and d_Q are statistically independent zero mean Gaussian random variables with the same variance σ_L^2 , A is the LOS component, u_I and u_Q are statistically independent zero mean Gaussian random variables with the same variance σ_N^2 , g_L and g_N denote the amplitude gain of the LOS and non-LOS path, respectively, and θ and φ denote the phase gain of the LOS and non-LOS path, respectively. It can be shown that the probability density function (pdf) of g_L , g_N and φ can be represented as [8]

$$p_L(g_L) = \frac{g_L}{\sigma_L^2} \exp\left(-\frac{g_L^2 + A^2}{2\sigma_L^2}\right) I_0\left(\frac{g_L A}{\sigma_L^2}\right) \quad (7)$$

$$p_N(g_N) = \frac{g_N}{\sigma_N^2} \exp\left(-\frac{g_N^2}{2\sigma_N^2}\right) \quad (8)$$

$$p_\varphi(\varphi) = \frac{1}{2\pi}, \quad 0 \leq \varphi < 2\pi \quad (9)$$

where $I_o(x)$ is the modified Bessel function of the first kind of the zero order

$$I_o(x) = \frac{1}{2\pi} \int_0^{2\pi} \exp(x \cos \psi) d\psi. \quad (10)$$

The received signal can be represented as

$$\mathbf{r} = [r_1 \ r_2 \ \dots \ r_N]^T \quad (11)$$

where r_i denotes the i -th chip of the received signal

$$r_i = h_L x_i + h_N x_{i-\Delta} + n_i \quad (12)$$

Here, n_i denotes the AWGN term in the i -th chip and Δ denote the amount of delay of the non-LOS path.

The PSK demodulator transforms the phase information of r_i into the magnitude,

$$y_i = f_{map}^{-1}(r_i) \quad (13)$$

where y_i is the PSK demodulated i -th chip signal represented as

$$y_i = s_i + e_i. \quad (14)$$

Here e_i denotes the PSK demodulation error due to the multi-path interference and AWGN.

The detection variable z_j for the j -th code can be obtained by despreading the PSK demodulated signal

$$z_j = \sum_{i=1}^N y_i c_i^j. \quad (15)$$

Since PSK demodulated signal y_i can be written in terms of quantization noise q_i and PSK demodulation error e_i as

$$y_i = \sum_{k=1}^{N_c} b_k c_i^k + q_i + e_i, \quad (16)$$

z_j can be rewritten as

$$z_j = b_j \sum_{i=1}^N c_i^j c_i^j + \sum_{k=1, k \neq j}^{N_c} b_k \left(\sum_{i=1}^N c_i^k c_i^j \right) + \sum_{i=1}^N q_i c_i^j + \sum_{i=1}^N e_i c_i^j. \quad (17)$$

Since $\sum_{i=1}^N c_i^j c_i^j = N$ and the spreading codes are orthogonal to each other, it can be shown that

$$z_j = N b_j + \sum_{i=1}^N q_i c_i^j + \sum_{i=1}^N e_i c_i^j \quad (18)$$

where the first term is the desired signal, and the second and third terms denote the quantization noise and the PSK demodulation error, respectively. Finally, the binary data is detected by

$$\hat{b}_j = \begin{cases} 1, & \text{if } z_j \geq 0 \\ -1, & \text{if } z_j < 0 \end{cases}. \quad (19)$$

III. Performance analysis

3.1 Quantization noise

Since the quantization introduces no correlation between the chips, we can assume that $q_i c_i^j, i=1,2, \dots, N$ are statistically independent and identically distributed random variables. Thus, assuming that N is not too small, the quantization noise $\sum_{i=1}^N q_i c_i^j$ can be approximated as a zero mean

Gaussian random variable with variance $N\sigma_q^2$ by the central limit theorem, where σ_q^2 is the variance of q_i .

The variance σ_q^2 can be calculated as

$$\sigma_q^2 = \sum_{v=1}^L \int_{\Phi_v} (x - m_v)^2 p_d(x) dx \quad (20)$$

where $p_d(x)$ is pdf of the sum of multiple codes d_i and the integration is performed over the quantization region Φ_v separately for each signal $x \in \Phi_v$ ($v=1, \dots, L$). The variance of quantization noise σ_q^2 highly depends on m_v and Φ_v . The optimum m_v and Φ_v minimizing σ_q^2 can be obtained using the Lloyd-max algorithm^[7]. Assuming that the number of multi-codes is not too small, the sum of multiple codes can be approximated as a Gaussian random variable. Since each chip of spreading code has unit power, the variance of d_i is equal to the number of multi-codes. Thus, the pdf of d_i can be approximated as

$$p_d(x) \cong \frac{1}{\sqrt{2\pi N_c}} \exp\left(-\frac{x^2}{2N_c}\right). \quad (21)$$

3.2 PSK demodulation error

The mean of PSK demodulation error $E\{e_i c_i^j | b_j, g_L, g_N\}$ for given b_j, g_L and g_N can be represented as (refer to Appendix)

$$E\{e_i c_i^j | b_j, g_L, g_N\} = b_j E\{e_i c_i^j b_j | g_L, g_N\} \quad (22)$$

where $E\{x\}$ denotes the expectation of x . Derivation of $E\{e_i c_i^j b_j | g_L, g_N\}$ can be found in Appendix. Denoting $\Gamma_{g_L, g_N} = E\{e_i c_i^j b_j | g_L, g_N\}$, the variance $\sigma_{e_i c_i^j}^2$ of $e_i c_i^j$ for given g_L and g_N can be represented as

$$\sigma_{e_i c_i^j}^2 = E\{|e_i c_i^j|^2 | g_L, g_N\} - (\Gamma_{g_L, g_N})^2 \quad (23)$$

where

$$E\{|e_i c_i^j|^2 | g_L, g_N\} = \sum_{v=1}^L \sum_{w=1}^L |m_w - m_v|^2 p(m_w, m_v | g_L, g_N) \quad (24)$$

where $p(m_w, m_v | g_L, g_N)$ is the probability that signal m_v is transmitted and signal m_w is detected for given channel gain g_L and g_N (Derivation of $p(m_w, m_v | g_L, g_N)$ can be found in Appendix). Since we can assume that $e_i c_i^j, i=1, 2, \dots, N$ are statistically independent and identically distributed, PSK demodulation error $\sum_{i=1}^N e_i c_i^j$ after the despreading can be approximated as a Gaussian random variable with mean $Nb_j \Gamma_{g_L, g_N}$ and variance $N\sigma_{e|g_L, g_N}^2$.

Considering the bias term $Nb_j \Gamma_{g_L, g_N}$, the detection variable z_j for the j -th user can be rewritten as

$$z_j = N(1 + \Gamma_{g_L, g_N})b_j + Q + D \tag{25}$$

where Q and D are independent zero mean Gaussian random variables with variance $N\sigma_q^2$ and $N\sigma_{e|g_L, g_N}^2$ denoting quantization noise and demodulation error, respectively. Note that Γ_{g_L, g_N} has a negative value, degrading the detection performance.

The bit error probability (BER) for given g_L and g_N can be represented as^[8]

$$P_{e|g_L, g_N} = \frac{1}{2} \operatorname{erfc} \left(\sqrt{\frac{N^2(1 + \Gamma_{g_L, g_N})^2}{N\sigma_q^2 + N\sigma_{e|g_L, g_N}^2}} \right) \tag{26}$$

where $\operatorname{erfc}(x) = 2\pi^{-1/2} \int_x^\infty e^{-t^2} dt$. Since the average BER can be obtained by integrating (26) over the channel fading gains g_L and g_N , the it can be obtained by

$$P_e = \int \int_{g_L, g_N} \frac{1}{2} \operatorname{erfc} \left(\sqrt{\frac{N(1 + \Gamma_{g_L, g_N})^2}{\sigma_q^2 + \sigma_{e|g_L, g_N}^2}} \right) p_L(g_L) p_N(g_N) dg_N dg_L \tag{27}$$

IV. Performance evaluation

To verify the analysis, the performance of two B-CDMA systems with $N=128$ and $N_c=64$ is evaluated by computer simulation in two-multi-path fading channel: One is 8-PSK system with $L=7$ with one guard phase and the other is QPSK system with $L=4$ without guard phase.

We use Walsh-Hadamard codes as the spreading code and Lloyd-max algorithm for the signal quantization. The channel condition can be characterized in terms of K and γ defined as

$$K = 10 \log_{10} \left(\frac{A^2}{2\sigma_L^2} \right) \tag{28}$$

$$\gamma = 10 \log_{10} \left(\frac{1}{2\sigma_N^2} \right) \tag{29}$$

We assume that the Rician path has unit power, i.e., $A^2 + 2\sigma_L^2 = 1$.

Fig. 3 and Fig. 4 depict the BER performance of B-CDMA systems associated with different quantization levels and interference power. It can be seen that the analytic results agree well with the simulation results but they are slightly better than the actual ones. This is mainly due to Gaussian approximation of error terms. In Fig. 3 (a), the B-CDMA with $L=4$ has floored BER performance at high SNR larger than 30dB unlike the DS-CDMA system, mainly due to the quantization noise. The effect of quantization noise can also be seen in Fig. 3 (b). Fig. 4 depicts the BER performance of B-CDMA with $L=7$. It can be seen that the performance of B-CDMA systems is improved as L increases. As a result, the BER flooring effect appears at a higher SNR with the use of $L=7$ compared to the use of $L=4$. It may be desirable to properly choose the quantization level according to the operation condition. It can also be shown that the performance of B-CDMA is highly depends on K and γ . With small K and/or γ , the BER performance of B-CDMA system may not be acceptable due to the large signal fading and/or large multi-path interference power. Thus, the B-CDMA system may mostly be applied to a mild environment such as satellite communication where strong LOS path exists with small multi-path power.

Fig. 5 depicts the performance of B-CDMA system for different values of N and N_c . Here, we assume that $L=7$ and $N=N_c/2$. The discrepancy between the analysis and simulation results is not negligible when N and

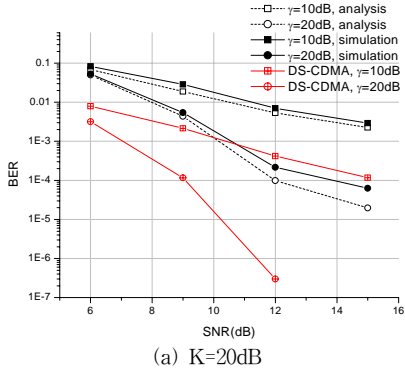
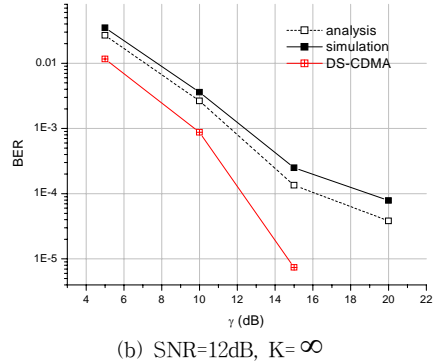


Fig. 3. BER performance with $L=4$ and $N_c=64$



(b) $SNR=12dB, K=\infty$

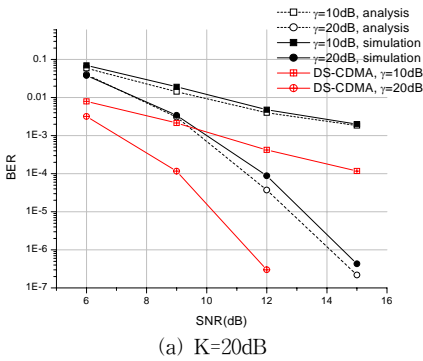
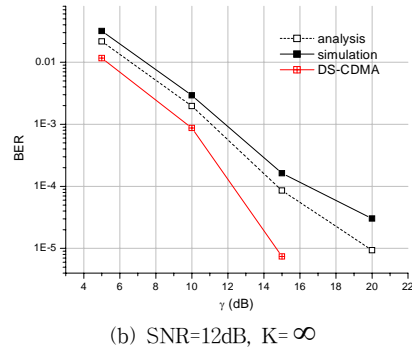


Fig. 4. BER performance with $L=7$ and $N_c=64$



(b) $SNR=12dB, K=\infty$

N_c are small. This is mainly due to the fact that the Gaussian approximation for the quantization noise and PSK demodulation error is not accurate for small values of N and N_c . But it can be seen that the difference is still in affordable range for small values of N and N_c .

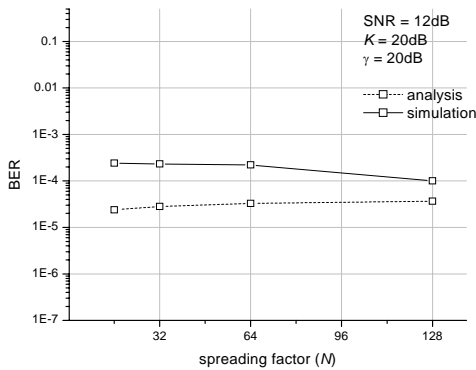


Fig. 5. BER performance with different N

V. Conclusion

In this paper, the performance of B-CDMA systems has been analyzed in terms of the BER in multi-path fading channel. Quantization noise and PSK demodulation error have been analyzed using Gaussian approximation assuming that the spreading factor is not too small. The analytic results have been verified by computer simulation. The B-CDMA can provide BER performance a few dB inferior to the DS-CDMA, while significantly reducing the implementation complexity. However, numerical results indicate that the B-CDMA system may mostly be applied to a mild environment where strong LOS path exists with small multi-path interference power. The analytic results can also be applied to other B-CDMA systems.

APPENDIX

$$\text{Derivation of } E\{e_i c_i^j b_j | g_L, g_N\}$$

Considering all the signal points, it can be seen that

$$E\{e_i c_i^j b_j | g_L, g_N\} = \sum_{v=1}^L \sum_{w=1}^L \sum_{d=\pm 1} \left\{ \begin{array}{l} (m_w - m_v) d \\ \cdot p(m_w, m_v | g_L, g_N) \\ \cdot p(c_i^j b_j = d | m_w, m_v) \end{array} \right\} \quad (A.1)$$

where $p(m_w, m_v | g_L, g_N)$ is the probability that signal m_v is transmitted and signal m_w is detected for given channel gain g_L and g_N .

A. Derivation of $p(m_w, m_v | g_L, g_N)$

Using the conditional probability, $p(m_w, m_v | g_L, g_N)$ can be rewritten as

$$p(m_w, m_v | g_L, g_N) = p(m_w | m_v, g_L, g_N) p(m_v). \quad (A.2)$$

Here, $p(m_v)$ is the probability of PSK signal point m_v represented as

$$p(m_v) \cong \int_{\Phi_v} \frac{1}{\sqrt{2\pi N_c}} \exp\left(-\frac{x^2}{2N_c}\right) dx \quad (A.3)$$

and $p(m_w | m_v, g_L, g_N)$ is the error probability that the PSK signal point is misdetected to m_w for given m_v, g_L and g_N . It can be shown that^[8]

$$p(m_w | m_v, g_L, g_N) = \int_{\Omega} \int_0^{\infty} \frac{r}{\pi E/\xi} \exp\left[-\left(\frac{r \cos(\phi - \rho_{\mu})}{\sqrt{E}(g_L + g_N \cos \phi)} \right)^2 - \left(\frac{r \sin(\phi - \rho_{\mu})}{\sqrt{E}g_N \cos \phi} \right)^2 \right] \frac{\xi}{E} dr d\phi \quad (A.4)$$

where E is the chip energy, equal to the energy of the PSK signal point, ξ is the ratio of the chip energy to AWGN spectral density, equal to E/N_o , ρ_{μ} is the phase of the l -th PSK signal point, and ϕ' is the sum of phase of $x_{i-\Delta}$ and ϕ of the non-LOS path. It can be assumed that ϕ' is uniformly distributed over $[0, 2\pi]$.

B. Derivation of $p(c_i^j b_j = d | m_w, m_v)$

Since $c_i^j b_j$ does not depend on m_w , we have

$$p(c_i^j b_j = d | m_w, m_v) = p(c_i^j b_j = d | m_v). \quad (A.5)$$

There are statistically $p(c_i^j b_j = 1 | m_v) N_c$ number of ones and $p(c_i^j b_j = -1 | m_v) N_c$ number of minus ones out of N_c multiple users' data ($c_i^k b_k, k=1, 2, \dots, N_c$) for given m_v . Thus, it can be shown that

$$m_v \cong [p(c_i^j b_j = 1 | m_v) - p(c_i^j b_j = -1 | m_v)] N_c. \quad (A.6)$$

Since $p(c_i^j b_j = 1 | m_v) + p(c_i^j b_j = -1 | m_v) = 1$, we have

$$\begin{aligned} p(c_i^j b_j = 1 | m_v) &\cong \frac{N_c + m_v}{2N_c}, \\ p(c_i^j b_j = -1 | m_v) &\cong \frac{N_c - m_v}{2N_c}. \end{aligned} \quad (A.7)$$

C. Derivation of $E\{e_i c_i^j | b_j, g_L, g_N\} = b_j E\{e_i c_i^j b_j | g_L, g_N\}$

It can be shown that $E\{e_i c_i^j b_j | g_L, g_N\}$ has a negative value. When a transmitted signal point m_v has positive amplitude, it is more likely that the PSK demodulation error $e_i (= m_w - m_v)$ has a negative value. Since m_v and q_i has zero mean and is uncorrelated with $c_i^j b_j$, it is more likely that $c_i^j b_j$ will be 1 rather than -1, causing $E\{e_i c_i^j b_j\}$ to have a negative value. Similarly, for negative values of m_v , it can be shown that the detection error e_i has a positive value rather than negative value and $c_i^j b_j$ would be -1 rather than 1. It can be seen that

$$\begin{aligned} E\{e_i c_i^j b_j | g_L, g_N\} &= \sum_{d=\pm 1} \sum_{\zeta} \zeta d p(e_i c_i^j = \zeta | b_j = d, g_L, g_N) p(b_j = d) \\ &= \sum_{d=\pm 1} d p(b_j = d) E\{e_i c_i^j | b_j = d, g_L, g_N\} \end{aligned} \quad (A.8)$$

where $p(b_j = 1) = p(b_j = -1) = 0.5$. Since the PSK demodulation error has zero mean,

$$E\{e_i c_i^j | g_L, g_N\} = \sum_{d=\pm 1} E\{e_i c_i^j | b_j = d, g_L, g_N\} p(b_j = d) = 0. \quad (A.9)$$

From (A.8) and (A.9), we can obtain that

$$\begin{aligned} E\{e_i c_i^j | b_j = 1, g_L, g_N\} &= E\{e_i c_i^j b_j | g_L, g_N\}, \\ E\{e_i c_i^j | b_j = -1, g_L, g_N\} &= -E\{e_i c_i^j b_j | g_L, g_N\} \end{aligned} \quad (A.10)$$

Denoting $E\{e_i c_i^j b_j | g_L, g_N\} = \Gamma_{g_L, g_N}$, it can be shown

$$E\{e_i c_i^j | b_j, g_L, g_N\} = b_j \Gamma_{g_L, g_N}. \quad (A.11)$$

REFERENCES

[1] H. S. An, S. M. Ryu and S. W. Na, "Introduction to Binary CDMA," *Proc. of JCCI*, VI-A.1, April 2002.

[2] S. M. Ryu, J. W. Kim, J. S. Mun and H. S. Kim, "Performance Comparison of PW/CDMA and DS/CDMA," *Proc. of JCCI*, pp. 615-618, April 2001.

[3] K. W. Ryu, Y. W. Park, H. S. An and S. M. Ryu, "A study on analysis of Clipping Error in Binary PW/CDMA System and Rejection Algorithm," *Proc. of JCCI*, VI-A.3, April 2002.

[4] C. Y. An, C. H. An, D. G. Kim and S. M. Ryu, Performance Analysis of Multi-Phased MC-CDMA System for transmitting the High Rate Data," *J. Korean Inst. of Commun. Sci.*, Vol.26, No.12, pp.1637-1646, 2001.

[5] S. P. Kim, M. J. Kim, H. S. An and S. M. Ryu, "A Constant Amplitude Coding for CS-CDMA System," *Proc. of JCCI*, VI-A.2, April 2002.

[6] I. G. Hong, A. M. An, W. M. Lee and S. M. Ryu, "Design of Signal Constellation for MP/CDMA," *Proc. of JCCI*, VI-A.4, April 2002.

[7] T. M. Cover, *Information Theory*, Wiley-Interscience, 1991.

[8] J. G. Proakis, *Digital Communications*, McGraw-Hill, 4-th ed., 2001.

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