한국통신학회논문지 '01-11 Vol.26 No.11B

Effect of Orthogonal Spreading on the Performance of Multipath Faded Multi-Code CDMA Systems

Chang Soon Kang* ***Regular Member***

ABSTRACT

This paper is concerned with the reverse link performance of multi-code CDMA systems in multipath fading environments. The degree of orthogonality loss among multiple spreading code channels is characterized as the orthogonality factor. It depends on various system parameters including multipath power profiles of propagation channels and the number of paths resolved at a Rake receiver. The effect of the parameters on the system performance is then investigated in terms of bit error rate and required signal quality. The results show that multipath delay power profiles dominantly affect mutual interference among multi-code channels and multipath combining gain by bandwidth expansion is not so great due to the increase of the mutual interference. Moreover, the orthogonality factor is derived as the value of between (1/m) and 1.

Ⅰ. Introduction

Code division multiple access (CDMA) techniques have many attractive features for application to second and third generation mobile communication systems. Two approaches for application of CDMA have been studied. These are a single-code CDMA (SC-CDMA) scheme that transmits user information on a single code channel [1], and a multi-code CDMA (MC-CDMA) technique that transmits user information with a high bit rate through multiple parallel code channels [2]. The MC-CDMA system offers the advantages of uniform and high processing gains for multiple traffic types, and can provide efficient implementation based on inherent parallelism, reduced inter-symbol interference (ISI) with a lower transmission rate, and flexible transmission of user information with a high data-rate based radio link availability [3].

The user signal power received at a base station is an important factor for determination of system performance because it is directly proportional to the user transmission power that restricts the availability of a limited power source of portable terminals. The user signal power in both CDMA systems is identical in the ideal case where spreading code channels are orthogonal [4]. However, in real environments the orthogonality is lost due to multipath propagation and different code channels in MC-CDMA systems interfere with each other [5], [6]. This mutual interference affects the user signal power of the systems.

The degree of the orthogonality loss depends on multipath delay power profiles of the propagation channel and the number of resolved paths at a Rake receiver. The effects of the power profiles and the resolved paths on the link capacity of SC-CDMA systems have been examined [7]. The orthogonality loss has been specified as the orthogonality factor in multipath fading channels [8], in which the factor was based on the signal-to-interference density ratios required for an SC-CDMA system with inter-cell interference and intracell interference. The link capacity and signal power in both of the SC- and MC-CDMA systems have also been investigated for various system parameters [9], dealing only

* 한국전자통신연구원 (cskang@etri.re.kr)
논문번호 : 010162-0628, 접수일자 : 2001년 6월 28일

with the complete loss of orthogonality among multi-code channels assigned to a user.

In this paper, the effect of orthogonal spreading on the reverse link performance of multipath faded MC-CDMA systems is investigated for various system parameters, such as multipath delay power profiles, spreading bandwidth, and multi-user interference. The degree of orthogonality loss due to multipath fading is also examined in terms of the signal to interference density ratio required for an acceptable bit error rate under given system parameters.

The rest of this paper is organized as follows. The system and propagation models considered are described in Section II. In Section III, the effect of orthogonal spreading on the reverse link performance of multipath faded MC-CDMA systems is evaluated by simulation. Conclusions are presented in Section IV.

II. System Description

1. System Model

In the MC-CDMA system considered, user information with a bit rate of R is transmitted after spreading with m parallel orthogonal code channels [2]. Thus, $R = mR1$, where $R1$ is the basic rate. When spreading codes are used in the ideal cases where the orthogonality among the code channels is maintained, mutual interference among the users code channels can be completely eliminated. However, mutual interference exists in real environments since orthogonality is lost due to multipath fading [5]. If perfect power control is assumed, then the bit energy-to-interference density ratio Eb/Nt received at a base station is maintained at a constant value. If Kmc users with a bit rate of R are conversing in a multiple cell MC-CDMA system, then the $(Eb/Nt)c$ for each code channel received at base station can be expressed as

$$\left(\frac{E_b}{N_t}\right)_c = \frac{P_1/R_1}{\{N_oW + I_{in} + I_o\}/W}$$
$$= \frac{P_1/R_1}{\{N_oW + m[(K_{mc}-1)+(1-\delta)]P_1 + I_o\}/W}, \quad (1)$$

where m is the number of spreading codes assigned to a user, $P1$ is the received signal power for each code channel, No is the thermal noise density, W is the spreading bandwidth, Iin is the inner cell interference, Io is the outer cell interference, and δ is the orthogonality factor. δ represe nts the extent of orthogonality loss, i.e., the normalized mutual interference affecting the same multi-code user. For example, δ = 1 corresponds to the perfect orthogonality such that a code channel does not interfere with the other channels assigned to the same multi-code user. When δ = 0.4, a mutual interference of 60 % remains for the same multi-code user. In addition, δ = $1/m$ represents the complete non-orthogonality such that orthogonality among the number of spreading codes of m is completely lost, and thus, the fraction of $(m-1)/m$ affects mutual interference for the same multi-code user. However, δ = 0 indicates that a base station receiver can not detect any desired user signal in all the multi-code channels because mutual interference for the same multi-code user is significantly increased. The orthogonality factor is characterized by simulation methodology to be discussed below.

In SC-CDMA systems, user information is transmitted with a single spreading code channel. Single-code user signals are always asynchronous in the reverse link, and thus, the signals do not have orthogonality in multipath fading environments. If Ksc users with a bit rate of R are allocated in a multiple cell SC-CDMA system, the Eb/Nt required for a user is obtained by substituting $m=1$, $\delta=1/m$, $Kmc = Ksc$, $R_1=R$, and $P1 = P$ into Eq. (1), where P is the received signal power for a user. The signal power in each system is proportional to user transmitting power, and is required to maintain an acceptable link quality. Hereafter, the subscripts sc and mc will be used to denote the SC-CDMA and MC-CDMA system, respectively.

2. The Orthogonality Factor

We characterize the degree of the orthogonality loss due to multipath fading (the orthogonality factor). In the reverse link of an MC-CDMA system, the user signal power received at a base station increases as the received interference increases. As a result, the *Eb/Nt* required for a multi-code user also increases to maintain a given link quality, measured as the bit error rate (BER). The required bit energy-to-interference density ratio in a nonfading channel, such as an additive white Gaussian noise (AWGN) channel, is lower than the required *Eb/Nt* in a multipath fading channel since the mutual interference due to orthogonality loss increases the received interference in the multipath fading channel. Therefore, the orthogonality factor of multi-code channels can be derived by comparing the effect of mutual interference among the multiple code channels assigned to a user on the required *Eb/Nt* in both AWGN and multipath fading channels. Thus, the orthogonality factor can be defined as

$$\delta \equiv \left(\frac{E_b}{N_o}\right)\left(\frac{E_b}{N_t}\right)^{-1}, \quad (2)$$

where *Eb/No* and *Eb/Nt* are the bit energy-to-interference density ratios in AWGN and multipath fading channels, respectively. The definition of Eq. (2) is adopted from [6], in which the values of *No* and *Nt* were considered as inter-cell interference approximated with Gaussian noise and intracell interference, respectively, in the forward link of an SC-CDMA system.

3. Propagation Model

The degree of the orthogonality loss depends on multipath delay power profiles of the propagation channel. Uniform and exponential distributions of the delay power profiles are considered. The uniform profile has *Lp* resolved paths with an equal average power. The exponential profile is a more realistic profile model where the average power decays exponentially as the path delay increases. The average of the squared path gains $E[|\xi_l|^2]$ of the l-th path is given by [5]

$$E[|\xi_l|^2] = \begin{cases} 1/L_p & \text{for } 0 \le l \le L_p - 1, \ \textit{uniform} \\ [1-\exp(-\varepsilon)]\exp(-\varepsilon l) & \text{for } 0 \le l, \text{ exponential} \end{cases} \quad (3)$$

where ε is the decay factor. In the exponential power profile, hereinafter, *(Lp)90%* will be used to represent the number of resolved paths whose total power equals 90% of the total average power.

Ⅲ. Performance Evaluation

1. Simulation Methodology

Fig. 1 shows the simulation model for derivation of the orthogonality factor in a single cell MC-CDMA system. First, user information is modulated with QPSK, spread with orthogonal Walsh codes, and randomized with a pseudo-

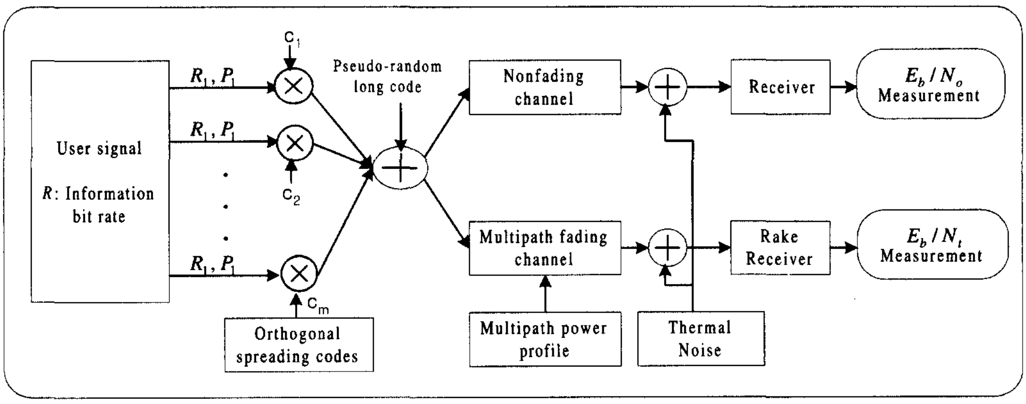

Fig. 1 Block diagram of simulation model in a single cell MC-CDMA system.

random long sequence. We investigate the orthogonality factor using simulation for an AWGN channel and multipath fading channels with two different delay power profiles. The simulations are performed for the system with only a single multi-code user. Thus, there is no other-user interference. Only mutual interference exists among multiple code channels (inter-code channel interference).

In the simulations, the parameters m = 6, *Rl = 64 kbps*, ε = 2.3/(*Lp*)90%, and *Lp* = 4, and 4 fingers at the Rake receiver are used. We generate a set of complex Gaussian path gains ξ_l's according to Eq. (3). This is repeated to obtain the average BER and the required *Eb/Nt* under AWGN and multipath fading channels (*Eb/No* in AWGN channel).

2. Effect of Orthogonal Spreading

As shown in Fig 2, for a target BER of 10^{-3}, $E_b/N_o \approx 7dB$, $(E_b/N_t)unif \approx 9dB$, and $(E_b/N_t)\exp \approx 10.2dB$ are given for the AWGN channel and multipath fading channels with uniform and exponential delay power profiles, respectively. Hence, from Eq. (2) we can obtain the orthogonality factor under the simulation conditions as 0.63 and 0.47 for uniform and exponential distributions, respectively. This indicates that the mutual interference among spreading code channels under a uniformly distributed multipath delay power profile can be more suppressed than for an exponentially distributed multipath delay power profile.

The number of resolved paths at the Rake receiver also affects the degree of orthogonality loss among multi-code channels. As the number of resolved path *Lp* increases, the multipath combining gain slightly increases (Fig. 3). For example, for a target BER of 10^{-3}, the combining gains of about 0.4 *dB* and 0.2 *dB* are achieved for uniform and exponential profiles, respectively, by a two-fold increase in the number of resolved paths. Hence, the orthogonality factors are 0.69 and 0.5 for the uniform and exponential profiles, respectively. With a two-fold increase in the number of resolved paths, the orthogonality factor increases by approximately 6%. The achieved gains are not great, because mutual interference among multi-code channels degrades the *Eb/Nt* performance (Fig. 3).

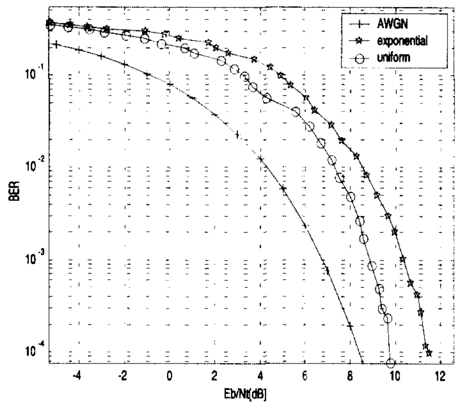

Fig. 2 Average BER versus required E_b/N_t for radio propagation channels; an AWGN channel and multipath fading channels with two different power profiles such as uniform and exponential distributions (m=6, L_p=4, the number of fingers = 4)

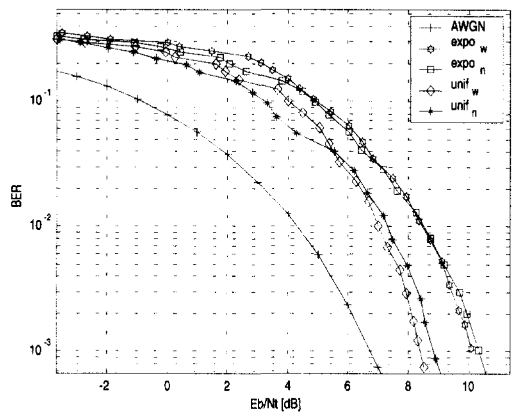

Fig. 3 Average BER versus required E_b/N_t for different multipath power profiles and the number of resolved paths (*unif*: uniform profile, *expo*: exponential profile, n: narrowband, and w: wideband): (narrowband case: processing gain = 60, R_l = 64 *kbps*, m = 6, L_p = 4, the number of fingers = 4, wideband case: processing gain = 120, R_l = 64 kbps, m = 6, L_p = 8, the number of fingers = 8).

Fig. 4 shows the effect of the decay factor in the exponential power profile on the orthogonality For a target BER of 10^{-3}, the *Eb/Nt*'s required for the exponential delay power profiles are given by 10.2 *dB* and 10.8 *dB* for the decay factors of 0.4 and 0.8, respectively. Hence, with a two-fold increase of the decay factor, the required *Eb/Nt* is increased by about 0.6 *dB*. Thus, the orthogonality factor is decreased by about 0.06. This means that mutual interference due to orthogonality loss is increased by 6% as a two-fold increase of the decay factor in the exponentially decaying multipath fading channel.

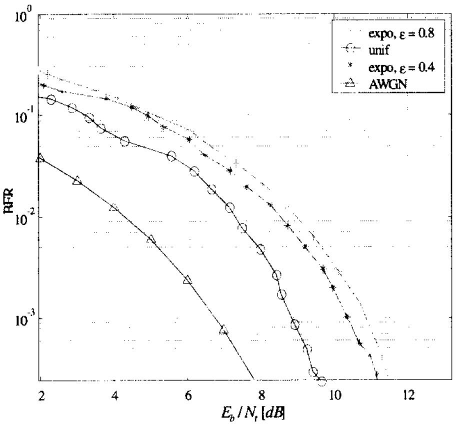

Fig. 4 Average BER versus the *Eb/Nt* required for a single user in multipath fading environments with different decay factor in the exponential power profiles (*unif*: uniform profile, *expo*: exponential profile, ε: decay factor in the exponential power profile)

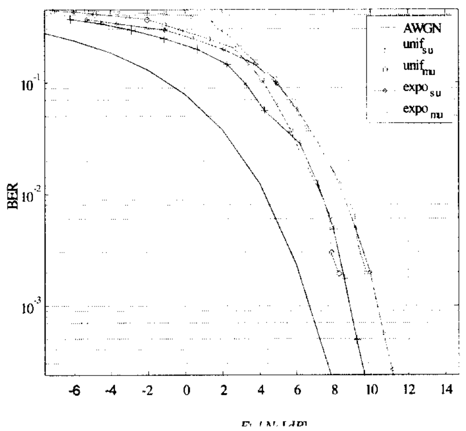

Fig. 5 Average BER versus the *Eb/Nt* required for single user and multi user cases in multipath fading environments with uniform and exponential power profiles (*unif*: uniform profile, *expo*: exponential profile, *su*: single user, and *mu*: multiple user)

To compare the effect of multi-user interference and mutaul interference on the required *Eb/Nt*, we perform another simulation. In this simulation, the multi-user interference is approximated with a Gaussian noise which has zero mean and variance of 10 *dB* over the thermal noise. Fig. 5 shows average BER against the *Eb/Nt* required for single user and multiple user cases in AWGN and multipath fading environments. For a higher BER (e.g., above 10^{-2}), the effect of the multi-user interference is greater than that of the mutual interference among multi-code channels. On the other hand, for a lower BER (e.g., below 10^{-2}) the effect of both the interference on the required *Eb/Nt* is similar to each other.

The degree of orthogonality loss varies with given fading parameter values. As a special case, when user information with very high bit rates (with a larger m) is transmitted on a severe multipath channel, the required *Eb/Nt* for multi-code users may be significantly increased due to an increase in mutual interference. As a result, a base station receiver can not detect any desired user signals from m spreading code channels in terms of an acceptable signal quality. Thus, the communication link may be disconnected (That is, *the link capacity of the system approaches zero* (See Appendix A)). In this case, the orthogonality factor approaches zero. Therefore, we can specify the orthogonality factor as the value $(1/m) \le \delta \le 1$ (For single-code systems with $m = 1$, mutual interference is absent).

Ⅳ. Conclusions

The reverse link performance of an MC-CDMA system in multipath fading environments is investigated according to various system parameters. The degree of orthogonality loss due to multipath fading is also characterized as the orthogonality factor. The results show that 1) multipath delay power profiles dominantly affect mutual interference among multi-code channels, 2) multipath combining gain by bandwidth expansion is not so great due to the increase of the mutual interference, and 3) the effect of multi-user interference is greater than that of the mutual interference among multi-code channels. Furthermore, the orthogonality factor significantly depends on the multipath delay power profiles. These results can be used for the capacity and signal power analyses of multipath faded multimedia CDMA systems, which is remained as a future study.

Appendix A

Physical meaning of $\delta=0$:

Inserting $\delta = 0$ into Eq. (1) for a single cell CDMA system with $N_o W \approx 0$, Eq. (1) can be rewritten as

$$\left(\frac{E_b}{N_t}\right)_c = \frac{(W/R_1)P_1}{m K_{mc} P_1} = \frac{W/R_1}{m K_{mc}} \equiv \gamma, \qquad \text{(A.1)}$$

where W/R_1 is the processing gain for each code channel, and γ is the target *Eb/Nt* required for an acceptable link quality. Hence, the maximum number of multi-code user that can be accommodated in the system, $K_{mc}^{\max}$ is obtained as

$$K_{mc}^{\max} = \frac{W/R_1}{m\gamma}, \qquad \text{(A.2)}$$

As shown in (A.2), if either *m* or approaches infinity, then the link capacity approaches zero, $K_{mc}^{\max} \approx 0$. Consequently, all communication links are not satisfied with a given acceptable link quality (e.g., the required *Eb/Nt*).

References

[1] A.J. Viterbi, *CDMA-Principles of spread spectrum communication*, Addison-Wesley, 1995.

[2] C.-L.I and R.D. Gitlin, "Multi-code CDMA wireless personal communications networks," in *Proc. ICC*, Seattle, WA, June 18-22, 1995, pp. 1060-1064.

[3] E. Dahlman and K. Jamal, Wide-band services in a DS-CDMA based FPLMTS system, in *Proc. VTC*, Atlanta, GA, Apr. 28-May 1, 1996, pp. 1656-1660.

[4] S.J.Lee, H.W. Lee, and D.K. Sung, Capacities of single-code and multi-code DS-CDMA systems accommodating multi-class services, *IEEE Trans. Vehic. Technol.*, vol. 48, no.2, pp. 376-384, March 1999.

[5] F. Adachi, Effects of orthogonal spreading and rake combining on DS-CDMA forward link in mobile radio, *IEICE Trans. Commun*, vol. E80-B, no. 11, pp. 1703-1712, Nov. 1997.

[6] T. Ojanpera and R. Prasad, *Wideband CDMA for third generation mobile communications*, Boston: Artech House, 1998.

[7] F. Adachi, Effects of orthogonal spreading and rake combining on DS-CDMA forward link in mobile radio, *IEICE Trans. Commun*, vol. E80-B, no. 11, pp. 1703-1712, Nov. 1997.

[8] T. Ojanpera and R. Prasad, *Wideband CDMA for third generation mobile communications*, Boston: Artech House, 1998.

[9] C.S. Kang, S.M. Shin, and D. K. Sung, Link capacity and signal power according to allocations of spreading codes and bandwidth in CDMA systems, *IEICE Trans. Commun.*, vol. E83-B, no. 4, pp. 858-860, April 2000.

강 창 순(Chang-soon Kang) 정회원

1984년 2월 : 경북대학교 전자공학과 졸업

1986년 8월 : 연세대학교 전자공학과 공학석사

2001년 2월 : 한국과학기술원 전기전자공학과 공학박사

1989년 10월~현재: 한국전자통신연구원 책임연구원

<주관심 분야> 이동통신, CDMA 무선링크 분석, 무선자원관리 (핸드오버, 전력제어, 부하제어 등)