論文 98-23-2-6

Combined Binary PPM/Biorthogonal Modulation for Direct-Sequence CDMA

Dong In Kim* *Regular Member*

직접시퀀스 부호분할 다원접속용 결합 이진 펄스위치/배직교 변조

正會員 김 동 인*

※본 논문은 정보통신연구관리단의 대학기초연구지원사업의 지원에 의하여 수행한 연구임.

ABSTRACT

A novel modulation format is proposed for cellular direct-sequence CDMA systems where a user-specific signature sequence is binary pulse position and biorthogonal modulated to form a set of biorthogonal data sequences. The modulation scheme trades the signal space used for signature sequences with that for modulation while a global space is fixed. The interference is mainly determined by the cross-correlation properties among sequences, but also affected by modulation. The effect is taken into account to evaluate the multi-user performance of the combined modulation. Compared to M-ary orthogonal modulation, the performance is shown to be almost the same while minimizing receiver complexity.

요 약

사용자 고유의 부호시퀀스를 이진 펄스위치 및 배직교 변조하여 배직교 데이터 시퀀스들의 집합을 형성하는 새로운 변조방식이 셀룰러 직접시퀀스 CDMA시스템에서 제안된다.

위 변조방식은 전체 신호공간이 유지되면서 부호시퀀스에 사용되는 신호공간과 데이터 변조용 신호공간 사이에 상호교환이 이루어진다. 사용자간 간섭은 부호시퀀스들의 상호상관 특성에 의해 주로 결정되지만 변조에 의해서도 영향을 받는다.

본 논문에서는 변조의 영향을 반영한 결합변조 방식의 성능을 평가하며, M진 직교변조와 비교하여 수신기의 복잡도를 최소화 하면서 동일한 성능을 얻을 수 있음을 보인다.

*서울시립대학교 전자공학과
論文番號:97097-0312
接受日字:1997年 3月 12日

Ⅰ. Introduction

We are concerned with an enhanced multi-user performance of cellular direct-sequence CDMA systems [1] by employing M-ary signaling while system complexity is minimized. This approach does not require an apriori knowledge on the cross-correlation of signature sequences compared to the multi-user receivers [2]. Unlike conventional M-ary orthogonal signaling [3], [4], it adopts binary pulse position modulation (PPM) that is embedded in the chip waveform, and also antipodal signaling for the Walsh/Hadamard orthogonal codes which results in biorthogonal modulation. It is referred to as the combined binary PPM/biorthogonal modulation that needs only $M/4$-ary orthogonal codes instead of M-ary ones. By exploiting this, it is allowed to greatly reduce receiver complexity when implementing the maximum-likelihood sequence detector.

For sufficiently large M, there is little difference in the multi-user performance between orthogonal and biorthogonal signaling [5], and binary PPM compensates for the loss in the processing gain of signature sequences by reducing the interference to a half. Here we note that the signal space used for sequences is traded with that for modulation, provided a global space is fixed. To investigate the performance, we need to characterize statistics on the interference generated by other users in view of the sequence properties and modulation. Comparison with M-ary orthogonal signaling is performed, and simulation results are provided to validate theoretical results. Finally, some applications to cellular CDMA communications are mentioned.

Ⅱ. Signal Characteristics

A combined binary PPM/biorthogonal modulation can be structured as follows. First, the binary PPM is embedded in the chip waveform which takes the form

$$v_k(t)=\phi(t-\lambda_k T_p) \qquad t\in[0,\, T_c). \tag{1}$$

Here $\phi(t)$ is any pulse of duration T_p, occupied in $[0, T_p)$, for a chip time $T_c=2T_p$ so that the chip rate T_c^{-1} is reduced by half while system bandwidth is fixed. The pulse position λ_k takes the values of 0 and 1 that is capable of conveying one-bit data of the kth user.

The second-stage biorthogonal modulation is based

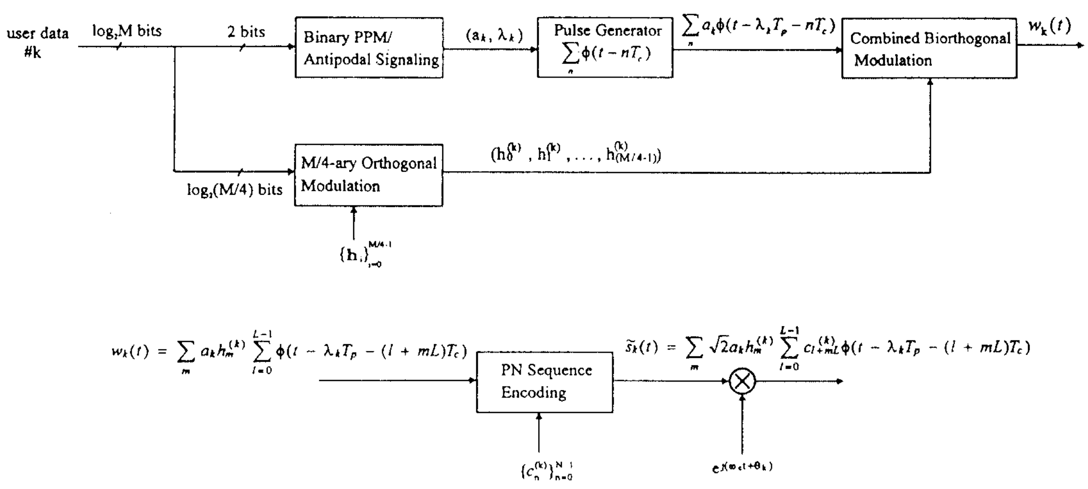

Fig. 1 Combined binary PPM/biorthogonal modulation for the kth user.

on the Walsh/Hadamard orthogonal codes with antipodal signaling that generates biorthogonal codes. It can be expressed in the form

$$w_k(t)=\sum_{m=0}^{M/4-1} a_k h_m^{(k)} \sum_{l=0}^{L-1} v_k(t-(l+mL)T_c) \quad t\in[0, T) \quad (2)$$

where a_k represents antipodal signaling associated with the kth user binary data ± 1, and the kth user's $M/4$-ary orthogonal codes $\mathbf{h}^{(k)}=(h_0^{(k)}, h_1^{(k)}, \cdots, h_{M/4-1}^{(k)})$, $h_m^{(k)}\in\{1, -1\}$, are generated by the Hadamard matrix. Note that $\{a_k \mathbf{h}^{(k)}\}$ become biorthogonal data sequences associated with the kth user's $M/2$-ary data.

To make each user's signal waveform discernible, the user-specific signature sequences $\{c_n^{(k)}\}$ $(k=1, 2, \cdots, K)$ are employed to have

$$\tilde{s}_k(t)=\sum_{m=0}^{M/4-1} \sqrt{2}\, a_k h_m^{(k)} \sum_{l=0}^{L-1} c_{l+mL}^{(k)} \phi(t-(l+mL)T_c-\lambda_k T_p)$$
$$t\in[0, T) \quad (3)$$

with $n=l+mL$. Here the complex envelope $\tilde{s}_k(t)$ is the baseband spread-spectrum signal for the kth user in Fig. 1. A symbol time T is related to $T=(M/4)LT_c$ for which L represents the amount of partial spreading by signature sequences. The signature sequences are statistically modeled a- random binary sequences by adopting long PN spreading sequences.

Ⅲ. Multi-user Performance

In the presence of background noise and interference, the multi-user performance is evaluated for the combined binary PPM/biorthogonal modulation. The received signal can be expressed by

$$\tilde{r}(t)=\tilde{s}_1(t)+\sum_{k=2}^{K} \tilde{s}_k(t-\tau_k)\exp(j\theta_k)+\tilde{n}(t) \quad (4)$$

where the first user is desired, K denotes the number of users, the channel delay τ_k of the kth user is uniformly distributed in $[0, T)$ and the unknown phase θ_k uniformly distributed in $[0, 2\pi)$, and $\tilde{n}(t)$ is a complex-valued white Gaussian noise with two-sided power spectral density N_o. A decision-directed sync estimation is assumed for the on-off chip pulses to acquire $\tau_1=\theta_1=0$.

A biorthogonal receiver in Fig. 2 consists of two

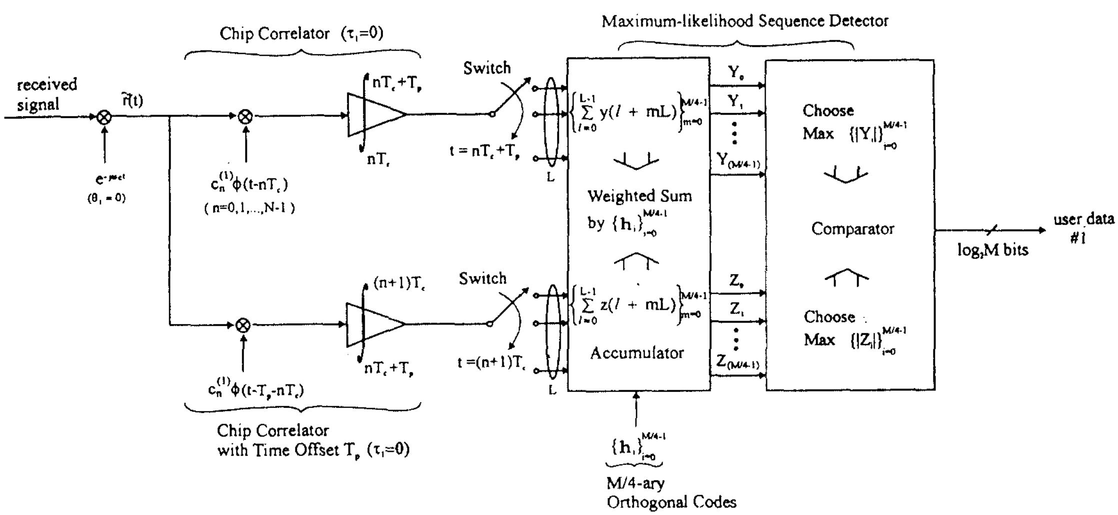

Fig. 2 Biorthogonal receiver structure implemented for the first user.

chip correlators, operated every T_c with time offset T_p, and the maximum-likelihood sequence detector to find the pulse position λ_1 and the $M/4$-ary orthogonal code $\mathbf{h}^{(1)}$ where the comparator is used to decide a sign information a_1. Compared to M-ary orthogonal codes, a great reduction in receiver complexity is allowed by adopting $M/4$-ary orthogonal codes here. The output of chip correlator assuming $\lambda_1 = 0$ is

$$y(n) = \frac{1}{\sqrt{2}} \int_{nT_c}^{nT_c+T_p} \mathrm{Re}\{\tilde{r}(t)\}\, c_n^{(1)} \phi(t - nT_c)\, dt$$

$$= a_1 h_m^{(1)} E_p + \sum_{k=2}^{K} I_k(n) + \eta(n) \tag{5}$$

with $n = l + mL$. Here the chip energy E_p is defined by $\int_0^{T_p} \phi^2(t)\, dt = E_p$, the noise term $\eta(n)$ is a zero-mean Gaussian random variable with variance $N_o E_p/2$, and the interference term due to the kth user becomes

$$I_k(n) = \begin{cases} [a_{k(n-s_k-1)} h^{(k)}_{\lfloor (n-s_k-1)/L \rfloor} c^{(k)}_{(n-s_k-1)} c_n^{(1)} R_\phi(\bar{\tau}_k)\, \delta(\lambda_{k(n-s_k-1)} - 1) \\ + a_{k(n-s_k)} h^{(k)}_{\lfloor (n-s_k) L \rfloor} c^{(k)}_{(n-s_k)} c_n^{(1)} \hat{R}_\phi(\bar{\tau}_k)\, \delta(\lambda_{k(n-s_k)})] \cos\theta_k, \\ a_{k(n-s_k-1)} h^{(k)}_{\lfloor (n-s_k-1) L \rfloor} c^{(k)}_{(n-s_k-1)} c_n^{(1)} [R_\phi(\bar{\tau}_k - T_p)\, \delta(\lambda_{k(n-s_k-1)}) \\ + \hat{R}_\phi(\bar{\tau}_k - T_p)\, \delta(\lambda_{k(n-s_k-1)} - 1)] \cos\theta_k \end{cases} \tag{6}$$

where $s_k T_c \le \tau_k < (s_k + 1) T_c$ for an integer s_k, $\bar{\tau}_k = \tau_k - s_k T_c$ is uniformly distributed in $[0, T_c)$, $\lfloor x \rfloor$ is an integer part of x, the delta function $\delta(u)$ is defined by $\delta(u) = 0$ if $u \ne 0$ and $\delta(0) = 1$, and the partial autocorrelation functions for $\phi(t)$ are defined by $R_\phi(\tau) = \int_0^{\tau} \phi(t)\phi(t + T_p - \tau)\, dt$ and $\hat{R}_\phi(\tau) = \int_\tau^{T_p} \phi(t)\phi(t - \tau)\, dt$ for $0 \le \tau \le T_p$. Note that $a_{k(m)}$ and $\lambda_{k(m)}$ represent the previous data symbols if $m < 0$, and otherwise current symbols. In the above the first equation holds for $0 \le \bar{\tau}_k < T_p$ and then for $T_p \le \bar{\tau}_k < T_c$.

Next, the output of chip correlator with time offset T_p is

$$z(n) = \frac{1}{\sqrt{2}} \int_{nT_c+T_p}^{(n+1)T_c} \mathrm{Re}\{\tilde{r}(t)\}\, c_n^{(1)} \phi(t - nT_c - T_p)\, dt$$

$$= \sum_{k=2}^{K} \hat{I}_k(n) + \hat{\eta}(n) \tag{7}$$

where the noise term $\hat{\eta}(n)$ is identical to $\eta(n)$, mutually independent, and the interference term $\hat{I}_k(n)$ is shown to be

$$\hat{I}_k(n) = \begin{cases} a_{k(n-s_k)} h^{(k)}_{\lfloor (n-s_k)/L \rfloor} c^{(k)}_{(n-s_k)} c_n^{(1)} [R_\phi(\bar{\tau}_k)\, \delta(\lambda_{k(n-s_k)}) \\ + \hat{R}_\phi(\bar{\tau}_k)\, \delta(\lambda_{k(n-s_k)} - 1)] \cos\theta_k, \\ [a_{k(n-s_k-1)} h^{(k)}_{\lfloor (n-s_k-1)/L \rfloor} c^{(k)}_{(n-s_k-1)} c_n^{(1)} R_\phi(\bar{\tau}_k - T_p)\, \delta(\lambda_{k(n-s_k-1)} - 1) \\ + a_{k(n-s_k)} h^{(k)}_{\lfloor (n-s_k)/L \rfloor} c^{(k)}_{(n-s_k)} c_n^{(1)} \hat{R}_\phi(\bar{\tau}_k - T_p)\, \delta(\lambda_{k(n-s_k)})] \cos\theta_k. \end{cases} \tag{8}$$

The maximum-likelihood sequence detector generates decision variables which are the weighted sums of correlated outputs by the $M/4$-ary orthogonal codes $\{\mathbf{h}_i\}$, $\mathbf{h}_i = (h_{i,0}, h_{i,1}, \cdots, h_{i,M/4-1})$ $(i = 0, 1, \cdots, M/4 - 1)$ from the Hadamard matrix. Such decision variables are

$$Y_i = \sum_{m=0}^{M/4-1} h_{i,m} \sum_{l=0}^{L-1} y(l + mL) \tag{9}$$

$$Z_i = \sum_{m=0}^{M/4-1} h_{i,m} \sum_{l=0}^{L-1} z(l + mL) \tag{10}$$

for $i = 0, 1, \cdots, M/4 - 1$. Joint statistics of $\{Y_i\}$ and $\{Z_i\}$ being modeled as Gaussian random variables are given by

$$\mathrm{var}(Y_i) = \mathrm{var}(Z_i) = \frac{1}{2}(K-1) N\, \mathbf{E}\{R_\phi^2(\bar{\tau}_k)\} + \frac{1}{2} \mathbf{E}_s \mathbf{N}_o \tag{11}$$

$$\mathrm{cov}(Y_i, Z_i) = \frac{1}{4}(K-1) N\, \mathbf{E}\{R_\phi(\bar{\tau}_k) \hat{R}_\phi(\bar{\tau}_k)\}. \tag{12}$$

The multi-user performance is evaluated in terms of the average probability of symbol error which can be expressed by

$$P(\varepsilon) = \mathbf{E}\{P(\varepsilon \mid Y_0 = \gamma > 0)\}$$

$$= 1 - \mathbf{E}\left\{ \Pr[\bigcap_{i=1}^{M/4-1} \{|Y_i| < \gamma\} \bigcap_{j=0}^{M/4-1} \{|Z_i| < \gamma\} \mid Y_0 = \gamma > 0] \right\}. \tag{13}$$

In the above we assume that the symbol $\{a_1=1, \lambda_1=0\ \mathbf{h}^{(1)}=\mathbf{h}_0\}$ was sent for the first user, and the expectation $\mathbf{E}$ is taken with respect to $\gamma>0$. Note that $\{|Y_i|<\gamma,\ |Z_i|<\gamma\}$ becomes a set of independent joint events for Gaussian modeled interference. Therefore, $P(\varepsilon)$ can be simplified to

$$P(\varepsilon)=1-\int_0^\infty \prod_{i=1}^{M/4-1} \Pr[|Y_i|<\gamma,\ |Z_i|<\gamma] \cdot \Pr[|Z_0|<\gamma,\ Y_0=\gamma]d\gamma. \tag{14}$$

Joint statistics in (11) and (12) along with Gaussian assumption yield

$$\Pr[|Y_i|<\gamma,\ |Z_i|<\gamma]=\int_{-\gamma}^{\gamma} \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{z_i^2}{2\sigma^2}\right)\left[1-2Q\left(\frac{\gamma+\rho z_i}{\sigma\sqrt{1-\rho^2}}\right)\right] dz_i \tag{15}$$

$$\Pr[|Z_0|<\gamma,\ Y_0=\gamma]= \begin{cases} \dfrac{1}{\sqrt{2\pi\sigma^2}} \exp[-(\gamma-E_s)^2/2\sigma^2][Q(\alpha)-Q(\beta)] & \text{if } \gamma<\rho E_s/(1+\rho), \\ \dfrac{1}{\sqrt{2\pi\sigma^2}} \exp[-(\gamma-E_s)^2/2\sigma^2][1-Q(-\alpha)-Q(\beta)] & \text{if } \gamma\geq\rho E_s/(1+\rho) \end{cases} \tag{16}$$

where $\sigma^2=\mathrm{var}(Y_i)=\mathrm{var}(Z_i)$ and $\rho\sigma^2=cov(Y_i,\ Z_i)$, $\alpha=\dfrac{\rho E_s-\gamma(1+\rho)}{\sigma\sqrt{1-\rho^2}}$ and $\beta=\dfrac{\rho E_s+\gamma(1-\rho)}{\sigma\sqrt{1-\rho^2}}$ for the symbol energy $E_s=NE_p(N=LM/4)$, and $Q(x)=\int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-u^2/2}du$. Now combining the results of (14)-(16), and performing a numerical integration, it allows to analyze the multi-user performance of the combined modulation.

Ⅳ. Results

For the range of interest, the average symbol error probability is computed via a numerical method as well as simulation. Specially, for $M=64,128,256$, $N=128,160,192$ ($L=8$, 5, 3), and $K=30$-55, $P(\varepsilon)$ is shown in Fig. 3 where $E_b/N_o=10$ dB (E_b bit energy) and a rectangular chip pulse is used. The numerical results are well in accord with ones from simulation to enable us to compare the combined modulation with M-ary orthogonal modulation. Note that for the latter, the number of chips/symbol N is adjusted to have the same bandwidth, namely, $N^*=2N$. Fig. 4 plots $P(\varepsilon)$ for both schemes with the same parameters above except $M=64$, $N^*=256$ and $M=128$, $N^*=320$ where the receiver complexity is on the order of $(M/4)(2N)/\log_2 M$

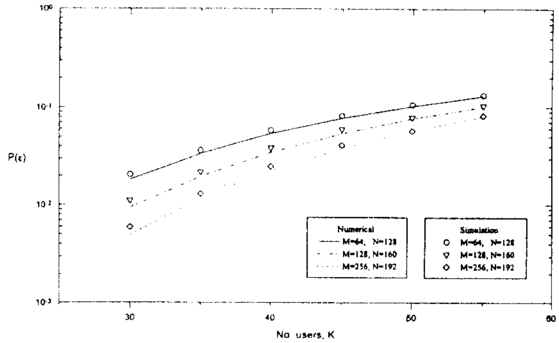

Fig. 3 Average symbol error probability $P(\varepsilon)$ as a function of K for the combined modulation when $E_b/N_o=10$ dB.

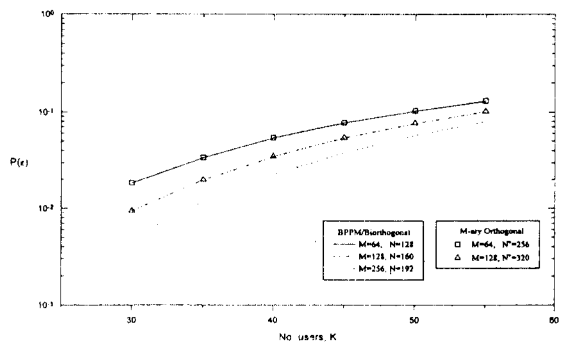

Fig. 4 Comparisons of $P(\varepsilon)$ as a function of K for the combined and M-ary orthogonal modulations when $E_b/N_o=10$ dB.

for the former and $MN^*/\log_2 M$ for the latter. It is observed that the combined modulation performs well for large $M=256$ with $N=192$ by employing $M/4=$ 64-ary orthogonal codes, which is comparable to $M=$ 64-ary orthogonal modulation with $N^*=256$ in view of complexity. We also notice that the two schemes present almost the same performance even with fixed $M=64$, 128 and $N^*=2N$.

V. Conclusion

A biorthogonal modulation combined with binary PPM has been proposed for direct-sequence CDMA systems which require an enhanced multi-user performance with applications to the cellular environment. The scheme minimizes receiver complexity by adopting the reduced $M/4$-ary orthogonal codes while maintaining almost the same performance relative to M-ary orthogonal modulation. With some constraints on the complexity, it is allowed to achieve higher CDMA capacity by increasing M, N to a certain limit in the combined modulation. Tradeoff between complexity and capacity offered by the combined modulation provides flexibility when designing a cellular CDMA system.

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김 동 인(Dong In Kim) 정회원
현재 : 서울시립대 전자전기공학부 부교수 재직