A Novel Modulation and Demodulation Technique for the Downlink of Spread Spectrum Multipath Channels

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***Abstract*—In this letter, a novel method for modulation and demodulation of user information bit in spread spectrum code-division multiple-access (CDMA) systems is proposed. Synchronous CDMA poses intrinsic protection against co-channel interference due to orthogonal spreading codes used. However, in the presence of multipath, signals lose their orthogonality property, leading to an increased cross correlation. In this letter, we show that the performance of the system will be close to single user system if we assign two codes to each user and these two codes are used for modulation and demodulation. The well-known maximum length sequence codes are good candidates for the present modulation and demodulation technique. The limiting factor to the system capacity is the maximum number of codes and the capacity is half of that number.**

***Index Terms*—Code-division multiple access (CDMA), demodulation, modulation, spread spectrum.**

I. Introduction

Synchronous code-division multiple-access (CDMA) systems have received considerable interest for some practical systems (e.g., multicasting networks requiring point to multipoint communication and the downlink of the intermediate CDMA standard IS-95) in which the synchronous assumption holds true. In this case when orthogonal codes are used, CDMA is effective against co-channel interference. However, multipath propagation distorts the code orthogonality, thus degrading the performance and capacity of the system. There are several algorithms for interference cancellation and multiuser detection in CDMA systems that improve the performance and increase the capacity of the system at the expense of increasing the complexity of the receiver. Most of these algorithms are designed for the uplink of CDMA systems, where it is assumed that the receiver knows the spreading codes of all users. This assumption is however not true for the downlink where the mobile unit only knows its own spreading code. It is worth noting that still the capacity remains less than half of the number of codes in some systems. In this paper, we develop a new method for modulation and demodulation of user information in the downlink of CDMA systems that is based on assigning two codes to each user. We focus on CDMA systems with processing gain of 127 for voice applications or data transmission rate of 9600 bps and the transmission bandwidth of $W = 1.25$ MHz, where the chip duration can be equal to 1 μs.

II. A New Modulation and Demodulation Method

We assign two signatures to each user who uses these two signatures to transmit information. Using maximum length sequence code it is possible to have a system that is not affected by multiple access interference (MAI) in the downlink in the presence of multipath propagation. Assume that each user has two spreading codes, say, c_k and c'_k, corresponding to two spreading waveforms, s_k and s'_k, $k = 1, 2, \ldots, K$. User k transmits s_k instead of 1 and s'_k instead of 0 (binary code modulation). We will use codes (e.g., maximum length sequence code) that have equal cross correlation, and we will show that the system performance will reach close to that of single user systems. Here we formulate these procedures. Assume that the ith bit of information to be transmitted to the kth user from the base station is $b_k(i)$. The corresponding transmitted base-band signal from the base station is given by:

$$x_k(t) = A\sum_i \overline{s}_k(t - iT), \quad k = 1, 2, \ldots, K \tag{1}$$

where A is the amplitude of the user signal, T is the transmitted symbol interval, $\overline{s}_k(t) = s_k(t)$ if $b_k(i) = 1$, and $\overline{s}_k(t) = s'_k(t)$ if $b_k(i) = 0$. The two spreading waveforms are given by

$$s_k(t) = \sum_{j=0}^{N-1} c_k(j)\Psi(t - jT_c), \quad 0 \le t \le T \tag{2}$$

$$s'_k(t) = \sum_{j=0}^{N-1} c'_k(j)\Psi(t - jT_c), \quad 0 \le t \le T \tag{3}$$

where N is the processing gain, c_k and c'_k are code sequences of ± 1 for user k, and $\Psi(t)$ is the chip waveform of duration $T_c = T/N$. We assume that no power control is employed so that user signals transmitted from the base station have the same amplitude. Although this assumption is not necessary, the use of power control may create problems similar to the near-far problem in traditional systems. By this assumption,

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the base-band received signal due to all users at kth mobile receiver is given by:

$$r_k(t) = \sum_{k'=1}^{K} \sum_{l=1}^{L} \alpha_{kl} x_{k'}(t - \tau_{kl}) + n(t) \quad (4)$$

where $n(t)$ is an additive white Gaussian noise, α_{kl} is the lth path channel gain, and τ_{kl} is the lth path time delay between kth user and base station transmitter. At the receiver the received signal is despreaded by desired user's two signature codes in two separated branches to form the decision variables. We decide on transmitted symbol according to the branch output that has greater real part. The idea for combating multipath effect is that when assigning two codes to each user it is important that these two codes have at least the first $L_{\max}$ elements in common, where $L_{\max} = \lceil \tau_{\max}/T_c \rceil$, $\tau_{\max}$ is the maximum difference between path delays of user k, and $\lceil . \rceil$ indicates the operation of rounding toward $+\infty$. When two maximum sequence codes have the same elements in the front, it is easy to show that the remaining parts of these two codes will have the same cross correlation with parts of other codes. Assume that the user of interest is user k and we drop the subscript of k from its decision variables. We demodulate the received signal using RAKE receiver which has one finger with the time delay and weight coefficient corresponding to the strongest path. Let the strongest path be the l_m-th path for user k. The decision variables in the two branches are obtained as

$$y_1(i) = \alpha_{kl_m}^* \int_{iT+\tau_{kl_m}}^{iT+T+\tau_{kl_m}} r(t) s_k \left(t - iT - \tau_{kl_m}\right) dt \quad (5)$$

$$y_2(i) = \alpha_{kl_m}^* \int_{iT+\tau_{kl_m}}^{iT+T+\tau_{kl_m}} r(t) s'_k \left(t - iT - \tau_{kl_m}\right) dt. \quad (6)$$

Assuming that the ith bit of user k is 1 and thus signal s is transmitted, we have

$$y_1(i) = A \left|\alpha_{kl_m}\right|^2 + I_1 + n_1 \quad (7)$$

$$y_2(i) = \rho A \left|\alpha_{kl_m}\right|^2 + I_2 + n_2. \quad (8)$$

If the ith bit of user k is 0, we have

$$y_1(i) = \rho A \left|\alpha_{kl_m}\right|^2 + I_1 + n_1 \quad (9)$$

$$y_2(i) = A \left|\alpha_{kl_m}\right|^2 + I_2 + n_2. \quad (10)$$

In the above, n_1 and n_2 are white Gaussian noise components

$$I_1 = (K-1) A\rho \left|\alpha_{kl_m}\right|^2 + \sum_{k'=1}^{K} \sum_{l=1, l \neq l_m}^{L} A \rho_{s(k',l)(k,l_m)} \alpha_{kl} \alpha_{kl_m}^* \quad (11)$$

$$I_2 = (K-1) A\rho \left|\alpha_{kl_m}\right|^2 + \sum_{k'=1}^{K} \sum_{l=1, l \neq l_m}^{L} A \rho_{s'(k',l)(k,l_m)} \alpha_{kl} \alpha_{kl_m}^* \quad (12)$$

where $\rho = \rho_{s(k',l_m)(k,l_m)}$, and $\rho_{s(k',l)(k,l_m)}$ and $\rho_{s'(k',l)(k,l_m)}$ are the correlation between lth path of the k'th user spreading waveform and that of desired user corresponding to the strongest path. We have

$$\rho_{s(k',l)(k,l_m)} = \int_{iT+\tau_{kl_m}}^{iT+T+\tau_{kl_m}} \overline{s}_{k'}(t - iT - \tau_{kl}) s_k \left(t - iT - \tau_{kl_m}\right) dt$$

$$\rho_{s'(k',l)(k,l_m)} = \int_{iT+\tau_{kl_m}}^{iT+T+\tau_{kl_m}} \overline{s}_{k'}(t - iT - \tau_{kl}) s'_k \left(t - iT - \tau_{kl_m}\right) dt.$$

Note that we have used the fact that $\rho_{s(k,l)(k,l)} = 1$ and we always have $\rho < 1$. We detect the ith bit of user k by comparing two decision statistics $\mathrm{Re}(y_1)$ and $\mathrm{Re}(y_2)$. We decide that the transmitted bit is 1 if $\mathrm{Re}(y_1)$ is greater than $\mathrm{Re}(y_2)$ and decide that the transmitted bit is 0 if $\mathrm{Re}(y_2)$ is greater than $\mathrm{Re}(y_1)$.

With the assumption that cross correlations of two signatures s and s' with other users' signatures are the same, and with the proper assigning of two codes to users and the fact that the shifted version of a maximum sequence code is another code, the components I_1 and I_2 are approximately the same. It is easy to show for the maximum length sequence with length of $N = 2^m - 1$ it is possible to find a set of $(N-1)/2$ two-codes that have the same first $m-1$ elements. Therefore, it is possible to support, for example, 63 users in the systems with a processing gain of 127 using this kind of codes. The important thing is that $L_{\max}$ should be chosen less than $m-1$ in this system. Referring to literature, e.g., [2] and [4], for an urban environment the maximum delay is less than 7 μs. Thus, the set of codes with length of 127 satisfy the condition. Note that the cross correlations between codes s_i and s'_j, s_i and s_j, and s'_i and s'_j are all equal to ρ for $i \neq j$, and since codes in the two branches have the first $L_{\max}$ elements in common, the cross correlations of the code in each branch with delayed version of other users' codes in different paths still remain equal, except for two codes (used by other users) whose shifted version might be one of the codes used in two branches. Since we demodulate according to the strongest path and the fact that power delay profile in cellular environment is exponentially decaying [1], the difference between the interference in the two branches of our scheme will slightly change the level of the white noise, and in the case of reasonably small white noise we can always make correct decisions.

III. Simulation Analysis

We simulated the synchronous CDMA with 63 users equal to half of the processing gain in multipath environment including three paths ($L = 3$) with time delays of 0,$3T_c$,$5T_c$, and channel gain of 0 dB, -4 dB, -10 dB. We assigned proper pair of codes to all users from a set of 127 codes. For comparison we also did the simulation for orthogonal CDMA using Hadamard codes in the same environment. The simulation results are compared between these two cases in Fig. 1 and compared to the theoretical result of single user systems [3] as well. As seen from the figure, the performance of the new method is immune to MAI and it is much closer to single user systems than the orthogonal

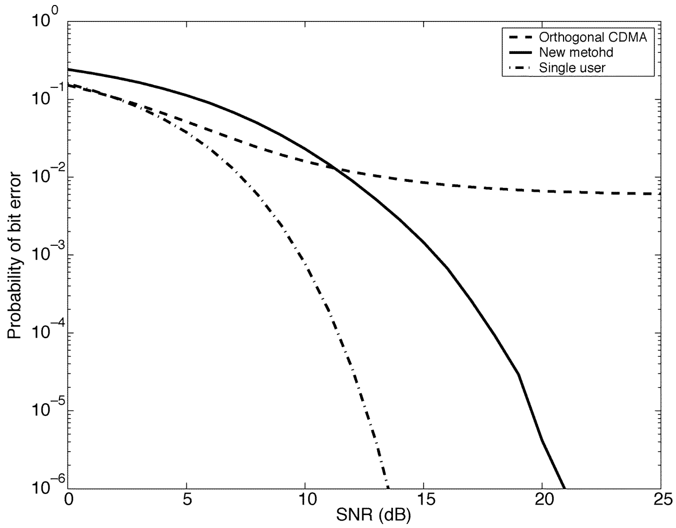

Fig. 1. Average probability of detection error for all active users.

CDMA. The simulation results in Fig. 1 is for single cell case with no inter-cell interference. However, the inter-cell interference does affect the system performance as well. In general, the effects of inter-cell interference on systems using the orthogonal CDMA and systems using our new method will be to shift the plots slightly to the right due to the increase of interference from a distant cell that uses the same frequency band.

IV. Conclusions

A novel modulation and demodulation technique was presented in this paper that is immune to MAI and has performance close to single user systems. The only limitation of this method is the use of spreading waveforms with equal cross correlations and proper assignment of two codes to users. The maximum length sequence is a well-known code sequence that satisfy the conditions in urban environment.

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