Orthogonalization Using Multicarrier Pre-Decorrelation in a Multipath Fading Channel

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SUMMARY Pre-decorrelation is a method of achieving orthogonalization between multiple signals on the forward link. This technique can achieve orthogonalization in a flat fading channel, however, the orthogonality does not clearly appear in a multipath fading channel because of interchip interference. In order to eliminate the effect of multipath and prevent interchip interference, multicarrier modulation can be employed. In this paper we propose a multicarrier pre-decorrelation technique which combines multicarrier modulation with pre-decorrelation. Computer simulation results show that the proposed technique can achieve orthogonalization in a multipath fading channel.

key words: orthogonalization, pre-decorrelation, multipath fading, multicarrier modulation

I. Introduction

Recently, direct sequence spread spectrum (DS-SS) code division multiple access (CDMA) has received considerable attention as a promising scheme for wireless communications because of advantages such as its potential for a higher capacity than other multiple access schemes[1],[2] and high flexibility in offering a variety of data services[3]. For the next generation of wireless communications, a variety of data services from low to high bit rates is required. To achieve high bit rate data transmissions on the forward link (base-to-mobile), approaches based on code multiplexing have been proposed[3]. In this system, multiple channels, i.e., multiple spreading sequences, are assigned for a mobile terminal. In this case equipment is needed to despread assigned multi-channel signals.

On the forward link, time synchronization among all multiplexed information bits must be maintained. Then orthogonalization using synchronous transmission can be employed in order to prevent co-channel interference occurring. A method of achieving orthogonalization between multiple signals is employing orthogonal sequences based on Walsh functions (also known as Hadamard matrices)[4]. These sequences have perfect orthogonality at zero time delay. Another method of achieving orthogonalization using a pre-decorrelating technique has been proposed[5],[6]. This technique can orthogonalize the multiple signals that are spread with the sequences which are cross-correlated.

In case the system is that in which multiple channels are assigned for a mobile terminal and orthogonal sequences are used, multiple matched filters are needed to despread all the assigned multi-channel signals at the receiver of the mobile terminal. Therefore, employing orthogonal sequences is not applicable from the viewpoint of the reduction of the complexity of a receiver in a mobile terminal.

In order to achieve high bit rate transmission and reduction of the mobile terminal complexity, here we employ a single matched filter system that can spread all the assigned multi-channel signals with only one matched filter. In the single matched filter system, cyclically shifted spreading sequences that are different only in the number of chip shifts are employed. Though these spreading sequences are cross-correlated, employing the pre-decorrelating technique can orthogonalize the multiple signals. Since pre-decorrelation is performed at the base station the receiver structure does not become more complex. Therefore by applying pre-decorrelation and the single matched filter system, orthogonalization and the reduction of the complexity of a receiver in the mobile terminal can be achieved at the same time.

However, since the pre-decorrelation technique can orthogonalize the multiple signals only in a flat fading channel[5],[6], the orthogonality does not clearly appear in a multipath fading channel because of interchip interference (ICI) caused by multipath. In order to reduce the effect of ICI, multicarrier modulation has been proposed[7]–[10]. Multicarrier modulation can lower the data rate in each carrier so that using the appropriate number of carriers eliminates the effect of multipath. In this paper, a multicarrier pre-decorrelation technique which combines multicarrier modulation with pre-decorrelation is proposed to achieve orthogonalization in a multipath fading channel. Since multicarrier modulation eliminates the effect of multipath, pre-decorrelation is able to be performed even in a multipath fading channel.

This paper is organized as follows. In Sect. 2, the channel model and the system model are described. In Sect. 3, the structure and the bit error rate (BER) performance of the proposed system are analyzed. Performance results obtained through computer simulation
are shown in Sect. 4. Section 5 presents our conclusions.

2. System Model

2.1 Radio Channel Model

The terminals and the base station are assumed to be placed in a room of a house or a building. Several propagation measurements have been performed to determine a typical propagation model in office buildings [11], [12]. In [11], [12], the one-sided exponential delay power density spectrum can be assumed as a multipath profile in an indoor wireless communications as shown in Fig. 1. This multipath power-delay profile can be expressed as

\[ \phi_c(\tau) = \frac{1}{\tau_{\text{rms}}} \exp \left( -\frac{\tau}{\tau_{\text{rms}}} \right) \]  

(1)

where \( \tau \) is the delay measured from the first arrival signal and \( \tau_{\text{rms}} \) is the root mean square (rms) delay spread [13].

Since DS-SS system can resolve multipath signals with delay of more than one chip duration, this channel model results in a fixed number of resolvable Rayleigh faded paths. When the maximum delay spread of the channel is \( \tau_{\text{max}} \), the number of resolvable paths \( L \) is given by [9]

\[ L = \left\lceil \frac{\tau_{\text{max}}}{T_c} \right\rceil + 1 \]  

(2)

where \( T_c \) is a chip duration and \( \lceil \cdot \rceil \) is the function that returns the largest integer less than or equal to its argument. We assume that \( \tau_{\text{max}} \) is the delay point that the power decays by 30 dB relative to the first arrival signal power. Thus a relationship between the maximum delay spread \( \tau_{\text{max}} \) and the rms delay spread \( \tau_{\text{rms}} \) can be expressed as

\[ \tau_{\text{max}} = 3\tau_{\text{rms}} \ln 10. \]  

(3)

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2.2 Single Matched Filter System

On the forward link of wireless communication systems, it is desirable to achieve high bit rate transmission and to reduce the complexity of the mobile terminal. To meet these two demands, a single matched filter system that utilizes cyclically shifted spreading sequences is proposed. In order to transmit a large amount of information, multiple channels, i.e., multiple sequences might be assigned for a mobile terminal. The cyclically shifted spreading sequences are generated from a same sequence. To distinguish signals transmitted from a base station at each mobile terminal, these spreading sequences are differentiated by the number of chip shifts as shown in Fig. 2. Therefore only one matched filter, which has twice as many taps as the period of the sequence, is needed at the mobile terminal to despread all the multi-channel signals that are assigned for the mobile terminal.

2.3 Multicarrier Modulation

Figures 3(a) and (b) show the block diagrams of a transmitter and a receiver for a multicarrier modulation system combined with pre-decorrelation. At the transmitting side, the bit stream with bit duration \( T_b \) is serial-to-parallel converted into \( N_c \) parallel branches,

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![Fig. 1](image1.png)

**Fig. 1** Typical example of indoor multipath power-delay profile.

![Fig. 2](image2.png)

**Fig. 2** Single matched filter system.
and pre-decorrelated. The new bit duration on each branch \( T \) is \( N_c \) times larger than the original bit duration \( T_b \). If the processing gain that is the number of chips per bit is fixed, as the number of carriers increases, the chip duration on each branch \( T_c \) increases proportionally such that \( T_c = N_c T_{c1} \), where \( T_{c1} \) is the chip duration for the single carrier case [7]–[10]. Applying Eq. (2) \( L \) is given by

\[
L = \left( \frac{\tau_{\text{max}}}{N_c T_{c1}} \right) + 1. \tag{4}
\]

Obviously from Eq. (4) the number of resolvable paths decreases as the number of carriers increases. If the number of carriers satisfies

\[
N_c > \frac{\tau_{\text{max}}}{T_{c1}} \tag{5}
\]

\( L = 1 \) and the channel is a flat fading channel for each carrier. Since only flat fading is experienced on each carrier at the receiver, the effect of the multipath is eliminated.

3. Theoretical Analysis

3.1 Multicarrier Pre-Decorrelation

In this paper, multicarrier modulation is combined with pre-decorrelation, so here we consider a multicarrier DS-CDMA system. Here we assume that one channel, i.e., one sequence is assigned for one terminal and there are \( N_s \) terminals which employ coherent binary phase shift keying in a cell. We also assume that multicarrier modulation eliminates the multipath interference, i.e., makes \( L = 1 \). Thus it can be considered that the channel on each branch is a flat fading channel. On the forward link, all multiplexed information bits arriving at a given receiver are time-synchronized. Then the received signal on the \( k \)th carrier of terminal \( m \) is given by

\[
r_{m,k}(t) = \alpha_{m,k} \sum_{i=1}^{N_s} \sqrt{2P_{i,k}} b_{i,k}(t) c_i(t) \cdot \cos(2\pi f_k t + \varphi_{m,k}) + n_{m,k}(t) \tag{6}
\]

where \( b_{i,k}(t) \), \( c_i(t) \) and \( P_{i,k} \) are, the information bit stream transmitted on carrier \( k \), the spreading sequence and the transmitted power on carrier \( k \) for the \( i \)th terminal respectively, and \( f_k \) is the \( k \)th carrier frequency. The information bit stream \( b_{i,k}(t) \) consists of consecutive bits \( \{b_{i,k}^j\} \) that take the values of \( \pm 1 \). The spreading sequence \( c_i(t) \) consists of a periodic train of chips taking values of \( \pm 1 \) in \( jT, (j+1)T \). The bit and chip waveforms are rectangular. Assuming that all possible information bits are equally likely, it suffices to restrict attention to a specific bit interval, e.g., \([0, T]\), dropping the time index \( j \). Also in Eq. (6), \( \alpha_{m,k} \) denotes the fading envelope of the \( k \)th carrier's signal received at terminal \( m \), that becomes Rayleigh distributed random variable, \( \varphi_{m,k} \) is the random phase which is uniformly distributed in \([0, 2\pi]\) and \( n_{m,k}(t) \) is additive white Gaussian noise (AWGN) with zero mean and two-sided power spectral density of \( N_0/2 \). The carrier frequencies are assumed to be assigned so that the frequency spectrum of the transmitted signal from each carrier does not overlap one another. Therefore interference from the other carrier is not contained.

Assuming perfect carrier, code and bit synchronization at the receiver, the output of the \( m \)th terminal's matched filter of carrier \( k \) is given by

\[
y_{m,k} = \int_0^T r_{m,k}(t)c_m(t) \cos(2\pi f_k t + \varphi_{m,k})dt \tag{7}
\]

where \([\cdot] \) means to filter out the high frequency components of \([\cdot] \). Then, it is shown that

\[
y_{m,k} = \alpha_{m,k} \sum_{i=1}^{N_s} \sqrt{\frac{P_{i,k}}{2}} T_{b,k} R_{mi} + \eta_{m,k} \tag{8}
\]

where \( R_{mi} \) is the cross-correlation between \( m \)th terminal's and \( i \)th terminal's spreading sequences, which is given by

\[
R_{mi} = \frac{1}{T} \int_0^T c_m(t)c_i(t)dt \tag{9}
\]
and $\eta_{m,k}$ is a zero-mean Gaussian random variable with variance $N_0 T/4$.

Equation (8) can be rewritten with matrix expression as

$$y_k = \frac{T}{2} A_k P_k b_k + n_k$$

(10)

where $b_k = [b_{1,k}, b_{2,k}, \ldots, b_{N_c,k}]^T$ is the information bit vector transmitted on carrier $k$, $A_k = \text{diag}(\alpha_{1,k}, \alpha_{2,k}, \ldots, \alpha_{N_c,k})$ is the diagonal matrix which denotes the fading envelopes of the $k$th carrier's signals, $P_k = \text{diag}(\sqrt{2P_{1,k}}, \sqrt{2P_{2,k}}, \ldots, \sqrt{2P_{N_c,k}})$ is the diagonal matrix which denotes the amplitude of the signals transmitted on carrier $k$, $R$ is the nonnegative definite matrix of normalized cross-correlation defined by Eq. (9) and $n_k = [\eta_{1,k}, \eta_{2,k}, \ldots, \eta_{N_c,k}]^T$ is the AWGN vector of carrier $k$ with independent components. $[.]^T$ denotes the transpose matrix of $[.]$.

To discharge the cross-correlation components in Eq. (10), a new information vector that linearly combines the inverse cross-correlation matrix $R^{-1}$ with active terminals' information bit vector $b_k$ is transmitted. This linear combining has been named pre-decorrelation. The new transmission information bit vector $b_{t,k}$ and the amplitude matrix $P_{t,k}$ are given by

$$P_{t,k} b_{t,k} = \beta_k R^{-1} P_k b_k$$

(11)

where $\beta_k$ is the positive scalar of carrier $k$ to keep the total transmission power constant, which satisfies

$$\beta_k^2 b_{t,k}^T P_k (R^{-1})^2 P_k b_k = \text{tr}(P_k^2)$$

(12)

where $\text{tr}$ denotes the trace.

When pre-decorrelation is employed, the output vector of the matched filters on carrier $k$ is written as

$$y_k = \frac{T}{2} A_k R P_{t,k} b_{t,k} + n_k$$

$$= \frac{\beta_k T}{2} A_k P_k b_k + n_k.$$  

(13)

Observing Eq. (13), cross-correlation components are discharged and orthogonalization between multiple signals at the receiver are achieved if flat fading is experienced on each carrier. The transmitter employing multicarrier pre-decorrelation is shown in Fig. 4.

3.2 BER Performance

From Eq. (13), the BER performance of terminal $m$ is given by [14]

$$P_e^m = \frac{1}{N_c} \sum_{k=1}^{N_c} \frac{1}{2} \int_0^\infty \left(1 - \sqrt{\frac{\beta_k^2 \gamma_{m,k}}{1 + \beta_k^2 \gamma_{m,k}}} \right) p(\beta_k^2) d\beta_k^2$$

(14)

where $p(\beta_k^2)$ is the probability density function of $\beta_k^2$ and $\gamma_{m,k}$ is the $k$th carrier's average received signal-to-noise ratio at terminal $m$, defined as

$$\gamma_{m,k} = E[\alpha_{m,k}^2] \frac{E_b}{N_0}$$

(15)

where $E[.]$ denotes the average value of $[.]$ and $E_b = P_{m,k} T$ is energy per bit. As it is shown later the BER performance deteriorates due to the scalar $\beta_k$.

4. Computer Simulation Results

The performance of proposed multicarrier pre-decorrelation was evaluated through computer simulation. The simulation parameters are shown in Table I. It is assumed that both the base station and mobile terminal antennas have an omni-directional beam pattern. A partial sequence of long M-sequence is used for spreading sequence.

Figure 5 shows the performance of BER vs. $E_b/N_0$ with the number of carriers $N_c$ as parameter when rms delay spread $\tau_{rms}$ is 50 nsec. It can be seen from Fig. 5
that the BER performance of the system employing pre-decorrelation is improved when compared with that of the system which does not employ pre-decorrelation for every $N_c$ due to orthogonalization between multiple signals. However, it is found that the performance of the conventional single-carrier pre-decorrelation system with $N_c = 1$ degrades due to ICI. On the other hand, the performance of the proposed multicarrier pre-decorrelation system with $N_c = 2$ or 4 is improved as the number of carriers $N_c$ increases. Especially, when $N_c = 4$, the effect of the multipath can be eliminated and orthogonalization can be achieved between the multiple signals in a multipath fading channel. Also, the BER performance of the single-terminal system with $N_c = 4$ is shown in Fig. 5. It is found that the BER performance of the multicarrier pre-decorrelation system with $N_c = 4$ for $N_u = 5$ is poorer than that of single-terminal system with $N_c = 4$. This degradation is caused by the scalar $\beta_k$.

Figure 6 shows the relation between the BER performance and rms delay spread $\tau_{rms}$ when $E_b/N_0$ is 35 dB. From Fig. 6, it is clear that the BER performance becomes poor as $\tau_{rms}$ increases. However, the degradation of the performance becomes less as $N_c$ increases. The rms delay spread of the 2.4 GHz band radio propagation channels in an indoor wireless environment should be less than 50 nsec[11] so that employing multicarrier pre-decorrelation with $N_c = 4$ can orthogonalize the multiple signals in an indoor wireless environment.

In a multicell system configuration, forward link power control is desirable to decrease excessive transmission power and thus reduce intercell interference [1], [2]. In this case, signals for other mobile terminals received by a mobile terminal, traveling through the same path, may have different powers. This can result in the same effect as the near-far problem in the reverse link.

In Fig. 7, this “near-far” environment is considered by setting different values of the undesired-to-desired signal power ratio. Here, the undesired signal is the signal addressed to another terminal than the receiving terminal and the desired signal is the signal addressed to the receiving terminal. Without loss of generality we consider the BER performance of the signal received at terminal 1. Therefore, the undesired-to-desired signal power ratio on each carrier is given by $P_i,k/P_1,k$, for $i=1,\ldots,5$, $k=1,\ldots,N_c$. Figure 7 shows the curves of BER of terminal 1 versus undesired-to-desired signal power ratio when rms delay spread $\tau_{rms}$ is 50 nsec and $E_b/N_0$ of terminal 1 is fixed at 35 dB. It can be seen from Fig. 7 that the BER performance of the system that does not employ pre-decorrelation is improved as the number of carriers $N_c$ increases due to the elimination of ICI. However even in case of $N_c = 4$, when ICI can be eliminated, the BER performance drastically becomes poor as the power of the undesired signal be-

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Simulation parameters</th>
</tr>
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<tbody>
<tr>
<td>Carrier frequency</td>
<td>2.471~2.497 GHz</td>
</tr>
<tr>
<td>Spreading modulation</td>
<td>BPSK</td>
</tr>
<tr>
<td>Data modulation</td>
<td>OPSK</td>
</tr>
<tr>
<td>Detection</td>
<td>Coherent detection</td>
</tr>
<tr>
<td>Spreading sequence</td>
<td>Long M-sequence (2^{25} - 1 chip cycle)</td>
</tr>
<tr>
<td>Processing gain</td>
<td>11</td>
</tr>
<tr>
<td>Data rate</td>
<td>2Mbps</td>
</tr>
<tr>
<td>Number of terminals/cell $N_u$</td>
<td>5</td>
</tr>
<tr>
<td>Fading</td>
<td>Multipath Rayleigh fading</td>
</tr>
<tr>
<td>Number of paths/carrier $L$</td>
<td>$\tau_{max}/T_c + 1$</td>
</tr>
<tr>
<td>Maximum Doppler shift</td>
<td>8 Hz</td>
</tr>
</tbody>
</table>

**Fig. 5** BER vs. $E_b/N_0$; $\tau_{rms} = 50$ nsec.

**Fig. 6** BER vs. rms delay spread $\tau_{rms}$; $E_b/N_0 = 35$ dB.
comes stronger. It is caused by “near-far” problem. On the other hand, pre-decorrelation should be able to prevent “near-far” problem occurring because of orthogonalization between multiple signals. However, when $N_c$ is 1 or 2, the orthogonality between multiple signals is lost due to ICI and thus the BER performance drastically degrades as the power of the undesired signal becomes stronger. On the other hand, when $N_c = 4$, the BER performance is almost invariant independent of the power of undesired signals because of elimination of ICI and orthogonalization between multiple signals.

5. Conclusion

In this paper, a new multiple signal orthogonalization technique in a forward link multipath fading channel has been proposed. The proposed system combines multicarrier modulation with pre-decorrelation. From the results obtained through computer simulation, the proposed multicarrier pre-decorrelation has been able to achieve eliminate the effect of multipath and orthogonalize the multiple signals in a multipath fading channel. The multicarrier pre-decorrelation system with 4 carriers was shown to be applicable to the indoor wireless environment.

References


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