High-Speed Synchronization Acquisition Methods of Quasi-Synchronous CDMA

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Abstract The quasi-synchronous direct sequence code division multiple access system can realize fast frame acquisition and interference-free performance if a shift orthogonal code is used as a spreading sequence set, and synchronization among users is quickly established within a permissible time interval. In this paper, we presents high-speed synchronization acquisition methods, which can be established by the correlation handling of one received data frame. They utilize one of the spreading sequences in the shift orthogonal code as a synchronization control sequence, and a matched filter bank that provides all the correlation functions between a received signal and any sequence. The effectiveness of the proposed methods, in which output is close to an impulse function, is shown by the synchronization error rate over the additive white Gaussian noise and Rayleigh fading channels.

Keywords: quasi-synchronous CDMA, synchronization acquisition, matched filter bank

1. Introduction

Wireless communication systems with high-speed synchronization acquisition, high-reliability transmission, and simultaneous multiple access can be flexibly applied to various applications, such as a high-performance remote controller and a reconfigurable dynamic wireless network. Those has the quasi-synchronous code division multiple access (QS-CDMA) system with cochannel-free performance, and uses a shift orthogonal code including an orthogonal code and a set of sequences with a zero correlation zone called the ZCZ code [1]-[7].

In accordance with synchronization control signal from a synchronization control unit located in a communication area, a transmitter sends a data frame signal consisting of control and data symbols multiplied by a spreading sequence, and a receiver detects the desired data symbols from the correlation between a received discrete signal and the spreading sequence assigned to the objective transmitter. In order to quickly establish synchronization among users within a permissible time interval, each user (transmitter / receiver) must to distinguish a signal for synchronization control and a received signal with high power, which consists of transmitting signals from users on a propagation channel, and detect the synchronization point of a data frame.

Synchronization acquisition (code acquisition) methods have been discussed in asynchronous spreading communications, that utilize a matched filter of a synchronization sequence [8]-[10]. The performance strongly depends on the autocorrelation function of the synchronization sequence, which should be impulsive, and it is difficult to realize high-speed acquisition in QS-CDMA such that the synchronization signal is transmitted independently with a high power data frame signal on time.

In this paper, three types of fast synchronization acquisition methods, which apply a sequence in a shift orthogonal code to the synchronization control sequence [11] and adopt the auto/crosscorrelation functions of the shift orthogonal code, are proposed. The correlation output between the synchronization control sequence and a received frame consisting of the synchronization control signal and data frame signals transmitted from users is close to an ideal impulse function, even if the spreading sequences do not possess good correlation properties. Therefore the synchronization acquisition will be established by correlation handling of one received frame.

The proposed methods are evaluated using the synchronization error rate (SER) for the signal-to-noise power ratio (SNR) and the sync-signal-to-interference power ratio (SIR) over the additive white Gaussian noise (AWGN) and Rayleigh fading channels, SIR means the ratio of the received average sync-signal power to the received data signal power per user.

The rest of the paper is organized as follows. In section 2., we first introduce two kinds of shift orthogonal codes with low aperiodic autocorrelation. One is an orthogonal code consisting of even shift orthogonal sequences (E-sequence) with low aperiodic autocorrelation included in complementary sequences [12]-[16], and the other is the ZCZ code consisting complementary sequences except the E-sequence. Next, QS-CDMA applying a se-
quence in a shift orthogonal code to the synchronization sequence is explained. This allows us to design a compact transmitter/receiver circuit [18], since a matched filter bank with few circuit elements, which can simultaneously calculate the correlation between a received discrete signal and any sequence in a shift orthogonal code, is available [17].

In Section 3, three types of synchronization acquisition methods using a matched filter bank are proposed. They will not require a shift orthogonal code with a very sharp aperiodic autocorrelation function. Furthermore, the orthogonal code may be more effective than the ZCZ code in the case that the synchronization point of a transmitter is set within one chip and a propagation channel is a flat fading environment, since the number of sequences in the orthogonal code is more than double that in the ZCZ code.

In section 4, the SERs of the conventional and proposed methods are evaluated by computer simulation over AWGN and Rayleigh fading channels. In section 5, the simulation results are summarized.

2. QS-CDMA Using a Shift Orthogonal Code

In this section, two types of shift orthogonal codes with good autocorrelation, which are constructed by using the even shift orthogonal sequence (E-sequence) included in complementary sequences, are introduced [16],[18], and the basic model of QS-CDMA is explained.

2.1 Shift orthogonal codes

Let \( A \) be a set of \( M \) binary sequences of period \( N \) defined by

\[
A = \{a^1, \cdots, a^m, \cdots, a^M\}
\]

where \( a^m \in \{1, -1\} \).

The periodic correlation function between sequences \( a^m \) and \( a^f \) is defined by

\[
R_{m,f}(\tau) = \sum_{i=0}^{N-1} d^m_i d^f_{(i+\tau) \mod N}
\]

where \( C_{m,f}(\tau) \) denotes the aperiodic correlation function defined by

\[
C_{m,f}(\tau) = \begin{cases} \sum_{i=0}^{N-1} d^m_i d^f_{i+\tau} & \text{for } 0 \leq \tau \leq N-1 \\ \sum_{i=0}^{N-1} d^m_{i-\tau} d^f_{i} & \text{for } 1 \leq N \leq \tau \leq 0 \\ 0 & \text{for } |\tau| \geq N \end{cases}
\]

Let \( A \) be a shift orthogonal (binary) code whose periodic correlation function is expressed as

\[
R_{m,f}(\tau) = \begin{cases} N & \text{for } \tau = 0, m = f \\ 0 & \text{for } \tau = 0, m \neq f \\ 0 & \text{for } 1 \leq |\tau| \leq Zcz \end{cases}
\]

In particular, \( A \) is called an orthogonal code for \( Zcz = 0 \), and ZCZ code for \( Zcz \neq 0 \), and is expressed as \( A(N, M, Zcz) \) at times. It is known [19] that the number of sequences is bounded by

\[
M \leq \frac{N}{Zcz + 1}
\]

Let us concentrate on two kinds of shift (binary) orthogonal codes with good aperiodic autocorrelation, \( A(2^n, 2^n, 0) \) and \( A(2^n, 2^{n-1}, 1) \), which achieve the upper bound of Eq. (6).

We concentrate on a Hadamard matrix \( H_n \) of order \( 2^n \) consisting of binary elements defined by

\[
H_n H_n^T = H_n^T H_n = 2^n I_n
\]

where \( I_n \) denotes the unit matrix of order \( 2^n \) and \( T \) the transpose of a matrix. The orthogonal code is equal to the set of rows in \( H_n \), expressed as

\[
A = H_n
\]

Let \( H_n \) be the Sylvester-type Hadamard matrix defined by

\[
H_n = \begin{pmatrix} H_{n-1} & H_{n-1} \\ H_{n-1} & -H_{n-1} \end{pmatrix} = (h_{m,x})_{0 \leq m,x < 2^n}
\]

where \( H_0 = (1) \).

Let \( e = (e_0, e_1, \cdots, e_{2^n-1}) \) be the E-sequence of length \( N \) whose aperiodic autocorrelation function takes a value of zero at any even shift except the zero shift, i.e., \( C_{e,N}(2l) = 0 \) for \( 0 < l < N/2 \). It is known that E-sequence is included in complementary sequences [12]. Let \( \delta_n \) be a diagonal matrix of order \( 2^n \) whose diagonal elements equal the E-sequence \( e \). the EO code, \( A_{EO}(2^n, 2^n, 0) \), is defined by

\[
A_{EO} = H_n \delta_n
\]

Similarly, the EZCZ code, \( A_{EZ}(2^n, 2^{n-1}, 1) \), is defined by

\[
A_{EZ} = [H_{n-1} \delta_{n-1}, H_{n-1} \delta_{n-1} \eta_{n-1}]
\]

where \( \eta_{n-1} \) denotes a diagonal matrix of order \( 2^{n-1} \), whose diagonal elements are expressed by \( \eta_{n-1} = diag(-1, 1, -1, 1, \cdots, -1, 1) \).

The logic functions of the shift orthogonal codes are introduced. Let \( \bar{x} = (x_0, x_1, \cdots, x_{2^n-1}) \) be the space \( V_k \) of binary\( k \)-tuples, whose elements are coefficients expressed as the binary expansion of an integer \( x(0 \leq x \leq 2^k - 1) \).

\[
x_k = x_0 2^0 + x_1 2^1 + \cdots + x_{k-1} 2^{k-1}
\]

Let us consider the logic functions of the shift orthogonal codes, \( A_{EO} \) and \( A_{EZ} \) of length \( 2^n \), which are expressed by

\[
a^m_k = (-1)^{a_{m,x}}
\]

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The logic function of $A_{EO}(2^n, N, 0)$ is expressed by

$$f_{A_{EO}}(m, x) = m_0x_0 \oplus m_1x_1 \oplus \cdots \oplus m_{N-1}x_{N-1}$$

$$\oplus y_1y_2 \oplus \cdots \oplus y_{N-2}y_{N-1}$$ (14)

where $\oplus$ denotes the addition over mod 2, and $y_j \in \{x_0, x_1, \cdots, x_{N-2}\}$ with $y_0 = x_0$ and $y_j \neq y_k$ for $j \neq k (\geq 1)$.

Similarly, the logic functions of $A_{EZ}(2^n, 2^{n-1}, 1)$ are given by

$$f_{A_{EZ}}(\hat{m}, x) = m_0x_0 \oplus m_1x_1 \oplus \cdots \oplus m_{N-2}x_{N-2}$$

$$\oplus y_1y_2 \oplus \cdots \oplus y_{N-3}y_{N-2}$$

$$\oplus x_0x_{N-1} \oplus x_{N-1}$$ (15)

where $0 \leq \hat{m} \leq 2^{n-1} - 1$, and $y_j \in \{x_0, x_1, \cdots, x_{N-2}\}$ with $y_0 = x_0$ and $y_j \neq y_k$ for $j \neq k (\geq 1)$.

It is known that the orthogonal code $A_{EO}$ consists of E-sequences, and $A_{EZ}$ consists of complementary sequences except the E-sequences [12],[16]. Note that if $x_0$ appears only once in the terms, $y_j \neq y_{j+1}$, the logic function generates all the E-sequences.

It is known that some in an orthogonal code $A_{EO}$ possesses autocorrelation properties that are better than some in the ZCZ code $A_{EZ}$ [18]. For example, the maximum merit factor $F$ of $A_{EO}$ of length 32 is 4.57 and that of $A_{EZ}$ is 3.56, where the merit factor $F$, indicating the sharpness of the autocorrelation function, is defined by

$$F = \frac{|C_{aw}(0)|^2}{2 \sum_{n=1}^{N-1} |C_{aw}(\tau)|^2}$$ (16)

2.2 QS-CDMA

In this subsection, QS-CDMA without a cochannel, which uses a shift orthogonal code as a spreading sequence set, is introduced.

Figures 1 and 2 depict QS-CDMA in a mobile ad hoc network, which is a self-configuring infrastructureless wireless network, and the time chart of the synchronization control signal from a sync-signal unit and transmitting signals from users ($U_i$). The synchronization control signal is sent for every same time interval, and along the synchronization control signal, data signals from many users are almost simultaneously transmitted through adequate modulation, PSK, FSK, ASK or QAM [2],[20].

The data frame signal is constructed using control and data symbols multiplied by an extended shift orthogonal sequence $\hat{a}^m$ of length $N + 2Z_{CZ}$ expressed as

$$\hat{a}^m = (d_{N-2}^m, \cdots, d_{N-Z_{CZ}+1}^m, d_N^m, \cdots, d_{N-1}^m)$$

$$Z_{CZ}$$

$$N$$

$$Z_{CZ}$$

(17)

The above extended sequence is necessary to maintain the zero correlation zone, even if a data symbol is changed. In this paper, it is assumed that $\hat{a}^m = a^m$ for an orthogonal code with $Z_{CZ} = 0$.

A receiver detects desired data symbols from the correlation between a received discrete signal and the spreading sequence assigned to the objective transmitter. If synchronization among users is established within permissible time interval, the cochannel is free.

In order to establish synchronization within the permissible time quickly, each user, who is both of a transmitter and a receiver, needs to distinguish between the synchronization control signal and a received signal with high power, is transmitted signals from users are multiplexed on a propagation channel, and to detect the synchronization point of a data symbol frame.

If a sequence in a shift orthogonal code is used as the synchronization sequence, a compact QS-CDMA unit (transmitter/receiver circuit) can be designed, as shown in Fig. 3, since the matched filter bank of a shift orthogonal code consisting of few circuit elements, which decrease from $O(N^2)$ to $O(N \log(N))$, can be utilized [17],[18].

3. New Synchronization Acquisition Methods

In this section, high-speed synchronization acquisition methods are presented and evaluated by SER with SIR over AWGN and Rayleigh fading channels.

As mentioned earlier, it is assumed that the sync-signal
consisting of a shift orthogonal sequence or repeated ones is transmitted for every fixed interval time, and the data frame signal from users is almost simultaneously transmitted outside the sync-signal interval. It is also assumed that the sync-signal and data frame signal are transmitted on the same frequency band from the viewpoint of frequency usage efficiency and hardware design facilitation.

Let $a^t$ be the sync-symbol sequence, which is one in a shift orthogonal code of length $N = 2^m$ in section 2. Let $\rho_m(t)$ be the correlation function between the received digital signal $r_i$ and the sequence $a^m$ in the shift orthogonal code defined by

$$\rho_m(t) = \sum_{i=0}^{N-1} r_i a^m(t)$$

where $t = 0$ means the synchronization point.

Method 0, denoting the conventional method regards the maximum absolute correlation value of $\gamma(t) = |\rho_0(t)|$ as the synchronization point $t = 0$.

In general, the synchronization circuit follows the timing of the synchronization point and needs to confirm it. Figure 4 depicts the output of $\gamma_0(t)$ for the use of the orthogonal code $AEO(32, 32, 0)$ when the number of simultaneous transmission users is $U = 8$, $SIR = P_s/P_r = 0$ dB, and $SNR = 10$ dB, where $P_s$ and $P_r$ denote the received average sync-signal power and the received average data signal power, respectively. Note that the total received signal power of $U$ users is $UP_r$.

It can be checked that the correlative output in the case of the ZCZ code $A(32, 16, 1)$ is almost the same as that in Fig. 4. Note that in general, $SNR = 0$ dB means a low sync-signal received power, and the total power of $SIR$ for 8 users is 9 dB.

The block diagram of the proposed methods is shown in Fig. 5. Three synchronization acquisition methods to quickly detect the synchronization point $t = 0$ are shown as follows.

Method 1:

$$\gamma_1(t) = \frac{|\rho_1(t)|}{1 + \sum_{m=2}^{M} |\rho_m(t)|}$$  \hspace{1cm} (20)

Method 1 detects the synchronization point by the emphasis of the sync-signal from the synchronous control unit, since it is independent of the data frames from users in time.

Method 2:

$$\gamma_2(t) = \frac{|\rho_1(t)|}{1 + \sum_{k=-ZCZ}^{ZCZ} \sum_{m=2}^{M} |\rho_m(t + k)|}$$  \hspace{1cm} (21)

Method 2 adds the emphasis of the zero correlation zone to the function of Method 1 in the case of using the ZCZ code.

Method 3:

$$\gamma_3(t) = \frac{1}{P} \sum_{p=0}^{P-1} \gamma_3(t + Lp)$$  \hspace{1cm} (22)

Where, $L$ denotes a chip interval corresponding to the sync-signal time interval, $P(=1)$ the chip length, and $e(0 \leq e \leq 2)$ one of the above methods.

Method 3 considers the average of the correlation processing in the sync-signal chip interval $L$, to improve the reliability of the above methods.

Figure 6 and 7 respectively depict the outputs of $\gamma_1(t)$ and $\gamma_2(t)$ under the same channel conditions as the case of Fig. 4 except for the use of the ZCZ code.
assumed that the synchronization gaps among users can be computer simulation using the parameters in Table 1. It is Rayleigh fading channels, which is the probability of ac-

Table 1 Parameters of simulation

<table>
<thead>
<tr>
<th>Shift orthogonal code</th>
<th>( A(32, 32, 0), A(32, 16, 1) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of users</td>
<td>( U = 1, 4, 8, 15 )</td>
</tr>
<tr>
<td>Number of sync-signals</td>
<td>( P = 1, 3 )</td>
</tr>
<tr>
<td>SIR</td>
<td>0 dB</td>
</tr>
<tr>
<td>Transmission environment</td>
<td>AWGN, Rayleigh fading</td>
</tr>
</tbody>
</table>

(ZCZ) over the AWGN channel are respectively shown in Fig. 8, where \( H \) denotes the EZCZ code and means a Hadamard orthogonal code. Similarly, the SERs of Methods 0-2 using \( A_{EO} \) and \( A_{EZ} \) over the AWGN channel and Rayleigh fading channel are shown in Fig. 9.

It is confirmed that Method 0 needs to always confirm and track the synchronization point, and Method 2 using the ZCZ code is superior to the others. Note that Method 1 using \( A_{EO} \) has a slightly better SER than Method 1 using \( A_{EZ} \), owing to the difference in these autocorrelation characteristics.

The SERs of Method 3 with \( P = 3 \) over AWGN and Rayleigh fading channels are shown in Figs. 10 and 11, respectively. Here only the result of SER using \( A_{EZ} \) is described, since the SER of Method 1 using \( A_{EO} \) is almost the same as that using \( A_{EZ} \). Note that Method 3 is very effective in the AWGN channel. A comparison of Fig. 8 and 9 for \( P = 1 \) with Fig. 10 and 11 for \( P = 3 \) shows that the SER of Method 3 is approximately 4.7 dB better. Actually it can be confirmed that SER improves in twice \( P \) as 3dB. The SER of Methods 0-2 for SIR with \( SNR = 20 \) dB are also shown in Fig. 12. Note that Methods 1 and 2 can maintain SER even if SIR and the number of transmitters increase.

5. Conclusion

In this paper, we proposed three types of high-speed synchronization acquisition methods using a matched filter bank of a shift orthogonal code and showed the effec-

Fig. 5 Block diagram of the proposed methods

Fig. 6 Output of Method 1

Fig. 7 Output of Method 2

4. SER Performance

The SER of the above methods over AWGN and flat Rayleigh fading channels, which is the probability of acquiring a wrong synchronization point, is investigated by computer simulation using the parameters in Table 1. It is assumed that the synchronization gaps among users can be settled within one chip interval.

The SERs of Methods 0-2 using \( A_{EO} \) (H) and \( A_{EZ} \)
tiveness of the methods by SER over AWGN and Rayleigh fading channels.

As a result, it is desirable that the synchronization control unit is installed in the places to be able to foresee more by users to provide an environment that is near to the AWGN channel. Further studies will include fast synchronization acquisition systems based on the proposed methods with a block coding technique [21] and MIMO technology [22], and communication systems in which the proposed methods are used as a decoding technique.

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