TWO-STAGE TIME-HOPPING SEQUENCES WITH ZERO CORRELATION ZONE FOR QUASI-SYNCHRONOUS THSS-UWB SYSTEMS

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ABSTRACT

We propose a novel time-hopping (TH) sequences design algorithm for quasi-synchronous time-hopping spread spectrum ultra wideband (THSS-UWB). Based on this algorithm, a new family of two-stage TH sequences with zero correlation zone (ZCZ) is constructed. THSS-UWB systems employing the proposed two-stage ZCZ TH sequences can be without multiple-access interference (MAI) and be more tolerant to the multipath problem when the shifts between sequences are in the range of ZCZ.

1. INTRODUCTION

Ultra wideband (UWB) radio technology has been used in the past for radar and remote sensing applications. Recently, however, it has been proposed for use in wireless communications where it was called THSS-UWB [1-2]. THSS-UWB is based on time-hopping code-division multiple-access (TH-CDMA). Then, TH technique plays an important role in THSS-UWB, and TH sequences with good correlation properties (less hits between TH sequences) are required. Based on the construction theory of frequency-hopping (FH) sequences, some TH sequences with good TH correlation properties have been constructed [3-7]. However, it is not possible to design the TH sequences with no hits at all because of the existence of Johnson bound between the TH sequences parameters [3]. Then, the MAI of asynchronous THSS-UWB systems will be inevitable. In order to solve the MAI problem in THSS-UWB applications, ZCZ TH sequences maintaining orthogonality within a local duration around the origin have been proposed [8-9]. The significance of ZCZ TH sequences is that, even there are relative delays between the transmitted TH sequences, the hit between TH sequences will not happen as long as the relative delay dose not exceed certain limit (or zone). Thus, the performance of THSS-UWB systems employing such sequences will be improved greatly.

The concept of ZCZ was firstly proposed for direct sequence (DS) in DS-CDMA systems [10]. For direct-sequence ultra wideband (DS-UWB) systems, ZCZ or zero correlation duration (ZCD) direct sequences were firstly presented in the literature [11-12]. The above studies are just suitable for direct sequence spread spectrum (DSSS) systems, not for frequency-hopping spread spectrum (FHSS) or THSS systems. In [13-14], ZCZ FH sequences were studied on the basis of matrix transform method and the known binary ZCZ sequences respectively, where it was also called no-hit zone (NHZ). However, the ZCZ property of these FH sequences will be destroyed when ZCZ FH sequences serve as TH sequences for THSS-UWB systems.

In this paper, a novel construction algorithm for ZCZ TH sequences suitable for use in THSS-UWB systems is proposed. Different from ZCZ TH sequences in [8-9], the ZCZ TH sequences proposed in this paper are based on multiple-stage sequences construction theory. We present construction algorithm of two-stage ZCZ TH sequences and investigate correlation properties of such sequences. Also, a construction example is presented.

2. ZCZ OF TIME-HOPPING SEQUENCES

For the convenience of the following analysis, we first introduce the necessary notation. In THSS-UWB, data are transmitted by using pulse position modulation (PPM)[1] or pulse amplitude modulation (PAM)[15] at a rate of many pulses per data symbol. Both modulation formats require the good correlation properties of TH sequences, namely good auto-correlation and cross-correlation properties. In PPM, the transmitted signal for user i may be expressed as

$$S^{(i)}(t) = \sum_{k=-\infty}^{+\infty} w(t - kT_f - c^{(i)}_{(k)_L} \cdot T_c - \delta d^{(i)}_{\lfloor k/N_S \rfloor}), \quad (1)$$

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where $c^{(i)} = \{c^{(i)}_{(k)_L}\}$ is a TH sequence assigned to user i. It is periodic with period of L and each sequence element is an integer in the range of $0 \le c^{(i)}_{(k)_L} \le N_h$, where $0 \le k \le L-1$ and the notation $(\cdot)_L$ denotes a modulo L operation. T_f is frame time, and T_c is TH slot time, satisfying $T_f = N \cdot T_c$.

Let $C = \{c^{(i)}\}$, $c^{(i)} = \{c^{(i)}_{(k)_L}\}$, $0 \le c^{(i)}_{(k)_L} \le N_h$, $1 \le i \le M$, $0 \le k \le L-1$, be a set of hopping sequences, where M is the maximum number of sequences in set $C = \{c^{(i)}\}$. When the hopping sequences serve as FH sequences, a good measure for the sequences is the well-known period Hamming correlation function defined by

$$H_{ij}(\tau) = \sum_{k=0}^{L-1} h[c^{(i)}_{(k)_L}, c^{(j)}_{(k+\tau)_L}],\ 0 \le \tau \le L-1, \tag{2}$$

where $h[c^{(i)}_{(k)_L}, c^{(j)}_{(k+\tau)_L}] = \begin{cases} 1, & c^{(i)}_{(k)_L} = c^{(j)}_{(k+\tau)_L} \\ 0, & c^{(i)}_{(k)_L} \ne c^{(j)}_{(k+\tau)_L} \end{cases}$.

When $C = \{c^{(i)}\}$ serve as TH sequences, the measure for TH sequences is more complicated than FH sequences, and can be defined as follows.

Definition 1 [16]: Let $c^{(i)}$ and $c^{(j)}$ denote two TH sequences with period L, $c^{(i)}, c^{(j)} \in C$, then TH periodic correlation function with shift τ can be expressed as

$$C_{ij}(\tau) = \sum_{k=0}^{L-1} h[(kN + c^{(i)}_{(k+a)_L})_{NL}, (kN + c^{(j)}_{(k)_L} + b)_{NL}]$$
$$+ \sum_{k=0}^{L-1} h[((k+1)N + c^{(i)}_{(k+1+a)_L})_{NL}, (kN + c^{(j)}_{(k)_L} + b)_{NL}], \tag{3}$$

where $\tau = aN + b$, $0 \le a \le L-1$, $0 \le b \le N-1$, then $0 \le \tau \le NL-1$.

It should be noted that, Hamming correlation function in Equation (2) describes the number of hits in terms of $\tau \propto T_f$, while Definition 1 is in terms of $\tau \propto T_c$. In Equation (2), $0 \le \tau \le L-1$, and in the case, the number of circular shifts in a period is L. However, in Equation (3), the number of circular shifts in a period is $(N-1)$ times more than L, namely NL. In terms of the diversity between TH and FH correlation function, it is possible that the hopping sequences with good FH correlation properties have bad TH correlation properties. For example, based on Definition 1, ZCZ will disappear when ZCZ FH sequences in [13-14] serve as TH sequences.

In Equation (3), shift τ satisfying $0 \le \tau \le NL-1$. When $\tau > NL-1$ or $\tau < 0$, there is $C_{ij}(\tau) = C_{ij}((\tau)_{NL})$, since TH correlation function is periodic. According to Definition 1, ZCZ of TH sequences can be defined as follows.

Definition 2 [9]: Let $C_{ij}(\tau)$ denotes correlation function value between two TH sequences $c^{(i)}$ and $c^{(j)}$ with period L, then ZCZ of TH sequences can be expressed as

$$C_{ii}(\tau) = \begin{cases} L, & \tau = 0 \\ 0, & 0 < |\tau| \le \dfrac{Z_{SCZ}}{2} \end{cases}, \tag{4}$$

$$C_{ij}(\tau) = 0,\quad 0 \le |\tau| \le \frac{Z_{CCZ}}{2},\quad i \ne j, \tag{5}$$

$$Z_{CZ} = min\{Z_{SCZ}, Z_{CCZ}\}, \tag{6}$$

where Z_{SCZ} denotes TH zero auto-correlation zone value, Z_{CCZ} denotes TH zero cross-correlation zone value, and Z_{CZ} denotes ZCZ value of TH sequences.

3. CONSTRUCTION AND ANALYSIS OF TWO-STAGE ZCZ TH SEQUENCES

This section gives the construction algorithm of two-stage ZCZ TH sequences, and then presents the proof for correlation properties of such TH sequences.

Proposed two-stage ZCZ TH sequences Construction: Let $F = \{f^{(i)}\}$, $f^{(i)} = \{f^{(i)}_{(k)_L}\}$, $0 \le f^{(i)}_{(k)_L} \le N_{fh}$, $1 \le i \le M$, $0 \le k \le L-1$, be a set of the known orthogonal FH sequences, and $E = \{e^{(i)}\}$, $e^{(i)} = \{e^{(i)}_{(k)_L}\}$, $0 \le e^{(i)}_{(k)_L} \le N_{eh}$, $1 \le i \le M$, $0 \le k \le L-1$, be a set of any hopping sequences, then two-stage ZCZ TH sequences with zero correlation zone Z_{CZ} can be expressed as

$$C = \{c^{(i)}\},\ c^{(i)} = \{c^{(i)}_{(k)_L}\},$$

$$c^{(i)}_{(k)_L} = f^{(i)}_{(k)_L}(N_{eh} + 1 + Z_{CZ}) + e^{(i)}_{(k)_L}, \tag{7}$$

$$Z_{SCZ} = Z_{CCZ} = Z_{CZ}, \tag{8}$$

where $0 \le c^{(i)}_{(k)_L} \le N_h = N_{fh}(N_{eh} + 1 + Z_{CZ}) + N_{eh}$, $1 \le i \le M$, $0 \le k \le L-1$, and $N = (N_{fh} + 1)(N_{eh} + 1 + Z_{CZ})$.

Obviously, the proposed sequences set $C = \{c^{(i)}\}$ has the same length L and family size M with FH sequences sets $F = \{f^{(i)}\}$ and $E = \{e^{(i)}\}$. When Z_{CZ} is fixed in terms of the requirement of practical THSS-UWB systems, two-stage ZCZ TH sequences can be constructed on the basis of Equation (7). Such sequences satisfy $C_{ij}(\tau) = 0$ and $C_{ii}(\tau) = 0$ (except for the zero shift auto-correlation) when shift τ is in the range of Z_{CZ}.

The principle of construction of two-stage ZCZ TH sequences can be depicted in Fig.1, where $Z_{CZ} = 6$, $N_{fh} = N_{eh} = 4$ and $c^{(i)}_{(0)_4} = f^{(i)}_{(0)_4}(N_{eh} + 1 + Z_{CZ}) + e^{(i)}_{(0)_4} = 25$. In the example of two-stage ZCZ TH sequences, a monocycle firstly hops to the second time slot position in control of the 1th stage TH sub-sequences $f^{(i)}_{(0)_4} = 2$. And then, it hops to the third time sub-slot position of the second time slot in control of the 2th stage TH sub-sequences $e^{(i)}_{(0)_4} = 3$.

According to Definition 1, the TH correlation properties of proposed two-stage ZCZ TH sequences can be proved as follows.

Proof: Let relative delay between sequences (or synchronization error of THSS-UWB system) λ is in the range of $|\lambda| \le \frac{Z_{CZ}}{2} \cdot T_c$, then it is obvious that $a = 0$ and $0 \le b \le Z_{CZ}$ for $C_{ij}(\tau)$ in Equation (3).

For any two two-stage ZCZ TH sequences $c^{(i)}$ and $c^{(j)}$, $c^{(i)}, c^{(j)} \in C$, according to Definition 1 and Equation (7), their TH periodic correlation function is given by

$$C_{ij}(\tau) = \sum_{k=0}^{L-1} h[(c^{(i)}_{(k)_L})_{NL}, (c^{(j)}_{(k)_L} + b)_{NL}] + \sum_{k=0}^{L-1} h[(N + c^{(i)}_{(k+1)_L})_{NL}, (c^{(j)}_{(k)_L} + b)_{NL}]$$

$$= \sum_{k=0}^{L-1} h[((f^{(i)}_{(k)_L} - f^{(j)}_{(k)_L})(N_{eh} + 1 + Z_{CZ}) + (e^{(i)}_{(k)_L} - e^{(j)}_{(k)_L}))_{NL}, b] + \sum_{k=0}^{L-1} h[((f^{(i)}_{(k+1)_L} - f^{(j)}_{(k)_L} + N_{fh} + 1)(N_{eh} + 1 + Z_{CZ}) + (e^{(i)}_{(k+1)_L} - e^{(j)}_{(k)_L}))_{NL}, b]. \quad (9)$$

i) We consider $i \ne j$.

For the first part of $C_{ij}(\tau)$ in Equation (9), because $F = \{f^{(i)}\}$ is a set of orthogonal FH sequences, then there is $f^{(i)}_{(k)_L} - f^{(j)}_{(k)_L} \ne 0$. Because of $0 \le e^{(i)}_{(k)_L}, e^{(j)}_{(k)_L} \le N_{eh}$, then $-N_{eh} \le e^{(i)}_{(k)_L} - e^{(j)}_{(k)_L} \le N_{eh}$. By combining $f^{(i)}_{(k)_L} - f^{(j)}_{(k)_L} \ne 0$ with $-N_{eh} \le e^{(i)}_{(k)_L} - e^{(i)}_{(k)_L} \le N_{eh}$, we can obtain that $((f^{(i)}_{(k)_L} - f^{(j)}_{(k)_L})(N_{eh} + 1 + Z_{CZ}) + (e^{(i)}_{(k)_L} - e^{(j)}_{(k)_L}))_{NL} \ge 1 + Z_{CZ}$. Also, because of $0 \le b \le Z_{CZ}$, we can further obtain that $\sum_{k=0}^{L-1} h[((f^{(i)}_{(k)_L} - f^{(j)}_{(k)_L})(N_{eh} + 1 + Z_{CZ}) + (e^{(i)}_{(k)_L} - e^{(j)}_{(k)_L}))_{NL}, b] = 0$.

For the second part of $C_{ij}(\tau)$ in Equation (9), because of $0 \le f^{(i)}_{(k+1)_L}, f^{(j)}_{(k)_L} \le N_{fh}$, then $-N_{fh} \le f^{(i)}_{(k+1)_L} - f^{(j)}_{(k)_L} \le N_{fh}$. Hence, we can obtain that $f^{(i)}_{(k+1)_L} - f^{(j)}_{(k)_L} + N_{fh} + 1 \ne 0$. Similar to the proof of the first part of $C_{ij}(\tau)$, there is $\sum_{k=0}^{L-1} h[((f^{(i)}_{(k+1)_L} - f^{(j)}_{(k)_L} + N_{fh} + 1)(N_{eh} + 1 + Z_{CZ}) + (e^{(i)}_{(k+1)_L} - e^{(j)}_{(k)_L}))_{NL}, b] = 0$.

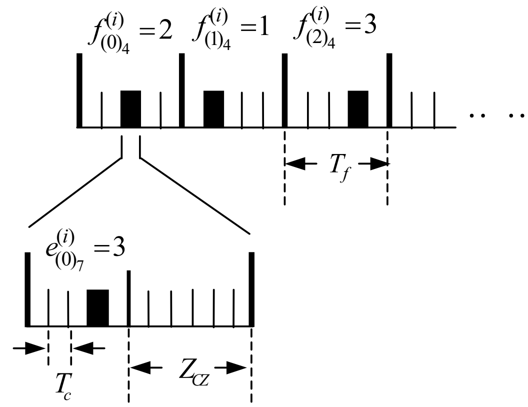

Fig.1 The construction of two-stage ZCZ TH sequences

According to the above analysis, we can obtain that $C_{ij}(\tau) = 0$ for $i \ne j$ when relative delay between sequences λ is in the range of $|\lambda| \le \frac{Z_{CZ}}{2} \cdot T_c$.

ii) We consider $i = j$.

When $i = j$, Equation (9) can be simplified as follows.

$$C_{ii}(\tau) = \sum_{k=0}^{L-1} h[0, b] + \sum_{k=0}^{L-1} h[((f^{(i)}_{(k+1)_L} - f^{(i)}_{(k)_L} + N_{fh} + 1)(N_{eh} + 1 + Z_{CZ}) + (e^{(i)}_{(k+1)_L} - e^{(i)}_{(k)_L}))_{NL}, b], \quad (10)$$

For the first part of $C_{ii}(\tau)$ in Equation (10), $\sum_{k=0}^{L-1} h[0, b] = L$ when $b = 0$, and $\sum_{k=0}^{L-1} h[0, b] = 0$ when $0 < b \le Z_{CZ}$.

For the second part of $C_{ii}(\tau)$ in Equation (10), because of $-N_{fh} \le f^{(i)}_{(k+1)_L} - f^{(i)}_{(k)_L} \le N_{fh}$, we can obtain that $f^{(i)}_{(k+1)_L} - f^{(i)}_{(k)_L} + N_{fh} + 1 \ne 0$. Similarly, there is $\sum_{k=0}^{L-1} h[((f^{(i)}_{(k+1)_L} - f^{(i)}_{(k)_L} + N_{fh} + 1)(N_{eh} + 1 + Z_{CZ}) + (e^{(i)}_{(k+1)_L} - e^{(i)}_{(k)_L}))_{NL}, b] = 0$.

Then, we can also obtain that $C_{ii}(\tau) = 0$ (except for the zero shift auto-correlation $C_{ii}(0) = L$) when $|\lambda| \le \frac{Z_{CZ}}{2} \cdot T_c$.

Q.E.D.

To show how Equation (7) works, we give an example. We use a known orthogonal set of FH sequences in [17]. For this FH sequences set $F = \{f^{(i)}\}$, $0 \le f^{(i)}_{(k)_L} \le N_{fh} = 6$, $1 \le i \le M = 7$ and $0 \le k \le L - 1 = 6$. Also, for convenience, let $e^{(i)}_{(k)_L} = f^{(i)}_{(k)_L}$ (note that $E = \{e^{(i)}\}$ can be any hopping sequences set satisfying $0 \le e^{(i)}_{(k)_L} \le N_{eh} = 6$ and $1 \le i \le M = 7$).

$$F=\{f^{(i)}\}:\begin{array}{ccccccccc} f^{(1)} & : & 2 & 4 & 6 & 3 & 1 & 0 & 5 \\ f^{(2)} & : & 1 & 2 & 0 & 5 & 4 & 6 & 3 \\ f^{(3)} & : & 5 & 6 & 2 & 4 & 3 & 1 & 0 \\ f^{(4)} & : & 3 & 1 & 5 & 2 & 0 & 4 & 6 \\ f^{(5)} & : & 0 & 3 & 1 & 6 & 2 & 5 & 4 \\ f^{(6)} & : & 6 & 0 & 4 & 1 & 5 & 3 & 2 \\ f^{(7)} & : & 4 & 5 & 3 & 0 & 6 & 2 & 1 \end{array}$$

Let $Z_{CZ}=4$, in terms of Equation (7), then ZCZ TH sequences set $C=\{c^{(i)}\}$ can be obtained as follows.

$$C=\{c^{(i)}\}:\begin{array}{ccccccccc} c^{(1)} & : & 24 & 48 & 72 & 36 & 12 & 0 & 60 \\ c^{(2)} & : & 12 & 24 & 0 & 60 & 48 & 72 & 36 \\ c^{(3)} & : & 60 & 72 & 24 & 48 & 36 & 12 & 0 \\ c^{(4)} & : & 36 & 12 & 60 & 24 & 0 & 48 & 72 \\ c^{(5)} & : & 0 & 36 & 12 & 72 & 24 & 60 & 48 \\ c^{(6)} & : & 72 & 0 & 48 & 12 & 60 & 36 & 24 \\ c^{(7)} & : & 48 & 60 & 36 & 0 & 72 & 24 & 12 \end{array}$$

From Definition 1, TH auto-correlation and cross-correlation values can be respectively expressed by

$$C_{ii}=\{\times\ \cdots\ \times\ 0\ 0\ 0\ 0\ \overbrace{\underset{\substack{\uparrow\\ \tau=0}}{7}\ \underbrace{0\ 0\ 0\ 0}_{Z_{CZ}=4}\ \times\ \cdots\ \times}^{N\cdot L=539}\},$$

for any i satisfying $1\le i\le M=7$.

$$C_{ij}=\{\times\ \cdots\ \times\ 0\ 0\ 0\ 0\ \overbrace{\underset{\substack{\uparrow\\ \tau=0}}{0}\ \underbrace{0\ 0\ 0\ 0}_{Z_{CZ}=4}\ \times\ \cdots\ \times}^{N\cdot L=539}\},$$

for any i, j satisfying $i\ne j$ and $1\le i, j\le M=7$.

4. CONCLUSIONS

A novel construction algorithm of two-stage ZCZ TH sequences for THSS-UWB systems is presented on the basis of the multiple-stage hopping theory and the known orthogonal FH sequences set. When the ZCZ value Z_{CZ} is fixed in terms of the requirement of practical THSS-UWB systems, two-stage ZCZ TH sequences can be constructed in terms of Equation (7). The performance of THSS-UWB systems employing such sequences will be improved greatly.

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