ON THE DESIGN OF FULL DUPLEX WIRELESS SYSTEM WITH CHAOTIC SEQUENCES

RUWU XIAO*
School of Electronics Engineering and Computer Science
Peking University, Beijing, China

GENG LI AND YUPING ZHAO
Department of Computer Science
Yale University, New Haven, CT, USA
and
School of Electronics Engineering and Computer Science
Peking University, Beijing, China

ABSTRACT. This paper proposes a novel approach for full duplex using chaotic sequences which is known as the asynchronous code-division duplex (Async-CDD) system. The Async-CDD system can transmit and receive signals at the same time and in the same frequency channel without time slot synchronization. The data rate of the Async-CDD system is 8 times higher than the conventional CDD system and is the same as a non-spreading system. The property of low block cross-correlation of the chaotic sequence allows the Async-CDD system achieve duplex interference suppression at any duplex delay. And the huge number of available code words/blocks of the chaotic sequence allows the Async-CDD system increase the data rate by increasing the number of multiplexed sub-channels. When both of the code length of the orthogonal chaotic code and the number of multiplexed sub-channels are 128, the orthogonal chaotic code provides 30.40 dBc self-interference suppression in average, which is 6.99 dB better than the orthogonal Gold code.

1. Introduction. In wireless communication systems, to distinguish between up-link and downlink is always a fundamental problem for achieving two-way communication links. There are two available duplex mode currently in use: the time division duplex (TDD), and the frequency division duplex (FDD) [16]. However, none of the methods mentioned above is able to achieve a full duplex system. Therefore, while the spectrum resources become more and more costly, to achieve a code division duplex (CDD) system, which could be able to transmit and receive signals at the same time slot and in the same frequency channel, has become a novel way to improve the transmission efficiency for next generation communication system. Based on the zero correlation zone (ZCZ) codes, [12] proposed the CDD system model. Subsequently, [9] analyzed the performance of the CDD system and pointed out that the CDD system could double the transmission efficiency comparing with the TDD or FDD system.

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* Corresponding author: Ruwu Xiao.
Since the length of the zero correlation zone is finite, the CDD system proposed in [12] is actually a synchronous or quasi-synchronous system. Nevertheless, when transmitting signals at the same time and in the same frequency, the receiver’s antenna would inevitably receive an high power interference signal transmitted by the local transmitting antenna [3, 8], which would bring a serious impact on the synchronization timing. Further more, due to the limited code number of the ZCZ sequences, the multi-channel data multiplexing has also been limited, thus lower the data rate eventually. As long as the data rate is less than half of the non-spreading system, then the transmission efficiency of the CDD system will be lower than the corresponding TDD system, which is contrary to the original intention of this full duplex system. Besides, the limited number of the ZCZ codes not only restricts the number of the users in the same cell, but also impedes the inter-cell interference cancellation performed by adopting different code blocks in different cells. Hence, many other scheme for implementing the full duplex system have been developed, such as smart antenna based self-interference suppression proposed in [4, 8], passive self-interference suppression proposed in [5], and analog/digital self-interference cancellation technology proposed in [2, 6, 17, 18].

However, with the continuous increasing of the carrier frequency and the moving speed of the device, the currently interference cancellation technology still can not provide enough dynamic range to satisfy the requirements of the practical application scene. Many new mathematical methods are used to study system level optimization problem [7, 13]. Then, in order to further suppress the self-interference signal by spread spectrum technology, an improved CDD system with chaotic sequence has been developed in this paper.

The proposed Async-CDD system adopts the orthogonal chaotic (OC) sequence as the spreading code. The OC sequence provides a large number of available code words and code blocks with better cross-correlation performance. In summary, the proposed Async-CDD system has the following advantages:

1. Suppressing the self-interference by spread spectrum gain, and this does not exclude other self-interference cancellation technology mentioned above.
2. The code words of the same code block are orthogonal, which allows increasing the transmission data rate by adopting multi-channel data multiplexing.
3. With the improved cross-correlation performance of the code words of different code blocks, there is not any specific synchronization requirement for the uplink and downlink signals that using different code blocks.

Section II establishes the system model of the Async-CDD system, and explains why ZCZ sequences is not suitable for implementing the CDD system. The theoretical analysis for the performance of the Async-CDD system is provided in Section III, and is verified by simulation. some conclusions are given in Section IV.

2. System model.

2.1. Application scenario. The CDD system distinguishes uplink and downlink signals by different spreading codes. It works in the scene shown in Fig. 1.

As shown in the figure, in the CDD system, the spreading code is denoted as follows:

$\{C_i, r, N\}, \quad r \in [1, N] \quad (1)$

(1) denotes code word $r$ from code block $i$, whose code length is $N$. In general, (1) can also be given by:
\( \{ C_{i,r,N}(n) \}, \quad r \in [1,N] \)

\((2)\) denotes the \( n \)-th code chip of code word \( r \) from code block \( i \), whose code length is \( N \).

Then, the uplink code block is denoted as \( \{ C_{U,p,N} \} \), while the downlink code block is denoted as \( \{ C_{D,q,N} \} \).

Let \( T_U[p,n,N] \) denotes the code stream spread by \( C_{U,p,N} \). Thus, the signal transmitted by the CDD system is given by:

\[
T_U(n) = \sqrt{\xi_{T,U}} \cdot \sum_{p=1}^P T_U[p,n,N]
\]

\(3\)

\[
T_D(n) = \sqrt{\xi_{T,D}} \cdot \sum_{q=1}^Q T_D[q,n,N]
\]

\(4\)

Wherein, \( \sqrt{\xi_{T,U}} \) is the normalized power of the code stream in the sub-channel. \( P \) and \( Q \) is the number of the multiplexed sub-channels or the code words number. \( N \) is the code word length. As for the uplink receive antenna, \( \alpha \) is the attenuation factor for the uplink signal \( T_U(n) \) through the free space, \( \beta \) is the attenuation factor for the downlink signal \( T_D(n) \) received in the uplink receive antenna. \( \frac{\alpha}{\beta} \) can also be understood as the ratio of the amplitude of the target signal and the self-interference signal in the receiver.

In order to eliminate the duplex self-interference, the cross-correlation performance of the spreading codes is required to be as follows:

\[
r_{pq}(m) = \frac{1}{N} \cdot \sum_{n=0}^{N-m-1} C_{U,p,N}(n) \cdot C_{D,q,N}(n+m)
\]

\(
m = 0
\)

Moreover, in order to eliminate the multi-path interference and achieve the multi-channel data multiplexing, the auto-correlation performance of the spreading codes is required to be as follows:

\[
r_{pp}(m) = \frac{1}{N} \cdot \sum_{n=0}^{N-m-1} C_{U,p,N}(n) \cdot C_{U,p,N}(n+m)
\]
It has been proved that there is not any spreading codes existing can achieve the ideal cross-correlation performance and the ideal auto-correlation performance simultaneously \[19\]. But there are still some spreading codes that satisfy the requirements approximately.

2.2. **The spreading code adopted in the conventional CDD system.** For the synchronous CDD system, assuming that there is not any synchronization error, then:

\[
\begin{align*}
r_{pq}(0) &= \frac{1}{N} \cdot \sum_{n=0}^{N-1} C_{U,p,N}(n) \cdot C_{D,q,N}(n) \\
&= 0
\end{align*}
\]

In that case, the interference between the uplinks and downlinks can be eliminated by means of despreading.

However, for an actual system, because of the propagation delay, the clock jitter and especially the high residual power of the self-interference signal, the devices in the CDD system are difficult to be synchronized perfectly. Thus, \[12\] proposed the CDD system based on ZCZ sequences. In the ZCZ sequence based CDD system, the auto-correlation performance is as follows:

\[
\begin{align*}
r_{pq}(m) &= \frac{1}{N} \cdot \sum_{n=0}^{N-m-1} C_{U,p,N}(n) \cdot C_{D,q,N}(n+m) \\
&= 0, \ |m| < \frac{W}{2}
\end{align*}
\]

where, \(W\) is the length of the zero correlation zones. In nature, the conventional CDD system is actually a quasi-synchronous code division duplex system. This system relaxed the requirements for synchronization to a certain extent, which means that the larger the value of \(W\), the lower the requirements for the synchronization. But as the value of \(W\) increases, the spreading gain would be decreased if the code length was the same. Correspondingly, the increasing of the code length caused by adding more zeros will lead to a data rate reduction in transmission, which is on the contrary to the original intention of the CDD system.

2.3. **Constraints of the spreading code for the CDD system.** In the spread spectrum system, if that the data rate is less than half of the non-spreading system, then the transmission efficiency of the CDD system would be lower than the corresponding TDD system. Hence, for the CDD systems, the code words number of the code blocks must be more than half of the code word length, so that the multiplexing channels number would be plenty enough to compensate the data rate decrease caused by spreading. Thus:

\[
P > \frac{N}{2}
\]  \hspace{1cm} (6)

According to the Tang-Fan-Matsufuji Bounds \[19\], the relationship between the code words number \(P\), code length \(N\) and the length of the zero correlation zones \(W\) is as follows:

\[
P \cdot W \leq N
\]  \hspace{1cm} (7)
Since $W \geq 2$, (7) can be simplified as follows:

$$P \leq \frac{N}{2} \quad (8)$$

Because (8) and (6) is contradictory, there is the conclusion that ZCZ sequence is not suitable for the CDD system. The better sequence should be adopted in the CDD system.

2.4. Specifications for evaluating the spreading code adopted in the Async-CDD system.

2.4.1. The within-block auto-correlation and cross-block cross-correlation. The spreading codes adopted in the Async-CDD system proposed in this paper should satisfy two basic requirement:

1. Different code words within the same code block must be orthogonal. Namely, the auto-correlation performance of different code words from the same code block should be zero. Then, the multi-channel data multiplexing could be adopted to increase the transmission data rate.

2. The cross-correlation performance of different code words from different code blocks should be as low as possible. Thus, the residual self-interference could be eliminated.

The within-block auto-correlation is defined in (9) to evaluating the orthogonality of the code words from the same code block. And the cross-block cross-correlation is defined in (10) to evaluating the cross-correlation performance of different code words from different code blocks:

$$r_{ii}(0) = \frac{1}{N} \sum_{n=0}^{N-1} C_{U,i,N}(n) \cdot C_{U,i,N}(n) = \delta_{ii} \leq \delta_{\text{min}}; \quad i \in [1, P] \quad (9)$$

$$r_{ij}(m) = \frac{1}{N} \sum_{n=0}^{N-m-1} C_{U,i,N}(n) \cdot C_{D,j,N}(n+m) = \delta_{ij,m} \leq \delta_{\text{max}}; \quad i \in [1, P], j \in [1, Q] \quad (10)$$

$$\delta_{\text{aver}} = \frac{1}{N^2} \sum_{i,j} \left[ \frac{1}{N} \sum_{m=-N+1}^{N-1} \delta_{ij,m} \right] \quad (11)$$

$\delta_{\text{max}}$ in (9) should be small enough to ensure that, without time slot synchronization, every device in the system can still eliminate the residual self-interference. This feature also allows the Async-CDD system to assign different code blocks to different cells for reducing the inter-cell interference. (10) indicates that the sub-channel multiplexing could be adopted to improve the system transmission data rate. Both the orthogonal Gold (OG) code [11,14,15] and orthogonal chaotic (OC) code [1,10] satisfy (9) and (10). The performance of the OG code and OC code are compared in the following section.

Notice that in this paper, without loss of generality, unless otherwise noted, $P$ is assumed to be equal to $Q$. 


2.4.2. The block-correlation. The block-correlation is defined in (12) to evaluate the self-interference suppression for two different code blocks.

\[ R(m, i) = \sum_{j=0}^{P-1} r_{ij}(m) \]  

(12)

where, \( m \) is actually the duplex delay between the uplink and downlink.

2.5. The orthogonal low block cross-correlation spreading code for the Async-CDD system.

2.5.1. Orthogonal gold code. The uplink OG codes are generated by the polynomials \([2 1 1]\) and \([2 1 7]\), while the downlink OG codes are generated by the polynomials \([2 1 1]\) and \([2 3 5]\). Thus, two code blocks whose code length is 128 chips are obtained. \( \delta_{\text{aver}} \) of these code blocks is 0.0686. Namely, in a variety of duplex delay conditions, the OG code provides 23.28 dBc of duplex self-interference suppression in average. That is the reason why the OG code is suitable for Async-CDD system. \( \delta_{\text{max}} \) of the OG code is 0.1123. Namely, in the worst case, the OG code can still provides 18.99 dBc duplex self-interference suppression.

In addition, the number of the available code words of the OG code is large. When the duplex delay is zero, the code words from the OG code block are all orthogonal. The orthogonal property of the OG code allows the system to increase the transmission data rate by multi-channel data multiplexing. Namely, although the spreading ratio is 128, there is not any data rate decrease if 128 sub-channel multiplexing were adopted. In other words, The Async-CDD system overcomes the low data rate disadvantage that existing in the quasi-synchronous CDD system.

The block-correlation performance of the OG code is shown in Fig. 2.

2.5.2. Orthogonal chaotic code. Compared to the OG code, the OC code is a better choice for the Async-CDD system.

The OC code adopted in this paper is an Logistic-Map chaotic spreading sequence. The map of this sequence is defined as follows:

\[ x(k+1) = \mu x(k)[1 - x(k)], x \in (0, 1); \]  

(13)
where, $\mu$ is 3.7. When $x(0)$ varies from 0.001 to 0.256 with step equals 0.001, a series of binary chaotic pseudo-random sequences are obtained. Then, these 256 code words are divided into two code blocks and are orthogonalized using the Gram-Schmidt orthogonalization method, respectively. Notice that, follow this process, a huge number of OC code blocks could be obtained by applying different $x(0)$.

$\delta_{\text{aver}}$ of these code blocks is 0.0214. Namely, in a variety of duplex delay conditions, the OC code provides 33.78 dB duplex self-interference suppression in average, which is 10.51 dBc higher than the OG code. $\delta_{\text{max}}$ of the OG code is 0.0574. Namely, in the worst case, the OG code can still provides 24.69 dBc of duplex self-interference suppression, which is 5.7 dBc higher than the OG code.

The block-correlation performance of the OC code is shown in Fig. 3.

![Figure 3. The block-correlation performance of the OC code](image)

As shown in Fig. 2 and Fig. 3, compared to the OG code, the OC code provides better duplex self-interference suppression performance.

However, the OC code is a multi-level sequence, which may lead to an increase of the peak to average power ratio (PAPR) of the despread signal.

3. **System performance.**

3.1. **The signal to noise and interference ratio (SINR).**

3.1.1. *General expression of the SNR in the CDD system.* Applying the definition given in (2) and (4), in AWGN channel, the received signal can be expressed as follows:

$$R_D(n) = \alpha \cdot T_U(n) + \beta \cdot T_D(n) + N_{\text{RMS}}(n)$$

$$= \alpha \cdot \sqrt{\xi_{T,U}} \cdot \sum_{p=1}^{P} T_U[p, n, N]$$

$$+ \beta \cdot \sqrt{\xi_{T,D}} \cdot \sum_{q=1}^{Q} T_D[q, n, N]$$

$$+ N_{\text{RMS}}(n)$$

where $N_{\text{RMS}}(n)$ is the white Gaussian noise.
In the correlation receiver, the despreading of the signal spread by $C_{U,p,N}$ can be described as in (14), wherein, $r_D(m)$ denotes the output signal of the correlator.

$$r_D(m) = \sum_{n=1}^{N-m-1} \left\{ \left[ \alpha \sqrt{\xi_{T,U}} \cdot \sum_{p=1}^{P} T_U[p,n,N] \right] + \beta \cdot \sqrt{\xi_{T,D}} \cdot \sum_{q=1}^{Q} T_D[q,n,N] ight\}$$

$+ N_{RMS}(n) \cdot C_{U,p,N}(n+m)$

$$= \left\{ \sum_{n=1}^{N-m-1} \left[ \alpha \sqrt{\xi_{T,U}} \cdot \sum_{p=1}^{P} T_U[p,n,N] \cdot C_{U,p,N}(n+m) \right] \right\}$$

$$+ \left\{ \sum_{n=1}^{N-M-1} \left[ \beta \sqrt{\xi_{T,D}} \cdot \sum_{q=1}^{Q} T_D[q,n,N] \cdot C_{U,p,N}(n+m) \right] \right\}$$

$$+ \left\{ \sum_{n=1}^{N-M-1} \left[ N_{RMS}(n) \cdot C_{U,p,N}(n+m) \right] \right\}$$

(14)

According to the theory of the correlator receiver, assuming that $r_D(m)$ would obtain the maximum value when $m = M$. Substituting (9) and (10) into (14) yields:

$$r_D(M) = \left\{ \sum_{n=1}^{N-M-1} \left[ \alpha \sqrt{\xi_{T,U}} \cdot N \cdot T_U[q,M,N] \right] \right\}$$

$$+ \left\{ \sum_{n=1}^{N-M-1} \left[ \beta \sqrt{\xi_{T,D}} \cdot \sum_{q=1}^{Q} \delta_{pq,M} \right] \right\}$$

$$+ \left\{ \sum_{n=1}^{N-M-1} \left[ N_{RMS}(n) \cdot C_{U,p,N}(n+M) \right] \right\}$$

(15)

Assuming that $N_{RMS}(n)$ is the Gaussian white noise of variance $\sigma$ and mean 0. The maximum value of $r_D(m)$ with $\sqrt{\xi_{T,U}} = \sqrt{\xi_{T,D}}$ is given by:

$$r_D(M) = (N - M - 1) \cdot \left[ \alpha \cdot N \cdot \sqrt{\xi_{T,U}} \cdot T_U[p,M,N] \right]$$

$$+ (\sigma + \beta \cdot \sqrt{\xi_{T,D}} \cdot \sum_{q=1}^{Q} \delta_{pq,M})$$

$$= (N - M - 1) \cdot \left[ \alpha \cdot N \cdot \sqrt{\xi_{T,U}} \cdot T_U[p,M,N] \right]$$

$$+ (\sigma + \beta \cdot \sqrt{\xi_{T,U}} \cdot \sum_{q=1}^{Q} \delta_{pq,M})$$

$$= (N - M - 1) \cdot \left[ \alpha \cdot N \cdot \sqrt{\xi_{T,U}} \cdot T_U[p,M,N] \right]$$

$$+ (\sigma + \beta \cdot \sqrt{\xi_{T,U}} \cdot \sum_{q=1}^{Q} \delta_{aver})$$

$$\leq (N - M - 1) \cdot \left[ \alpha \cdot N \cdot \sqrt{\xi_{T,U}} \cdot T_U[p,M,N] \right]$$

$$+ (\sigma + \beta \cdot \sqrt{\xi_{T,U}} \cdot \sum_{q=1}^{Q} \delta_{max})$$
Hence, the SINR becomes:

\[
\text{SINR}(M) = \frac{\left(\alpha \cdot N \cdot \sqrt{\xi_{T,U} \cdot T_U[p,M,N]}\right)^2}{\left(\sigma + \beta \cdot \sqrt{\xi_{T,U} \cdot Q \cdot \delta_{\text{aver}}}\right)^2}
\]

\[
= \frac{\left\| \alpha \cdot T_U[p,M,N] \right\|^2}{(N \cdot \sqrt{\xi_{T,U} + \sigma^2 \cdot Q \cdot \delta_{\text{aver}}} + \beta)^2}
\]

(16) indicates that the duplex self-interference suppression provided by spreading can be written as:

\[
C(p,q) = 20 \cdot \log_{10} \left( \frac{1}{N \cdot \sum_{m=-N+1}^{N-1} \delta_{pq,M}} \right)
\]

(17)

\[
C_{\text{aver}} = 20 \cdot \log_{10} \left( \frac{N}{Q \cdot \delta_{\text{aver}}} \right)
\]

(18)

\[
C_{\text{worst}} = 20 \cdot \log_{10} \left( \frac{N}{Q \cdot \delta_{\text{max}}} \right)
\]

(19)

\[
C_{\text{aver}} \geq C_{\text{worst}}(M)
\]

(20)

where \(C(p,q)\) denotes the suppression capability of the code word \(p\) of the uplink signal to the code word \(q\) of the downlink signal. \(C_{\text{aver}}\) denotes the average self-interference suppression, and \(C_{\text{worst}}\) denotes the least self-interference suppression provided by spreading.

\(C_{\text{aver}}\) with different \(N\) in Async-CDD system are shown in Table 1.

### Table 1. The Average Duplex Self-interference Suppression Performance with Different \(N\)

| Code Type | \(N\) | \(Q\) | \(C_{\text{aver}}\) (dBc) | \(C_{\text{worst}}\) (dBc) |
|-----------|------|------|-----------------|-----------------|
| OG        | 128  | 128  | 23.28           | 18.99           |
|           | 512  | 512  | 29.80           | 27.21           |
|           | 1024 | 1024 | 32.68           | 31.18           |
| OC        | 128  | 128  | 33.79           | 24.69           |
|           | 256  | 256  | 37.11           | 26.35           |
|           | 512  | 512  | 39.77           | 26.95           |
|           | 1024 | 1024 | 42.65           | 25.29           |

As is shown in the table, compared to the OG code, the OC code provides better self-interference suppression in average or in the worst case.

The derivation above can be easily extended to multiple-input multiple-output (MIMO) scene.

3.1.2. The self-interference suppression with different duplex delay. Firstly, the system parameters adopted in our simulation are given in Table 2. For the fairness of the comparison, the number of the multiplexed sub-channel are set to 16 in all the three compared CDD systems, although the number of the multiplexed sub-channel available for the Async-CDD system is much greater than 16.

For different combinations of \(p\) and \(q\), the spreading code provides different duplex self-interference suppression. The self-interference suppression performance for different code words are evaluated in Table 3. In the table, 'The number of \(C(p,q) \leq 24\) dBc' denotes the number of possible combinations of \(p\) and \(q\) that makes \(C(p,q)\) less than 24 dBc.
Table 2. System parameter of the compared system

|                | N   | W   | Max. Q | Q   |
|----------------|-----|-----|--------|-----|
| CDD            | 128+8 | 8   | 16     | 16  |
| Async-CDD with OG code | 128 | -   | 128    | 16  |
| Async-CDD with OC code | 128 | -   | 128    | 16  |

Table 3. The self-interference suppression performance with different delay

|                | Q     | N    | The number of $C(p,q)$ ≤ 24 dBc | The number of $C(p,q)$ ≤ 28 dBc | The number of $C(p,q)$ ≤ 30 dBc |
|----------------|-------|------|---------------------------------|---------------------------------|---------------------------------|
| CDD with ZCZ code | 16    | 128  | 0                               | 168                             | 256                             |
| Async-CDD with OG code | 16    | 128  | 225                             | 256                             | 256                             |
| Async-CDD with OC code | 16    | 128  | 0                               | 10                              | 33                              |

For a total number of 2048 possible code words combinations, Table 3 indicates that, in the quasi-synchronous CDD system, when synchronization failure or there is not any time slot synchronization, there are 168 possible code words combinations that make duplex self-interference suppression less than 28dB. While in the Async-CDD system which adopts the OC code as the spreading code, the number of the possible code words combinations which makes the duplex self-interference suppression performance less than 28 dB is only 10.

3.2. The data rate. One severe drawback of the conventional CDD system is the decreased data rate caused by spreading. The limited number of the code words is the reason why the data rate decreases. As discussed in section 2.2, the number of the ZCZ code available for the quasi-synchronous CDD system is low, hence decreases the number of the multiplexed sub-channels $P$. Whereas, the Async-CDD system provides higher data rate that is the same as a non-spreading system.

To increase the data rate, $P$ is required to be as close to the code length $N$ as possible. The relationship between $P$, $N$, the baseband bit energy versus noise power ($Eb/N0$) and the signal to noise ratio (SNR) can be expressed in (21).

$$SNR = \frac{Eb}{N0} - 10 \log_{10}(N_{sam}) - 10 \log_{10} \frac{N}{P} + 10 \log_{10}(\log_2 K) + 10 \log_{10} 2$$ \hspace{1cm} (21)

where, $N_{sam}$ is the interpolation factor and $K$ is the modulation order.

It can be seen from (21) that when the multiplexing number $P$ equals to the code length $N$, spreading does not contribute for improving the $Eb/N0$ of the receiver. Hence, $P$ is recommended to be greater than $\frac{N}{2}$ but less than $N$.

3.3. The compatibility to other self-interference cancellation schemes. The residual self-interference suppression provided by the spreading code adopted in the Async-CDD system is independently to the analog front end of the receiver or the digital signal processing performed by the baseband unit. Thus, other self-interference cancellation schemes introduced in section I are still available, which could further eliminate the duplex self-interference.
4. Conclusion. This paper proposed a new concept of the asynchronous code-division duplex system which is able to achieve full duplex with neither time slot synchronization nor data rate decrease. The chaotic sequence with its property of low block cross-correlation and huge number of available code words/blocks is excellent suitable for the proposed Async-CDD system. When both of the code length of the orthogonal chaotic code and the number of the multiplexed sub-channels are 128, the orthogonal chaotic code provides 30.40 dBc self-interference suppression in average, which is 6.99 dB better than the orthogonal Gold code.

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E-mail address: ugdjm@pku.edu.cn
E-mail address: ligeng66@aliyun.com
E-mail address: yuping.zhao@pku.edu.cn