Abstract — A timing and sampling frequency synchronization scheme, based on the preamble and the pilots, is given in this paper, for the 60GHz OFDM system specified in the IEEE802.15.3c standard. Based on the Gray complementary sequences, an anti-multipath separated sliding correlation detection (SSCD) algorithm is first proposed, and the positions of the correlation peaks are averaged to increase the anti-noise capability of timing. The possible residual lag error is corrected and moved to the range of cyclic prefix by adopting its tolerance to timing error. Then, a method doing phase equalization combined with integer sampling deviation pre-correction (PE-ISDPC) is proposed for sampling frequency synchronization, also exploiting the cyclic prefix tolerance to the integer sample deviation to reduce the implementation complexity. Simulation shows that the system has a good time and frequency synchronization performance, and the overall scheme has a low complexity.

Index Terms — Ultra Wide Band, OFDM, synchronization, timing, carrier frequency offset, sampling frequency offset

I. INTRODUCTION

Ultra-Wide Band (UWB) system is applied to the short-distance (<10m) high-speed wireless communication, due to the high transmission rate, strong anti-multipath ability and low power spectral density, etc. 3-10GHz is the first developed bandwidth to support the UWB communication. Both IEEE802.15.3a and ECMA-368 are the high-speed communication standards [1]. With the growth of communications and the exhaustion of low frequency resources, every country gradually develops 60GHz band. In the 60GHz UWB system, the wireless data transfer rate is above 5 Gbit/s in ten meters. In the future, it will be used in the fields of wireless personal area network, wireless high-definition multimedia interface, automotive radar, medical imaging, etc [2]. The advantages such as high band efficiency, strong resistance to symbol interference and frequency selective fading make Orthogonal Frequency Division Multiplexing (OFDM) irreplaceable in conditions of the high-speed data communication and serious multipath interference. Besides, OFDM has been suggested as one of the physical layer schemes of the 60GHz high-speed communication, and it has been applied to non-compressed high definition video, audio transmission, two-way high-speed data transmission interface, etc.

In OFDM systems, symbol timing offset (STO) causes inter-symbol interference (ISI) and Sampling Frequency Offset (SFO) brings Inter-Carrier Interference (ICI) as well as ISI. Although there are some literatures on synchronization algorithm for OFDM systems, few takes timing synchronization and sampling frequency synchronization into consideration at the same time, especially for the 60GHz IEEE802.15.3c standard. For example, a time-frequency synchronization scheme based on the multi-band OFDM system is proposed in [3], but the maximum correlation algorithm in fine timing is so sensitive to multipath that the timing position is severely affected, which brings serious timing error. In [4], coarse channel estimation based on training sequences is proposed, then the timing position is detected through the channel estimation information and repeated iteration. By this way, the algorithm is extremely complex though its precision is great. In [5], fine timing is achieved according to the minimum energy ratio between adjacent windows which is insensitive to multipath, and it is only applicable to zero guard interval based OFDM systems. The channel impulse response can be directly gotten based on Golay complementary sequences because of its good complementary performance, and its principle and application to signal detection are described in [6]. For sampling frequency synchronization, ref. [7] gives a sampling frequency correction method through frequency-domain phase estimation combined with time-domain Farrow interpolation, but oversampling must be implemented in receiver and the structure of interpolation filter is very complex. Ref. [8] explains a sampling frequency synchronization scheme by non-oversampling frequency-domain phase equilibrium combined with time-domain window moving, however, it is difficult to move window backward in hardware. In [9], the SFO estimation algorithm based on iteration is proposed for MB-OFDM-UWB system and good performance is achieved even in the conditions of a large integer sampling deviation.

On the basis of the previous studies, we put forward a timing and sampling frequency synchronization scheme considering both system performance and complexity of the 60GHz OFDM system. Based on Gray complementary sequences, a method of the traditional correlation detection combined with the anti-multipath Separated Sliding Correlation Detection (SSCD) is proposed for frame detection, coarse and fine timing.

©2016 Journal of Communications
Meanwhile the positions of the correlation peaks are averaged to increase the anti-noise ability. Thus, the improvement of the fine timing accuracy provides more CP tolerance for time-domain pre-correction of sampling deviation. Then, a sampling frequency synchronization method is proposed based on phase equalization combined with integer sampling deviation pre-correction (PE-ISDPC). In addition, because the tolerance of CP is used to avoid time-domain interpolation or window moving operation, the complexity of the system is reduced. The simulation proves that the performance of the time-frequency synchronization scheme proposed in this paper is good and the complexity of the overall scheme is low.

II. SYNCHRONOUS DEVIATION MODEL AND SYSTEM PARAMETER

A. Timing Synchronization Deviation Model

The STO includes timing advance and timing lag. If timing advances and does not exceed the scope of CP, the \(k\)-th sub-carrier data of the \(i\)-th symbol before Fast Fourier Transform (FFT) in receiver can be expressed as

\[
R_{ik} = e^{-j2\pi dk/N}S_{ik} + W_{ik}
\]

while the timing location lags, it is

\[
R_{ik} = e^{-j2\pi dk/N}S_{ik} + \text{ISI}_{ik} + W_{ik}
\]

where \(N\) is the FFT window length, \(d\) is the timing deviation, \(S_{ik}\) is the \(k\)-th sub-carrier data of the \(i\)-th symbol before FFT in transmitter, \(\text{ISI}_{ik} = e^{-j2\pi dk/N} \sum_{m=0}^{d-1} (y_{i,m+k}-y_{i,m}) e^{-j2\pi mk/N}\) represents where \(N\) is the FFT window length, \(d\) is the timing offset, \(S_{ik}\) is the \(k\)-th sub-carrier data of the \(i\)-th symbol before FFT in transmitter, \(\text{ISI}_{ik} = e^{-j2\pi dk/N} \sum_{m=0}^{d-1} (y_{i,m+k}-y_{i,m}) e^{-j2\pi mk/N}\) represents its ISI and \(W_{ik}\) is white Gaussian noise. Obviously, if timing advances and does not exceed CP, only the phase rotation of frequency-domain data is brought rather than ICI, and it presents its linear increase with the increase of sub-carrier number. So there is a chance to study the low-complexity synchronization scheme, namely the advanced STO is allowed and it can be flexibly corrected by channel equalization. However, if timing lags, it brings both the phase rotation and the sampling deviation, the complexity of the system is increased to 4 sub-bands with 2.16GHz each bandwidth. And one single band is used to implement the OFDM system in the high-speed data transfer mode. In the system, the number of sub-carriers is 512, including 336 information sub-carriers, 16 pilot sub-carriers and 160 empty sub-carriers. After FFT, the time-domain OFDM symbol of length 576 is composed of 512 data and 64 CP. It can achieve 5.775 Gbit/s data transfer rate based on 64QAM modulation and 5/8 LDPC encoding mode.

In addition, IEEE802.15.3c denotes the frame structure as the standard and emergency mode. The specific frame structure is described in [10]. Here we do research on synchronization based on the frame structure under the standard mode, which is consisted of preamble, frame header and data. The preamble includes frame synchronization sequences, frame delimiter and channel estimation sequences. The preamble synchronization sequences are composed of 48 repeated Golay sequence \(b_{128}\) of length 128. Besides, the channel mode 1 to 8 (CM1–CM8) recommended by the IEEE802.15.3c working group describes eight kinds of 60GHz UWB channel, which are used to describe the LOS and NLOS channel in the environment of office, library and desktop.

B. Sampling Synchronization Deviation Model

When SFO does not cause time-domain integer sampling deviation, the \(k\)-th sub-carrier data of the \(i\)-th symbol after FFT in receiver can be expressed as

\[
I_{ik} = S_{ik}I_{ik} + \sum_{m=0}^{N-1} S_{im}I_{mk} + W_{ik}
\]

where \(S_{ik}\) is the \(k\)-th sub-carrier data of the \(i\)-th symbol before IFFT in receiver,

\[
I_{ik} = \frac{\sin(\pi k \beta)}{N \sin(\pi k \beta / N)} e^{j \pi (N - 1 - 2i(N + N_e) k) / N} + \frac{\sin(\pi k \beta)}{N \sin(\pi k \beta / N)} e^{j \pi (1 - k + \beta \mu m - k) / 2 \pi (N + N_e)} + \frac{\sin(\pi k \beta)}{N \sin(\pi k \beta / N)} e^{j \pi (1 - k + \beta \mu m - k) / 2 \pi (N + N_e)}
\]

where \(\beta\) is the normalized sampling frequency offset and \(W_{ik}\) is white Gaussian noise. It can be seen that the amplitude fading \(\frac{\sin(\pi k \beta)}{N \sin(\pi k \beta / N)}\) of the received sub-carrier is related to the sub-carrier number. Besides, the phase offset \(\frac{\pi k \beta}{N} [N - 1 + 2i(N + N_e)]\) is related to the number of both the sub-carrier and symbol. Thus, the bigger the number is, more serious the affection is. In addition, the brought ICI makes the SNR loss.

When SFO causes the time-domain integer sampling deviation (every \(1/\beta\) sampling point), according to the proposed synchronization deviation model, SFO only causes ICI if timing advances and does not exceed CP, and on contrary it also causes ISI at the same time. It lays a theoretical foundation for this paper researching the sampling deviation pre-correction scheme based on the stated CP tolerance.

C. System Parameters

IEEE802.15.3c standard specifies a 60GHz UWB system, and the band of 57.24GHz–65.88GHz is divided to 4 sub-bands with 2.16GHz each bandwidth. And one single band is used to implement the OFDM system in the high-speed data transfer mode. In the system, the number of sub-carriers is 512, including 336 information sub-carriers, 16 pilot sub-carriers and 160 empty sub-carriers. After FFT, the time-domain OFDM symbol of length 576 is composed of 512 data and 64 CP. It can achieve 5.775 Gbit/s data transfer rate based on 64QAM modulation and 5/8 LDPC encoding mode.

In addition, IEEE802.15.3c denotes the frame structure as the standard and emergency mode. The specific frame structure is described in [10]. Here we do research on synchronization based on the frame structure under the standard mode, which is consisted of preamble, frame header and data. The preamble includes frame synchronization sequences, frame delimiter and channel estimation sequences. The preamble synchronization sequences are composed of 48 repeated Golay sequence \(b_{128}\) of length 128. Besides, the channel mode 1 to 8 (CM1–CM8) recommended by the IEEE802.15.3c working group describes eight kinds of 60GHz UWB channel, which are used to describe the LOS and NLOS channel in the environment of office, library and desktop.
and coarse timing, fine timing, and sampling frequency synchronization.

![Diagram of synchronization algorithm](image)

**A. Frame Detection and Coarse Timing**

Frame detection references classic S&C method [11], using the repeated Golay sequence $b_{128}$ in the preamble to calculate the normalized sliding autocorrelation, which acts as the judgment and it can be expressed as

$$C_i = \frac{\sum_{n=0}^{127} r_{i+n}^* r_{i+n+128}}{\sum_{n=0}^{127} r_{i+n}^* r_{i+n}}$$

(4)

where $r_i$ is the received baseband sample, and $i=1,2,...$ is its number.

![Sliding correlation value in a frame](image)

The sliding correlation method adopted by coarse timing is sensitive to multipath. Once the timing location is disturbed by multipath channel interference, there is a large error. Thus, the fine timing method with the anti-multipath ability is used to further reduce the STO and it provides more CP tolerance for the time-domain pre-correction of integer sampling deviation.

**B. Fine Timing**

Ref. [6] shows that Golay complementary sequences used for timing synchronization achieve an ideal autocorrelation performance and have a significant advantage for resisting multipath interference. In this paper, the Golay sequence $b_{128}$ in the preamble is disassembled to Golay complementary sub-sequences as

$$b_{128} = [b_{32} \ b_{32} \ \tilde{a}_{32} \ b_{32}]$$

(6)

According to the characteristic of Golay complementary sequences, we can know that $a_{32}$ and $b_{32}$ have the complementary property. And according to the sequence structure described in (6), we propose a normalized SSCD method by using two sets of information window, and the judgment is

$$C_i = \frac{\sum_{n=0}^{31} r_{i+n}^* r_{i+n+64} + \sum_{n=0}^{31} r_{i+n}^* r_{i+n+128}}{\sum_{n=0}^{31} r_{i+n}^* r_{i+n}}$$

(7)
Equation (7) shows that the result is 0 when the window slides to \( a_{32}, \ a_{32}, \ a_{32} \) and the result is 2 when the window slides to \( b_{32}, b_{32}, b_{32} \). Moreover, it gets a better noise immunity than single window correlation detection.

Fig. 3 shows the separated sliding correlation in range of the synchronization sequences in the preamble and the operation begins from the determined coarse timing position. Through simulation we also determine a threshold, and when \( C_i \) rises over \( G_i \), \( i=1 \) is set at the same time. Then, detect the peak positions in the range of \( M \) successive windows with length 64 that \( M \) peak positions are recorded as \( i_{peak, m} \) \( m=1,2,...,M \). Furthermore, to greatly smooth the noise and improve the fine timing accuracy, the \( M \) peak positions are averaged and the first peak position is regarded as the fine timing position \( i_m \).

\[
i_m = \frac{\sum_{m=1}^{M} i_{peak, m} + 64(m - 1)}{M}
\]

(8)

The standard synchronization sequences are composed of 48 \( b_{128} \), so there are 96 correlative peaks in all. In practice, \( M \) is weight considering both the estimation performance and implementation complexity.

After fine timing synchronization, the residual timing error is controlled in a small range. Then, to avoid generation of ISI, pre-correction to lag timing should be done to makes the possible residual deviation fall into the range of CP, thus the timing position after correction is

\[
i_{\hat{m}} = i_m - \delta_{\hat{m}}
\]

(9)

where \( \delta_{\hat{m}} \) is the largest lag deviation which can be gotten by simulation.

Fig. 3. Separated sliding correlation peak for fine timing

C. Carrier Frequency Capture

This paper makes full use of the guard interval absorptivity to the advanced STO and proposes the PE-ISDPC method to avoid the complex interpolation filter or the interpolation and extraction structure which are difficult in hardware implementation.

It is assumed that there are \( J \) pilot sub-carriers in an OFDM symbol, \( Z_{s,i} \) and \( P_{s,i} \) are respectively the \( j \)-th pilot data on the \( k \)-th sub-carrier of the \( i \)-th symbol in transmitter and receiver, \( j=1,...,J, \ k \in K \), where \( K \) is the number set of the sub-carriers which carries the pilot data. As shown in (3), denote the phase rotation of the \( j \)-th pilot of the \( i \)-th symbol as

\[
\theta_{j,i} = k \cdot s_i
\]

(10)

where \( \theta_{j,i} = \text{angle}(Z_{s,i}, P_{s,i}) \), \( s_i = -\pi[5N-1+2(i_1+N_{s,i})]/N \). \( s_i \) is estimated by the Minimum Mean Square Error (MMSE) method [12] and can be expressed as

\[
\hat{s}_i = \frac{\sum_{k} k_i \theta_{j,i} \sum_{k} k_i^2}{\sum_{k} k_i^2}
\]

(11)

According to the estimated \( \hat{s}_i \) and the sub-carrier index, we compensate the phase rotation of all the sub-carriers in the \( i \)-th symbol.

SFO causes frequency-domain phase rotation, meanwhile its cumulative effect causes time-domain integer sampling deviation in one frame. Denote the integer deviation as \( Z \), so \( Z \) can be gotten by

\[
Z = \left[ N_{\text{frame}} / f_s \right] = \left[ N_{\text{frame}} / f_s \right]
\]

(12)

where \( \left[ x \right] \) represents the largest integer which is smaller than \( x \), \( T_{\text{frame}} \) is the time of one frame, \( N_{\text{frame}} \) is the total number of samples in one frame, \( f_s \) is the sampling frequency in the transmitter, \( f_s \) is the absolute SFO and \( \beta \) is the normalized SFO.

When the sampling frequency in receiver is larger than that in transmitter, there are \( Z \) samples more of one frame in the receiver, whereas on contrary a decrease of \( Z \) samples. It means that the biggest STO caused by the SFO cumulative effect in one frame is \( Z \) advanced or lagged. According to the model given in the previous section, we can know that if timing offset advances and does not exceed the range of CP, ISI does not exist, otherwise ISI is produced. Therefore, on the condition of \( \gamma_{f_s} + \delta_{f_s} + 2Z \leq N_{s} \), where \( \gamma_{f_s} \) and \( \delta_{f_s} \) is the maximum advanced offset and the maximum lag offset after fine timing respectively, pre-processing that make the symbol timing positions advance \( Z \) can be operated in the timing position adjustment module. Thus, expression (9) can be modified as

\[
i_{\text{timing}} = i_m - Z = i_m - \delta_{f_s} - Z
\]

(13)

In that way, when the system is affected by a positive SFO (the sampling frequency of the receiver is bigger than that of the transmitter), the biggest STO advances \( Z \); while considering a negative SFO, since \( Z \) positions is advanced during pre-processing, the lag symbol timing will not happen. In summary, when the SFO or the frame length is small, the integer STO caused by SFO could be totally absorbed by CP due to the introduced pre-processing. Specifically, the standard specifies the maximum relative frequency offset of the oscillator is \( \pm 20 \text{ ppm} \). So the maximum normalized frequency offset produced by the two oscillators in transmitter and receiver is 40ppm. If the sampling frequency in the baseband is 2.16GHz, the maximum absolute offset is
2.16GHz×40ppm=86.4KHz. Besides, the standard also specifies the maximum number of the symbol in one frame is 512, so that the corresponding maximum integer sampling deviation in one frame can be calculated by (12) that $Z = \lfloor N_{frame} \beta \rfloor = \lfloor 576 \times 512 \times 40 \text{ppm} \rfloor = 11$.

IV. PERFORMANCE SIMULATION

In the simulation of the 60GHz OFDM system suggested by IEEE802.15.3c standard, the performance of the proposed synchronization scheme is investigated. The system operates in the high-speed mode (5.775 Gbit/s), and the simulation parameters reference the fourth part of the previous second section.

Fig. 4. False and missing alarm probability under different thresholds

Fig. 4 reveals the false and missing alarm probability under different thresholds in CM1 and CM2, when SNR is 0dB. As it shows, the frame detection is the most accurate with a threshold in the range of [0.14, 0.16] that 0.15 is chosen as the adopted threshold for the system.

Fig. 5. MSRE performance of coarse timing

Fig. 5 is the MSRE curves of coarse timing in Gaussian and multipath channels. It can be seen that the timing accuracy declines orderly conform to the order of Gaussian channel, CM1 and CM2. It means that the timing error gets worse with the increase of multipath mean square delay. When SNR is 15dB, the MSRE in the three channels are about 1.2 and 4. In CM2, with the increase of SNR, the MSRE is stabilized on about 5 samples. The reason for this is that coarse timing just utilizes the repeated sequence for the sliding correlation detection, it is unable to resist multipath interference. On contrary, it is sensitive to multipath, so fine timing is needed to further reduce the error.

Fig. 6. MSRE performance of fine timing

Fine timing uses Golay complementary sequence to do the anti-multipath SSCD operation, and the positions of many correlation peaks are averaged to confirm the fine timing location. Fig. 6 shows the MSRE curves of fine timing in Gaussian and multipath channels. It presents that fine timing accuracy is significantly improved contrasting with that of coarse timing. When the SNR is 15dB, the MSRE in the three channels is $2 \times 10^{-3}$, $6 \times 10^{-3}$ and $8 \times 10^{-2}$ respectively. It reveals that the algorithm is insensitive to multipath and the residual deviation is controlled in a very small range that can offer redundancy for the sampling deviation. To avoid the impact of timing lag, lag pre-correction is needed after fine timing.

Fig. 7. BER performance of the system

In Gaussian channel, different normalized SFOs including 0, 20ppm, 40ppm, are added to the simulation. The longest frame including 512 OFDM symbols are designed in a frame. Fig. 7 shows the BER curves of the system with the proposed timing and sampling frequency synchronization scheme. It shows that the ideal system
which has no SFO achieves the best performance. When the SFO is introduced, the BER is slightly higher but close to the ideal curve, which shows the robustness of the proposed scheme. When the SNR is 25dB, the BER gets the magnitude of $10^{-5}$.

V. CONCLUSION

For the 60GHz OFDM system specified in IEEE802.15.3c standard, this paper first gives the synchronous deviation model, and then presents a timing and sampling frequency synchronization scheme based on the preamble and the pilots. An anti-multipath separated sliding correlation detection algorithm is proposed based on the Golay complementary sequences, and the positions of the correlation peaks are averaged. And a method doing phase equalization combined with integer sampling deviation pre-correction is also proposed for sampling frequency synchronization. It is shown in the simulation that when the SNR is 25dB, the magnitude of BER is $10^{-5}$ in conditions of the highest transmission rate and the worst synchronization error.

ACKNOWLEDGEMENT

The study is supported by the National Natural Science Foundation of China (No. 61302062), the Natural Science Foundation of Tianjin for Young Scientist (No. 13JCQNJC00900) and the foundation of Tianjin Key Laboratory for Civil Aircraft Airworthiness and Maintenance (No. 1040030205).

REFERENCES


Yue Li was born in China, 1991. She is engaging in a wireless communication research for the master’s degree in the major of electronics and information systems in Tianjin Polytechnic University.

Jin Tao was born in China, 1990. She is engaging in a wireless communication research for the master’s degree in the major of electronics and information systems in Tianjin Polytechnic University.

Li-Jun Ge was born in Tianjin, China, 1984. He earned the Bachelor Degree of Engineering in the major of Electronics Science and Technology in Nankai University, Tianjin, China, 2006. Subsequently, he did graduate study in the major of Communication and Information Systems in the same university. In 2008, he became a Ph.D. candidate in the same major. After five-year graduate study, he got the Doctor Degree of Engineering in Nankai University, Tianjin, China, 2011. From 2008 to 2010, he was a teaching assistant in Nankai University teaching communication related experiment courses. At present, he is an associate professor in Communication Engineering Department of Electronics and Information Engineering School of Tianjin Polytechnic University and also do research work in Tianjin Key Laboratory for Civil Aircraft Airworthiness and Maintenance of Civil Aviation University. During the past three years, he was in charge of several projects supported by the nation or the city and published many academic papers. His research interests include OFDM and OFDM-UWB wireless communication technologies.