Symbol Synchronization Technique for Visible Light Communications using CAZAC-OFDM Scheme

Yuji Yoshihashi, Takuya Kazama, Masahiro Muraguchi
Department of Electrical Engineering, Tokyo University of Science
6-3-1 Niijuku, Katsushika-ku, Tokyo, 125-0051, Japan
E-mail: 4319582@ed.tus.ac.jp, 4318518@ed.tus.ac.jp, murag@ee.kagu.tus.ac.jp

***Abstract*— Ordinary Orthogonal Frequency Division Multiplexing (OFDM) receivers acquire OFDM symbol synchronization in the preamble period and retain synchronization by using correlation of guard-intervals. In this paper, we propose a new technique of OFDM symbol synchronization for Visible Light Communication (VLC) using OFDM scheme with Constant Amplitude Zero Auto-Correlation (CAZAC) precoding, CAZAC-OFDM, which enables to avoid the use of the preamble and guard-intervals. Moreover, we can find out an accurate OFDM symbol timing after checking only two symbol size of Fast Fourier Transform (FFT) points with arbitrary start timing, even though those stride over two adjacent OFDM symbols.**

Keywords-OFDM; FFT; CAZAC; VLC; Synchronization.

I. INTRODUCTION

In recent years, with the rapid development of wireless communication technology, various communication services are deployed, but as the communication traffic volume increases, frequency bands available for communication are being exhausted. Therefore, studies on VLC technology using Light Emitting Diodes (LED) are under way [1][2]. This is because LEDs have features, such as high-speed responsiveness, low power consumption, and ease of dissemination due to low cost [3].

However, depending on the frequency characteristic of the LED, the usable bandwidth is limited, and it is difficult to obtain enough communication speed. Therefore, a VLC technique utilizing an OFDM scheme capable of improving frequency utilization efficiency has been studied. Here, the OFDM scheme is commonly adopted in wireless systems, Wireless Fidelity (WiFi), Long Term Evolution (LTE), Digital Video Broadcasting - Terrestrial (DVB-T), etc., due to its great advantage of high spectrum utilization that is about twice the spectral efficiency of a single carrier scheme.

The OFDM scheme, however, requires highly accurate OFDM symbol synchronization, and if the synchronization is not performed accurately, demodulated data will be collapsed because of losing orthogonality between subcarriers. Therefore, ordinary OFDM receivers for burst packet transmission systems, such as the 802.11 Wireless Local Area Network (WLAN) systems, acquire symbol synchronization in the preamble period and retain synchronization by using correlation of Guard-Intervals (GIs). On the other hand, continuous (non-burst) transmission systems, such as Digital TeleVision (DTV) systems, acquire symbol synchronization mainly by using correlation of GIs, because those systems cannot employ preamble scheme [4].

As OFDM signal is essentially a sum of multiple subcarrier signals aligned in frequency domain, its probability density function in time domain resembles Gaussian distribution. The CAZAC precoding makes time-domain signal of M-ary Quadrature Amplitude Modulation (M-QAM) OFDM signal into time-domain signal of M-QAM single-carrier signal with some phase rotation [5] - [9]. This single-carrier wave-form in OFDM with CAZAC precoding, CAZAC-OFDM, enables superficially normal data output through the FFT and the CAZAC decoding even though the FFT processing executes by using sample points over two adjacent OFDM symbols, although the output data becomes a value of incorrect signal point in the M-QAM constellation. Among various input data, null data is still null at the output ports of the CAZAC decoder, and if we allocate null data at a fixed position in the OFDM symbols, we can estimate the deviation from the aureate symbol timing position by checking the null data port-number of the CAZAC decoder.

In this paper, we propose a new technique of symbol timing estimation for visible light communications using CAZAC-OFDM scheme, which enables to avoid the use of the preamble and guard-intervals. In the case of visible light communications, which is one of typical Line-Of-Sight (LOS) communications, it is not necessary to employ the GI aiming at preventing interference between adjacent OFDM symbols because we do not need to consider multipath channels. Moreover, the GI has a demerit of leading to a decrease in data rate.

By simulations, we have acquired an accurate OFDM symbol synchronization after checking only two symbol size of FFT points with arbitrary start timing, even though those stride over two adjacent OFDM symbols. Here, we used only one null data per one OFDM symbol, and did not use a preamble or guard interval. Therefore, our symbol synchronization technique makes it possible to maximize throughput of visible light OFDM systems.

The remainder of this paper is organized into sections as follows: Section 2 gives an overview of symbol synchronization in a conventional OFDM scheme and Section 3 gives an overview of CAZAC-OFDM. Section 4 presents the proposed scheme that makes use of the features of CAZAC-OFDM and Section 5 presents the performance

Copyright (c) IARIA, 2019. ISBN: 978-1-61208-727-6

evaluation and simulation results of the proposed scheme. Finally, we conclude the paper in Section 6.

II. VISIBLE LIGHT OFDM

A. Visible Light Communication (VLC)

Visible light communication is a communication technology utilizing light visible to the human eye. Communication is enabled by modulating this visible light. The transmitted light is received by a light receiving element, such as a photodiode, and the data is reproduced by demodulating. As a light source, LEDs are mainly used for their characteristics, such as high-speed responsiveness and low power consumption. Also, since LEDs are widely used as lighting in various places in everyday life, visible light communication using LEDs is expected because existing infrastructure equipment can be used for communication as it is.

B. OFDM scheme

The OFDM scheme is a type of multicarrier modulation and is a scheme in which data is divided into several subcarriers and transmitted in parallel.

On the transmission side, data is divided into N data by serial-parallel conversion, quadrature modulation is performed, and data is transmitted on different carrier waves. At this time, Inverse Fast Fourier Transform (IFFT) is performed after primary modulation of the data sequence. An input signal after mapping by primary modulation is defined as X (length N), and a nth OFDM time signal corresponding thereto as x[n] is defined as

$$x[n] = \frac{1}{N}\sum_{k=0}^{N-1} X[k]e^{j\frac{2\pi}{N}kn} \quad (1)$$

where $X[k]$ is the frequency-domain signal, and N is the number of subcarriers. After IFFT, a guard interval is inserted and the OFDM symbol is generated.

On the receiving side, the data is restored by demodulating the signal by the reverse procedure of the transmitting side using the corresponding n subcarriers.

Also, in the frequency domain, since the peak values of the respective subcarriers are arranged to satisfy mutual orthogonality, it is possible to efficiently use the frequency band and send the data.

C. Symbol synchronization

In the OFDM scheme, when FFT processing is not performed at the correct position, the data collapses on the receiving side. Therefore, highly accurate symbol synchronization is indispensable for demodulating data.

There are mainly two symbol synchronization methods in the OFDM scheme [4].

As shown in Figure 1, by using the fact that the correlation value becomes maximum when the signal matches the known sequence, the head of the symbol is detected, and synchronization is enabled.

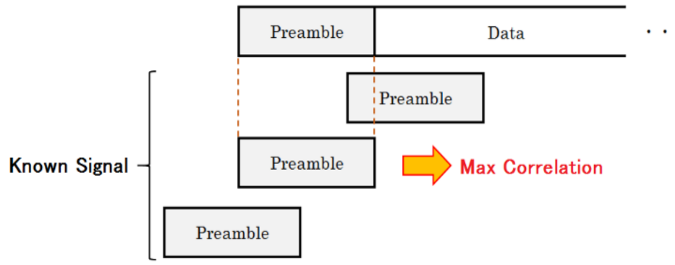


Figure 1. Symbol synchronization method using preamble

As shown in Figure 2, the other is a synchronization method that is performed by autocorrelation using guard intervals.

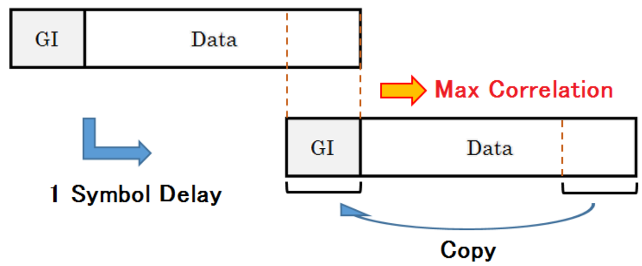


Figure 2. Symbol synchronization method using Guard Interval

This is since the rear part of the symbol is copied and added to the head and the correlation with the waveform delayed by the original one symbol length is maximized, the beginning of the symbol is detected, and synchronization can be performed.

III. CAZAC-OFDM

The CAZAC sequence is also called a constant amplitude zero auto-correlation sequence, and is a sequence having characteristics that the amplitude is constant in both the time domain and the frequency domain [5].

The OFDM scheme precoded using this CAZAC sequence is called CAZAC-OFDM. In the OFDM precoding process, a Zadoff-Chu sequence, which is one type of CAZAC sequence, is used.

The Zadoff-Chu sequence $C(k)$ is defined as

$$C(k) = \begin{cases} \exp\left(j\frac{\pi r k^2}{L}\right) & : L \text{ is even} \\ \exp\left(j\frac{\pi r k(k+1)}{L}\right) & : L \text{ is odd} \end{cases} \quad (2)$$

$$k = 0,1,\ldots,L-1$$

where L is the sequence length, r is the sequence number, and r takes an arbitrary integer value prime to L. In this case, when CAZAC precoding is used for OFDM, the sequence length L is a power of 2. The reason for this is based on the FFT size in OFDM.

Therefore, if $r = 1$ and $L = N^2$ in (2), since L is an even number, the Zadoff-Chu sequence $C(k)$ can be expressed as (3).

$$C(k) = \exp\left(j\frac{\pi k^2}{N^2}\right) \tag{3}$$
$$k = 0,1,\dots,N-1$$

From (3), CAZAC precoding is expressed by (4) using Nth order complex square matrix M. Here, the matrix M is obtained by rearranging (3) in the row direction.

$$M = \frac{1}{N}\begin{bmatrix} c_0 & c_1 & \cdots & c_{N-1} \\ c_N & c_{N+1} & \cdots & c_{2N-1} \\ \vdots & \vdots & \ddots & \vdots \\ c_{(N-1)N} & c_{(N-1)N+1} & \cdots & c_{N^2-1} \end{bmatrix} \tag{4}$$

On the transmission side, precoding is performed by multiplying the matrix of (4) with the mapping data before IFFT, so that a time signal in CAZAC-OFDM can be obtained.

The signal X' after CAZAC precoding in the case where the data string to be transmitted is $X = [X_0, X_1, \cdots, X_{N-1}]$ is given by (5).

$$X' = M \cdot X = \frac{1}{N}\begin{bmatrix} c_0 & c_1 & \cdots & c_{N-1} \\ c_N & c_{N+1} & \cdots & c_{2N-1} \\ \vdots & \vdots & \ddots & \vdots \\ c_{(N-1)N} & c_{(N-1)N+1} & \cdots & c_{N^2-1} \end{bmatrix} \cdot \begin{bmatrix} X_0 \\ X_1 \\ \vdots \\ X_{N-1} \end{bmatrix} \tag{5}$$

Since IFFT processing is performed on this equation, the time signal $x(n)$ of CAZAC-OFDM of the nth sample after the IFFT can be finally defined as (6) [5].

$$x(n) = C_{\left(\frac{N}{2}-n\right)mod(N)} \cdot X_{\left(\frac{N}{2}-n\right)mod(N)} \tag{6}$$

Therefore, the signal point at this time is as shown in Figure 3.

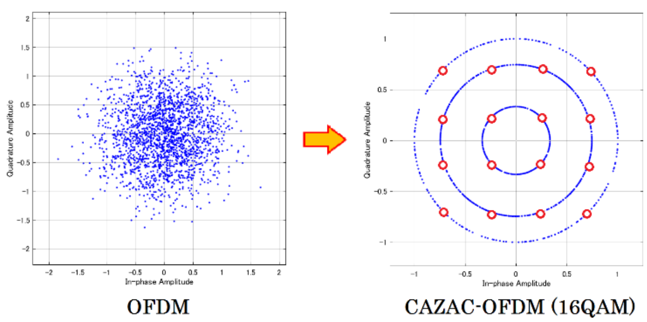


Figure 3. Time domain Signals of OFDM and CAZAC-OFDM

From Figure 3, it is confirmed that the waveform of the time signal of CAZAC-OFDM is obtained by phase-rotating the value of the mapping data, and the amplitude becomes constant as compared with ordinary OFDM.

Also, from (6), the relationship between the symbols before and after the CAZAC precoding and the IFFT processing on the transmission side is shown in Figure 4.

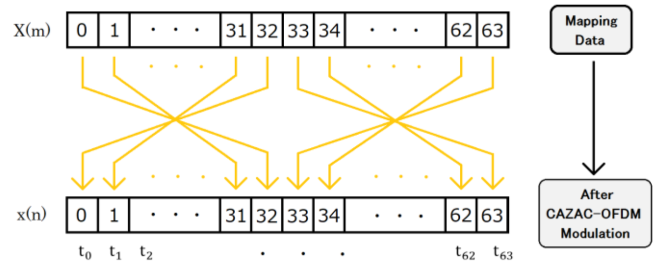


Figure 4. Symbol configuration before and after

From Figure 4, it is confirmed that the positions of the values before and after the CAZAC precoding and the IFFT processing are exchanged and uniquely determined. Also, before and after CAZAC decoding and FFT processing on the receiving side, they are exchanged in the same way.

In the symbol synchronization method proposed in this paper, we use the characteristics where this value is swapped.

IV. PROPOSED METHOD

A. Proposed symbol composition

In the ordinary OFDM scheme, symbol synchronization is performed by using correlation characteristics of preamble and guard-interval. However, we do not need to consider the multipath environment in visible light communication, so we assume that the guard-interval, which is originally intended to absorb delayed waves due to multipath, is unnecessary.

Therefore, utilizing the characteristics of the transmission waveform by CAZAC precoding, symbol synchronization is achieved by inserting null data instead of guard-interval on the transmitting side and detecting null on the receiving side. Therefore, the configuration of the symbol is as shown in Figure 5.

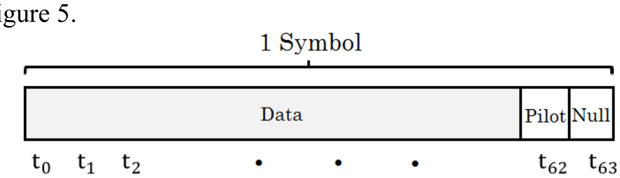


Figure 5. Proposed symbol composition

Here, one symbol is composed of 64 subcarriers, one null for synchronization and one pilot signal are inserted in the last part of the symbol in the time domain. We consider that at least one is enough to detect nulls, so the number of nulls inserted is one.

In the ordinary OFDM scheme in wireless communication, four pilot signals are inserted, but this time we have proposed one symbol configuration. The reason is that the main role of the pilot signal is phase correction and amplitude correction, and usually we do not consider that the amplitude and phase rotation abruptly change in a short period of symbol time, so we think that enough estimation and correction are possible by taking the moving average of the pilot signal.

Copyright (c) IARIA, 2019. ISBN: 978-1-61208-727-6

Here, the symbol configuration before and after modulation on the receiving side is shown in Figure 6.

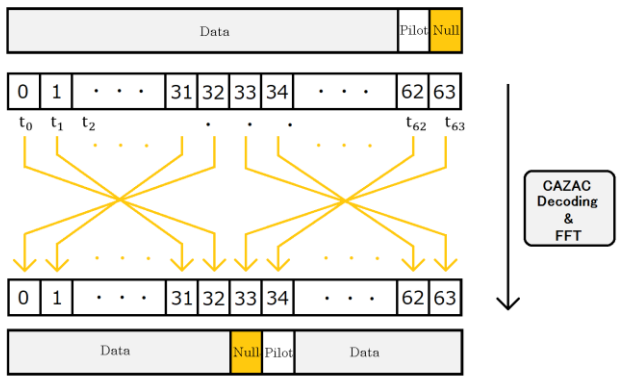


Figure 6. Symbol configuration before and after CAZAC decoding and FFT.

As shown in Figure 6, when CAZAC decoding and FFT processing are performed on the receiving side, the null data is outputted with the value being 0 being replaced with the center position.

By utilizing this fact, synchronization is enabled by detecting the null and correcting the position of the FFT processing.

B. *Null detection and synchronization method*

In the ordinary OFDM scheme, there is a problem with data collapsing when FFT points stride over two adjacent OFDM symbols. Even though we insert nulls on the sender side, we cannot detect nulls without accurate synchronization and FFT processing at the correct position. Therefore, highly accurate timing estimation is necessary, and FFT processing cannot be performed at an arbitrary timing.

However, in CAZAC-OFDM, even though FFT points stride over two adjacent OFDM symbols, data does not collapse, and the values of signal points at different points are output. Among them, null data is output as it is null and the direction and amount of deviation from the proper synchronous position can be accurately detected from the output port number.

Here, in FFT processing the received data, the case where it is performed at the correct position and at an arbitrary position are shown in Figure 7.

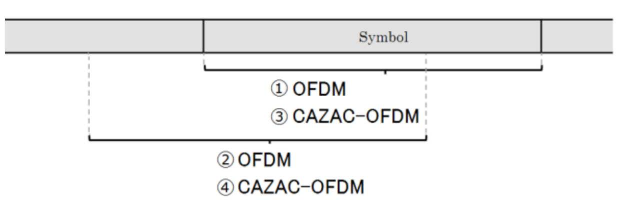


Figure 7. FFT points position

Here, ① and ③ are cases where FFT processing is performed at the correct position, and ② and ④ are cases where FFT processing is performed at an arbitrary position. Moreover, ① and ② are ordinary OFDM scheme without CAZAC, and ③ and ④ are CAZAC-OFDM with CAZAC. The output of two symbols after FFT processing at this time is shown in Figure 8. The waveform is the absolute value of the value of the data.

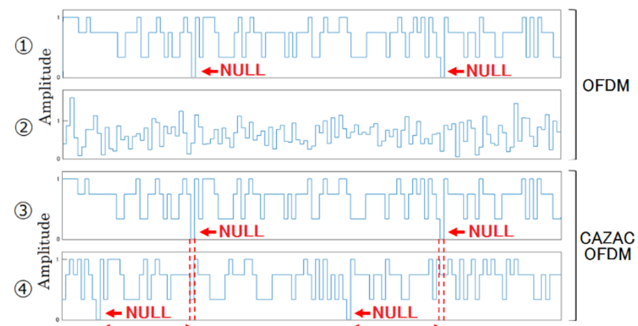


Figure 8. The contents of data in two symbols after FFT

As shown in Figure 8, since FFT processing is performed at the correct position in ① and ③, the output data does not collapse and outputs completely the same value, and the null is output to the place of X (33).

It can be seen that, if the FFT processing is performed at an arbitrary timing in the output of ② in the ordinary OFDM scheme, the data collapses and the magnitude of the amplitude becomes uneven. Also, the null inserted on the transmitting side is completely collapsed, it cannot be detected, and synchronization cannot be performed.

However, in the proposed method with CAZAC, even though FFT processing is performed at an arbitrary position that is not a correct position, the data does not collapse, and the data is exchanged between the symbols, but the null data is output as null. Also, from Figure 6, since the positions of the values before and after the CAZAC decoding and the FFT are uniquely determined, by comparing with the position of the null after performing the FFT processing at the correct position, we can estimate the deviation.

Here, in ④ in Figure 8, nulls are output at the location of X (10), so it is seen that the FFT points are shifted by 24 samples as compared with the place of null in ③.

Therefore, in the proposed CAZAC-OFDM, it is unnecessary to estimate the timing of highly accurate symbols before performing FFT processing, and even though FFT processing is performed at arbitrary timing, highly accurate synchronization is achieved.

Detection of null is done by minimum value judgment, as follows: perform CAZAC decoding and FFT processing at an arbitrary timing, and then take the absolute value and make the minimum value determination. Since null has a value of 0 and no data other than null has a value of 0, null can be reliably detected by performing the minimum value determination.

However, this is a case of a communication environment in an ideal state, and some noise occurs in actual

Copyright (c) IARIA, 2019. ISBN: 978-1-61208-727-6

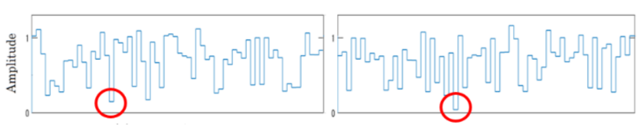
communication. When noise is added, data other than null may be detected by the minimum value determination, making it difficult to detect the correct null.

Therefore, before the minimum value judgment is made, the system configuration is constructed in which the value of the flowing data is accumulated in the section where one symbol and the minimum value judgment is made for the cumulative sum. As a result, even though the detection of the null is mistaken for the data of one symbol, the accuracy of detection of the null can be improved by accumulating the data of the next symbol.

We provide an example to explain the minimum value judgment when two symbols are accumulated after adding noise. The waveforms of (a) and (b) of Figure 9 are obtained by dividing the received data for two symbols into data for each individual symbol. When the minimum value is determined for each piece of data, the position of the minimum value is detected. Here, the correct detection position of this null is assumed to be the 26th position. In (b), the position of the minimum value is the 26th position and the null detection succeeds, whereas in (a) the position of the minimum value is the 18th position, and the null detection is incorrect.

As described above, when noise is added, the detection of null may fail in the minimum value determination with only one symbol. To solve this, take the cumulative sum. Figure 10 shows a waveform of a data value obtained by taking the cumulative sum of two symbols.

When accumulating the data values of (a) and (b) in Figure 9, it becomes as shown in Figure 10, the minimum value clearly appears and the detection of null succeeds.



(a) Data value for 1 symbol (b) Data value for 1 symbol
Figure 9. Minimum value determination for one symbol

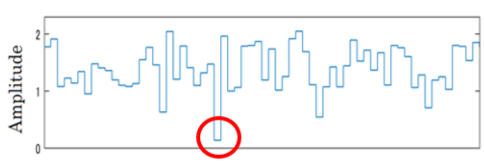


Figure 10. Minimum value determination with cumulative sum of 2 symbols

Therefore, even though the detection of the null is mistaken for the data of one symbol, the accuracy of detection of the null can be improved by accumulating the data of the next symbol.

V. PERFORMANCE EVALUATION BY SIMULATION

A. *Simulation specification*

To evaluate the performance of the proposed method, simulation was performed according to the specifications in Table I. The simulation is performed in MATLAB using communications system toolbox.

Also, the system configuration of the transmission and reception proposed in this paper is shown in Figure 11.

TABLE I. SIMULATION SPECIFICATION.

Primary modulation	16QAM
Secondary modulation	CAZAC-OFDM
Data Rate	58.125 Mbps
Bandwidth	15 MHz
Carrier frequency	15 MHz
Data size	62
Number of pilots	1
Null data length	1
FFT size	64

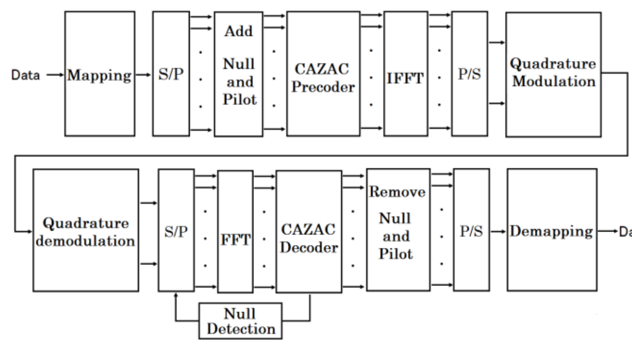


Figure 11. The proposed CAZAC-OFDM system

B. *Simulation result (BER)*

Figure 12 shows the BER characteristics when the proposed method is simulated with the specifications in Table 1.

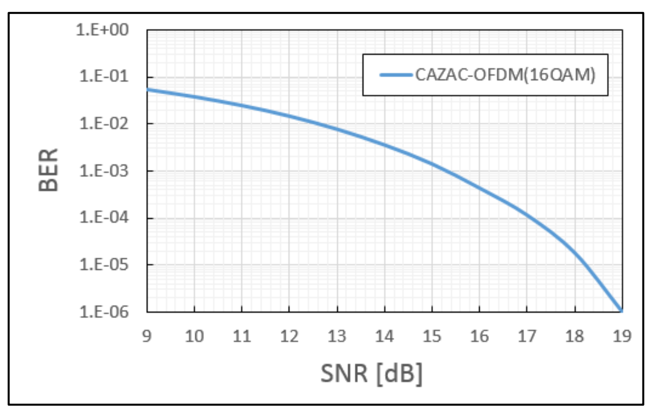


Figure 12. BER characteristics

Figure 12 shows the BER characteristics when a signal is received at the correct timing at which there is no synchronization deviation from the beginning by inserting

Copyright (c) IARIA, 2019. ISBN: 978-1-61208-727-6

one null and one pilot. From this result, it is understood that the error rate, which is the reproducible range, falls within the range of 10^{-3} or less when SNR is 16 or more.

Even though the receiving side performs FFT processing at an arbitrary timing, null is instantaneously detected by the minimum value judgment, and the cutout position of the FFT points is corrected. Therefore, it can be confirmed that the BER characteristic almost agrees with the value shown in Figure 12 regardless of the timing at which the FFT processing is performed.

C. Simulation result (Null detection success rate)

Figure 13 shows the detection success probability of null when simulated with the specifications in Table 1. Here, for detection, we compared the detection success probabilities of nulls when the minimum value judgment is performed on the cumulative sum for one symbol and two symbols, giving three symbols.

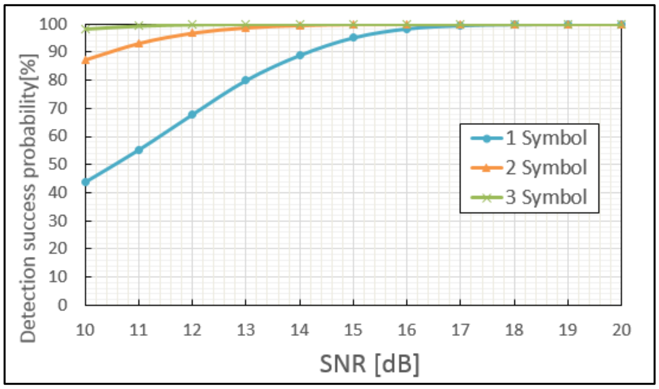


Figure 13. Comparison of null detection success probability

From the result of Figure 13, when null detection was performed only for one symbol, the probability of success became 100% when the SNR was 20 or more. Likewise, in the case of the cumulative sum of two symbols, the success probability became 100% when the SNR was 16 or more, and, in the case of the cumulative sum of 3 symbols, the SNR was 13 or more.

From this result, it is found that the detection success probability of null improves as the number of symbols to be accumulated increases. Therefore, it was confirmed that highly accurate synchronization can be achieved by increasing the number of symbols required for detection even in an environment with great influence of noise with low SNR.

Moreover, from the results in Figure 12, SNR was 16 or more in the proposed method where the error rate falls within the range of 10^{-3} or less. Therefore, when the SNR is 16 or more, the detection success probability becomes 100% when the number of symbols to be accumulated is at least two.

From the above results, it was confirmed that highly accurate symbol synchronization can be performed without failure by judging the cumulative sum of the two symbols by the minimum value.

VI. CONCLUSION

In this paper, we show that the amplitude of the OFDM signal is constant by using CAZAC precoding and inserted null data can be extracted as null. Also, we verified that null data can be extracted without corruption even though FFT points that stride over two adjacent OFDM symbols. We verified that, by using this characteristic, it is possible to perform synchronization with enough performance after checking only two symbol size of FFT points with arbitrary start timing.

REFERENCES

[1] A. Jovicic, J. Li, and T. Richardson, "Visible light communication: opportunities, challenges and the path to market", IEEE Communications Magazine, pp.26-32, Dec. 2013.
[2] H. Elgala, R. Mesleh, and H. Haas, “Indoor broadcasting via white LEDs and OFDM,” IEEE Transactions on Consumer Electronics, pp.1127-1134, Aug. 2009.
[3] G. Cossu, A. M. Khalid, P. Choudhury, R. Corsini, and E. Ciaramella, “3.4 Gbit/s visible optical wireless transmission based on RGB LED,” Opt. Exp., pp. B501-B506, Dec. 2012.
[4] T. M. Schmidl and D. C. Cox: “Robust frequency and timing synchronization for OFDM,” IEEE Transactions on Communications, pp.1613-1621, Dec. 1997.
[5] R. Ishioka, T. Kimura, and M. Muraguchi, “A Proposal for a New OFDM Wireless System using a CAZAC Equalization Scheme,” in AICT’2017, no. 1, pp. 47–51, 2017.
[6] K. Miyazawa, T. Kimura, and M. Muraguchi, “Proposal of visible light OFDM system with CAZAC equalization,” 23rd Asia-Pacific Conference on Communications (APCC), pp.491-496, Dec. 2017.
[7] Y. Sugai, Y. Shirato, T. Kimura, and M. Muraguchi, “PAPR and Spectral Control Procedure for OFDM Wireless Systems Using CAZAC Equalization,” in AICT’2018, pp. 75–80, 2018.
[8] T. Onoda, R. Ishioka, and M. Muraguchi, “Proposal of Power Saving Techniques for Wireless Terminals,” in AICT’2018, pp. 115–120, 2018.
[9] T. Kazama, K. Miyazawa, and M. Muraguchi, “Time-domain signal management for OFDM signals,” 5th International Conference on Wireless and Mobile Network (WiMNeT 2018), pp.23-35, Nov. 2018.