Implementation and Evaluation of Synchronized SS-CDMA Using Wireless Two-Way Interferometry (Wi-Wi)

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***Abstract*—Synchronized spread spectrum code division multiple access (SS-CDMA) is very effective for increasing the capacity and reducing the interference with a rapid spread of Internet of things (IoT) devices. Since the synchronized SS-CDMA requires receiving timing synchronization, it is essential to realize transmission timing control of each node using space-time synchronization. In this paper, we investigate precise time synchronization between nodes using Wireless Two-Way Interferometry (Wi-Wi). The measurement results show that the standard deviation of offset (σ) was less than 30 ns. Furthermore, we implement a synchronized SS-CDMA communication function on Universal Software Radio Peripheral (USRP). The bit error rate (BER) characteristics are evaluated with different offsets of initial timing synchronization of the Wi-Wi module. It is found that BER characteristics when two signals are transmitted simultaneously become smaller as the Wi-Wi offset becomes smaller. For an offset of around 12 ns, the degradation of BER compared to the case with 1 transmission signal is negligibly small. As a result, we reveal that simultaneous communication between two terminals is possible without large degradation.**

***Index Terms*—synchronized SS-CDMA, transmission timing control, time synchronization, software defined radio**

I. Introduction

In recent years, the Internet of things (IoT) devices have been spreading rapidly, and further growth is expected in the future. In particular, industrial applications are expected to grow remarkably due to the expansion of smart factories and smart cities. As a result, the increase of autonomous transmissions by nodes and the increase of radio interference due to the expansion of frequency sharing will become a serious problem, especially in the uplink where information is sent from each node to the network.

Synchronized spread spectrum code division multiple access (synchronized SS-CDMA) [1]–[4] is a highly efficient communication method to solve these problems. Fig. 1 shows a conceptual diagram of synchronized SS-CDMA using space-time synchronization. We consider that multiple nodes transmit signals to an access point (AP) at the same time using the same frequency. In the local communication area of the red broken line area in Fig.1, space-time synchronization is established, i.e., a state in which multiple distant nodes are synchronized by sharing a single clock and each node knows the other's location. For realizing space-time synchronization, the local clock of each node is assumed to be synchronized with those of AP by using reference signals.

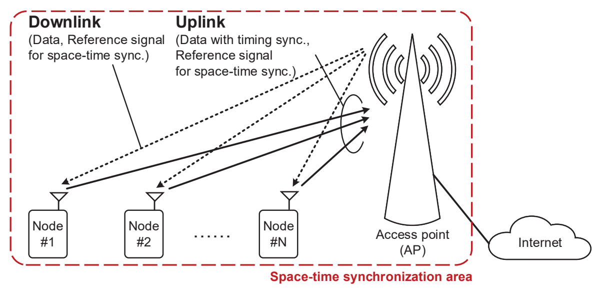

Fig. 1. Conceptual diagram of synchronized SS-CDMA with space-time synchronization.

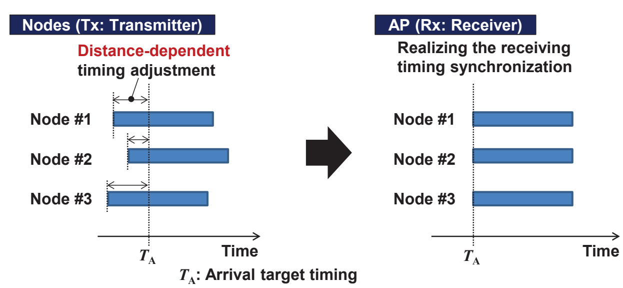

Fig. 2. Conceptual diagram of transmission timing control with space-time synchronization.

Fig. 2 shows the conceptual diagram of transmission timing control with space-time synchronization. All nodes transmit their modulated signals at a suitable time so that all signals arrive at the AP at the same time. By grasping each other's location using space-time synchronization, each node can control the transmission timing according to the distance to the AP. This enables synchronization of the reception timing

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between uplink signals.

In the synchronized SS-CDMA with synchronization of reception timing between the uplink signals, orthogonal codes such as orthogonal M-sequence is used as spreading codes. The orthogonal code here refers to the code whose cross-correlation value is zero at zero phase shift. It can suppress the interfering node signals after the despreading because of orthogonality realized by using orthogonal code with timing synchronization. Therefore, highly accurate space-time synchronization is essential for realizing the synchronized SS-CDMA.

For using highly accurate space-time synchronization, we have proposed to use Quasi-Zenith Satellite System (QZSS) and Global Positioning System (GPS) positioning signals in our previous works [1]–[3]. However, the application of satellite positioning systems is difficult when considering indoor applications, such as smart factories.

Wireless Two-Way Interferometry (Wi-Wi) has been proposed as a technique to achieve local space-time synchronization even indoors [5], [6]. It achieves highly accurate space-time synchronization using only wireless two-way communication between distant nodes, and is applicable to indoor environments. Hereinafter, the terminal implementing this technology is called Wi-Wi module.

The implementation and evaluation of the transmission timing control function using this Wi-Wi module and Universal Software Radio Peripheral (USRP) have been performed [4]. The results confirmed that a highly accurate transmission timing control function has been achieved.

In this paper, we implement and evaluate the communication function of synchronized SS-CDMA using Wi-Wi module and USRP. Note that in this paper, for a feasibility investigation, only the time synchronization function is implemented and evaluated. In Sect. II, the Wi-Wi technology is described simply. In Sect. III, we will evaluate the initial time synchronization accuracy of the Wi-Wi module, called timing offset in this paper, by measuring and comparing the 1 pps signals output by the two time-synchronized Wi-Wi modules. In Sect. IV, we implement the communication function of synchronized SS-CDMA on USRPs. The bit error rate (BER) of the implemented communication functions is evaluated through practical measurements when two signals are transmitted simultaneously. Finally, in Sect. V, we will conclude this paper.

II. Overview of Wi-Wi

In this section, we briefly explain Wi-Wi, a wireless two-way time comparison technology [5], [6]. The Wi-Wi module (Release 6) used in this implementation is shown in Fig. 3.The left one is the leader module and the right one is the follower module. They communicate with each other using the antenna in the 920 MHz band. Two types of antennas are available: an on-board antenna and an external antenna, which can be selected. The maximum number of time slots that are used for transmitting the time comparison signal of each module is 50. In this evaluation, eight time slots are prepared in advance, and up to seven follower modules can communicate with one leader module in a time-shared manner. The two ports on the right side output 10 MHz and 1 pps signals, respectively.

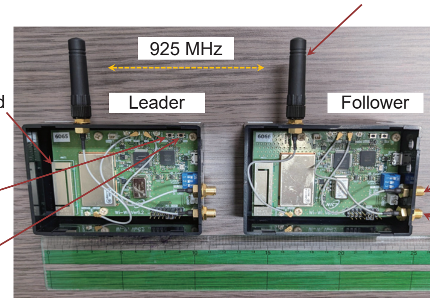


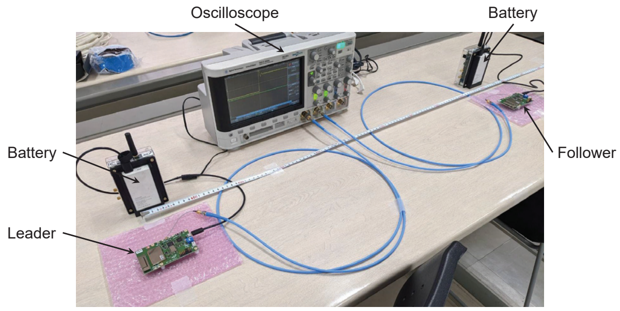
Fig. 3. Photograph of Wi-Wi module (Release 6).

It has already been demonstrated that Wi-Wi can be used to measure clock variations with high accuracy of ps order [5]. This was made possible by applying carrier-phase two-way satellite frequency transfer (TWCP) [7], which uses carrier phase for time and frequency comparison between the two nodes. Therefore, by using the 10 MHz signal output by the synchronized Wi-Wi module as the clock reference signal, the clock between the two USRP terminals can be synchronized with high accuracy of ps order. In the same way, it has already been demonstrated that mm-order accuracy distance variation measurement is possible by using Wi-Wi [6]. In the Wi-Wi module, the internal clock (36 MHz) of the follower is fine-tuned so that the phases of the carrier wave in the 920 MHz band are aligned in the leader and follower. This state in which the phases of the carrier wave are synchronized is called phase lock. In the phase-locked state, the phase does not shift significantly, but the error of the first time difference measurement exists as an offset that should be evaluated for realizing synchronized SS-CDMA.

III. Evaluation of Timing Offset of 1 pps Output from Wi-Wi Module

In this section, we evaluate of the offset of the 1 pps signal output from the two Wi-Wi modules. We have previously evaluated the Wi-Wi module (Release 2) and confirmed that the standard deviation (σ) of the initial time synchronization error (offset) was nearly equal to 130 ns through actual measurement and evaluation [4]. In this evaluation, the Wi-Wi module (Release 6) with improved initial time synchronization accuracy and number of simultaneous connections was used. Fig. 4(a) shows the measurement system. The on-board antenna of the Wi-Wi module was used for wireless communication between the leader and follower modules, and the output 1 pps signal was input to channels 1 and 2 of the oscilloscope (Keysight DSO-X 3034A), respectively. An equal-length cable was connected between the 1 pps signal output port and the oscilloscope.

Fig. 4(b) shows an example of the oscilloscope screen. The yellow waveform at the top is the output signal of the leader.



(a) Measurement system

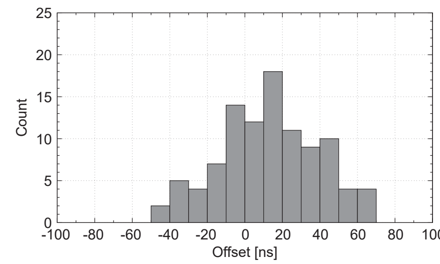
(b) Example of the oscilloscope screen

Fig. 4. Photograph of measurement system.

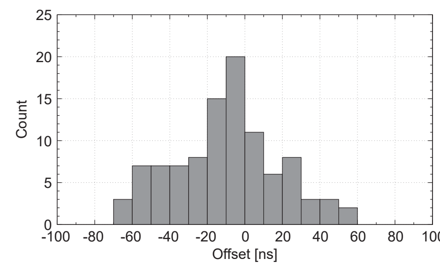
The green waveform at the bottom is the output signal of the follower. The values surrounded by the orange dashed frame are the measured values of the timing offset. In this measurement, we recorded the measured values displayed on the screen of the oscilloscope.

The Wi-Wi module started communication for synchronization with pressing the "Lock" button and locked the 1 pps signal in a time-synchronized state by comparing each other's time for a few to 10 seconds. After that, it maintained the time synchronization until the "Reset" button is pressed. In this evaluation, the Wi-Wi modules were reset and locked 100 times for each distance and the timing offset after each lock was recorded. The histograms were made under different distances between modules from 100 cm to 200 cm. Measurements were conducted in a laboratory on the fifth floor of the East Building of the Research Institute for Nanodevices, Hiroshima University. The measurement was performed in a stationary environment with no movement of the module during the Lock operation and no change in the surrounding radio environment.

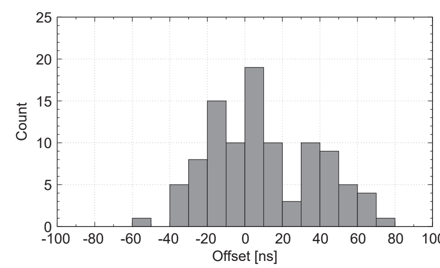
Figs. 5(a), 5(b), and 5(c) show the measurement results when the distance between the leader and follower modules is 100 cm, 150 cm, and 200 cm, respectively. The horizontal axis indicates offset, and the vertical axis indicates count. The distribution tended to be close to a normal distribution centered around offset 0 in all cases. Table I summarizes the standard deviation (σ) and average of the measured offsets. The standard deviation was less than 30 ns in all cases. Also, the average were ranging from -9.5 to 13.2 ns. Therefore, it is clear that Wi-Wi is capable of achieving highly accurate initial time synchronization.



(a) Distance of 100 cm



(b) Distance of 150 cm



(c) Distance of 200 cm

Fig. 5. Evaluation of timing offset.

TABLE I
MEASUREMENT RESULTS OF THE OFFSET.

Wi-Wi	Distance [cm]	σ [ns]	Average [ns]
Release 6	100	26.3	13.2
	150	27.9	-9.5
	200	28.6	10.5
Release 2 [4]		~ 130	

IV. IMPLEMENTATION AND EVALUATION OF SYNCHRONIZED SS-CDMA COMMUNICATION FUNCTION USING USRP

In this section, we implement a synchronized SS-CDMA communication function by synchronizing with an external reference signal in USRP, and evaluate the BER performance. In this evaluation, the pps signal of the Wi-Wi module (Release 6) that offset was evaluated in Sect. III was used as the external reference signal for USRP.

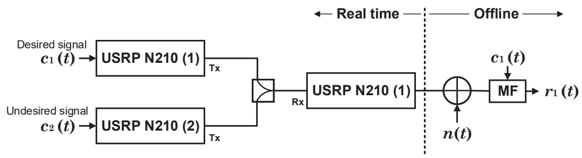


Fig. 6. Block diagram of transmitter and receiver system (2 TX).

A. Overview of the implemented system

Fig. 6 shows a block diagram of the transmitter and receiver system in the 2 TX case. Desired signal $c_1(t)$ and undesired signal $c_2(t)$ created in MATLAB were transmitted from the transmit port (Tx port) of USRP (1) and (2), respectively. The two signals were combined by a combiner and inputted to the receive port (Rx port) of USRP (1). The received signals were then passed through matched filters (MFs) for $c_1(t)$ and $c_2(t)$ and despreading processing was performed off-line using MATLAB. In the case of 1 TX, only USRP (1) was used. The signal $c_1(t)$ was sent from the Tx port of USRP (1) and received at the Rx port of USRP (1).

B. Transmission signal

Fig. 7 shows structure of the desired signal $c_1(t)$ and undesired signal $c_2(t)$ in Fig. 6. They consist as follows. First, a 13th-order M-sequence was created for two cycles as a preamble to determine the arrival time of the signal. Generated polynomials (1, 3, 4, 13) and (4, 5, 7, 8, 9, 10, 13) were used for $c_1(t)$ and $c_2(t)$, respectively. As a guard chip, 10 chips of "-1" is added at the end of the preamble to prevent interference in case of time deviations. Next, 5×10^6 bit signals were randomly generated, and spread by using a 16-period orthogonal M-sequence generated from a fourth-order M-sequence of the generator polynomial (1, 0, 0, 1). The phase of the fourth-order M-sequence used in the generation was shifted by 2 chips between $c_1(t)$ and $c_2(t)$. This is because the offset σ of the Wi-Wi time synchronization signal is less than 30 ns, and the simultaneously transmitted signal from the USRP synchronized to the Wi-Wi does not deviate more than 1 chip at a sampling rate (12.5 MHz in this implementation). The 8×10^7 chip created here is called to as the "communication part" in this paper. Finally, in end part, the same 13th-order M-sequence as the preamble part is added for one cycle each to confirm that it has received all signals. The above signals were combined, and guard chip were added to the beginning and end of the signal. In this way, the two signals $c_1(t)$ and $c_2(t)$ of 80,024,603 chip were saved as the transmission signal and used for the measurement. Binary phase-shift keying (BPSK) modulation was used for transmission.

C. Off-line despreading processing

The despreading process on the right side in the Fig. 6 was performed offline using MATLAB. First, we extracted the first 80,050,000 chips of the signal received by the USRP. This extracted received signal was passed through the MF created from the 13th-order M-sequence to check the position of the correlation peak in the preamble part. Since $c_1(t)$ and $c_2(t)$ were transmitted simultaneously, ideally the correlation peaks of $r_1(t)$ and $r_2(t)$ would appear at the same time. However, if there is offset in the Wi-Wi module, the chip on which the peak appears is shifted, and the position of the chip at which the communication part begins varies from transmitter to transmitter. Next, this correlation peak was used to find the location of the signal where the communication part spread by the orthogonal M-sequence begins. 8×10^7 chip are extracted from the position where the communication part starts, and after adding noise $n(t)$ in MATLAB, they are passed through an MF created from a fourth-order orthogonal M-sequence. Here, $n(t)$ is the additive white Gaussian noise (AWGN) using the noise power corresponding to the energy per bit to noise power spectral density ratio (E_b/N_0). To determine the noise power, the signal power was calculated by averaging the correlation peaks of the fourth-order orthogonal M-sequences in the communication part. The output of the MF was demodulated, and the BER for each E_b/N_0 was calculated four times by comparing it with the signal of the communication part created in MATLAB, and the average was taken as the result of BER evaluation. Only the desired signal $c_1(t)$ was used to evaluate BER.

D. Details of measurement system

Figs. 8 and 9 show the block diagram and the photograph of the measurement system in the case of 2 TX, respectively. The colored wires in Fig. 8 represent combinations of equal-length cables. The 1-pps signal of output of each Wi-Wi module was branched by the power divider. One of them was input to the USRP and the other one to the oscilloscope to measure the timing offset of the 1-pps signal output from the Wi-Wi module. The 10 MHz reference signal output from Wi-Wi was input to each USRP with frequency synchronization using the Wi-Wi module. The created transmission signals $c_1(t)$ and $c_2(t)$ were output from the Tx ports of USRP (1) and (2), respectively. These signals were combined by a power combiner and input to the Rx port of USRP (1). In the case of 1TX, it made a measurement system in the same way. The transmission signal $c_1(t)$ was output from the Tx port of USRP (1) and input to the Rx port of USRP (1) through the power combiner. The 50 Ω terminator was installed on the vacant port of the power combiner to prevent signal reflections. To improve the accuracy of the BER evaluation, it repeated these measurements four times, while Wi-Wi took the same offset. Since there was an initial phase difference between the transmitter and the receiver, the average value of the phase rotation of the received signal was stored as a complex number in advance, and the phase rotation was corrected by applying the complex conjugate of the stored rotation to the result through the MF.

This experiment was conducted the same location of Sect. II, using a wired connection between USRPs and a wireless connection between Wi-Wi modules (distance: 50 cm). The transmission timing control function of USRP was the same as in the [4], and the function shown in the [8] was used. The

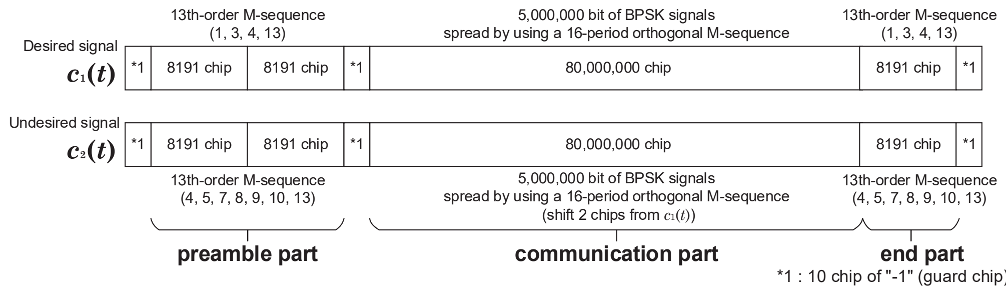


Fig. 7. Structure of the transmission signals.

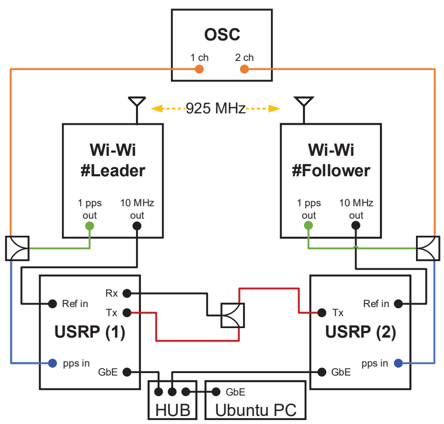


Fig. 8. Block diagram of measurement system (2 TX).

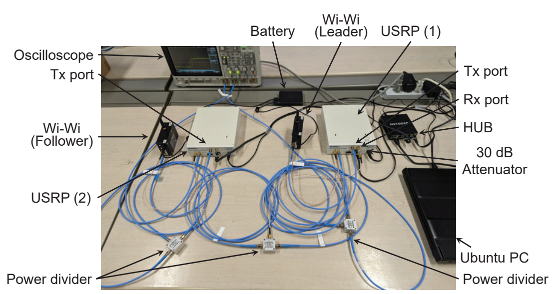


Fig. 9. Photograph of measurement system (2 TX).

USRP was controlled by an Ubuntu personal computer (PC) through a local area network (LAN) cable and a switching hub. The sampling rate and chip rate were configured to be 12.5 MHz and 12.5 Mchip/s, respectively.

E. Evaluation result of BER

Fig. 10 shows the BER measurement results of 1 TX and 2 TX together with the theoretical values of BPSK synchronous detection. The vertical axis indicates BER, and the horizontal axis indicates E_b/N_0 in the range of 1 to 10 dB in 1 dB increments. The black solid line shows the BPSK theoretical values and the purple solid line shows the average

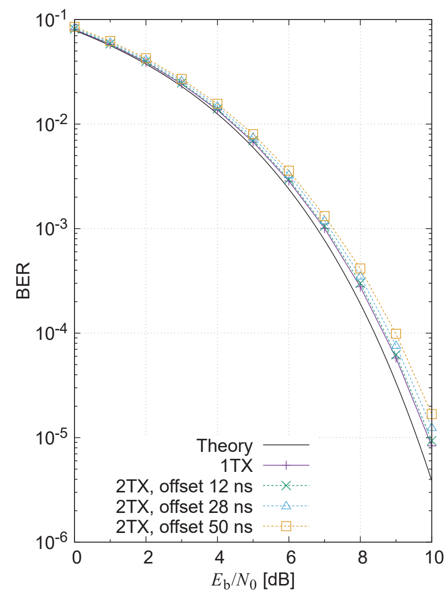


Fig. 10. Measurement results of BER.

BER of 1 TX. The dashed lines shows the average BER of 2 TX. The measurements for three different offsets (12 ns, 28 ns, and 50 ns) are shown by cross, triangular, and circular markers, respectively. In the case of 1 TX, E_b/N_0 degraded by around 0.2 dB compared to the theoretical value of BPSK synchronous detection at BER of 10^{-3}. This is considered being a degradation of characteristics caused by the measurement system including USRP. In the case of 2 TX, E_b/N_0 degraded by around 0.04 dB, 0.14 dB, and 0.24 dB, when the offset was 12 ns, 28 ns, and 50 ns, respectively, compared to value of 1 TX, at BER of 10^{-3}. As a result of BER evaluations, setting the shift of the orthogonal M-sequence to 2 chip, which is sufficiently larger than the Wi-Wi offset (σ), it is clear that the degradation of BER characteristics due to inter-channel interference becomes smaller as the offset becomes smaller. In particular, the BER difference was less than 0.1 dB when the offset was approximately 12 ns compared to the 1 TX case, as confirmed by actual measurements.

V. Conclusions

In this paper, we implemented and evaluated the communication function of synchronized spread spectrum code division multiple access (SS-CDMA) using Wireless Two-Way Interferometry (Wi-Wi) module and Universal Software Radio Peripheral (USRP). At first, we investigated the precision of initial time synchronization of the Wi-Wi module. The measurement results show that the precision of initial timing synchronization of the Wi-Wi module (σ) was less than 30 ns in the case of wireless connection with a distance of from 1 to 2 m. Next, we implemented transmission communication function on USRP synchronized by reference signals of Wi-Wi module. As a result of the bit error rate (BER) measurement of the implemented system, we reveal that the simultaneous communication between two terminals is possible without large degradation.

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References

[1] S. Kameda, K. Ohya, R. Shinozaki, H. Oguma, and N. Suematsu, "Experimental evaluation of synchronization accuracy considering sky view factor for QZSS short message synchronized SS-CDMA," IEICE ComEX, vol. 7, no. 9, pp. 322–327, Sep. 2018.

[2] S. Kameda, A. Taira, Y. Miyake, N. Suematsu, T. Takagi, and K. Tsubouchi, "Evaluation of synchronized SS-CDMA for QZSS safety confirmation system," IEEE Trans. Veh. Tech., vol. 68, no. 5, pp. 4846–4856, May 2019.

[3] S. Kameda, K. Ohya, H. Oguma, and N. Suematsu, "Experimental evaluation of synchronized SS-CDMA transmission timing control method for QZSS short message communication," IEICE Trans. Commun., vol. E102–B, no. 8, pp. 1781–1790, Aug. 2019.

[4] S. Kameda, Y. Honma, N. Suematsu, S. Yasuda, and N. Shiga, "USRP implementation of transmission timing control function for synchronized SS-CDMA using wireless two-way interferometry (Wi-Wi)," 12th International Conference on Ubiquitous and Future Networks (ICUFN 2021), Virtual Conference, Aug. 2021.

[5] N. Shiga, K. Kido, S. Yasuda, B. Panta, Y. Hanado, S. Kawamura, H. Hanado, K. Takizawa, and M. Inoue, "Demonstration of wireless two-way interferometry (Wi-Wi)," IEICE ComEX, vol. 6, no. 2, pp. 77–82, Feb. 2017.

[6] S. Yasuda, R. Ichikawa, Y. Hanado, S. Kawamura, H. Hanado, H. Iwai, K. Namba, Y. Okamoto, K. Fukunaga, T. Iguchi, and N. Shiga, "Horizontal atmospheric delay measurement using wireless two-way interferometry (Wi-Wi)," Radio Sci., vol. 54, no. 7, pp. 572–579, Jul. 2019.

[7] M. Fujieda, T. Gotoh, F. Nakagawa, R. Tabuchi, M. Aida, and J. Amagai, "Carrier-phase-based two-way satellite time and frequency transfer," IEEE Trans. Ultrason. Ferroelectr. Freq. Control, vol. 59, no. 12, pp. 2625–2630, Dec. 2012.

[8] T. Nakahama, Y. Yamada, and S. Kameda, "Example GNU radio implementations of phase alignment between USRP devices," IEICE Tech. Rep., vol. 120, no. 238, SR2020-34, pp. 74–81, Nov. 2020.