Evaluation of Transmission Timing Control Error for QZSS Short Message SS-CDMA Communication System

Hiroshi OGUMA, Rei KAWAI
Department of Electronics and Computer Engineering
National Institute of Technology, Toyama College
1-2 Ebie-Neriya, Imizu, Toyama, 933-0293 Japan
oguma@nc-toyama.ac.jp

Suguru KAMEDA
Research Institute for Nanodevices
Hiroshima University
1-4-2 Kagamiyama, Higashi-Hiroshima, Hiroshima, 739-8527 Japan
kameda3@hiroshima-u.ac.jp

Noriharu SUEMATSU
Research Institute of Electrical Communication
Tohoku University
2-1-1 Katahira, Aoba-ku, Sendai, Miyagi, 980-8577 Japan
noriharu.suematsu.a3@tohoku.ac.jp

Abstract**—** We have proposed a short message communication system using the Quasi-Zenith Satellite System (QZSS), which can be used as a safety confirmation system in the event of a disaster. Since the proposed system uses the accurate time and position information obtained from the QZSS to control the transmission timing, it is important to evaluate the time synchronization accuracy to realize the system. We construct a transmission timing control error evaluation system using FPGA, and measure and evaluate it. The clock frequency error is estimated to be within 5 ppm when the clock frequency is 100 MHz, while the delay is around 6 ms, which corresponds to the maximum transmission control time under the assumed environment. These results indicate that the timing control accuracy is sufficient to realize the proposed system.

Keywords—Satellite Communication, Quasi-Zenith Satellite System (QZSS), Global Positioning System (GPS), Spread Spectrum (SS), Code-Division Multiple-Access (CDMA), Field Programmable Gate Array (FPGA)

I. INTRODUCTION (*HEADING 1*)

When the Great East Japan Earthquake struck in March 2011, the coastal areas were hit by a massive tsunami, resulting in the loss of terrestrial telecommunications infrastructure such as mobile and fixed-line telephones. In addition, terrestrial telecommunications infrastructure that was not damaged by the tsunami also became unusable due to congestion caused by traffic concentration and power outages. Therefore, after the Great East Japan Earthquake, the operation of a location short message communication system using the Quasi-Zenith Satellite System (QZSS) was planned as a safety confirmation system that does not depend on terrestrial communication infrastructure [1],[2]. This system utilizes a geostationary satellite located at 140 degrees east longitude to enable two-way communication of location information and simple Twitter-like data/messages via satellite from personal wireless terminals that can be installed in cell phones and car navigation systems.

QZSS consists of multiple Quasi-Zenith Satellites (QZS) with asymmetric figure-8 orbits that orbit the earth at the same speed as the earth's rotation and can stay at a high elevation angle, almost at the zenith of Japan, for around eight hours. It is expected to enable highly accurate positioning at all times, even in areas where it is difficult to receive Global Positioning System (GPS) signals, such as urban areas with many high-rise buildings and mountainous areas.

Let us consider the necessary conditions for short message communications described above. First, the short message communication should be performed using a personal wireless terminal that can be installed in a cellular phone or car navigation system to enable direct communication with the satellite. Assuming that the system is installed in a mobile terminal, it is necessary to communicate directly with a satellite at a distance of around 39,000 km using a low-gain antenna with a limited transmitting power of around 1 W and near omni-directionality. Next, the system must be congestion-free to accommodate a large number of victims in the event of a large-scale disaster such as the Great East Japan Earthquake. The target capacity of the short message communication function indicated by the Cabinet Office is more than 3 million messages per hour [2]. The frequency bandwidth available for satellite communications is limited, and the system must be able to achieve very high frequency utilization efficiency. To meet this requirement, we have developed a system that achieves high spreading gain by spreading Spread Spectrum (SS) using long spread codes, and a system that accommodates a large number of users by utilizing the long spread codes for Code-Division Multiple-Access (CDMA) [3]-[17]. In the SS-

CDMA scheme, the user multiple-access of CDMA needs to be very dense to accommodate many terminals. Therefore, it is necessary to synchronize users precisely in the time and frequency domain and to ensure code orthogonality among users. QZSS is a positioning system unique to Japan, which allows for a high elevation angle and provides more accurate time and location information in a wider coverage area than conventional GPS. The proposed SS-CDMA system is characterized by synchronizing the uplink signals of all users at the time of satellite arrival and ensuring code orthogonality by controlling the timing and frequency of transmission and sending short messages at each terminal using such highly accurate positioning information.

We have calculated the time synchronization accuracy required to achieve 100% user coverage in SS-CDMA using computer simulations, experimentally evaluated the time synchronization accuracy in SS-CDMA using software, and evaluated the time synchronization accuracy using an Field Programmable Gate Array (FPGA) and a Central Processing Gate Array (CPU). We have also developed a transmission timing control system using an FPGA and a CPU [13]. This paper describes the construction and evaluation of a system using a single-chip FPGA with a CPU.

In Sect. II, an overview of the synchronous SS-CDMA system using satellite positioning signals is described, and in Sect. III, a transmission timing control system using a single-chip FPGA with a CPU is developed and the time synchronization accuracy of the system is evaluated.

II. Synchronous SS-CDMA system using satellite positioning signals

A. *Overview of Synchronous SS-CDMA Scheme*

Fig. 1 shows a schematic diagram of the synchronous SS-CDMA system, in which positioning signals are provided by QZSS and GPS satellites to obtain highly accurate time and location information. The terminal sends an uplink signal to a QZSS geostationary satellite with a terminal identification number assigned to each mobile terminal, accurate location information, and a short message. The uplink signal is returned via the satellite to the unaffected ground hub station, where it is reverse-diffused and demodulated. The demodulated information is stored in the management server and can be viewed by the client using a browser.

This section describes the mechanism of highly accurate synchronization control between terminals using satellite positioning signals. Since the communication target of the proposed system is a satellite that is around 39,000 km away, the round trip time is around 0.52 seconds, which is very large, and there are many terminals that wish to communicate. Therefore, it is necessary to realize the system without using feedback control. Fig. 2 shows the terminal functional block of a synchronous SS-CDMA system that achieves inter-user orthogonality through feed-forward control. Using the positioning and timing information provided by the positioning signals, the system encodes, modulates, and spreads the signals in the same way as a general spread spectrum system, controls the transmission timing and frequency, and transmits a message to the satellite. Since the control is performed using the positioning signals provided, the above two types of control can be realized without a feedback structure such as a closed-loop control system. This section describes a method to realize direct communication with a satellite at around 39,000 km using a mobile terminal. The proposed system uses synchronous SS-CDMA for direct communication with satellites with low power consumption, which can be installed in mobile terminals such as cell phones and car navigation systems, and for communication to accommodate many terminals simultaneously. The synchronous SS-CDMA system uses spread spectrum to achieve spread gain to enable low-power communications. Assuming that the transmitting power

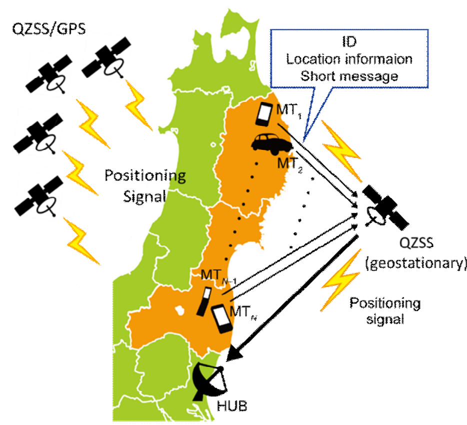

Fig. 1 Location and short message communication system using QZSS. [13]

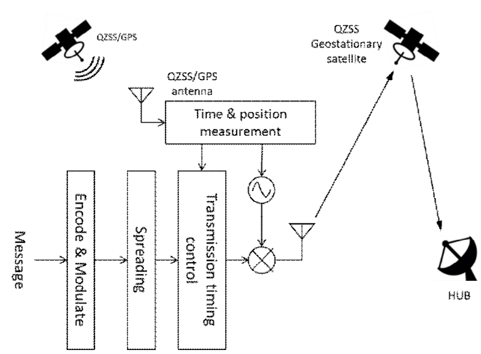

Fig. 2 Block diagram of synchronized SS-CDMA communication. [13]

of the mobile terminal is 1 W and that the required S/N = 8 [dB] at the satellite arrival point, a spreading gain of around 40 dB is required to establish a line between the terminal and the satellite. This can be achieved by using a long spreading code with a code length of around 10000. This long spreading code is also used for code division multiple access. Using a spread code with a code length of 10000, the target is to achieve simultaneous communication of several 1000~10000 terminals (capacity factor of several 10~100 %). The capacity factor is defined as the number of multiple access users divided by the spreading code length. The time unit allocated to a group for simultaneous communication is called a slot, and time-division multiplexing using multiple slots achieves the capacity of several million users per hour [6].

B. Transmission timing control in synchronous SS-CDMA

This section describes the details of transmission timing control in the synchronous SS-CDMA system and describes the factors that cause errors in the arrival timing of radio waves to satellites during transmission timing control, and the timing control accuracy required. Each terminal first obtains its own position and current time with high accuracy using positioning signals obtained from QZSS. This short message communication system is designed for a wide disaster area such as the Great East Japan Earthquake, and terminals wishing to communicate with each other are scattered over a very wide area. Therefore, differences in terminal positions among terminals scattered on the ground cause differences in the time it takes for the uplink signal to reach the satellite. Therefore, the transmission timing of radio waves is adjusted according to the propagation delay obtained by calculating the propagation distance from each terminal to the geostationary satellite using the acquired information on the position of the terminal, the position of the satellite, and the time of day, to realize synchronization and code orthogonality of the uplink signals of all terminals when they reach the satellite. The time and location information replayed at the terminal is used to achieve time synchronization among users.

Both the time and location information used for transmission timing control are generated using positioning signals, and errors occur due to differences in the number of visible satellites and satellite positioning environments such as multipath. These errors cause errors in the timing of arrival of radio waves transmitted from mobile terminals to satellites. This error in the timing of arrival at the satellite may affect the code orthogonality of the radio wave transmitted from each terminal when it arrives at the satellite.

Fig. 3 shows a schematic diagram of the factors that cause satellite arrival timing errors in a synchronous SS-CDMA system. The components of satellite arrival timing error include terminal time deviation, propagation delay calculation error, and transmission timing control error. The terminal time deviation is the deviation between terminals in the current time calculated by each user terminal from the satellite positioning signal. The terminal time deviation causes a difference in the arrival time of the uplink signal from each user terminal to the satellite, which degrades the transmission characteristics. Propagation delay calculation error is an error in the calculation of the propagation distance and time to a satellite caused by an error in the position of the user terminal calculated from the satellite positioning signal. The presence of propagation delay calculation errors causes errors in the transmission timing of each user terminal depending on the direction and magnitude of the position error, resulting in differences in the arrival timing of the uplink signal to the satellite, which degrades the transmission characteristics. Furthermore, transmission timing control errors occur when each user terminal controls its transmission timing and transmits signals.

We have evaluated the allowable error in satellite arrival timing to achieve a user coverage ratio of nearly 100 % in a synchronous SS-CDMA system by computer simulation. It was found that a user coverage ratio of almost 100 % can be achieved if the satellite arrival timing error is within around 56 ns [4],[5],[16]. Furthermore, experimental evaluation using a GPS receiver has confirmed that the propagation delay calculation error and terminal time deviation are within around 20 ns. Therefore, whether the transmission timing control error is within 30 ns of the satellite arrival timing error is an indicator for the realization of a transmission timing control system.

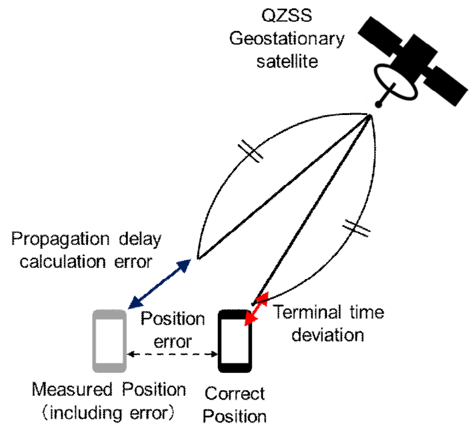

Fig. 3 Factors of satellite reception timing error.[13]

III. Construction of a Transmission Timing Control System

This section describes a hardware-based transmission timing control system. It was found that a software-based transmission timing control system cannot achieve the required time synchronization accuracy due to software delays, so it was considered necessary to construct the transmission timing control system in hardware. Therefore, the transmission timing control system is constructed using FPGAs. After the PPS signal is generated, the signal transmission timing is controlled by delaying the signal transmission by a specific amount of time from the generation of the PPS signal in accordance with the transmission timing calculated based on the position information. The transmission timing calculation unit analyzes National Marine Electronics Association (NMEA) data obtained from QZSS/GPS receivers and calculates the amount of delay after the generation of the PPS signal based on position information. The transmission timing calculation unit requires CPU functionality because it needs to analyze serial communications and perform advanced computational processing. Therefore, a CPU-IP core is implemented on FPGA [13],[15] and used as the transmission timing calculation unit. The delay control unit receives the delay data calculated by the transmission timing calculation unit and transmits a signal delayed by the set delay after the PPS signal is generated. We evaluate the terminal time deviation that occurs during the transmission timing control. The time difference between the reference time signal and the control signal output by the timing control is measured, and the terminal time deviation is calculated.

A. System construction

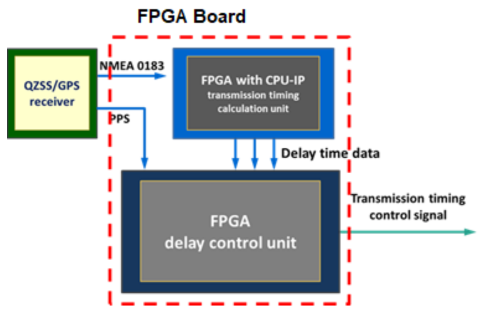

Fig. 4 Block Diagram of Transmission Timing Control System.

Fig. 4 shows a block diagram of the transmission timing control system to be constructed. The transmission timing control system consists of a QZSS/GPS receiver, a transmission timing calculation unit, and a delay control unit. Except for the QZSS/GPS receiver, the transmission timing calculation section and the delay control section are hardware components. Since the transmission timing control system is designed to be connected to a mobile terminal and to be used with a high-speed operating clock, it is implemented in FPGA logic, which can be converted to Large-Scale Integrated circuit (LSI) in consideration of the future miniaturization and speed increase of the system. Therefore, the system is implemented in FPGA logic, which can be converted to LSI in consideration of future system miniaturization and speed. Fig. 5 shows an FPGA board that implements the transmission timing calculation and delay control sections. The FPGA board is a Terasic C5GX with Intel's Cyclone V FPGA chip. The board is mainly used for system prototype development, and includes a Random Access Memory (RAM) chip, a 50 MHz clock, and toggle switches on the board.

B. Index for evaluation of transmission timing control errors

In this section, at first, it is explained to evaluate transmission timing control errors, based on the method used to determine the transmission timing. The specific objective of the transmission timing control is the sign orthogonality of messages sent from each mobile terminal when they reach the satellite. Since the QZSS location short message communication system is designed for use within the Japan area, the maximum possible delay in controlling the transmission timing can be estimated. The maximum possible delay can be estimated. In addition, the delay control unit uses a counter to control the transmission timing. Since the delay control unit uses a counter to control the transmission timing, it can be assumed that there is a correlation between the size of the delay and the transmission timing control error. Therefore, it can be said that the evaluation of the transmission timing control error should be based on the maximum delay. The amount of delay that determines the timing of transmission is determined by the distance between the satellite and the mobile terminal. Fig. 6 shows an example of controlling the timing of packet transmission from a terminal, in which the amount of delay after the PPS signal is generated is calculated from

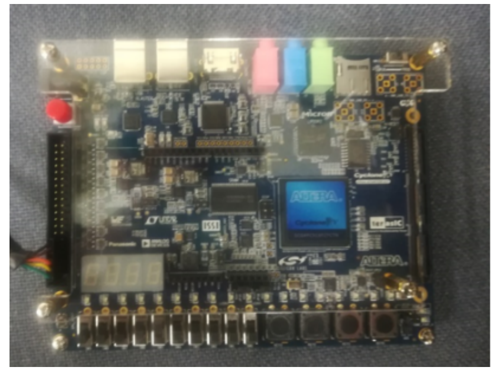

Fig. 5 FPGA board to implement a transmit timing control system.

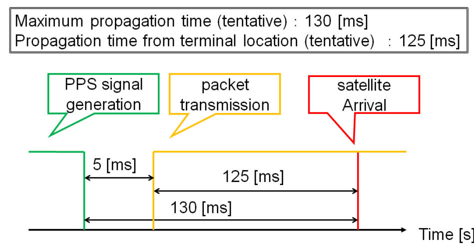

Fig. 6 Example of control of transmission timing.

position information obtained from the QZSS/GPS receiver. In this study, it is assumed that the mobile terminal located farthest from the geostationary satellite to be communicated with in the Japan region sends a message at the same time when the PPS signal is generated. Therefore, the mobile terminal closest to the geostationary satellite in the Japan region is the terminal that sends messages the slowest, and the difference between the maximum propagation time and minimum propagation time is the maximum delay. Since it is difficult to obtain the coordinates of the Japan area, the coordinates of electronic reference points located throughout Japan are used as the coordinates of the Japan area. The maximum delay was estimated for Wakkanai City, Hokkaido, the location with the longest propagation time to the geostationary satellite, and for Ogasawara Village, Tokyo, the location with the smallest propagation time. The difference in propagation time between the two locations was around 5.6 ms. Since the transmission timing error is caused by the frequency stability of the internal clock of the terminal, the transmission timing control error at a delay of around 6 ms, which corresponds to the maximum transmission control time, is the value that serves as the axis for evaluating the transmission timing control system.

C. Method of Measuring Transmit Timing Control Error

This section describes the measurement method of the transmission timing control error. Fig. 7 shows a photograph of the measurement system. Since the transmission timing control system is used to measure the transmission timing control error, the actual QZSS/GPS receiver is not used, but pseudo NMEA data is generated, and the obtained delay is used to generate a

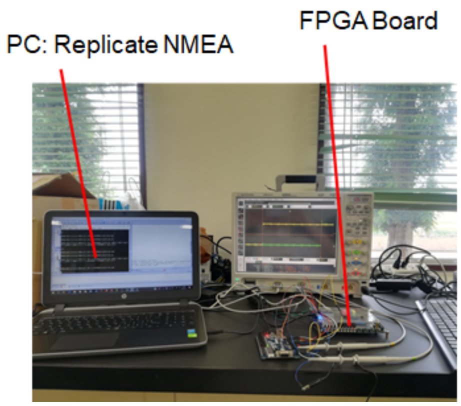

Fig. 7 Measurement system for transmission timing control error.

pseudo-PPS signal to observe the relationship between the amount of delay and the transmission timing control error. The relationship between the amount of delay and the transmission timing control error is observed. The pseudo-NMEA data is generated on a PC using terminal software, and the pseudo-PPS signal is generated by a toggle switch. Transmit timing control errors are measured using an oscilloscope. An Agilent DSO9254A oscilloscope (sampling rate: 20 GSa/s) is used. The time between the generation of the pseudo-PPS signal and the transmission of the trigger signal is measured, and the difference from the original delay is used as the transmission timing control error. The transmission timing control error is measured at various delay levels, with at least 100 measurements for each level of delay. The difference between the measured delay and the original delay is calculated using a self-written Python script.

D. *Transmission timing control error measurement results*

Fig. 8 shows the pseudo-PPS signal and trigger signal observed on an oscilloscope. In advance, NMEA data for testing is input to the PC side to obtain a predetermined delay and sent to the transmission timing calculation section. The delay control section receives the delay data calculated by the transmission timing calculation section and sends a signal delayed by the set delay after the PPS signal is generated. In other words, the time between the transmission of the pseudo-PPS signal and the trigger signal is measured, and the difference between the original delay and the delay is the transmission timing control error. Fig. 9 shows the relationship between the measured delay and the transmission timing control error. In Fig. 9, the actual measured value of the transmission timing control error for a delay of 6 ms, which corresponds to the maximum transmission control time, which is the axis of evaluation, is approximately 50 ns, failing to meet the target of 30 ns. However, since the transmission timing control error is considered to be strongly dependent on the performance of the counter in the delay control section, it can be said that the frequency error of the clock driving the counter has a significant impact on the transmission timing control error, and since the operation of the delay control section is based on the counter, the required clock frequency accuracy for

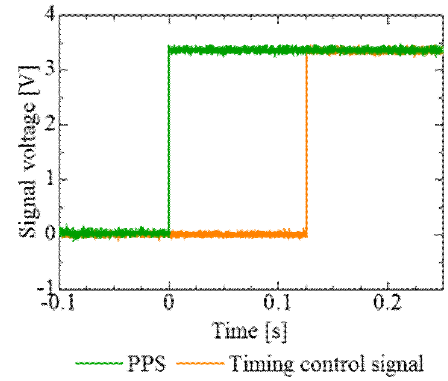

Fig. 8 Pseudo-PPS signal and trigger signal.

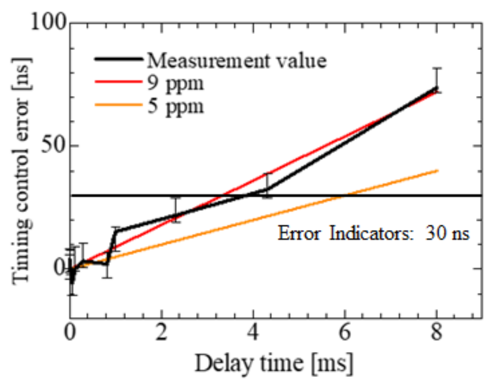

Fig. 9 Delay and transmit timing control error.

the constructed transmission timing control system can be estimated as follows Since the operation of the delay control unit is based on the counter, it is possible to estimate the clock frequency accuracy required for the constructed transmit timing control system from the measurement results. The frequency error of the clock currently used on the FPGA was estimated to be around 9 ppm for a clock frequency of 100 MHz, as shown by the red line in Fig. 9. Therefore, the estimated clock frequency error within 30 ns for a 6 ms delay is within 5 ppm for 100 MHz, as shown by the orange line. Although there may be other factors other than the clock frequency error, such as the difference in timing between the PPS signal and the clock drive, the clock frequency error is the factor that has the greatest impact on the transmission timing control error. In the Long Term Evolution (LTE) terminal standard, which is the communication method used in cell phones and smartphones, the required frequency accuracy is within 0.01 ppm [18], and a clock frequency accuracy of within 5 ppm relative to 100 MHz is a sufficiently realistic value. Therefore, the clock frequency accuracy of within 5 ppm for 100 MHz is a sufficiently realistic value. Therefore, the required transmission timing control accuracy can be achieved by using a clock with sufficiently high accuracy in the transmission timing control system.

IV. CONCLUTION

In this paper, we report the construction, measurement, and evaluation of a transmission timing control error evaluation system for short message SS-CDMA communications using the Quasi-Zenith Satellite System (QZSS) on an FPGA. The clock frequency error is estimated to be within 5 ppm for 100 MHz, which is within 30 ns when the delay is 6 ms, which corresponds to the maximum transmission control time under the assumed environment. From these results, it can be concluded that the timing control accuracy is sufficient to realize the proposed system.

ACKNOWLEDGMENT

A part of this work is supported by JSPS KAKENHI Grant Number JP JP16KK0139 and 21H01319.

REFERENCES

[1] Quasi-Zenith satellite system navigation service, interface specification for QZSS ver. 1.8, http://qz-vision.jaxa.jp/USE/is-qzss/DOCS/IS-QZSS_18_E.pdf.

[2] A level of aspiration paper of project amd business using QZSS, http://www8.cao.go.jp/space/pdf/qzs/suijyunsyo.pdf (in Japanese).

[3] T. Takahashi, Y. Miyake, F. Yamagata, H. Oguma, S. Kameda, N. Suematsu, T. Takagi, and K. Tsubouchi, "Large-capacity QZSS location and short message system using frame slotted ALOHA with flag method," 24th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2013), pp.3280-3285, Sep. 2013.

[4] A. Taira, Y. Miyake, S. Kameda, N. Suematsu, T. Takagi, and K. Tsubouchi, "QZSS location and short message communication system against big disasters," Vietnam-Japan Internatinal Sympoaium on Antennas and Propagation 2014 (VJISAP 2014), pp.229-234, Jan. 2014 (invited).

[5] A. Taira, Y. Miyake, S. Kameda, N. Suematsu, T. Takagi, and K. Tsubouch, "System stability or SS-CDMA location and short message communication using QZSS," Asia-Pacific Microwave Conference 2014 (APMC 2014), pp.947-949, Nov. 2014.

[6] T. Takahashi, Y. Miyake, S. Kameda, A. Taira, F. Yamagata, H. Oguma, N. Suematsu, T. Takagi, K. Tsubouchi, "QZSS short message SS-CDMA communication system: high efficient access control scheme using flag signal," IEICE Trans. Commun., vol.J97-B, no.11, pp.1096-1105, Nov. 2014.

[7] Y. Miyake, A. Taira, S. Kameda, H. Oguma, N. Suematsu, T. Takagi, K. Tsubouchi, "Transmit performance with timing and frequency error of QZSS SS-CDMA short message communication system," IEICE Trans. Commun., vol.J98-B, no.4, pp.397-405, Apr. 2015.

[8] N. Suematsu, S. Kameda, Y. Miyake, T. Takahashi, A. Taira, T. Takagi, and K. Tsubouchi, "QZSS SS-CDMA location and short message communication system," Vietnam-Japan Microwave 2015 (VLMW 2015), Aug. 2015 (invited).

[9] K. Ohya, T. Takahashi, S. Kameda, H. Oguma, A. Taira, N. Suematsu, T. Takagi, and K. Tsubouchi, "Efficient random access control scheme with reservation channel for QZSS short message SS-CDMA communication," IEEE Wireless Communications and Networking Conference 2016 (WCNC 2016), pp.2611-1616, Apr. 2016.

[10] K. Ohya, S. Kameda, H. Oguma, A. Taira, N. Suematsu, T. Takagi, and K. Tsubouchi, "Experimental evaluation of timing synchronization accuracy for QZSS short message synchronized SS-CDMA communication," 27th Annual IEEE Internatinal Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2016), pp.493-498, Sep. 2016.

[11] K. Ohya, S. Kameda, H. Oguma, and N. Suematsu, "Experimental evaluation of transmission timing control method for QZSS short message synchronized SS-CDMA communication," Proc. 9th International Conference on Ubiquitous and Future Networks (ICUFN 2017), pp.361-366, Jul. 2017.

[12] S. Kameda, K. Ohya, H. Oguma, and N. Suematsu, "QZSS short message synchronized SS-CDMA communication," Proc. International Conference on Solid State Devices and Materials (SSDM 2017), pp.,341-342, Sep. 2017 (invited).

[13] R. Kawai, H. Oguma, S. Kameda, and N. Suematsu, "Construction of transmission timing control system using FPGA for QZSS short message synchronized SS-CDMA communication," Proc. 8th International Conference on ICT Convergence (ICTC 2017), pp.218-223, Oct. 2017.

[14] 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.

[15] H. Oguma, R. Kawai, T. Asai, M. Motoyoshi, S. Kameda, N. Suematsu, "Transmitting timing calculation unit with CPU on FPGA for QZSS short message SS-CDMA communication," SmartCom 2018, SR2018-60, pp.5-6, Oct. 2018.

[16] 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.

[17] 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.

[18] LTE Technical Specification. ETSI TS 136 101 V10.3.0 (2011-06).