A TDoA-Based Localization Using Precise Time-Synchronization

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***Abstract*— Reliabilities for the technologies of position detection mean the measurement errors in the position detection. Presently, there are many different technologies used in position detection. But, as signal receiver operating in different locations are used to detect precise positions of objects located at long distances, it is hard to know when a object's or user's-terminal devices send a signal[1]. In this case, the technology using the ToA (Time of Arrival) is impossibly unreliable, and the TDoA (Time Difference of Arrival) technology is the more suitable[2]. If a TDoA-based electric surveillance system fails to achieve precise time-synchronization between devices for separation distance operation, it is impossible to obtain correct TDoA values from signals sent by signal receiver, and such a failure to obtaining the correct values directly affects location estimation error. In this respect, precise time-synchronization between signal receivers for separation distance operation is a core technology in detecting TDoA-based locations.**

In this paper the accuracy of the proposed and improved time-synchronization and measurement of error of TDoA-based location detection technology is evaluated, and, thus, TDoA-based location measurement error is greatly improved with the proposed method for time-synchronization error reduction.

***Keywords*—Localization, Time-Synchronization, TDoA, GPS synchronization, TPSN, Time stamping**

I. INTRODUCTION

As shown below in Figure 1, the TDoA based electronic position detection system is comprised of signal reception devices isolated by space (a minimum of 4 is needed for 3-dimensional location determinations.), center control system for location calculation, and wireless communication unit for communication between them.

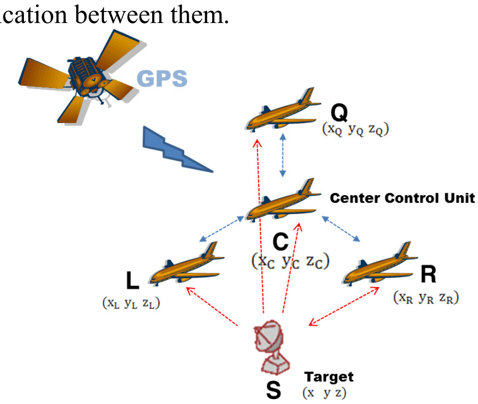

Figure 1. A TDoA based location detect system

In order to develop a TDoA-based electric surveillance system that detects long-distance threats and threat location in real time, each of the following is required: 1) high-sensitivity digital signal receiver technology; 2) technology for precise time-synchronization between signal receiving devices for separation distance operation[3]-[7]; and 3) real-time technology to estimate and trace threat location with the use of TDoA. If a TDoA-based electric surveillance system fails to achieve precise, time-synchronization between devices for separation distance operation, it is impossible to obtain correct TDoA values from signals sent by signal receivers, and such a failure to obtain the values directly affect location estimation errors. In this respect, the technology for achieving precise time-synchronization between signal receivers for separation distance operation is a core technology in detecting TDoA-based locations.

For each isolated signal receivers, the summary of time-synchronization method has two types as following.

- Common clock system
- Distributed clock system

The distributed clock system is segmented below.

- Transponder synchronized system
- Independent GPS Synchronization
- Common view GPS synchronization
- Two-way GPS synchronization

The synchronization method of the proposed system use the GPS(Global Positioning System) [8], and is to be used for overcoming the performance limitation of the Common view GPS synchronization system, which uses a two-way communication system. Also, using the time-synchronization protocol for exchanging the time stamp message, reduces the burden of hardware realization for the two-way communication link construction and adds the flexibility of system.

The proposed system uses the a highly accurate OCXO(Oven Controlled Crystal Oscillators), hardware design to improve the oscillator's accuracy, using the GPS timing signal, time difference estimation using the two-way communication link, and time-synchronization protocol. It applies the compensation algorithm for correcting the synchronization error of the receiver's clock offset and skew. It shows decrease of location detection errors using TDoA by reducing the time-synchronization errors within 5nsec.

II. Related Works

A. Wired Network Time-Synchronization

The synchronization method through the wired network of the proposed system is based on the IEEE1588.The IEEE1588 is a defined standard for synchronization of real-time clocks between nodes in distributed communication system [9].

The IEEE1588 selects the PTP (Precision Time Protocol) for time- synchronization and performs time-synchronization using Ethernet or Wireless LAN (Local Area Network) generally [10]-[12]. For the time-synchronization method of the wired network, the NTP (Network Time Protocol) has been widely used. However, in the case of the NTP, without the consideration of the hardware required to reduce errors of time-synchronization, it is the method that depends on time-synchronization through time stamp message exchange and, it result in a very large amount of error. In contrast, the IEEE1588 considers the hardware required to reduce the time-synchronization error. So during network connection, it can support a more accurate time-synchronization service compared with the NTP.

The IEEE 1588 is situated as an important component of the decentralized measurement equipment and control system of the network environment requiring the real-time time-synchronization under 1μsec error. In the long term, this technology could be linked to test/measurement equipment, and industrial automation under regional space.

B. Wireless Network Time-Synchronization

The traditional time-synchronization techniques based on the wired network are difficult to apply in the wireless network environment without change through distinct character of wireless communication (Low power operation, Mobility and Network automatic formation). For time-synchronization in the wireless network environment, the following items should be considered.

- Other resources to process communications, energy and the wireless network
- Expansion of the wireless network
- Time-synchronization infrastructure for the wireless network
- The node set of the wireless network

1) TPSN

TPSN is one of the time-synchronization protocols suitable to the wireless network environment. It starts from the root node for time-synchronization and forms the hierarchical structure network having the level. To check the synchronization between the node exchanging time stamp message and higher level node, by calculating the offset and delivery delay it corrects the angle.

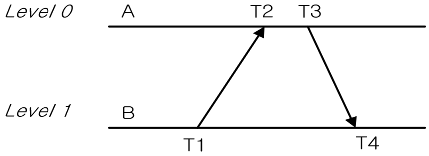

Figure 2. Two step message exchange of TPSN

Figure 2 shows the course of putting together the synchronization of sensor B in sensor node A's timer through the two step message exchange of the TPSN. In Figure 2 T1 shows sensor node B's transmission time, T2 is sensor node A's reception time of message, T3 is sensor node A's transmission time of the Ack message and T4 is sensor node B's ACK message reception time.

When the two step message exchange is finished, the sensor node B can look for the timer offset(Δ) and electric wave delay time(d) through the following formula and when correcting by adding Δ in one's timer value, it can maintain sensor A's timer and the synchronization.

$$\Delta = \frac{(T_2 - T_1) - (T_4 - T_3)}{2}$$

$$d = \frac{(T_2 - T_1) + (T_4 - T_3)}{2}$$

2) Time-Synchronization Error in Wireless Network

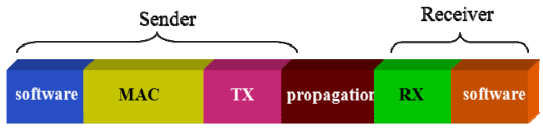

Figure 3. Delay model in process of time stamp message transmission

Figure 3 has modelled the packet delay that occurred in the course of exchanging the packet (for the time stamp message transmission) between two receivers in the wireless link. The packet delay can be classified as three types of delays - delay in transmission process, electric wave delay in the process of delivering through the wireless link, and delay in the reception process.

The delay in transmission process is formed as send time occurring through the time-synchronization application software, the required access time accessing to wireless channel in the MAC layer and the needed transmission time delivering the packet bit by bit in the physical layer. Also, in the delay of reception course, it is composed of the receive time needed to deliver the time stamp message to the time-synchronization application and the reception time needed to putting up to the MAC layer by receiving the bit stream from physical layer.

The time-synchronization error occurred through the physical clock [13], [14]. For the CPU's external clock, it uses the crystal oscillator. In the case of the correction radiator, it maintains the clock of the applicable frequency but through aging, temperature, or humidity and in the case of the supply voltage's changes, it causes the clock of a slightly skewed frequency from the actual applicable frequency. Through this clock skew, although the synchronization is put together in a particular moment between receivers, the two receiver clock time becomes more distant as time goes by. Therefore, in the case of special purposes such as long term or electronic operation, full consideration for time-synchronization is needed and the algorithm development is required to achieve accurate synchronization.

III. PROPOSED SYSTEM

For time-synchronization of less than 5nsec synchronization error between the isolated operation signal receiver of a TDoA based electronic surveillance system, the goal of precise time-synchronization using the GPS clock synchronization and two-way data link-based clock error correction.

The structure of proposed system is shown in Figure 4.

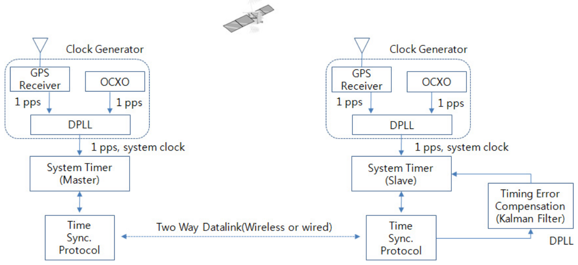

Figure 4. Proposed time-synchronization system

In the next section we will explain the structure, hardware, and algorithm of the proposed system, in detail.

A. Clock Generator

The clock generator used in the master and slave node is comprised of a GPS receiver, DPLL, OCXO, temperature sensor, oscillator drift compensation algorithm in Figure 5.

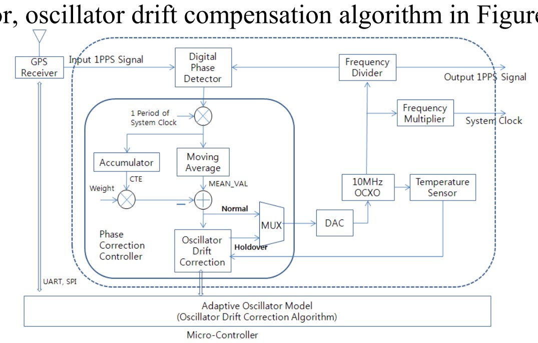

Figure 5. Clock generator

The DPLL is used to perform synchronization in the OXCO of 1 PPS signal providing the GPS receiver and forming the system clock (1 GHz) which has a high frequency stability of about 0.001 ppb (parts per billion). While for the 1 PPS signal of GPS receiver inputting in DPLL, it has the short term jitter of 30ns through the effect of reflection and electric wave speed changes of ionization layer, multi-path reception and others.

Because the generated the signal through the GPS satellite's atomic clock which has high stability, it can reduce the jitter to 0.3ns by filtering through the loop filter of DPLL. In case of GPS signal that is not received, it uses the Holdover mode which can maintain a high level of frequency stability. For this, it uses the DPLL and Kalman filter of frequency change characters following the OCXO's temperature and time that is the synchronization of GPS timing signal. By modeling to adaptive, it maintains the OCXO high level of frequency stability in the condition where it is not being synchronized to the GPS's timing signal.

B. Two-Way Communication Link

As mentioned before, in the proposed time-synchronization system, to achieve accurate time-synchronization between the isolated application signal receiver, it uses the two way communication link that is known as the best method. In this method, it uses the time stamp message in the two way communication link between master and slave node and the delays are mutually offset when the two way is same in the course of delivering the clock phase. Therefore the clock difference estimation is possible for two receivers. To make the two way delay of time stamp message same, it needs the delay change not occur by processing all processing as hardware. Also it is better to do time-stamping in the nearest part of transmission medium connecting to the node's physical layer.

As shown Fig. 6, when using the time-stamping in the physical layer, the uncertainty factor in the transmission and reception course is the propagation time. When the master and slave node is a short baseline and the LOS is secured, the two-way electric wave delay difference is small, and so an accurate estimation of clock difference between the two nodes is possible. For this reason, in the proposed time-synchronization system, it performs the time-stamping of the physical layer.

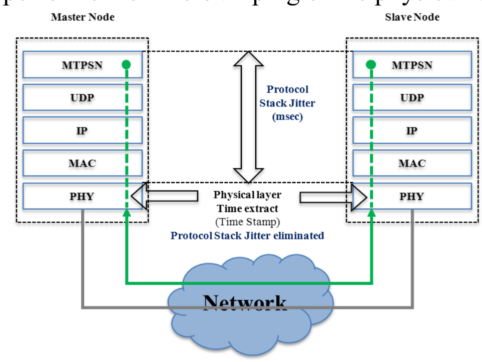

Figure 6. Time stamping in physical layer

C. Hardware Structure and Communication Method

In Figure 7, we have showed the hardware structure of proposed time-synchronization system. As shown in the Figure7, the proposed time-synchronization system is formed of clock formation class (Including the GPS receiver), CPU, FPGA, RF Frontend, DAC, ADC, Ethernet and others.

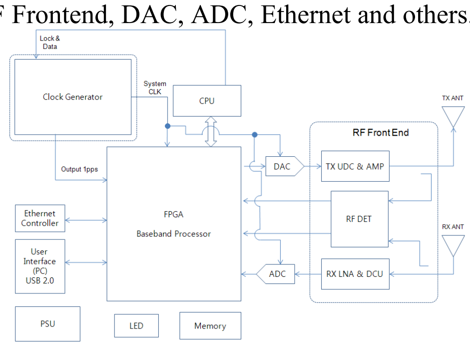

Figure 7. Hardware Structure

The wireless data link uses the SDR(Software Defined Radio) and realizes it. The reason of proposing the RF transceiver of SDR form is because the RF transceiver is difficult to control the timing in hardware and avoiding the occurring delay change is not easy.

When using the proposed SDR based RF transceiver, the performing of time-stamping is possible and can minimize the delay change in the two way data link. The wireless modem performed in the FPGA and part that is not is processed in the high speed CPU (or DSP) as software. While in the time-synchronization system, it supports the Ethernet outside of the wireless data link and make possible the time-synchronization using the IEEE1588 PTP protocol.

In terms of convenience, the CPU used the TI's DSP processor, which has a high-speed DSP core and an ARM RISC core and makes the high-speed signal processing easy, as well as providing TCP/IP protocol stack support.

D. RF Frontend

Figure 8 shows the detailed block for the module category.

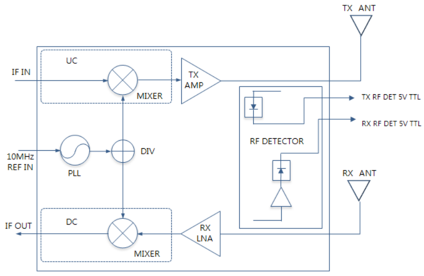

Figure 8. RF Frontend module

As mentioned, it uses the time stamping form of physical layer in the proposed time-synchronization system to minimize the delay change. For this, it uses the RF detector in the transceiver antenna to capture the time of RF signal in the antenna of RF Frontend module. When RF signal is detected in the RF Detector, it informs the FPGA through the physically connected pin. In the FPGA, when detection signal get input via the connected pin with RF Frontend module, the system timer value is latched and time stamping is possible in hardware.

E. Time-synchronization Protocol & Error Correction

Figure 9 explains the time-synchronization protocol MTPSN movement used in the proposed time-synchronization system. The MTPSN has improved the TPSN protocol and the time stamp message number needed in time-synchronization has been reduced sharply comparing to the TPSN. It can reduce the wireless data link burden and shorten the time for time-synchronization. In Figure 10, ΔT means clock difference (Offset) between the mater and slave node.

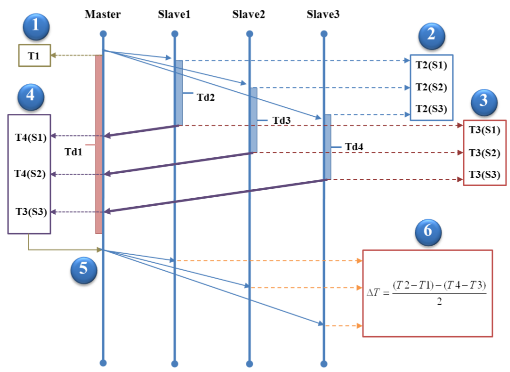

Figure 9. Synchronization between Nodes using the MTPSN

The movement order of TPSN is progressed as number order in Figure 9 (It is as follows)

- It sends the broadcasting SyncInt message for initial synchronization
- It stores T2 time information after receiving the SyncInt message
- After sending the SyncPulse message for each slave step by step, stores the T3 time information
- When not receiving the three SyncPulse during Td1 time request retransmission.
- SyncAck message broadcasting including T1 and T4 time information
- Correct the ΔT using T1, T2, T3, T4 after receiving the SyncAck

IN the RBS (Reference Broadcast Synchronization)[6] or TPSN[7], it could correct the offset between clocks. However, the crystal oscillator, it moves by contraries without moving through same frequency through environmental factors such as temperature, humidity and others. The offset correction is good in short-term stability but has disadvantage in maintaining long-term stability. On the other hand, the skew correction maintains the long-term stability. By considering the two corrections, we reflect the corrected offset value as the new input of skew correction and we can estimate the skew value minimizing the estimation errors through the Recursive Least Squares and Kalman filter[15].

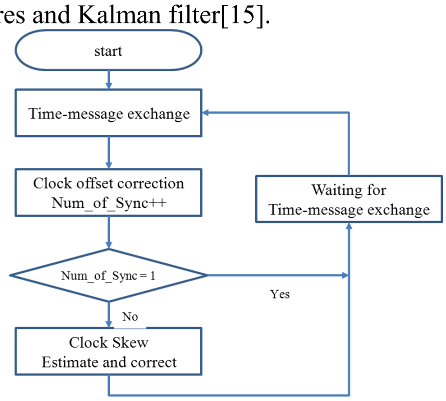

Figure 10. Offset & Skew Estimation Flow Chart

In Fig. 10, we have shown the process for estimating the clock offset and skew. In the proposed system, with the clock offset and skew Gaussian distribution, the time-synchronization error is corrected using the Kalman filter.

IV. EVALUATION

The proposed system has the time-synchronization error under 5nsec. We have assumed the system having time-synchronization error of 10nsec, 15nsec, 20nsec including 5nsec and applied to the TDoA algorithm. And, after comparing the estimated result, we have evaluated the performance based on this result.

A. TDoA algorithm

TDoA uses the different time reaching the RF receivers away in space for RF transmitter's signal. First of all, we measure the TDoA value of the RF receiver pair away in the two spaces. Using the RF transmitter's location known in advance, and the measured TDoA value, we have completed the location estimation using TDoA.

1) 2-Demension TDoA

The time-synchronization must be in achieved between receivers (BS).

The TDoA value TBS1,BS2, TBS1,BS3, TBS2 and BS3 having BS are three. The two pair curve is the users' terminal locations and it is used to estimate the locations of two dimensions, three BS is needed. As shown in Figure 11

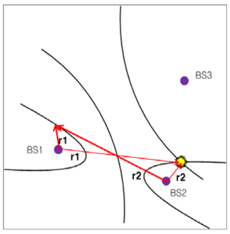

Figure 11. Wireless location detection using TDoA (2-demensions)

$$\text{TDoA(Time Difference of Arrival)} \quad \Delta t_{12} = \frac{r_1}{c} - \frac{r_2}{c}$$

$$\text{Hyperbola}: \; r_1 - r_2 = c\Delta t_{12}$$

2) 3-Demension TDoA

The target location meeting one TDoA value is the all point of the two leaf-like curved surfaces. Three dimensional location follow up is possible for over four TDoA values when the target (transmitter) is in the earth's surface. Three dimensional location follow up is possible when there is over three TDoA values. As shown in Figure 12

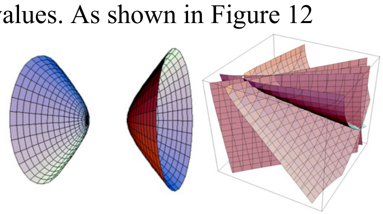

Figure 12. Wireless location detect using TDoA (3demension)

3) Simulate TDoA based Location Estimation

As shown in Figure 1, when there is a transmitter or receiver formed by coordinates, it estimates the transmitter's location. Based on the formula below, it looks for each electric wave reaching time and calculates the next. Through calculation, the three of two leaf-like curved surfaces occurs and transmitter location is decided.

- Each electric wave reaching time

$$T_L = \frac{1}{c}(\sqrt{(x-x_L)^2 + (y-y_L)^2 + (z-z_L)^2} \quad T_C = \frac{1}{c}(\sqrt{(x-x_C)^2 + (y-y_C)^2 + (z-z_C)^2}$$

$$T_R = \frac{1}{c}(\sqrt{(x-x_R)^2 + (y-y_R)^2 + (z-z_R)^2} \quad T_Q = \frac{1}{c}(\sqrt{(x-x_Q)^2 + (y-y_Q)^2 + (z-z_Q)^2}$$

- TDoA(C coordinates starting point)

$$\Gamma_L = T_L - T_C = \frac{1}{c}(\sqrt{(x-x_L)^2 + (y-y_L)^2 + (z-z_L)^2} - \sqrt{x^2 + y^2 + z^2}$$

$$\Gamma_R = T_R - T_C = \frac{1}{c}(\sqrt{(x-x_R)^2 + (y-y_R)^2 + (z-z_R)^2} - \sqrt{x^2 + y^2 + z^2}$$

$$\Gamma Q = T_Q - T_C = \frac{1}{c}(\sqrt{(x-x_Q)^2 + (y-y_Q)^2 + (z-z_Q)^2} - \sqrt{x^2 + y^2 + z^2}$$

- Three of two leaflike curved surface formula

$$0 = A_1x + B_1y + C_1z + D_1$$

$$0 = A_2x + B_2y + C_2z + D_2$$

$$0 = A_3x + B_3y + C3z + D_3$$

4) Location Estimation

By assuming the four receivers, it acquires the total of six TDoA values, as in Figure 13. Through the measurement errors, as the six-pair curved surfaces doesn't have one intersecting point, optimization is needed to minimize the location errors. When performing the location estimation through the Minimum Square Error (MSE), the constraint (Pair curved surfaces equation) number is great, and the location error is decreased.

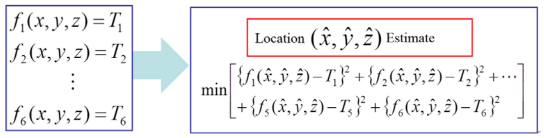

Figure 13. Location Estimation

B. Location Estimation Following the Receiver Arrangement Distance

When changing the electronic detection distance up-to 10km~50km as shown in Figure 14 with a 10-km unit, we have compared the result through the simulation. To minimize the location error as the optimization step, we do the location estimation through the MSE, the x', y', z' values coming out from the above location estimation and location of actual target's distance difference, we drew the location error. In the cases of a location error drawn from the actual target standard and the location estimation through MSE, we have perfomed the operation 100 times each.

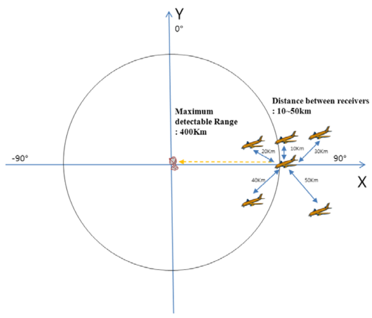

Figure 14. Change of arrangement bewteen recivers

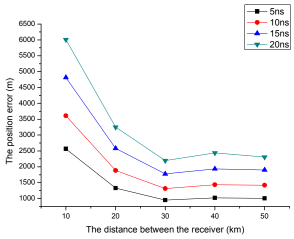

Figure 15. The result following arrangement between receivers and target

The time-synchronization error of 5nsec has an average 1865 m of error comparing 20nsec. When the electronic detection distance is far, it can have accurate location information. Fact that the electronic detection distance is far shows electronic detectors are distributed in an open surface. As actual target and electronic detector distance difference occurs, the area forming the pair curve becomes small. A small area means the location range decreasing comparing to the large area when the distance difference is occurred little. Based on this, the TDoA basis location estimation is achieved and has the result as above.

C. Location Estimation following the Receiver's Orbit

In Figure 14 It is assumed that the distances between the receivers are 30km. When the receiver group moves like as circle, we have tested how the average location estimation value is affected and how it progressed through four orbits, as shown in Figure16.

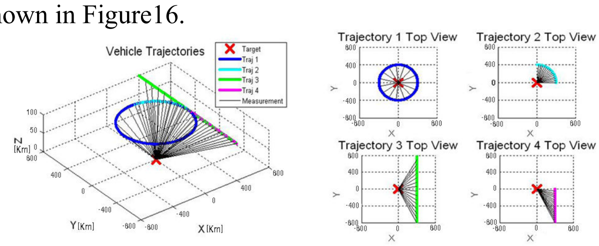

Figure 16. Receivers orbit

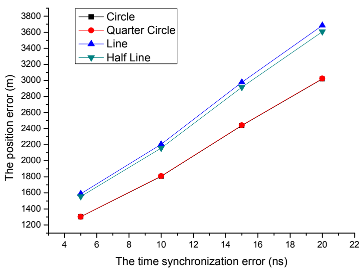

Figure 17. Result following the orbit change between Target and Receiver

V. Conclusions

In this paper, we have applied the hardware and compensation algorithm to reduce time -synchronization errors. Based on this, we have presented a system that has a time-synchronization error within 5nsec. The proposed system with a time-synchronization error under 5nsec has a minimum 1250m, maximum 3441m, and average 1867m error, compared to the 20nsec system. It is shown that the location estimation system performance has increased by 24.2% on average

For the proposed system, we are planning to reduce error to within 1nsec by using the time-synchronization error correction algorithm and highly accurate OCXO. Also, forming the actual system connecting TDoA and FDoA, we will show improvement of location estimation system performance.

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