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Contents

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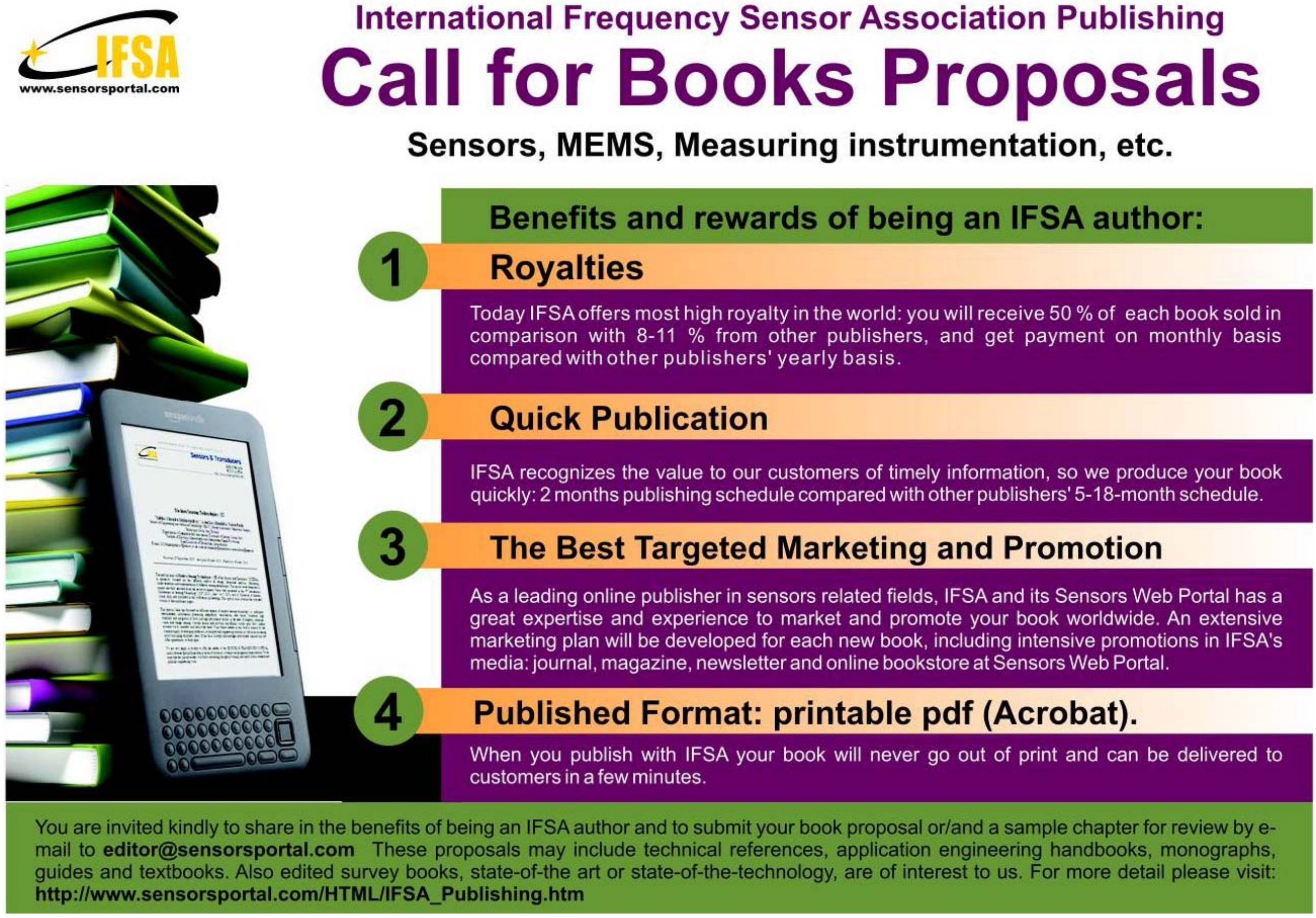

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A High-Precision RF Time-of-Flight Measurement Method based on Vernier Effect for Localization of Wireless Sensor Networks

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Abstract: This paper presents the fundamental principles of a high-precision RF time-of-flight (ToF) measurement method based on the vernier effect, which enables the improvement of time measurement resolution, for accurate distance measurement between sensor nodes in wireless sensor networks. Similar to the two scales of the vernier caliper, two heterogeneous clocks are employed to induce a new virtual time resolution that is much finer than clocks' intrinsic time resolution. Consecutive RF signal transmission and sensing using two heterogeneous clocks generates a unique sensing pattern for the RF ToF, so that the size of the RF ToF can be estimated by comparing the measured sensing pattern with the predetermined sensing patterns for the RF ToF. RF ToF measurement experiments using this heterogeneous clock system, which has low operating frequencies of several megahertz, certify the proposed RF ToF measurement method through the evaluation of the measured sensing patterns with respect to an RF round-trip time of several nanoseconds. *Copyright © 2011 IFSA.*

Keywords: Vernier effect, Heterogeneous clocks, RF time-of-flight, RF round-trip time.

1. Introduction

Recently, wireless sensor networks (WSNs) have been widely used in many industrial and civilian application areas like emergent environments for search and rescue, factories for condition based maintenance, buildings for infrastructure health monitoring, homes to realize smart homes, or even in bodies for patient monitoring [1]. In order to complete the assigned tasks of WSNs, the process by which a sensor node tries to determine its own location after deployment is indispensible; thereby, sensor nodes can successfully provide measured information with their own position information. In addition, a very accurate ranging technique between sensor nodes is also absolutely required for successful WSN localization. For that reason, for the last several years, various range-based localization methods using RF (radio frequency) signals have been proposed to provide WSN localization [2, 3]. As one of the most representative range-based WSN localization methods, the received signal strength (RSS)-based localization method has numerous defects that obstruct the stable localization of sensor nodes in WSNs [4, 5]. As another approach to substitute for RSS-based methods, the time-of-flight (ToF)-based method has attracted wide attention in recent years since an RF ToF system can require only little hardware overhead and has the potential for meter level accuracy, simple signal processing and good wall penetration [6]. However, since it is very difficult to accurately measure an RF ToF of several nanoseconds in a local space as limited as a WSN area, RF ToF-based WSN localization is still challenging; furthermore, there have been only a few studies of RF ToF-based WSN localization methods such as the UWB-based methods, and these methods are too complicated and expensive to extensively apply to WSN localization [7, 8]. Therefore, we pay attention to the cost-effective and easy-to-handle RF ToF measurement method based on the vernier effect for the purpose of the realization of a reliable RF ToF-based localization method. In order to measure considerably small time intervals in the range of nanoseconds, the principle of the vernier caliper has been applied to various time measurement systems that have limited measurement capability [9, 10]. Likewise, applying the principle of the vernier caliper, it is possible for even a low-precision time measurement system to improve measurement performance enough to accurately estimate RF ToF of several nanoseconds.

In this paper, the basic principles of the RF ToF estimation methodology based on the vernier effect are presented. Similar to the vernier caliper, which consists of two different scales, two heterogeneous clocks are adopted in order to bring about the vernier effect, which enhances the time measurement performance by the generated virtual time resolution. The proposed methodology enables the performance enhancement of the time measurement system, which has intrinsically very poor time measurement performance due to the use of a microcontroller that has a low operating clock frequency in the range of several megahertz, to the point that it is possible to realize precise distance ranging with a distance measurement resolution of several centimeters, which is enough to accurately measure the short distance between sensor nodes in WSNs. The remainder of the paper is organized as follows. In Section 2, we point out the two critical problems of one-way RF ToF measurement using a clock system having an identical low operating frequency. Then, as a solution to the problems indicated in Section 2, the principle of the high-precision RF ToF measurement method based on the vernier effect is fully introduced in Section 3; in addition, in Section 4, an advanced sensor node structure, which is called the *synch-free RF ToF measurement system*, is presented to solve the clock synchronization problem between sensor nodes which perform the RF ToF measurement task based on the proposed methodology. Section 5 gives the experimental setup and discusses the results of the short-range RF ToF measurement tests. The experimental results of RF ToF estimation through unique sensing pattern acquisition for the RF round-trip time validate the application possibility of the precise RF ToF estimation using the proposed methodology for WSN localization. Finally, this paper is concluded in Section 6.

2. RF Time-of-Flight Measurement using Identical Clock System and its Critical Problems

2.1. Localization of Sensor Nodes in Wireless Sensor Networks

Fig. 1 shows the wireless sensor networks; the sensor nodes in three networks (#1~#3) carry out the measurement tasks using the equipped sensors, and the command nodes collect information, which is measured by the sensor nodes in the three WSN workspaces, by connecting with the host nodes. Each sensor node in the networks autonomously computes its own location, which is indispensable to the completion of the measurement tasks, using the RF ranging results with only limited interactive communication with nearby sensor nodes. Fig. 2 gives a simple diagram of a pair of sensor nodes, which perform the one-way RF ToF (denoted as t_f) measurement task in the workspace of Fig. 1. Each sensor node has an RF transceiver, which carries out the function of either RF signal transmitter or RF signal receiver depending on the direction of the RF ToF measurement flow; the right sensor node estimates the RF ToF by receiving the RF signal transmitted from the left sensor node.

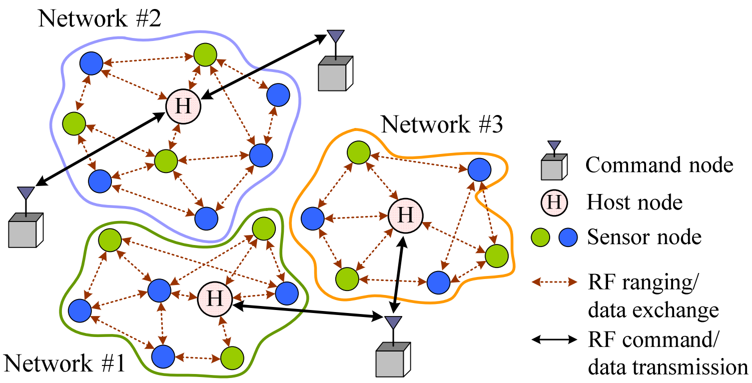


Fig. 1. Wireless sensor networks and RF ranging.

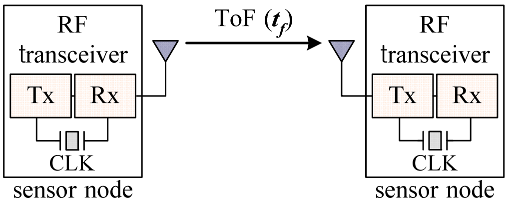
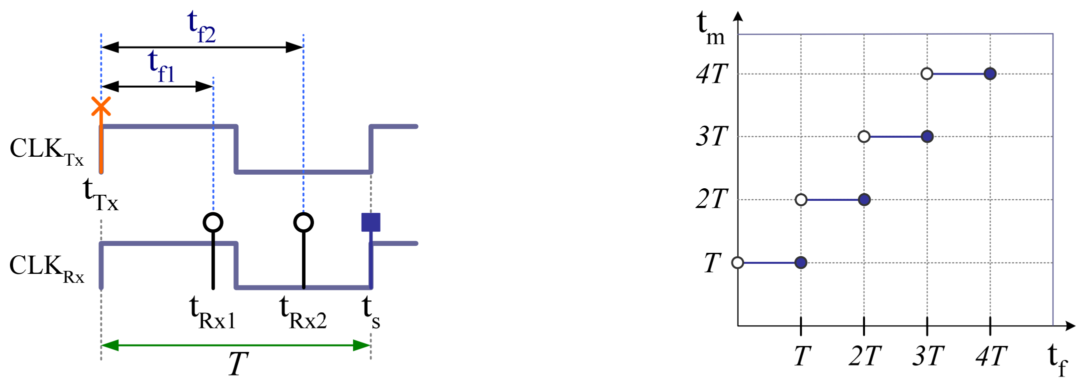


Fig. 2. One-way RF ToF measurement between a pair of sensor nodes.

2.2. The First Critical Problem: Quantization Error of RF Time-of-Flight Measurement using Identical Operating Clock Frequencies

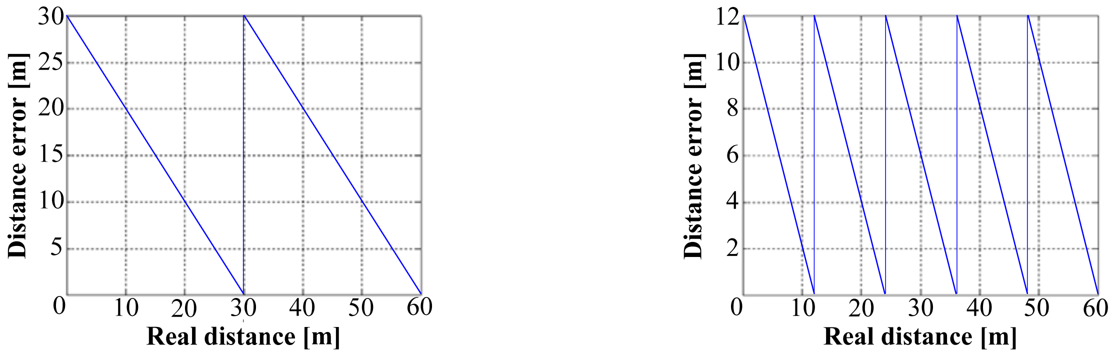
As is broadly known, the velocity of propagation of an RF signal is approximately equal to the speed of light in vacuum (c=3×10^8 [m/sec]). Compared to GPS (Global Positioning System), in which even low precision clock systems can be allowed to measure the phase delay of the RF signal due to the sufficient distant range between a GPS receiver and GPS satellites, there are a number of limitations to getting a reliable estimation of RF ToF in short distances of the sub-meter to several-meter range. Among the limitations, the quantization error of RF ToF measurement is considered to be one of the most critical problems that should be conquered for the successful RF ToF measurement between sensor nodes. In the case in which the operating clocks of the two sensor nodes shown in Fig. 2 are identical and have a considerably low operating frequency of several megahertz (e.g., 8 [MHz]), there is severe quantization error with respect to the short-range RF ToF measurement, as shown in Fig. 3. Under the assumption that signal processing in micro-controllers is performed at the rising edge of the operating clock and the propagation time of the RF impulse is used for RF ToF measurement, it can be assumed that the RF impulse transmission (denoted as T_x), as shown on the left side of Fig. 3, is performed at the rising edge of the operating clock (denoted as CLK_{Tx}) of the left sensor node, and that the received RF impulse is sensed at the 1st rising edge of the operating clock (denoted as CLK_{Rx}) of the right sensor node posterior to the received RF impulse. Then, provided that the rising edges of the operating clocks of both sensor nodes are synchronized, the RF impulses with two different ToF (denoted as t_{f1} and t_{f2}) arrive at different receiving time points (denoted as t_{Rx1} and t_{Rx2}) in the sampling period of CLK_{Rx} after being transmitted at the transmission time point (denoted as t_{Tx}) of CLK_{Tx}. In this case, the sensing time points for the received RF impulses are all equal to t_s. As a result, as can be seen in the right side of Fig. 3, the measured propagation time (denoted as t_m) for the RF impulses with different ToF, which is smaller than a sampling period of CLK_{Rx} (i.e., $0<t_f<T$), is equivalent to T. Fig. 4 shows the quantization error patterns of the distance estimation based on the RF ToF measurement using identical low operating clock frequencies; e.g., the left side of Fig. 4 shows the quantization error of distance estimation in the case in which the operating clock frequencies of the two sensor nodes in Fig. 2 are both 10 [MHz].



(a) Timing of impulse detection

(b) Quantization error

Fig. 3. RF ToF measurement using identical operating clocks.



(a) 10 [MHz]

(b) 25 [MHz]

Fig. 4. Quantization error of distance estimation.

Accordingly, the operating clock, of which the time resolution is smaller than the quantity of the allowable ToF measurement error, is absolutely required to solve the problem of the quantization error of RF ToF measurement between sensor nodes that are located within a relatively short distance area. However, it is technically very difficult to implement a reliable RF ToF measurement system using identical high operating clock frequencies since it is basically not an easy matter to fabricate a clock source (e.g., a crystal oscillator) that can guarantee an operating frequency high enough to enable us to measure the RF ToF exactly in a short distance of the sub-meter to several-meter range. In addition, even if there were such an operating clock commercially available from the merchandise in stock, its high cost would also lead to an economic burden in using it for implementing a large number of sensor nodes in WSNs.

2.3. The Second Critical Problem: Clock Synchronization between Sensor Nodes in Wireless Sensor Networks

There is no global clock or common notion of time among sensor nodes in WSNs. Furthermore, each sensor node has an internal clock that ticks at its own rate, and clocks in sensor nodes may not remain synchronized all the time, though they might be synchronized when they start to move. For that reason, clock synchronization, which means the process of ensuring that physically distributed sensor nodes have a common notion of time, is necessary for successful RF ToF measurement between sensor nodes. However, it is not an easy matter to make sensor nodes, which carry out the RF ToF measurement task, hold the knowledge of RF signal transmission time in common. The traditional clock synchronization methods used in wired networks cannot be applied to WSNs, which require several features: the ability to dynamically adapt to handle sensor mobility and scalability, low-energy consumption and powerful computation of localization. Therefore, clock synchronization between sensor nodes can also be regarded as one of the most critical problems to be solved for realizing reliable RF ToF measurement between sensor nodes.

3. Principle of High-Precision RF Time-of-Flight Measurement Method based on Vernier Effect

3.1. Heterogeneous Clock System and New Virtual Time Resolution

Fig. 5 shows a well-known vernier caliper; it has two different scales (main scale and vernier scale), for which the unit scales are λ and μ, where $\lambda > \mu$. The ratio of the two unit scales is N to $N-1$, where N is a positive integer. The vernier scale enables the reading of a more precise distance than is possible by directly reading a uniformly-divided straight main measurement scale. The vernier effect of the vernier caliper may refer to the generation of a new virtual scale. Eq. (1) gives the new virtual scale/distance-resolution (denoted as Δ), which is much finer than the two unit scales (λ and μ) of the vernier caliper. The difference of the two unit scales, $\lambda-\mu$, plays the role of the new virtual scale (Δ).

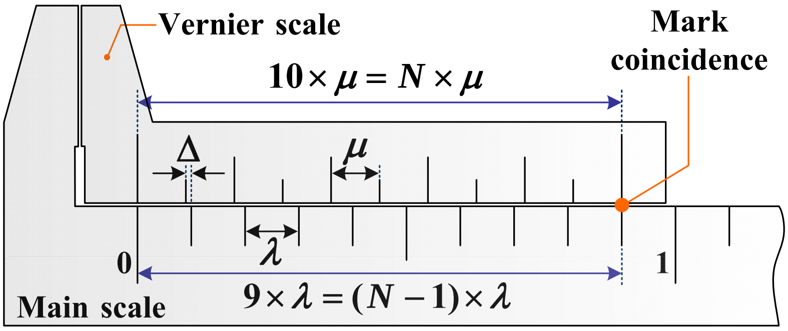


Fig. 5. Vernier caliper and its scales.

$$\Delta = \lambda - \mu = \lambda - (1 - 1/N)\times\lambda = \lambda/N\,, \tag{1}$$

where $\lambda:\mu=N:(N-1)$ and N is a positive integer.

Applying the principle of the vernier caliper to the clock system generates significant effects that enable us to precisely measure the propagation time taken to transmit the RF signal over a very short distance of several meters. Fig. 6 shows the structure of the sensor node that has both an RF impulse transmitter and a receiver, which are operated by two separated clocks (CLK_A and CLK_B); the time periods of CLK_A and CLK_B are denoted by T_A and T_B, respectively. In the case in which the two clocks are heterogeneous (i.e., $T_A \neq T_B$) and the ratio of the time periods of the two clocks is N to $N-1$ (e.g., 10:9, 8:7, and so on) as in Eq. (2), the new virtual time resolution (Δ), which is similar to the virtual distance resolution of the vernier caliper, is generated as in Eq. (3). The new virtual time resolution (Δ) is equal to the difference of the time periods of the two heterogeneous clocks, and its time span is much shorter than the time periods of the two heterogeneous clocks; i.e., $\Delta \ll T_A$ & T_B.

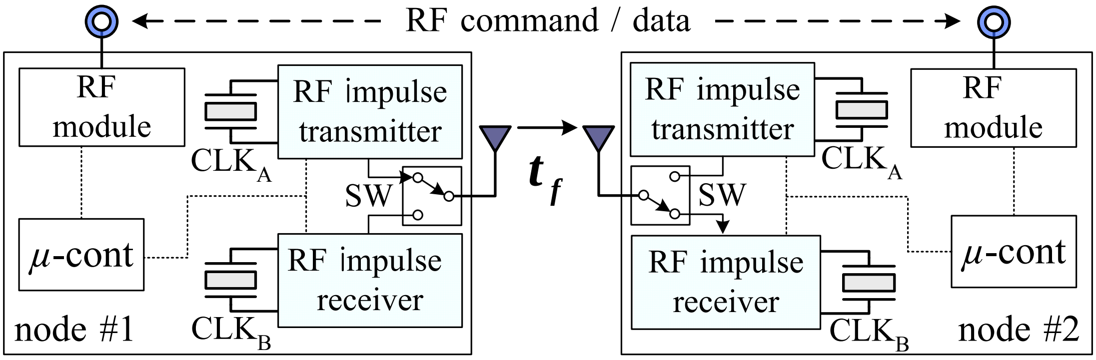


Fig. 6. Structure of a sensor node with heterogeneous operating clocks.

$$T_A : T_B = N : (N-1), \tag{2}$$

$$\Delta = T_A / N = T_B / (N-1) = T_A - T_B, \tag{3}$$

Even two heterogeneous clocks having quite low operating frequencies (e.g., several kilohertz) can be allowed to generate a new virtual time resolution (Δ) of several-picoseconds, regardless of the size of their operating frequencies. Based on Eq. (3), it is theoretically possible that the variation of the combination of two heterogeneous clocks will enable us to flexibly change the size of the new virtual time resolution (Δ) without any constraints. That is, to change the difference of the time periods of the two heterogeneous clocks allows us to control the size of the new virtual time resolution (Δ). Accordingly, the new virtual time resolution (Δ) is a main key to the measuring of the extremely small propagation time of the RF signal.

3.2. Principle of RF Time-of-Flight Measurement Based on Vernier Effect

Fig. 7 shows the acquisition of a unique sensing pattern ($\boldsymbol{v}=\{1, 0, 1, 1\}$) with respect to $t_f=3\Delta$ through the consecutive one-way RF impulse transmission and sensing using the heterogeneous clocks of the two sensor nodes shown in Fig. 6, which has the following condition, $T_A:T_B=N:(N-1)=4:3$. If there is any received RF impulse (denoted as R_x) within a sampling period of CLK_B of the RF impulse receiver of node #2 in Fig. 6, the sensing bit ($v_1 \sim v_4$) for the received RF impulse is designated as 1-digit; otherwise, it becomes 0-digit.

Basically, the difference of the time periods of the two heterogeneous clocks itself is meaningless if the RF impulse transmission and sensing using the two heterogeneous clocks is limited to a single operation. On the other hand, as can be seen in Fig. 7, consecutive RF impulse transmission and sensing using the two heterogeneous clocks satisfying Eq. (2) leads to unique sensing patterns with respect to the RF ToF, of which the size is classified into multiples of Δ; consequently, the difference (Δ) becomes effective as a new virtual time resolution. Table 1 gives a set of sensing patterns with respect to the RF ToF in the range of $0<t_f\leq(N-1)\Delta$. Provided $T_A:T_B=N:(N-1)$ and $\Delta=T_A-T_B$, where N is a positive integer, there are $(N-1)$-unique sensing patterns (**v**) depending on the range of RF ToF, and each sensing pattern (**v**) consists of N-sensing bits (v_i, i=1~N), i.e., $\boldsymbol{v}=\{v_1, v_2, \ldots, v_N\}$. In addition, it can be seen that the entries of the diagonal (↙) from the N^{th} sensing bit (v_N) of the first sensing pattern in Table 1 are all zero. Consequently, RF ToF estimation with a new virtual time resolution as large as Δ can be realized by comparing the measured sensing pattern with the predetermined unique sensing patterns according to the size of the RF ToF.

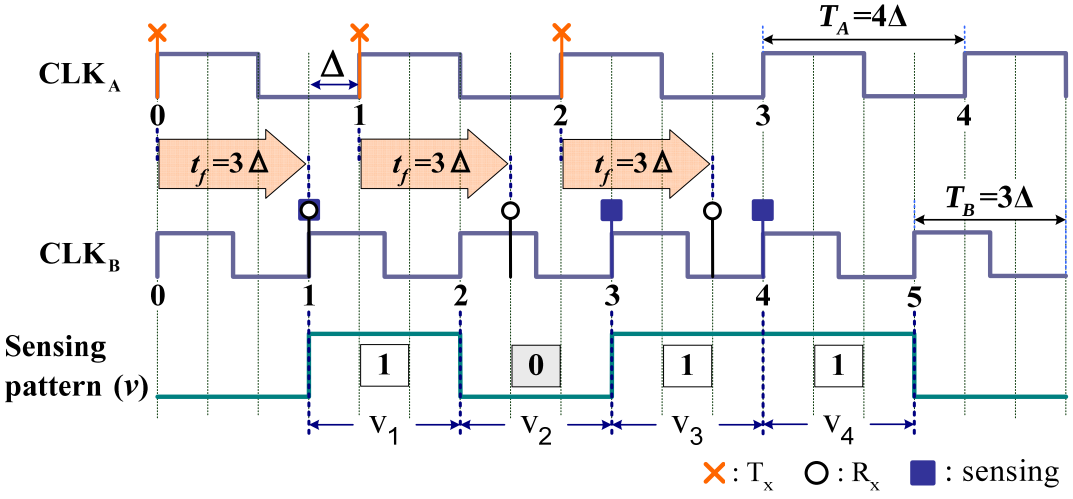


Fig. 7. One-way RF ToF sensing pattern acquisition when $t_f=3\Delta$.

Table 1. A set of sensing patterns for $0<t_f\leq(N-1)\Delta$, provided $T_A:T_B=N:(N-1)$.

v	v_1	v_2	⋯	v_{N-1}	v_N
$0<t_f\leq\Delta$	1	1	⋯	1	0
$\Delta<t_f\leq2\Delta$	1	1	⋯	0	1
⋮	⋮	⋮	⋰	⋮	⋮
$(N-2)\Delta<t_f\leq(N-1)\Delta$	1	0	⋯	1	1

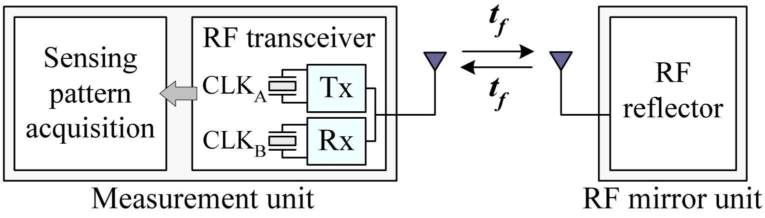
Table 2 shows the general form of the sensing patterns in the range of $k(N-1)\Delta<t_f\leq(k+1)(N-1)\Delta$ where $k\geq0$. The set of sensing patterns in the range of $0<t_f\leq(N-1)\Delta$ is a basic form that represents the general form of the sensing patterns. As can be seen in Table 2, there are $(k+N)$-sensing bits (v_1~v_{k+N}); here, the sensing bits from v_1 to v_k are all replaced with zero-bit, and those from v_{k+1} to v_{k+N} are filled by shifting the sensing bits (v_1~v_N) of the sensing patterns in the range of $0<t_f\leq(N-1)\Delta$ to the right of the k-bit position. For instance, when ToF is in the range of $(N-1)\Delta<t_f\leq2(N-1)\Delta$ and k=1, the first sensing bits (v_1) of the sensing patterns are all zero, and the entries of (v_2~v_{N+1}) are filled by shifting the sensing bits (v_1~v_N) of the set of sensing patterns in the range of $0<t_f\leq(N-1)\Delta$ to the right of the one-bit position. Accordingly, the sensing patterns for the RF ToF can be theoretically infinitely represented using the general form of the sensing patterns.

Table 2. General form of sensing patterns when $k(N-1)\Delta < t_f \leq (k+1)(N-1)\Delta$, $k \geq 0$.

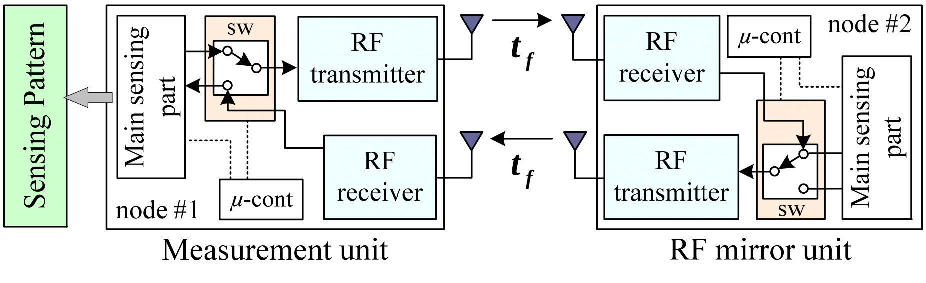
v	v_i, $i = 1 \sim k$ (when $k \geq 1$)			v_{k+1}	v_{k+2}	$\cdots$	v_{k+N-1}	v_{k+N}
	v_1	$\cdots$	v_k					
$k(N-1)\Delta < t_f \leq \{k(N-1)+1\}\Delta$	0	$\cdots$	0	1	1	$\cdots$	1	0
$\{k(N-1)+1\}\Delta < t_f \leq \{k(N-1)+2\}\Delta$	0	$\cdots$	0	1	1	$\cdots$	0	1
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\iddots$	$\vdots$	$\vdots$
$\{k(N-1)+(N-2)\}\Delta < t_f \leq (k+1)(N-1)\Delta$	0	$\cdots$	0	1	0	$\cdots$	1	1

4. Proposal of Advanced Sensor Node Structure to Solve Clock Synchronization Problem

In order to realize one-way RF ToF sensing pattern acquisition based on the vernier effect, the clock synchronization between the two heterogeneous clocks used for the RF signal transmission and sensing is indispensible. For that reason, as can be seen in Fig. 8 (a), a novel RF ToF measurement scheme, which is called the *synch-free RF ToF measurement system,* consisting of a measurement unit and an RF mirror unit, is proposed to measure the sensing pattern for the RF ToF as well as to provide solutions to the two critical problems introduced in sections 2.2 and 2.3. The measurement unit transmits the RF signal to the RF mirror unit and determines the unique sensing pattern after receiving the RF signal, which is retransmitted from the RF mirror unit, and the RF mirror unit just retransmits the received RF signal like a mirror reflecting light; therefore, due to the structural characteristics of the *synch-free RF ToF measurement system*, the sensing pattern is obtained with respect to the RF round-trip time, not with respect to the RF ToF. In order to apply the basic concept of the *synch-free RF ToF measurement system* to the sensor nodes in WSNs, the structure of the sensor node needs to be practically converted in order to simultaneously function as both a measurement unit and an RF mirror unit, as can be seen in Fig. 8 (b); therefore, the two functions of the sensor node are selectively carried out depending on the role of the sensor node for the pattern acquisition.



(a) Conceptual diagram of synch-free RF ToF measurement system.



(b) Pair of sensor nodes organizing synch-free RF ToF measurement system

Fig. 8. Synch-free RF ToF measurement system and advanced sensor node structure.

5. Experiment and Results

5.1. Practical Implementation of Synch-Free RF ToF Measurement System

Since RF impulse processing for RF ToF measurement is basically not an easy matter, it is very difficult in practice to implement a high-precision RF ToF measurement system that can measure a sensing pattern with respect to the propagation time of the RF impulse. For that reason, instead of an RF impulse, the phase-delay of the pulse signal is used to measure the unique sensing pattern. The RF mirror unit has a very simple structure, consisting of an RF controller, as shown in Fig. 9. On the other hand, the measurement unit is made up of four main parts, as follows.

- Clock part: Two heterogeneous clocks are simultaneously generated using the main crystal oscillator; therefore, it is easy to detect the synchronized time point of the two generated heterogeneous clocks. The sensing pattern is measured based on the two generated heterogeneous clocks of the measurement unit.
- Pulse signal generator: This generates the consecutive pulse signals used as the baseband signal of the RF carrier; the synchronized time point of the two heterogeneous clocks is detected by the clock synch detector in order to make the reference time point of the consecutive pulse signals.
- RF controller: The RF transmitter in the RF controller modulates the information of the generated consecutive pulse signals and transmits the RF carrier to the RF mirror unit. The RF receiver restores the original information contents of the consecutive pulse signals from the received RF carrier.
- ToF estimator: This determines the sensing pattern according to the size of the total delayed time (denoted as t_M), which consists of the RF round-trip time (denoted as $t_{RT}=2t_f$) and the entire RF signal processing time (denoted as $t_{PR}=2t_D+t_R$) taken by the RF controllers in both units, by comparing the restored information of the consecutive pulse signals with CLK_B.

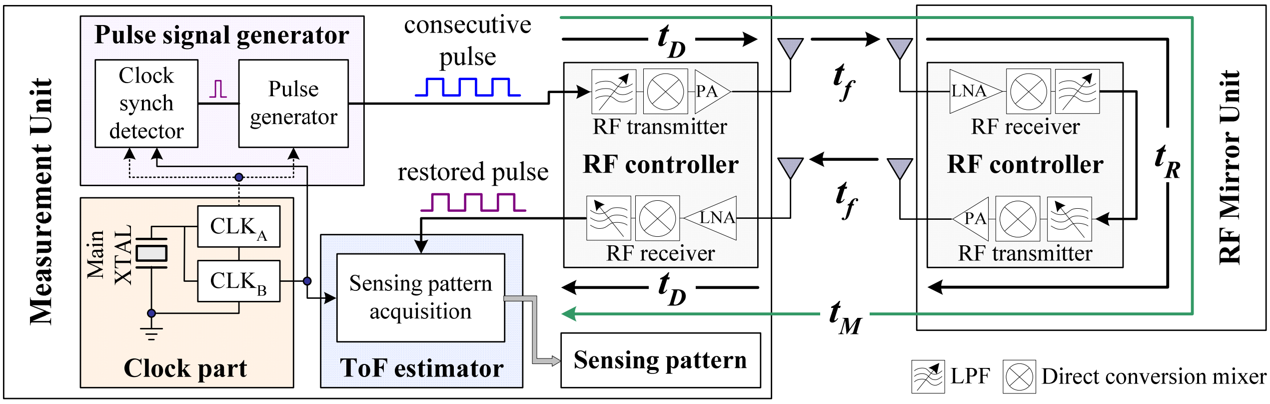


Fig. 9. Structure of synch-free RF ToF measurement system using consecutive pulse signal.

5.2. Sequence of Sensing Pattern Acquisition for RF Round-Trip Time

Under the assumption that the RF signal processing time, which is taken for the modulation and demodulation in the RF controllers of Fig. 9, is constant, the sensing pattern acquisition for the RF round-trip time using the *synch-free RF ToF measurement system* is performed in five steps, as follows.

1) *Generating two heterogeneous clocks*
Two heterogeneous clocks, which are generated at the clock part of the measurement unit shown in Fig. 9, are synchronized and satisfy the following condition, T_A:T_B=N:(N−1), where N is a positive integer, and T_A and T_B are the time periods of CLK_A and CLK_B, respectively.

2) *Modulation of the generated (N−1)-pulse signals and transmission*
Based on CLK_A, the pulse signal generator in the measurement unit generates the consecutive pulse signals, of which the number of pulses is (N−1). Therefore, the time span between each rising edge of the generated pulse signals is also equivalent to T_A, and the total time width of (N−1)-pulse signals is equal to $(N-1)\times T_A$. The data for the generated (N−1)-pulse signals are loaded by the RF transmitter into the RF carrier using the QPSK (Quadrature Phase-Shift Keying) modulation method; then, the modulated RF carrier is transmitted to the RF mirror unit.

3) *Reflecting the modulated RF carrier with an RF mirror unit*
After receiving the RF carrier, including the information of (N−1)-pulse signals, the RF mirror unit directly retransmits it to the measurement unit.

4) *Restoring the original information from the reflected RF carrier*
The RF receiver of the measurement unit restores the original information of the consecutive (N−1)-pulse signals from the received RF carrier. The restored pulse signals become the t_M-delayed (N−1)-pulse signals.

5) *Determining sensing pattern for the RF round-trip time*
First, the sensing pattern for the total delayed time (t_M) is determined by analyzing the state, which depends on whether or not each rising edge of the restored consecutive (N−1)-pulse signals lies in the sampling periods of CLK_B. And then, in the case in which the total RF signal processing time (t_{PR}) is a multiple of $(N-1)\Delta$, the sensing pattern for the RF round-trip time is acquired by filtering the zero sensing bits for the total RF signal processing time among the entire sensing bits for the total delayed time (t_M). On the contrary, if the total RF signal processing time is not equivalent to a multiple of $(N-1)\Delta$, CLK_B should be compensated for by offsetting the time lag of the total RF signal processing time in order to correctly obtain the sensing pattern for only the RF round-trip time.

Fig. 10 shows an example of the time sequence of sensing pattern acquisition for the RF round-trip time when two heterogeneous clocks are at frequencies of 8 [MHz] and 10 [MHz], respectively; the consecutive 4-pulse signals are made from CLK_A based on the condition of $T_A:T_B=N:(N-1)=5:4$. The sensing pattern for the total delayed time (t_M), which is over T_B or $k(N-1)\Delta$ where k=1, N=5 and Δ=25 [ns], is determined to be $\boldsymbol{v}=\{0, 1, 1, 0, 1, 1\}$ by comparing the restored 4-pulse signals with CLK_B; it is confirmed that RF ToF over $k(N-1)\Delta$, where $k \geq 1$, has a sensing pattern in which the values from the first sensing bit to the k^{th} sensing bit (i.e., $v_1 \sim v_k$) are zero, as presented in Table 2. Here, since the total RF signal processing time (t_{PR}) is approximately 4Δ ($=T_B$), the first sensing bit (v_1) can be considered as the sensing bit for the total RF signal processing time. Accordingly, by filtering the first sensing bit, the correct sensing patterns ($\boldsymbol{v}=\{1, 1, 0, 1, 1\}$) for the RF round-trip time can be acquired.

5.3. Experimental Setup

The developed experimental device shown in Fig. 11 is used for the certification of the principle of the high-precision RF ToF measurement method based on the vernier effect. A MAX2830 RF transceiver is put to multi-purpose use as a direct modulator and demodulator for the RF controller in the measurement unit as well as in the RF mirror unit. For a simple and plain verification process for the proposed principle of the high-precision RF ToF measurement method based on the vernier effect, the new virtual time resolution and the ratio of the time periods of the two heterogeneous clocks are chosen to be 25 [ns] and 5:4, respectively, as can be seen in Table 3. In the clock part of the measurement unit, two heterogeneous clocks are dependently generated from the main 80 [MHz] crystal oscillator using 5-stage and 4-stage Johnson counters, respectively. Table 4 gives the test distance and its corresponding RF round-trip time (t_{RT1}~t_{RT4}); test distance indicates the physical interval between an RF communication antenna of a measurement unit and that of an RF mirror unit.

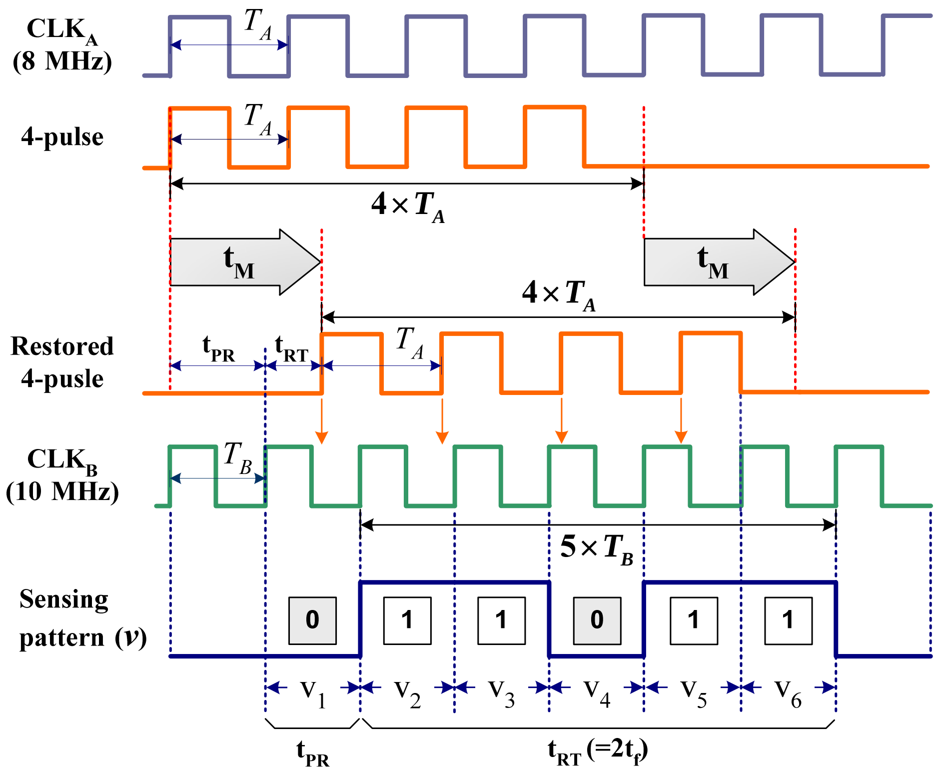


Fig. 10. Sequence of sensing pattern acquisition for RF round-trip time.

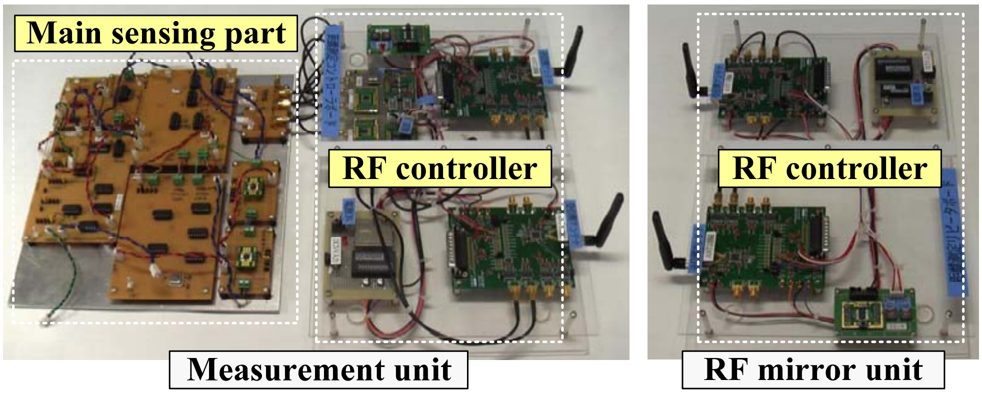


Fig. 11. Prototype of synch-free RF ToF measurement system.

Table 3. Heterogeneous clocks and their new virtual time resolution.

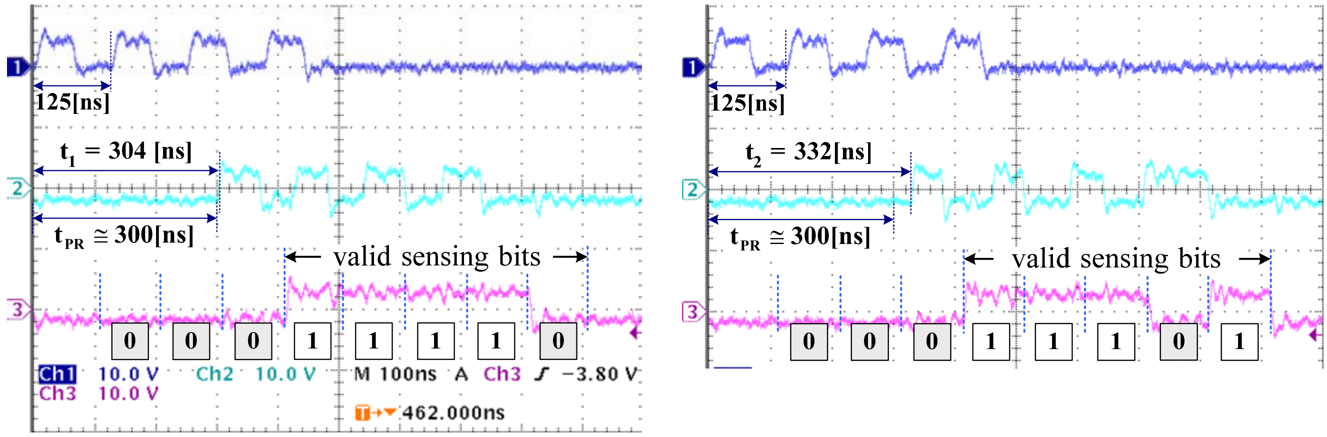
Heterogeneous clocks	**CLK$_A$ (T_A)**	**CLK$_B$ (T_B)**
	8 [MHz] (125 [ns])	10 [MHz] (100 [ns])
***N* and *N*−1**	T_A:T_B = N:(N−1) → 125[ns]:100[ns]=5:4	
New virtual time resolution (Δ)	Δ= T_A/N [= $T_B/(N-1)$ = $T_A - T_B$] =25[ns]	

Table 4. Test distance and its corresponding RF round-trip time (t_{RT}).

Distance [m]	1	5	9	13
RF round-trip time, t_{RT1}~t_{RT4} [ns]	6.6	33	59.4	85.8

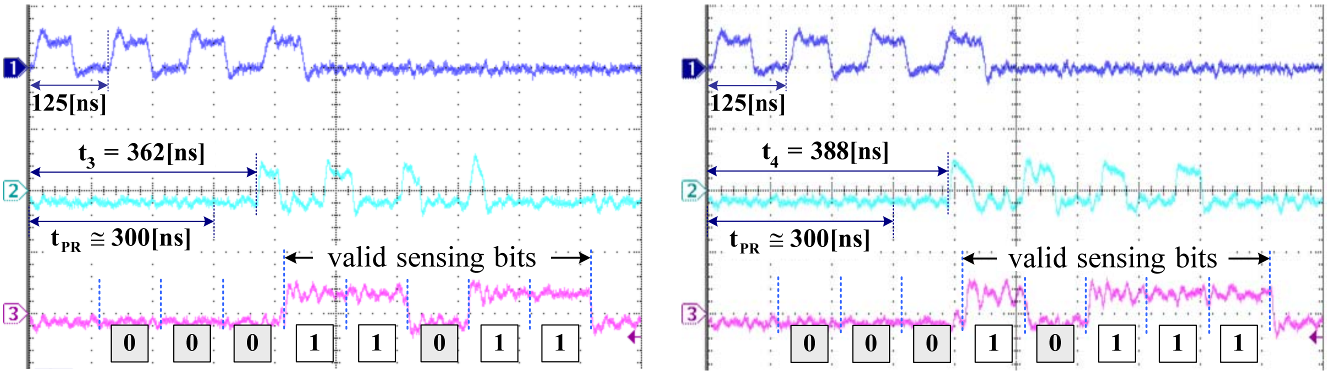
5.4. Experimental Results and Analysis

Using the developed prototype of the *synch-free RF ToF measurement system*, we have carried out experiments to acquire the unique sensing patterns for the RF round-trip time in an indoor corridor. In order to acquire only the line-of-sight propagation of the RF signal, we have removed the presence of physical objects that hinder the line-of-sight between the measurement unit and the RF mirror unit; however, there could be an effect of an indirect path RF signal (e.g., RF signal reflected from the wall and the ceiling of the hallway) due to the experiments taking place in the hallway of the building. Fig. 12 and Table 5 show the results of the measured sensing patterns with respect to the four total delayed times (t_1~t_4), each of which consists of the RF round-trip time corresponding to the four test distances and the entire RF signal processing time (t_{PR}).



(a) t_1=304 [ns]

(b) t_2=332 [ns]



(c) t_3=362 [ns]

(d) t_4=388 [ns]

1 4-pulse 2 restored 4-pulse 3 sensing pattern

Fig. 12. Experimental sensing pattern results for the four total delayed times (t_M: t_1~t_4).

The signal waveforms in Fig. 12 are made up of three kinds of signals: the generated four-pulse signals that are made from CLK_A; the restored four-pulse signals after being demodulated by the RF receiver in the measurement unit; and the result of the measured sensing pattern for the total delayed time (t_M). Based on the general form of the sensing patterns in Table 2, it is considered that the results in Table 5 are the sensing patterns with respect to the total delayed time (t_M) in the range of $k(N-1)\Delta < t_M \le (k+1)(N-1)\Delta$ where $k=3$, $N=5$ and $\Delta=25$ [ns]; therefore, the first three sensing bits ($v_1 \sim v_3$) in Table 5 are all zero. Fig. 13 and Table 6 give the least-squares line (LSL) through the four total delayed times ($t_1 \sim t_4$) measured by an oscilloscope. It is shown that the slope of the total delayed time with respect to the distance is 7.05 [ns/m]; in addition, it can be inferred that the total RF signal processing time (t_{PR}) has a constant value of 297.15 [ns].

Table 5. Sensing patterns for the four total delayed times (t_M: $t_1 \sim t_4$), where $\Delta=25$ [ns].

	Invalid data			**Valid data**				
	v_1	v_2	v_3	v_4	v_5	v_6	v_7	v_8
$12\Delta < t_1 \le 13\Delta$	0	0	0	1	1	1	1	0
$13\Delta < t_2 \le 14\Delta$	0	0	0	1	1	1	0	1
$14\Delta < t_3 \le 15\Delta$	0	0	0	1	1	0	1	1
$15\Delta < t_4 \le 16\Delta$	0	0	0	1	0	1	1	1

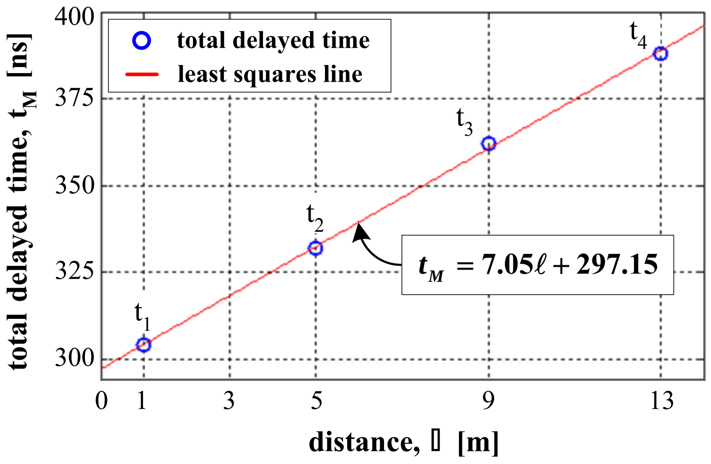


Fig. 13. Least-squares line through total delayed time (t_1, t_2, t_3 and t_4).

Table 6. Total delayed time and its LSL.

t_M [ns]				**LSL**	
t_1	t_2	t_3	t_4	slope	RF signal processing time ($t_{PR}=2t_D+t_R$)
304	332	362	388	7.05 [ns/m]	297.15 [ns]

It takes approximately 6.66 [ns] for RF signal to travel one meter back and forth. Therefore, the slope of the RF round-trip time with respect to the distance can be approximately 6.66 [ns/m]. Since the virtual time resolution of 25 [ns] is generated in order to measure the RF round-trip time (t_{RT}), the time resolution for the one-way propagation time of the RF signal is originally 12.5 [ns], and its corresponding one-way distance resolution is 3.75 [m]. Fig. 14 gives the expected sensing patterns for the RF round-trip time in the range of $0<t_{RT}\leq 4\Delta$, where Δ is 25 [ns]; each sector (*A* to *D*) represents the area of RF round-trip time/distance, of which the sensing pattern is same. It is confirmed that the slope of the LSL shown in Fig. 13 is close to the ideal slope (≈6.66 [ns/m]) of the RF round-trip time with respect to the distance shown in Fig. 14; as a result, it is considered that the measured sensing patterns in Fig. 12 for the four total delayed times (t_1~t_4) are valid. In addition, it can be considered that the estimated total RF signal processing time (t_{PR}) of 297.15 [ns] is approximately 12Δ (=300 [ns]); that is, $t_{PR}\approx k\times(N-1)\Delta$ where $k=3$, $N=5$ and $\Delta=25$ [ns]. Therefore, among eight sensing bits (v_1~v_8), as shown in Table 5, which constitute a sensing pattern for the total delayed time (t_M), the former three sensing bits (v_1~v_3) indicate the total RF signal processing time (t_{PR}), so that they can be considered as invalid data. By filtering these three pieces of invalid data (v_1~v_3) from the entire eight sensing bits (v_1~v_8) in Table 5, the latter five sensing bits (v_4~v_8) reconstitute the correct sensing patterns for the RF round-trip time (t_{RT1}~t_{RT4}=6.6~85.8 [ns]), as in Table 7; accordingly, it is confirmed that the sensing patterns for the RF round-trip time are the same as the expected sensing patterns shown in Fig. 14. Consequently, using the measured sensing patterns for the RF round-trip time, it is possible to estimate the size of RF ToF.

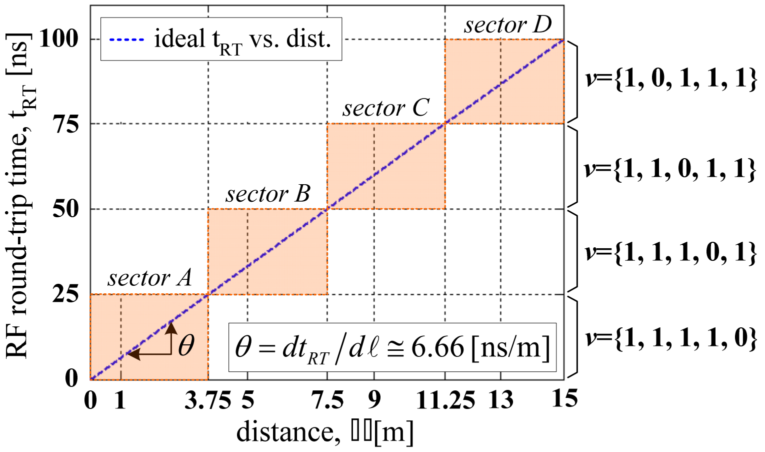


Fig. 14. Expected sensing pattern (***v***) vs. distance/round-trip time.

Table 7. Sensing patterns for the RF round-trip time (t_{RT}: t_{RT1}~t_{RT4}), where Δ=25 [ns].

v	v_1	v_2	v_3	v_4	v_5
$0.0 < t_{RT1} \leq 1.0\Delta$	1	1	1	1	0
$1.0\Delta < t_{RT2} \leq 2.0\Delta$	1	1	1	0	1
$2.0\Delta < t_{RT3} \leq 3.0\Delta$	1	1	0	1	1
$3.0\Delta < t_{RT4} \leq 4.0\Delta$	1	0	1	1	1

6. Conclusions

This paper presents the basic principles of high-precision RF ToF measurement, to which the principle of the vernier caliper is applied, as a novel RF ToF measurement methodology for WSN localization; in addition, it gives a detailed description on the *synch-free RF ToF measurement system*, which is proposed as a solution to the problem of clock synchronization between sensor nodes that carry out the one-way RF ToF sensing pattern acquisition task based on the vernier effect. The set of sensing patterns determined by the proposed method has a fixed form in which the entries of the diagonal from the top right bit of the set of sensing patterns are all zero; accordingly, it is easy to predetermine the set of sensing patterns with respect to the size of RF ToF using the general form of the sensing patterns. The RF ToF measurement tests using the proposed methodology confirm that it is possible for the clock system, of which the intrinsic time measurement resolution is too low to measure the RF ToF, to estimate the RF ToF in the range of nanoseconds using the acquired unique sensing patterns for the RF round-trip time. In conclusion, it is expected that the proposed methodology based on the vernier effect can be applied to the development of different kinds of precise measurement systems as well as to high-precision positioning for the WSNs.

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