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Proposal of generalized vernier effect and its practical advantage for RF time-of-flight ranging between sensor nodes in wireless sensor networks

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ABSTRACT

Accurate ranging technique is indispensable for node localization in wireless sensor networks (WSNs), and there are various ranging techniques/systems using physical characteristics of RF signals. The RF time-of-flight (ToF) ranging technique in a short distance is still difficult to implement since both a high precision clock system and complex signal processing are required to exactly measure RF ToF. This paper presents an improvement of time resolution based on the generalized vernier effect (GVE) by which it is possible to accurately measure short-range RF ToF using low operating clocks of several megahertz. The GVE-based RF ToF measurement methodology is certified through experiments to measure a singular sensing pattern with respect to RF round-trip time using a prototype of the synch-free RF ToF measurement system, which is a practical RF ToF ranging system for application to the localization of WSNs.

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1. Introduction

To localize sensor nodes in wireless sensor networks (WSNs) is essential to complete important tasks such as monitoring environmental conditions within those networks, object tracking and controlling physical conditions. For that reason, there are several kinds of RF-based localization methods to get the quantitative position data of sensor nodes in WSNs. RF-based localization techniques can be classified into three main groups depending on the parameter that is used to determine position, as follows: received signal strength (RSS) method, angle-of-arrival (AoA) method and time-of-flight (ToF) method.

The RSS-based localization method has been actively studied because it is technically less complicated, and hence less expensive. In addition, it is possible with this method to use existing wireless infrastructures (e.g., WLAN access points, ZigBee nodes, etc.); however, it must be considered that uncertainty of the measured RSS value increases due to the fact that most of existing wireless infrastructure has not been designed for accurate RSS measurement [1–3]. On the other hand, RSS-based methods do not provide stable performance for the reliable localization of sensor nodes in WSNs since the accuracy of RSS-based method is limited by signal level fluctuations due to interference from other signals, noise or multi-path propagation caused by signal propagation issues (e.g., reflection, refraction and scattering), which occur in indoor scenarios, and the level of RSS sharply decreases in a non-linear and unpredicted fashion with distance [4–7].

The AoA-based techniques have been proposed to estimate the position of sensor nodes by means of the knowledge of the angle of arrival (AoA) of RF signal in sensor nodes. Though there are several advantages to AoA-based localization, such as its having few measuring units for 3-D/2-D positioning and no requirement of clock synchronization between measuring units, it requires relatively large, complex and expensive hardware (e.g., an antenna array) [8].

The ToF-based localization method in WSNs uses the RF signal propagation time from one sensor node to another. In a broad sense, the ToF-based method includes not only time-of-arrival (ToA), but also time-difference-of-arrival (TDoA); however, the name ToF is commonly used to refer to ToA. Compared to RSS-based and AoA-based methods, the RF ToF-based localization method is considered more attractive since an RF ToF system can require little hardware overhead and has the potential for meter level accuracy, simple signal processing and good wall penetration. What is more, RF ToF ranging can occur in short bursts and in a frequency hopped fashion, thereby reducing the chance of interference and unwanted detection; it also, essentially, has a linear dependence on distance in free space [9].

Nevertheless, RF ToF measurements for short ranging are fundamentally challenging because of the high signal speed and low tolerance for clock synchronization error. Likewise, reliable RF ToF-

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based localization for WSNs remains unsettled because it is very difficult to accurately measure the propagation delay of an RF signal in such a local space as a limited WSN area at which sensor nodes are located. Besides, all sensor nodes have to be precisely synchronized for direct RF ToF measurements between sensor nodes in WSNs.

One of the existing RF ToF-based localization methods requires the use of UWB (ultra wide band) devices in order to achieve enough time resolution [10,11]. Though UWB methods have distinctive advantages (e.g., high immunity to interference from other radio systems, high multi-path immunity, high data rate and accurate resolution capability), and are more accurate than RSS-based methods, the network infrastructure using UWB devices is too complicated and expensive to extensively apply to WSN localization. Therefore, it is necessary to develop a cost-effective and easy-to-handle RF ranging system with good resolution and accuracy. In the measurement area, there have been studies to measure considerably small time intervals in the range of picoseconds (10^{-12}) to nanoseconds (10^{-9}) using the vernier effect, which enables us to measure accurately the time between two independent occurrences [12,13]. On the basis of the vernier effect, we propose a short-range RF ToF measurement methodology for WSN localization [14–16]. However, the proposed methodology, based on the conventional vernier effect (CVE), has a limitation in that the ratio of the time periods of the two heterogeneous clocks, which are used for generating the new virtual time resolution, is restricted to N to $N-1$; that is, when the time periods of the two different operating clocks used for CVE are T_A and T_B ($T_A \neq T_B$), respectively, their relation should be the following, T_A:T_B = N:$N-1$ (N is a positive integer).

In this paper, we propose a generalized vernier effect (GVE), which is the generalized principle of CVE, as another new fundamental methodology not only to generate a new type of virtual time resolution precise enough for short-range RF ToF measurement, but also to overcome the limited heterogeneous clock combinations of CVE. In the following sections, the limitations of CVE are pointed out, and the principle of GVE and the RF ToF estimation methodology based on GVE are represented in detail. The characteristics of RF ToF estimation based on GVE are compared with those based on CVE, and are verified through experiments of RF ToF estimation using a developed prototype of the RF ToF ranging system called the synch-free RF ToF measurement system.

2. Proposal of generalized vernier effect and precise RF time-of-flight ranging

2.1. Limitations of conventional vernier effect

Using simultaneously a main scale and a vernier scale of the conventional vernier caliper (CVC), shown in Fig. 1, generates the vernier effect, which allows a distance measurement to be read more precisely than directly reading a uniformly divided straight measurement scale. Similar to two scales of CVC, the two heterogeneous clocks, having different operating frequencies in a time measurement system, can be utilized to lead to the vernier effect. The vernier effect, which is due to the use of two heterogeneous clocks, generates a new virtual time resolution, which is equivalent to the amount of difference between the time resolutions of the two heterogeneous clocks and allows for a much more accurate time measurement than is possible by directly measuring the time using the intrinsic time resolution of the operating clock [16]. However, there is a limitation in deciding on the two heterogeneous clocks to generate the new virtual time resolution. Similar to conventional vernier caliper (CVC), of which the ratio of unit scales of the two heterogeneous scales (main and vernier scale) is

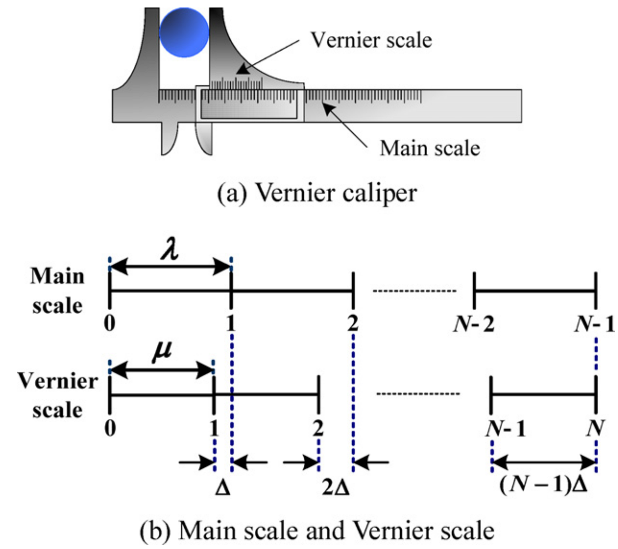

Fig. 1. Conventional vernier caliper (CVC). (a) Vernier caliper. (b) Main scale and vernier scale.

N to $N-1$, the two heterogeneous clocks used for the conventional vernier effect (CVE) are allowed only when the time periods of their operating frequencies have a ratio of N to $N-1$ (e.g., 10:9, 8:7, and so on), where $N \in \mathbf{Z}^+$, that is, N is an element of the set of positive integers.

As mentioned previously, the newly generated virtual time resolution due to CVE is equivalent to the difference of inherent time resolution of the two heterogeneous clocks. If the amount of the new virtual time resolution is not much smaller than that of the time resolution of the two heterogeneous clocks, the operating frequencies (f_A and f_B) of the two clocks are totally distinguishable from each other; that is, $f_A \neq f_B$. Therefore, it is relatively easy to select two heterogeneous clocks, which satisfy the condition to generate the targeted virtual time resolution, from the stocks of commercially available products. For example, the two clocks of f_A (=8 [MHz]) and f_B (=10 [MHz]) are commercially found with ease for the targeted virtual time resolution of 25 [ns], which is not much smaller than the time resolution (125 [ns] and 100 [ns]) of the two clocks.

On the other hand, a critical problem occurs in particular when the targeted new virtual time resolution is considerably smaller than the intrinsic time resolution of the two heterogeneous clocks and is getting exceedingly small/precise. In this case, the operating frequencies (f_A and f_B) of the two heterogeneous clocks become approximately the same as each other; that is, $f_A \cong f_B$. In other words, the more precise the targeted virtual time resolution is, the more uncertain the difference of the time periods of the two heterogeneous clocks is. For instance, for the targeted virtual time resolution of 1 [ns] using two heterogeneous clocks having around 8 [MHz] operating frequency, the operating frequencies of the selected clocks can be, for example, f_A (=8 [MHz]) and f_B (=7.9365 [MHz]). Here, f_B (=7.9365 [MHz]) is not easily obtained from the commercial products of the crystal oscillator or other similar clock sources. In addition, even if it is possible to get a clock source of 7.9365 [MHz], it is difficult to exactly generate the targeted new virtual time resolution of 1 [ns] since the difference of the time periods of the two clock sources would vanish due to frequency variation/clock drift due to the frequency stability of the clock sources.

For that reason, we propose the GVE in order to overcome the above-mentioned critical problem of CVE as well as to enlarge the

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