Wireless Synchronized One-Way Ranging Algorithm with Active Mobile Nodes

Yoon-Seok Nam, Bub-Joo Kang, Jae-Doo Huh, and Kwang-Roh Park

ABSTRACT—In this letter, we propose a one-way ranging algorithm that is based on wireless synchronization with measured timestamps and clock frequency offsets. In our proposed algorithm, an active mobile node initiates a ranging procedure by transmitting a ranging frame, and the anchor nodes report their timestamps for the received ranging frame to a reference anchor node. The synchronization of a pair of nodes is provided with instantaneous time information, and the corresponding difference of distances can be calculated.

Keywords—Ranging, positioning, TWR, SDS-TWR, OWR, wireless OWR.

I. Introduction

IEEE802.15.4 has defined a low data rate, low power consumption, and low cost medium access control (MAC) and physical layer (PHY) specification for wireless personal area networks (WPANs). Also, alternate PHYs employing a chirp-spread spectrum (CSS) or ultra-wideband (UWB) signaling have been defined in IEEE802.15.4a [1]. For the UWB, there is an optional ranging capability.

Ranging between two nodes is typically performed by two-way ranging (TWR) or a symmetric double-sided TWR (SDS-TWR) scheme in the absence of clock synchronization, or one-way ranging (OWR) in synchronization. While asynchronous ranging schemes reduce the error due to imperfect synchronization between devices, frequency offsets of off-the-shelf crystal oscillators can still result in time measurement errors. In multipath and noisy environments, the first peak detection of a ranging frame involves estimation errors presented by a white Gaussian random variable [2]. In comparison with TWR algorithms, OWR reduces the processing delay by decreasing the number of frames transmitted for ranging among nodes. In this letter, we investigate an OWR scheme in wireless sensor networks that does not maintain physical synchronization. The frequency offsets of the nodes are the key element for accurate ranging. Reference broadcast synchronization [3] and timing-sync relating timestamps between nodes allow post-facto synchronization. We describe how to estimate the frequency offsets and establish wireless instance virtual synchronization for a pair of nodes.

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Yoon-Seok Nam (phone: +82 54 770 2273, email: ysnam@dongguk.ac.kr) is with the Department of Information and Communication Engineering, Dongguk University, Gyeongju, Rep. of Korea, and was with the IT Convergence Technology Research Laboratory, ETRI, Daejeon, Rep. of Korea, for joint research. Bub-Joo Kang (email: bjkang@dongguk.ac.kr) is with the Department of Information and Communication Engineering, Dongguk University, Gyeongju, Rep. of Korea, and is with the Broadcasting & Telecommunications Convergence Research Laboratory, ETRI, Daejeon, Rep. of Korea.

Jae-Doo Huh (email: jdhuh@etri.re.kr) and Kwang-Roh Park (email: krpark@etri.re.kr) are with the IT Convergence Technology Research Laboratory, ETRI, Daejeon, Rep. of Korea.

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II. Proposed Ranging and Positioning Algorithm

The key issue for OWR is the means to maintain wireless network synchronization among anchor nodes. In IEEE 802.15.4a, a wired backbone of anchor nodes may be used for network synchronization. In our proposal, wireless synchronization between a pair of anchor nodes is established when a ranging frame is received. An example of a wireless sensor network supporting location estimation is shown in Fig. 1.

In the figure, the sensor network consists of an anchor node group, a mobile node group, and a location server. The anchor node group includes nodes N_A, N_B, N_C, and N_D. The mobile node group includes mobile nodes N_{M1} to N_{MK}, with N_M representing them. Node A is connected to a location server and becomes a reference node to construct node pairs. The distances between the anchor nodes are d_{AB}, d_{AC}, and d_{AD}. The distances between a mobile node and the anchor nodes are D_A, D_B, D_C, and D_D. We assume that most calculations for range and position would be performed at the location server.

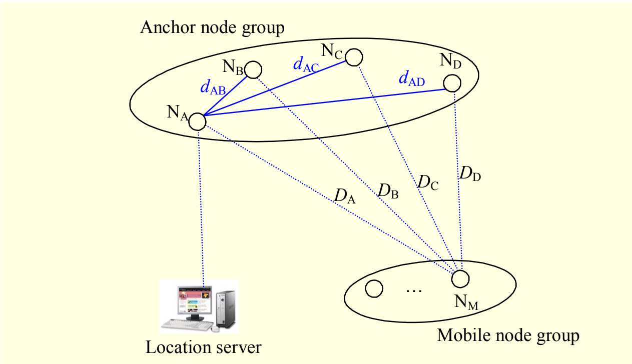

Fig. 1. Wireless sensor network supporting location estimation.

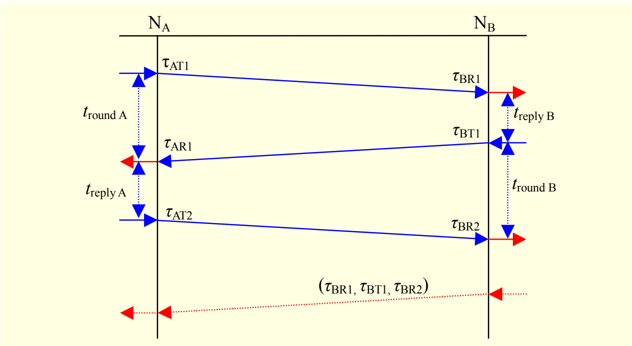

Fig. 2. Frame exchange of SDS-TWR.

The frequency offsets of a crystal oscillator are normally represented in units of parts per million (ppm). The frequencies of nodes A and B are described by an equation with ppm ratings from reference frequency f_R, such as $f_A=f_R(1+e_A)$ and $f_B=f_R(1+e_B)$. Here, e_A and e_B are the frequency offsets of nodes A and B, respectively. Therefore, a known frequency offset provides any node with the precise synchronization described in (1).

$$f_R=\frac{f_A}{1+e_A}=\frac{f_B}{1+e_B}. \tag{1}$$

Figure 2 shows an exchange of ranging frames in SDS-TWR. The SDS-TWR involves a pair of successive transmissions and receipts in addition to the time-of-flight (TOF) process.

In the figure, we assume that nodes A and B are anchor nodes, and that the distance between nodes A and B is known. The interval between two consecutive transmitting events and the interval between two consecutive receiving events are equal, that is,

$$\tau_{AT2}-\tau_{AT1}=\tau_{BR2}-\tau_{BR1}. \tag{2}$$

The intervals are described by the counter interval multiplied by the inverse of the node frequency:

$$\tau_{AT2}-\tau_{AT1}=\frac{n_{AT2}-n_{AT1}}{f_A},\ \tau_{BR2}-\tau_{BR1}=\frac{n_{BR2}-n_{BR1}}{f_B}. \tag{3}$$

Therefore, the relation between two nodes is established as

$$\frac{n_{AT2}-n_{AT1}}{1+e_A}=\frac{n_{BR2}-n_{BR1}}{1+e_B}. \tag{4}$$

A TOF can be estimated by the instant counter values, the frequency offsets, and the reference frequency described by

$$4t_p=t_{roundA}-t_{replyA}+t_{roundB}-t_{replyB}$$
$$=\frac{(n_{AR1}-n_{AT1})-(n_{AT2}-n_{AR1})}{f_R(1+e_A)}+\frac{(n_{BR2}-n_{BT1})-(n_{BT1}-n_{BR1})}{f_R(1+e_B)}. \tag{5}$$

The distance is known and gives a directly calculated TOF:

$$t_p=\frac{d_{AB}}{c},\quad c=3\times10^8\ \text{m/s}. \tag{6}$$

With a known distance and measured counter values, the frequency offsets e_A and e_B can be found by solving (4), (5), and (6). Other modified TWR involving a pair of successive transmissions and receipts can be used in the sense of estimating the frequency offsets.

Figure 3 shows the proposed wireless OWR. In Fig. 3(a), a mobile node transmits a ranging frame at a local timestamp n_M. The frame arrives at the anchor nodes at the times of n_{MA}, n_{MC}, and n_{MD}. Then, each anchor node transmits a ranging frame, including its receipt time information for a received ranging frame, to reference node A. We denote the departure timestamps for nodes B, C, and D by n_B, n_C, and n_D, respectively. The arrival times at node A for the transmitted ranging frames of other

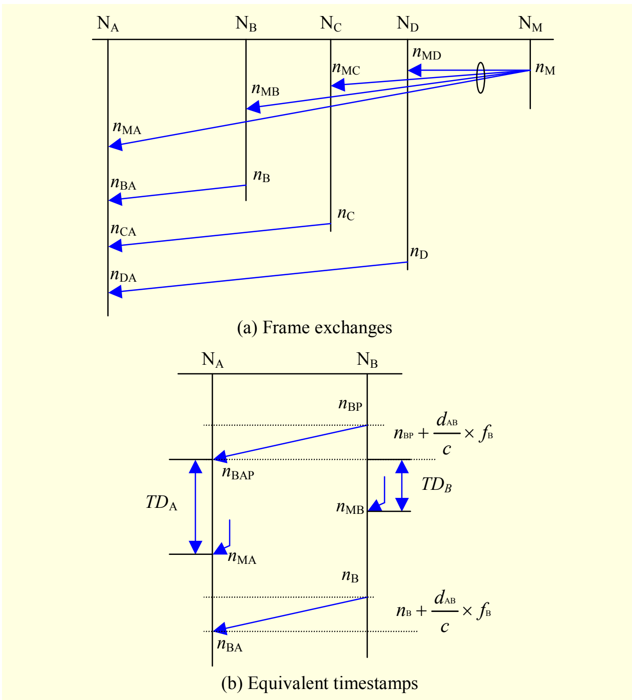

Fig. 3. One-way ranging with an active mobile node.

anchor nodes are n_{BA}, n_{CA}, and n_{DA}, respectively. Here, timestamp n_M of a mobile node is useless and is never transferred. However, n_B, n_C, and n_D need to be transferred to node A.

With the pair of nodes A and B, both sides of (7) indicate the same instance with a different timestamp:

$$n_{BA} \Leftrightarrow n_B + \frac{d_{AB}}{c} \times f_B. \quad (7)$$

Figure 3(b) shows the frame transmissions from node B to node A. The previous timestamps of n_B and n_{BA} are denoted by n_{BP} and n_{BAP}, respectively. With the previous values, the following equation is also true and practical:

$$n_{BAP} \Leftrightarrow n_{BP} + \frac{d_{AB}}{c} \times f_B. \quad (8)$$

The difference of the timestamps from reference instance n_{BAP} to the instance of received times n_{MA} and n_{MB} is obtained and multiplied by each period of the local oscillator, which yields the differences in real time:

$$TD_A = \frac{n_{MA} - n_{BAP}}{f_A}, \quad TD_B = \frac{n_{MB} - (n_{BP} + \frac{d_{AB}}{c} \times f_B)}{f_B}. \quad (9)$$

Therefore, the difference in distance from a mobile node to node A and a mobile node to node B is

$$D_{BA} = D_B - D_A = (TD_B - TD_A) \times c. \quad (10)$$

Similar relations can be described for the node pair A and C and pair A and D. The differences in distances can be applied to the time difference of arrival (TDOA) to estimate the location of a mobile node.

III. Simulation Results and Conclusions

Our proposed one-way ranging algorithm is evaluated using a simulation conducted with five anchor nodes in a 10×10×3 meter area. We assumed that a ranging counter runs at a nominal 64 GHz.

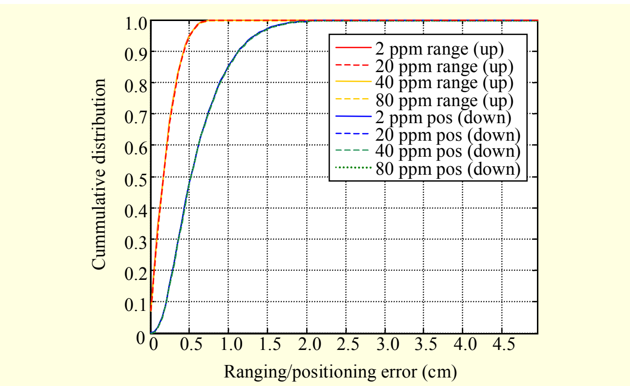

Fig. 4. Ranging and positioning errors according to frequency offsets in a noise-free environment.

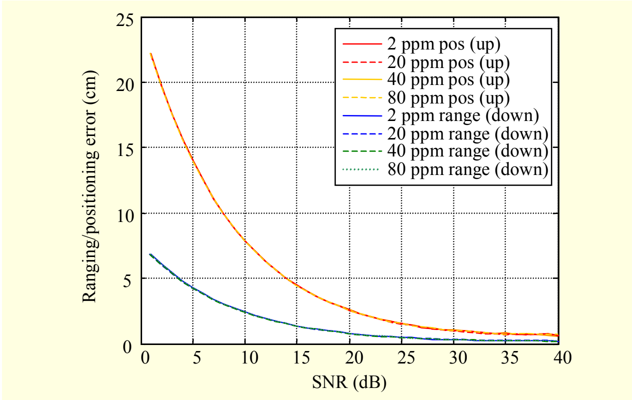

Fig. 5. Average ranging and positioning errors by SNR.

First, the frequency offsets are estimated, and a mobile node transmits a ranging frame. Then, the anchor nodes transfer timestamps. The reference anchor node collects the related timestamps, calculates the differences in distance and the TDOA, and then estimates the position of the mobile node.

Figures 4 and 5 show the simulation results of the ranging and positioning errors for the proposed active-mode OWR. The frequency offsets of 2, 20, 40, and 80 ppm represent ±1, ±10, ±20, and ±40 ppm, respectively. The four ranging and four positioning curves of the different frequency offsets are almost consistent. In the ideal noise-free case of Fig. 4, the maximum ranging difference error is about 0.918 cm, which is less than 2×c/64 GHz. Figure 5 shows average ranging and positioning errors by signal-to-noise ratio (SNR). As the SNR increases, the ranging and positioning errors are approximated to 0.20 cm to 0.24 cm and 0.57 cm to 0.68 cm at 40 dB, which are close to 0.22 cm and 0.63 cm in a noise-free environment. In this letter, we proposed a wireless OWR in active mode and evaluated its performance. Further studies on jitter, transfer delay, SNR, and other postprocessing should be considered in practical measurements.

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