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A Ranging Scheme for Asynchronous Location Positioning Systems

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***Abstract*—In a real-time locating system which does not require time synchronization among nodes, it takes a very long time to complete a ranging process for a single location estimation. Long ranging time makes mobile nodes consume a significant amount of battery power and limits the number of mobile nodes that a single fixed node can handle during a specific time interval. Therefore, it is crucial to shorten the ranging time in asynchronous locating systems without degradation in ranging or locating accuracy. In this paper, we propose an asynchronous two-way ranging scheme which reduces ranging time by replying with multiple packets to a single ranging request. The algorithm reduces ranging time by 17% or more, compared to that of existing methods.**

***Index Terms*—ranging, ranging time, RTLS**

I. INTRODUCTION

THE last few years have witnessed a growing interest in the application of real-time locating systems (RTLS) in such fields as asset management, yard or parking lot management, lost child tracking, and so on. Such interest has fueled a wealth of research and development efforts that are moving rapidly into commercialization and standardization.

Ranging technique is the most fundamental and important technology in developing an RTLS system. Ranging is a process or a method to determine the distance between two nodes. Ranging schemes can be classified into two categories: synchronous ranging schemes and asynchronous ranging schemes. The former needs a global synchronization among fixed nodes or among mobile nodes as well as fixed nodes. On the other hand, the latter does not need time synchronization among any nodes.

In a synchronous ranging scheme as depicted in Fig. 1, the ranging process is one-way or unidirectional in general. That is, a mobile node just broadcasts a beacon signal periodically with departure time and fixed nodes around the mobile node receive the beacon signal and measure the arrival time. Distance is calculated by multiplying the signal propagation speed with the time difference between arrival time and departure time of a beacon signal. Time difference between two nodes can be obtained easily because the two nodes are synchronized globally. However, synchronizing every node is not an easy task and requires an expensive and precise oscillator to mitigate clock offset and/ or clock drift [1]-[2].

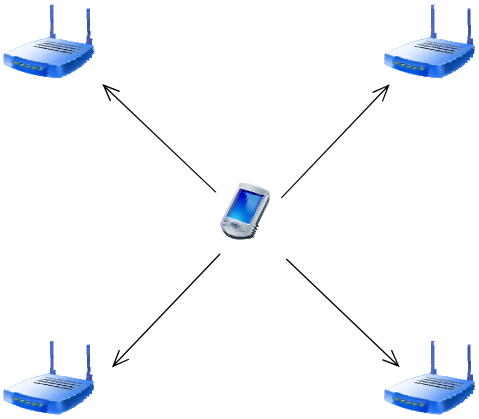

Fig. 1. Ranging in a synchronous ranging architecture.

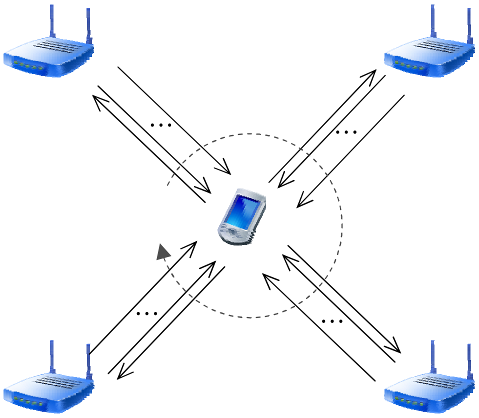

Fig. 2. Ranging in an asynchronous ranging architecture.

In an asynchronous ranging scheme represented in Fig. 2, by contrast, each node uses its own clock or timing information instead of using a global synchronization [3]-[4]. For this reason, each mobile node has to measure a round-trip time to obtain the propagation time between two nodes. That is, the ranging is bidirectional or two-way. Since the asynchronous ranging scheme does not require time synchronization, it is embodied with relatively simple circuitry. As shown in Fig. 2, however, a mobile node has to measure distances to couples of fixed nodes in a sequential manner to estimate a location. A series of ranging operations makes the asynchronous ranging scheme have longer ranging and locating time than synchronous counterparts.

Long ranging time makes mobile nodes stay in active or wake-up mode longer. It implies large power consumption, which implies again short battery lifetime. Since mobile nodes have a finite battery capacity, large power consumption is one of

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the most critical issues. Furthermore, long transaction time limits the number of mobile nodes handled by a fixed node in a specific time interval. Therefore, it is first and most important to shorten the ranging time in asynchronous ranging schemes. Nevertheless, studies are focusing on the improvement of ranging accuracy [1]-[2]. To the best of my knowledge, this is the first research on the issue of ranging time reduction.

In this paper, therefore, we suggest a ranging protocol which reduces ranging time fairly, keeping ranging accuracy high. The main idea of the proposed scheme is to reply with multiple acknowledgment packets to a single ranging request.

This paper is organized as follows: In Section II, we review a well-known asynchronous ranging scheme. In Section III, we propose a novel asynchronous ranging scheme and analyze it in terms of ranging accuracy and ranging time. In Section IV, performance of the proposed ranging scheme will be evaluated in terms of scalability and battery lifetime. In Section V, finally, we conclude this paper after addressing the importance of a short ranging time and its benefit.

II. RANGING BY SDS-TWR

In general, a ranging process in the asynchronous ranging scheme is composed of three phases as shown in Fig. 3. During the scanning phase, a mobile node scans and selects fixed nodes that will take part in the ranging phase, simply by exchanging a pair of scanning and acknowledgment packets. Typically, fixed nodes are drafted according to the received signal strength, the order of arrival, and so on.

In the ranging phase, the mobile node performs ranging with the fixed nodes selected in the scanning phase. The ranging is either symmetric or asymmetric. After completing the ranging process, distances to each fixed node are calculated and reported to a location server in the reporting phase. Depending on the ranging scheme, the scanning phase or the reporting phase can be removed or performed by fixed nodes. Here, we consider the ranging phase only unless mentioned separately.

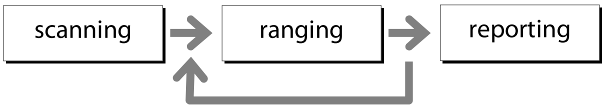

Fig. 3. An asynchronous ranging scheme is composed of three phases in general: scanning, ranging, and reporting phases.

In some cases, ranging data may fluctuate considerably even though mobile nodes remain stationary. It is due to the vagaries of RF propagation or the interferences such as reflection, refracttion, and so like. As such, commercial RTLS solutions repeat the ranging process. Practically, however, the ranging phase is just iterated several times, as shown in Fig. 3.

Fig. 4 depicts the symmetric double-sided two-way ranging (SDS-TWR) scheme described in the IEEE 802.15.4a standard [5]. The first 4 packets compose the ranging phase and the other two packets compose the reporting phase. As shown in the figure, SDS-TWR exchanges packets and uses each node's timing information separately at both sides to measure the propagation delay between two nodes.

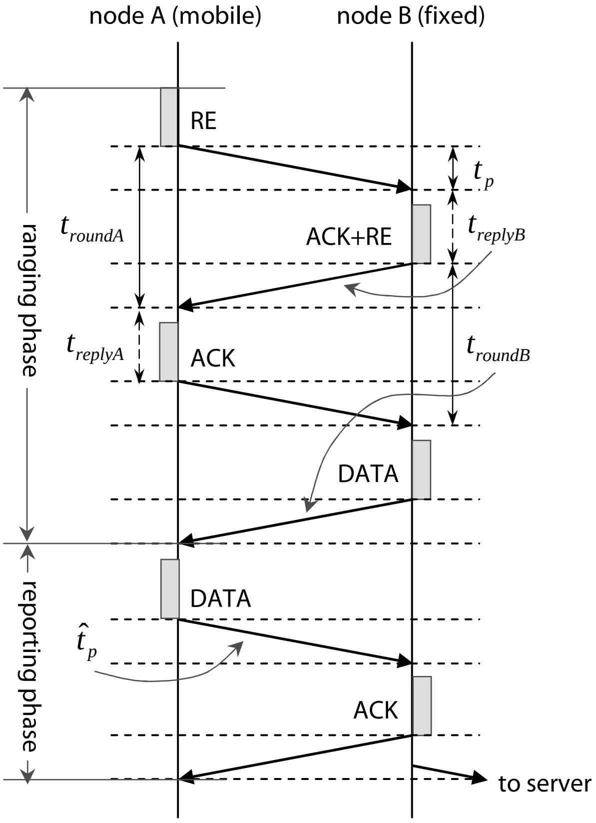

Fig. 4. Symmetric Double-Sided Two-Way Ranging (SDS-TWR) scheme.

In this ranging scheme, node A (mobile node) triggers a ranging procedure by transmitting a ranging request packet (REQ) at first. Then, node B (fixed node) replies with an ACK+REQ packet. This packet is used for an acknowledgement to the ranging request from node A and for another ranging request from node B. It is also used to inform node A of the reply time t_{replyB} at node B.

The reply time of node B is the time interval between the arrival time of the last bit of the REQ packet and the departure time of the last bit of the ACK+REQ packet. In fact, t_{replyB} is precalculated considering the packet length, data rate, processing capacity of nodes, and so on and written in the ACK+REQ packet before transmitting it.

On receiving the ACK+REQ packet, node A measures the round-trip time t_{roundA} and returns an ACK packet back to node B. In a similar manner, node A and node B measure the reply time t_{replyA} at the mobile node and the round-trip time t_{roundB} at the fixed node, respectively. Actually, this is the end of the ranging phase. However, node B has to transmit a DATA packet to let the mobile node calculate the propagation time $\hat{t}_p$. The DATA packet includes the round-trip time measured at the fixed node. Then, node A calculates the propagation time as explained later and transmits it to the location server.

A. *Propagation Time of SDS-TWR*

In Fig. 4, the round-trip times of SDS-TWR at each node are as follows:

$$t_{roundA} = 2t_p + t_{replyB} \tag{1}$$

$$t_{roundB} = 2t_p + t_{replyA} \tag{2}$$

Summing (1) and (2) and arranging it in terms of propagation time t_p, then the flight time becomes

$$t_p = \frac{1}{4}\left\{\left(t_{roundA} - t_{replyB}\right) + \left(t_{roundB} - t_{replyA}\right)\right\}. \tag{3}$$

However, t_p in (3) represents an ideal propagation time. It could be influenced by clock offset, clock drift, and others. Therefore, $\hat{t}_p$ calculated by node A could be different from t_p. The influence of clock offset or clock drift on the ranging or locating accuracy is also an important topic in developing an RTLS system. However, the subject is beyond the scope of this paper. Readers who interested in this issue may refer to References [1]-[2].

B. *Ranging Time of SDS-TWR*

The ranging time of SDS-TWR can be calculated roughly with the number of packets exchanged between the two nodes during the ranging and reporting phase. It is possible because the propagation time is negligible compared to the packet transmission time and to the packet processing time. As shown in Fig. 4, SDS-TWR exchanges 4 packets for ranging and 2 packets for reporting the ranging result. That is, 6 packets are exchanged.

As mentioned previously, it is needed to repeat SDS-TWR several times in certain circumstances to enhance ranging or locating accuracy. Let m denote the iteration times. (Here, it is assumed that we iterate only the ranging phase unless stated otherwise.) Then, SDS-TWR has to exchange $4m+2$ packets for m iterations. (When we repeat both the ranging phase as well as the reporting phase, $6m$ packets have to be exchanged.) Let t_{proc} be the average time for packet transmission at a given data rate and for packet processing. Then, the ranging time of SDS-TWR is

$$RT_{SDS-TWR} = (4m+2)\cdot t_{proc} \tag{4}$$

We assumed here that the packet lengths of REQ packet, ACK+REQ packet, ACK packet, and DATA packets are equal to one another.

In general, the length of packets is in the order of several hundred bits and data rate is less than 1 Mbps in wireless sensor networks. It means that it takes several to tens of milliseconds for a fixed node to complete the whole ranging process. To provide scalability to a certain extent, therefore, it is desirable to use as few packets as possible in the ranging process.

III. RANGING BY SS-TWR-MA

In Section II, we learned that it is important to decrease the number of packets exchanged between two nodes. To this end, we come up with an asymmetric ranging scheme which uses several ACK packets to a single ranging request. This idea is illustrated in Fig. 5.

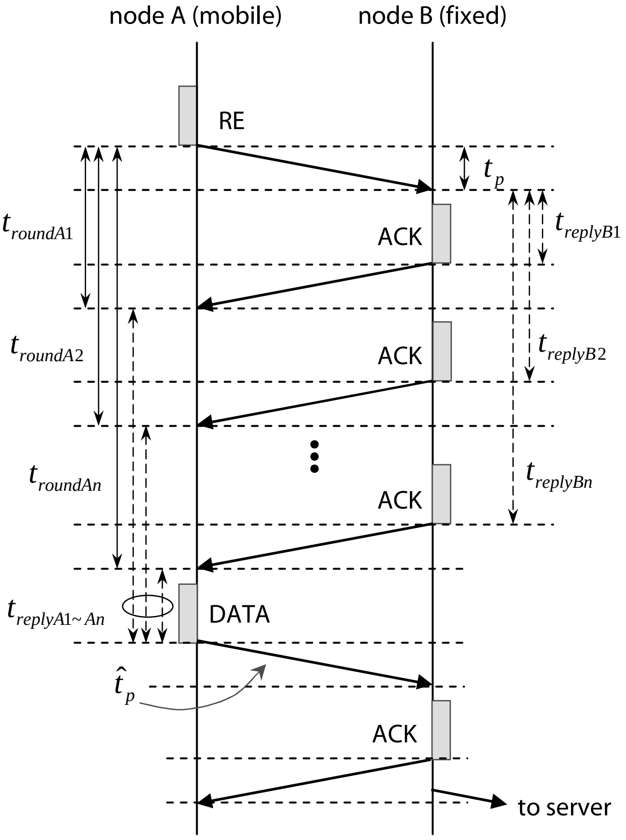

Fig. 5. Single-sided two-way ranging scheme using multiple ACK packets (SS-TWR-MA).

As shown in the figure, node A initiates the ranging process by transmitting a ranging request packet. Then, node B replies with several ACK packets in a sequential manner. The ACK packets are transmitted successively, considering its length, data rate, processing delay in the opposite node, and so on. Each ACK packet contains the reply time which is the duration between the last bit of the received REQ packet and the last bit of ACK packet itself. As we mentioned in the previous section, the reply time is written in the ACK packets right before it is transmitted. This is possible because the processing and delivering time of an ACK packet is known in advance.

To minimize the variation in the reply time, the reply time might be delivered with an extra DATA packet after transmitting ACK packets. In this case, ACK packets are transmitted without any software process. In this paper, however, we will not consider this scheme because the hardware implementation to handle the ACK packets is beyond the scope of this paper.

Here let's make two assumptions for later analysis, which is fairly natural. For n ACK packets, the reply times have the relations below:

$$t_{replyB1} < t_{replyB2} < \cdots < t_{replyBn}.$$

Similarly, the round-trip times have the relations below:

$$t_{roundA1} < t_{roundA2} < \cdots < t_{roundAn}$$

A. *Propagation Time of SS-TWR-MA*

In Fig. 5, the round-trip times of SS-TWR-MA are

$$t_{roundAi} = 2t_p + t_{replyBi} \quad \text{for } 1 \le i \le n. \tag{6}$$

Arranging (6) in terms of t_p, then we have

$$t_p = \frac{1}{2n}\sum_{i=1}^{n}\left(t_{roundAi} - t_{replyBi}\right). \tag{7}$$

When $n = 2$ in SS-TWR-MA, it becomes

$$t_p = \frac{1}{4}\left\{\left(t_{roundA1} - t_{replyB1}\right) + \left(t_{roundA2} - t_{replyB2}\right)\right\}, \tag{8}$$

which corresponds to the propagation time of SDS-TWR. Only difference is that the round-trip times are considered only at node A. That is, asymmetrical.

With SS-TWR-MA, we can calculate the distance between two nodes even though one or several ACK packets are lost during the transmission. Let k imply the number of ACK packets arrived at node A successfully, then (7) becomes

$$t_p = \frac{1}{2k}\sum_{i=1}^{n}\left(t_{roundAi} - t_{replyBi}\right),$$

where $0 < k \le n$. If no ACK packets are lost, then $k = n$. If there are lost ACK packets, then the timing variables for the lost ACK packets have a null value in the above equation.

B. *Ranging Time of SS-TWR-MA*

The ranging time of SS-TWR-MA is calculated approximately by counting the number of packets exchanged between two nodes. As shown in Fig. 5, SS-TWR-MA requires variable numbers of ACK packets for ranging and 2 more packets for reporting. Considering the number of ranging measurements, SS-TWR with 2 ACK packets corresponds to SDS-TWR.

As stated earlier, we may iterate the ranging process couples of times to get a stabler ranging result. With SS-TWR-MA, however, we are requested simply to increase the number of ACK packets for a single ranging request. Then, $n+3$ packets are required for ranging and reporting when we use n ACK packets. As a consequence, the ranging time of SS-TWR-MA becomes

$$RT_{SS-TWR-MA} = (n+3)\cdot t_{proc}. \tag{9}$$

Table 1 compares the number of packets exchanged for the two ranging schemes. As shown in the table, the number of packets is increased rapidly in SDS-TWR. On the other hand, SS-TWR-MA needs only one more packet whenever the iteration count increases by one. It implies that the ranging time reduction effect becomes bigger as we repeat the ranging process as many times as possible.

Table 1. Comparison of the number of packets exchanged for ranging and reporting. m and n stand for the repetition times in SDS-TWR and the number of ACK packets in SS-TWR-MA, respectively.

m or n	1	2	3	4	5	6
SDS-TWR	6	10	14	18	22	26
SS-TWR-MA	4	5	6	7	8	9

When $n = 2$ in SS-TWR-MA, it corresponds to $m = 1$ in SDS-TWR. When we iterate SDS-TWR twice ($m = 2$), SS-TWR-MA requires 4 ACK packets. Fig. 6 compares the number of packets required for different values of m and n. The figure tells us that we can reduce the number of packets required for ranging and reporting at least 17% when $m = 1$ and $n = 2$. For $m = 3$ and $n = 6$, we can reduce it as much as 46%.

A ranging algorithm provides a stabler ranging result when more range measurements are used. The numbers beside the dashed lines in Fig. 6 designate the number of range measurements for both ranging algorithms. For 10 packets exchanged, for example, SS-TWR-MA can conduct 7 ranging measurements even though SDS-TWR does it only 4 times. It means that SS-TWR-MA can provider a stabler ranging result than SDS-TWR.

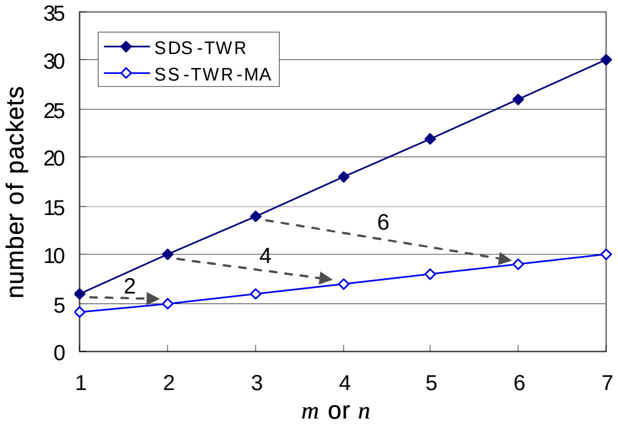

Fig. 6. Comparison of the number of packets required for SDS-TWR and SS-TWR-MA for different number of iteration (*m*) or different number of ACK packets (*n*).

IV. PERFORMANCE EVALUATION

In the previous Section, we analyzed the ranging time and the stability of ranging results obtained by the proposed SS-TWR-MA algorithm. In this Section, we evaluate the scalability of the locating system using the proposed algorithm and the battery lifetime of the mobile nodes numerically with practical values.

In reality, the length of REQ and DATA packets is longer than that of ACK packet and dependent on the ranging architecture. However, we assume here that their length is equal to one another and 300-bit long for the sake of explanation. In usual wireless sensor networks, data rate of the wireless communication channel is narrower than 1 Mbps. Assuming 1 Mbps here for simplicity, it takes 0.3 msec to transmit either packet serially to the other side. Assuming that the handling time is 1.5 msec at each node including the guard time between consecutive packet transmissions, then the processing time t_{proc} becomes 1.8msec.

A. *Number of Mobile Nodes handled by A Fixed Node*

In locating positioning systems, scalability can be defined either as the number of mobile nodes handled by a fixed node during a specific time interval or as the number of fixed nodes connected to a locating server at the same time. In this paper, we adopt the former definition since the latter is usually determined by the space where the locating system is deployed, rather than by the system performance or something else.

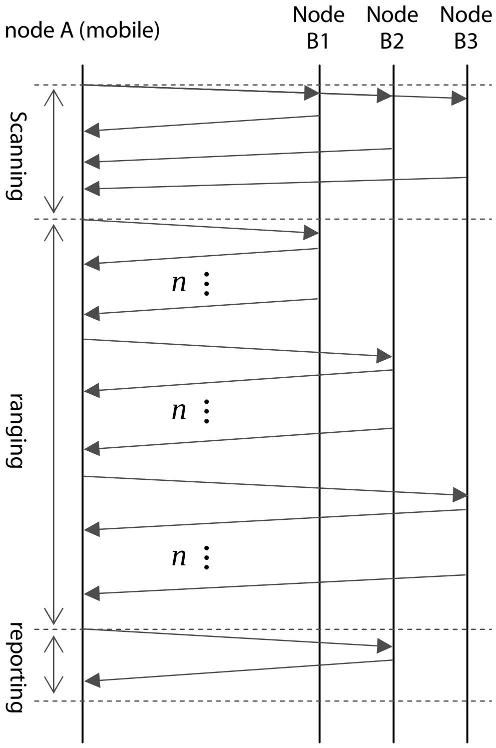

Fig. 7. Locating process using SS-TWR-MA for 3 fixed nodes. *n* denotes the number of ACK packets used to reply to a ranging request packet.

The number of mobile nodes that can be handled by a fixed node during a specific time interval is determined by such factors as total ranging time, processing and memory capacity of fixed nodes, and so on. However, such systematic parameters as processing capacity and memory capacity are fixed when it is developed. In this paper, therefore, we investigate the scalability of location positioning systems in terms of the total ranging time. As we scrutinized in the previous section, the total ranging time is determined by the number of packets used in scanning, ranging, and reporting phases.

In order to assess the scalability of locating systems, let's assume that location is determined in 2 dimensional space. It means that at least 3 fixed nodes must take part in location positioning process. However, we further assume that only 3 fixed nodes participate in and there are no errors occurred during the locating procedure.

Then, the locating system using SS-TWR-MA has to exchange 15 packets for a location determination when we reply with 2 ACK packets to a ranging request. (4 packets for scanning, 9 (=3x3) packets for ranging, and 2 packets for reporting) Here, we assumed that mobile nodes exchange reporting packets just once for three ranging results, as shown in Fig. 7, instead of exchanging reporting packets for each ranging with each of 3 fixed nodes. On the other hand, the locating system using SDS-TWR requires 18 (=4+3*4+2) packets.

For comparison, let's also consider SS-TWR-MA using 4 and 6 ACK packets, each of which corresponds to iterating SDS-TWR twice and thrice. In these cases, SS-TWR-MA requires 21 (=4+3*5+2) and 27 (=4+3*7+2) packets, respectively. SDS-TWR requires 32 (=4+(3*4+2)*2) and 46 (=4+(3*4+2)*3) packets, respectively. These numbers are tabulated in Table 2 as well as the total ranging time and the scalability. We assumed here that the ranging phase of SDS-TWR is repeated for the same scanning result but that the ranging result is reported separately for every iteration.

As shown in the table, SS-TWR-MA can support mobile nodes 23% more than SDS-TWR. For 6 range measurements, SS-TWR-MA can support 67% more and it gets bigger as the iteration times increases. Note that the time required for SS-TWR-MA to make 6 range measurements is shorter than that for SDS-TWR to make 4 range measurements. The numbers in Table 2 are obtained under the assumptions that there are no packet exchanges among fixed nodes and that there is no interleaving in using RF channel. If we consider hidden node problem also, the numbers becomes smaller.

Table 2. Performance comparison between SDS-TWR and SS-TWR-MA for different numbers of range measurements when 3 fixed nodes are used. (A: total number of packets exchanged for a location estimation, B: total ranging time, C: the number of mobile nodes that a fixed node can support during 1 second.)

ranging times	SDS-TWR			SS-TWR-MA		
	A	B	C	A	B	C
2	18	32.4ms	30	15	27.0ms	37
4	32	57.6ms	17	21	37.8ms	26
6	46	82.8ms	12	27	48.6ms	20

Fig. 8 shows the scalability of the locating system using SS-TWR-MA for different numbers of ACK packets. For this graph, we used the same assumptions: 3 fixed nodes and 1 second of locating frequency. As shown in the figure, the scalability is in inverse proportion to the number of ACK packets used to reply to a single ranging request. If we want the locating system using SS-TWR-MA to support more than 50 mobile nodes totally, the number of ACK packets must be less than 8 since a fixed node has to support at least 17 mobile nodes. For the system to support more mobile nodes with the same ACK packets, we have to increase the locating frequency. If we increase the locating frequency to 2 seconds, the scalability becomes twice straightforwardly.

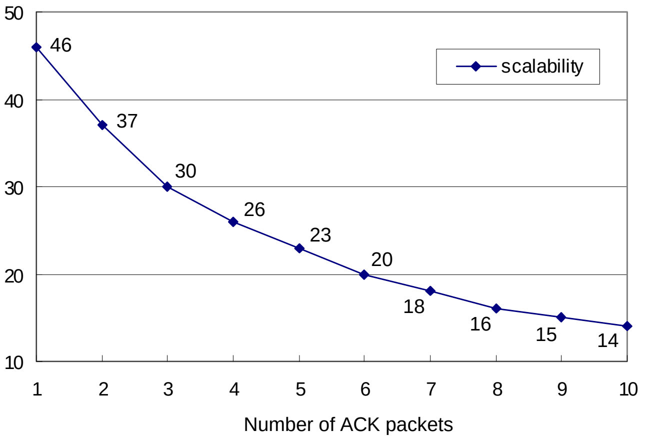

Fig. 8. Scalability of a fixed node when we use SS-TWR-MA as a ranging algorithm. The locating system is composed of 3 fixed nodes and the locating frequency is 1 second.

B. *Battery Lifetime of Mobile Nodes*

Power consumption is one of the most important issues in the area of wireless sensor networks since mobile nodes can carry finite amount of battery capacity with themselves. In this subsection, we look into the effect of ranging time to the battery lifetime.

Mobile nodes alternate its operational mode between active and sleep modes to reduce its power consumption as much as possible. Let t_{active} and t_{sleep} denote the time duration of active and sleep modes, respectively. p_{active} and p_{sleep} stand for the amount of the power consumption during active and sleep modes, respectively. Assuming that C designate the battery capacity used in a mobile node, then the battery lifetime can be calculated as follows:

$$LT = \frac{C_{total}}{24 \times \dfrac{t_{active} \cdot p_{active} + t_{sleep} \cdot p_{sleep}}{t_{active} + t_{sleep}}} \text{ (days).} \qquad (12)$$

Let's substitute variables in (12) with practical numbers. The numbers are from the RTLS solution developed by Samsung Networks Inc. by using the IEEE 802.15.4 and IEEE 802.15.4a technologies [6]. In the system, p_{active} = 60 mA and p_{sleep} = 20 µA. We use the lithium polymer battery, whose capacity is 720 mAh, in mobile nodes. t_{active} is equal to the total ranging time. That is, it can be calculated by multiplying t_{proc} with the number of packets used in scanning, ranging, and reporting phases. t_{sleep} corresponds to the difference between the locating frequency and t_{active}. For example, if the transmission frequency is 1 second, then $t_{sleep} = 1000 - t_{active}$ msec.

Fig. 9 shows the battery lifetime for different locating frequency intervals. Here we assume that SDS-TWR is iterated twice and 4 ACK packets are used for SS-TWR-MA. As shown in the figure, we can use battery more effectively with SS-TWR-MA when the locating frequency is short. For example, we can use battery 50% longer with SS-TWR-MA when the frequency is 1 second (12 days vs. 8 days). When the frequency is 20 seconds, we can use 35% longer with SS-TWR-MA (173 days vs. 128 days). It means that the proposed ranging algorithm is more appropriate for real-time applications such as visitor tracking than for non-real-time applications such as asset management.

V. CONCLUSION

In this paper, we proposed an asynchronous single-sided two-way ranging algorithm. The algorithm uses multiple ACK packets to reply to a single ranging request. This approach reduces the ranging time and the location estimation time by 17% or more, compared to the conventional asynchronous double-sided ranging algorithm, SDS-TWR. In terms of locating time, the proposed algorithm can reduce 23% or more. These effects get bigger when we iterate the ranging scheme several times to get a stabler ranging result.

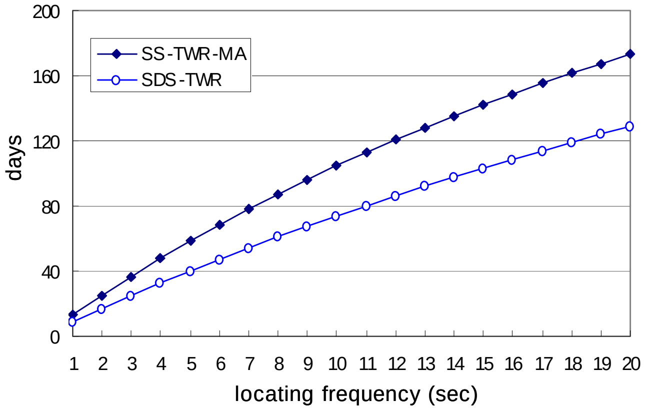

Fig. 9. Comparison of the battery lifetime for different transmission frequency of location information.

Short ranging time can be understood from three different viewpoints. First, it prolongs the battery lifetime of mobile nodes. Secondly, it provides the scalability to RTLS systems. That is, a fixed node can support more mobile nodes. Finally, it is an attribute appropriate to real-time locating systems.

The proposed ranging algorithm might be subject to the clock drift or the clock offset as other synchronous asymmetric ranging algorithms do. Therefore, the ranging error must be manipulated for precise location positioning. In our system, it was less than 1 mete and can be negligible when mobile nodes move continually or continuously.

We also developed the symmetrical version of SS-TWR-MA and are developing a pseudo-synchronous ranging algorithm for TOF (time of flight) based locating systems.

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