# Efficient Congestion Control Utilizing Message Eavesdropping in Asynchronous Range-Based Localization

Hoon Choi, Yunju Baek, and Ben Lee

**Asynchronous ranging is one practical method to implement a locating system that provides accurate results. However, a locating system utilizing asynchronous ranging generates a large number of messages that cause transmission delays or failures and degrades the system performance. This paper proposes a novel approach for efficient congestion control in an asynchronous range-based locating system. The proposed method significantly reduces the number of messages generated during the reader discovery phase by eavesdropping on other transmissions and improves the efficiency of ranging by organizing the tags in a hierarchical fashion in the measurement phase. Our evaluation shows that the proposed method reduces the number of messages by 70% compared to the conventional method and significantly improves the success rate of ranging.**

**Keywords: Locating system, message eavesdropping, RTLS, congestion control.**

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Hoon Choi (phone: +82 10 4175 4579, hara@eslab.re.kr) and Yunju Baek (corresponding author, yunju@pusan.ac.kr) are with the School of Computer Science and Engineering, Pusan National University, Busan, Rep. of Korea.

Ben Lee (benl@eecs.oregonstate.edu) is with the School of Electrical Engineering and Computer Science, Oregon State University, Corvallis, OR, USA.

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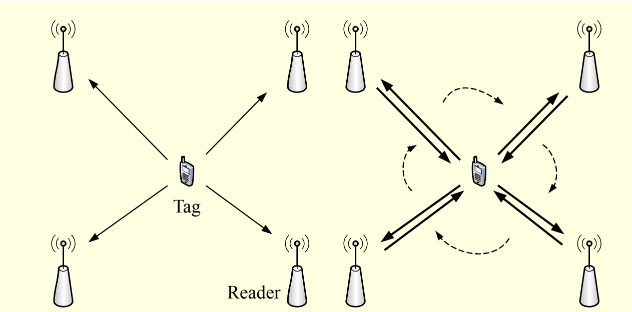
## I. Introduction

A real-time locating system (RTLS) enables tracking, identifying, and managing of target objects and thus is an important basis for various applications, such as logistics automation, military, and transportation systems. An RTLS consists of three components: tags, readers, and a location engine. Tags are attached to mobile objects, whereas readers are installed at stationary structures at known positions in the field. The distances between a tag and readers are measured using wireless communication, which is referred to as *ranging*. Then, the location engine determines a tag's location using the positions of the readers and the measured values.

The ranging method can be classified as either synchronous or asynchronous. In synchronous range-based localization, each tag broadcasts a short message to its adjacent readers, as shown in Fig. 1(a). This method requires all the nodes to be globally synchronized [1]-[3], which imposes additional processing and implementation overhead on the system. On the other hand, asynchronous ranging is a cooperative method for determining the distance between two nodes (see Fig. 1(b)). Unlike synchronous ranging, the advantage of this method is that precise time synchronization is not required and relatively accurate distance measurements can be obtained [4]. However, when the asynchronous ranging method is applied to a locating system, its peer-to-peer mechanism causes an excessive number of messages, leading to transmission delay or failure [5].

Therefore, this paper proposes an operational protocol that uses an efficient congestion control mechanism to reduce the




(a) Synchronous ranging (b) Asynchronous ranging

Fig. 1. Ranging architecture: (a) uses only one message for ranging but precise time synchronization is needed, and (b) uses numerous messages for ranging.

**Algorithm 1.** Pseudocode for the conventional tag-centric method.

```
Sleep during T_sleep
  // Reader discovery phase
Broadcast M_blink
while T_ACK do
    if M_ACK received then
        Put M_ACK· ReaderID on L_reader
  //Measurement phase
for ReaderID in L_reader do
    r ← Perform ranging with ReaderID
    Put r on L_ranging
Send L_ranging to Location Engine
```

• $M_{blink}$: blink message, $M_{ACK}$: ACK message, $L_{reader}$: list of readers, $L_{ranging}$: set of measured values, $T_{sleep}$: sleep period, $T_{ACK}$: waiting time for collecting $M_{ACK}$, *ReaderID*: reader, *r*: ranging value

number of messages and collisions during the operations of an asynchronous range-based locating system. This is achieved with the following two novel features. First, the number of messages generated during the reader discovery phase (RDP) is reduced by having tags *eavesdrop* on messages between other tags and readers. Second, in the measurement phase (MP), the transmission order of the tags is organized in a hierarchical fashion, based on the overheard information and measured distances, to mitigate collisions among them.

## II. Background

In asynchronous ranging, a tag sends a message to a reader in its transmission range, and then the reader replies to the tag, as shown in Fig. 1(b). During this process, the tag measures the transmission time ($t_t$) and the arrival time ($t_a$) of the message. If the processing time of a reader is defined as $t_{proc}$, the propagation time between the tag and the reader can be calculated as $(t_a{-}t_t){-}t_{proc}/2$, and the distance is given by $t_p{\cdot}v$, where $v$ is the speed of light.

Because this ranging method is based on a peer-to-peer mechanism, each tag needs to discover its adjacent readers to perform ranging with them. Therefore, a conventional asynchronous range-based localization requires two phases to estimate the location of a tag, whereas a synchronous ranging needs only one message.

For an efficient operation of asynchronous range-based localization, several methods have been proposed. These methods can be either reader-centric or tag-centric.

In a reader-centric method, all tags are scheduled in a centralized manner to avoid collision. Therefore, the reader sends to each tag its adjacent reader list and assigns an order for sequential ranging among other tags. Hwang proposed an asynchronous virtual slot-based ranging (AVSR) [6]. In this method, one reader sends a request packet to all the tags. Afterward, each tag tries to detect ACK messages from other tags utilizing clear channel assignment (CCA) and sends an ACK message to the reader if the channel is clear. If the channel is not clear, the tag tries to send the message in the next virtual slot.

Kim and others suggested a ranging protocol similar to AVSR [7]. Initially, all tags are in a sleep status, and the system chooses one reader as a network coordinator. The coordinator broadcasts a signal to all the tags to wake them up, and all the tags reply with a request packet to the coordinator using IEEE 802.15.4a. After the coordinator collects information from the tags, it sends a ranging message to each tag with its adjacent reader information in sequence. This method uses the sleep and waking-up functions of a tag to avoid collisions among tags as well as to save energy.

In these methods, each tag operates during its own time slot assigned by the reader and is able to reduce delaying or dropping of messages due to congestion or collision with other tags. Nevertheless, these systems operate well only in a one-hop environment because the reader provides a tag with its predefined reader list. In addition, the system generates relatively more messages than the tag-centric method.

In the tag-centric method, all the tags try to collect their adjacent readers' information and sequentially perform ranging with them. Kim [5] and Choi and others [8] proposed ranging protocols using the tag-centric method. Algorithm 1 shows a pseudocode for the conventional tag-centric method (hereafter, the conventional method). First, in the RDP, each tag broadcasts a blink message ($M_{blink}$) to nearby readers, and the readers reply to the tag with ACK messages ($M_{ACKs}$). Then, each tag constructs a list of readers ($L_{reader}$) to perform ranging based on the ACKs collected from the readers within its range. In the MP, a tag measures the round-trip time by exchanging messages with each reader in $L_{reader}$. Afterward, the location engine estimates the positions of the tags using measured values as well as other information [9], [10].

This method can be applied to a one-hop environment because a tag tries to search for its adjacent readers. In addition, each tag adjusts its own blink period depending on the network environment.

However, the conventional method has the following problems as the number of tags increases:

- *Message congestion*: During the discovery phase, each tag must broadcast a blink message and receive ACK messages from adjacent readers. Hence, the number of messages generated increases as the number of tags increases. Message congestion causes delays or transmission failures and thus degrades the system performance.
- *Independent ranging operation*: A tag exchanges two or more messages with each adjacent reader during asynchronous ranging. However, when all the tags try to perform ranging at the same time, collisions occur and the measurements will contain errors or even fail. In addition, this operation can minimize the location error caused by the difference in ranging time with its adjacent readers when a tag moves.

## III. Proposed Method

This section proposes a tag-centric congestion control method for mitigating the aforementioned problems. The proposed method utilizes an eavesdropping mechanism, by which each tag listens to other tags' messages from readers, and ranging occurs sequentially based on the information that results from eavesdropping. Algorithm 2 shows the pseudocode for the proposed method. In summary, the proposed method works as follows:

1) Each tag listens for other tags' blink messages for a randomized time. If a tag does not hear any blink messages from other tags, it broadcasts a blink message, as in the conventional method, and becomes the *master node*. If a tag hears another tag's blink message, then it starts eavesdropping on ACK messages from the readers to the tag that sent the blink message.

2) If a tag hears one or more ACK messages, it sends a tag-ACK message ($M_{TACK}$) to the master node and becomes a *member node*. After this, the member nodes can skip the blink-ACK mechanism of the conventional RDP; thus, no additional messages are generated. Then, the master node performs ranging with readers that sent ACKs one by one, and the ranging result is sent to the location engine.

3) After ranging, the master node sends a command message to its member nodes in *sequence*. A member node that receives this message performs ranging with the readers on which it has eavesdropped and replies to the master node with the result. Since the ranging order of the tags is predetermined and thus serialized by the master node, each ranging process will experience less contention and interference from other communications.

**Algorithm 2.** Pseudocode for the proposed method.

// Decide Tag's role – master or member node
*myStatus* ← *MasterNode*
**while** $T_{ev}$ **do**
    **if** $M_{blink}$ received **then**
        *myStatus* ← *MemberNode*
        break
//Reader discovery phase of master node
**if** *myStatus* = *MemberNode* **then**
  Broadcast $M_{blink}$ within communication range
    **while** $T_{TACK}$ **do**
        **if** $M_{ACK}$ received **then**
            put $M_{ACK}$·*ReaderID* on $L_{reader}$
        **else if** $M_{TACK}$ received **then**
            put $M_{TACK}$·*MemberID* on $L_{member}$
// Measurement phase of master node
    **for** *ReaderID* in $L_{reader}$ **do**
        *r* ← Perform ranging with *ReaderID*
        Put *r* on $L_{ranging}$
    send $L_{ranging}$ to Location Engine
    **for** *MemberID* in $L_{member}$ do
        Send $M_{cmd}$ to *MemberID*
        **while** $T_{result}$ **do**
            **if** $L_{ranging}$ received **then**
                send $L_{ranging}$ to Location Engine
// Reader discovery phase of member node
  **else if** *myStatus* = *MemberNode* **then**
    **while** $T_{ACK}$ **do**
        **if** $M_{ACK}$ eavesdropped **then**
            put $M_{ACK}$·*ReaderID* on $L_{reader}$
    send $M_{TACK}$ to master node
    **while** $T_{cmd}$ **do**
        **if** $M_{cmd}$ eavesdropped **then //** not to this tag
            reset $T_{cmd}$ // restart timer of $T_{cmd}$
        **else if** $M_{cmd}$ received **then //** to this tag
// Measurement phase of member node
            **for** *ReadeID* in $L_{reader}$ **do**
                *r* ← Perform ranging with *ReaderID*
                put *r* on $L_{ranging}$
            send $L_{ranging}$ to master node

• $M_{blink}$: blink message, $M_{ACK}$: ACK message, $M_{cmd}$: command message, $L_{reader}$: list of readers, $L_{member}$: list of members, $L_{ranging}$: set of measured values, $T_{ev}$: eavesdrop period, $T_{ACK}$: waiting time for collecting $M_{ACK}$, $T_{result}$: waiting time of receiveing $L_{ranging}$ from a member node, $T_{cmd}$: waiting time for receiveing $M_{cmd}$ from a master node, *ReaderID*: reader, *MemberID*: member tag, *r*: ranging value

Note that there can be two or more master nodes simultaneously because a tag may not hear other tags' blink messages due to collision or interference. In this case, collisions between different master-member groups can occur. Nevertheless, the proposed method still generates a significantly smaller number of messages and failures than the conventional method generates. This is because, unlike the conventional method in which all the tags contend for the medium to transmit messages, only the master nodes from different master-member groups contend to transmit messages in the proposed method.

At the beginning of the RDP, each tag listens for a blink message for a certain amount of time. At the same time, the tag also eavesdrops on other messages, such as TACK, ACK, and ranging messages. If the tag hears any one of these messages but does not hear a blink message, it means that other tags and readers have either already completed the blink-ACK mechanism or are in the MP. Thus, the tag extends the eavesdropping time until the next cycle of localization. This approximately synchronizes the tags and also minimizes the number of master nodes.

After the reader discovery and ranging, the location engine estimates the position of each tag using the measured values and the locations of the readers. The location estimation is performed using multilaterlation when three or more ranging values are available [11]. If the trajectory of each mobile object is simple and predefined, the location is estimated using only one or two measured distances, but its accuracy is lower [12].

## IV. Evaluation

Our evaluation starts with the estimation of the number of messages generated for each method based on the number of readers and tags deployed in an area. Suppose $n_r$ and $n_t$ represent the number of readers and tags, respectively. In the conventional method, each tag generates $M_{conv}$ messages to perform location estimation based on the following equation:

$$M_{\text{conv}} = 1 + n_{\text{r}} + R \cdot n_{\text{r}}, \tag{1}$$

where $R$ is the number of messages for ranging between a reader and a tag. In contrast, the number of messages generated by the proposed method, $M_{prop}$ is given by

$$\begin{aligned} M_{\text{prop}} &= (1 + n_{\text{r}} + R \cdot n_{\text{r}}) \cdot p + 1 \cdot (1 - p) \\ &\quad + (1 + R \cdot n_{\text{r}}' + 1) \cdot (1 - p) \end{aligned} \tag{2}$$

$$= 3 - 2p + pn_{\text{r}} + pRn_{\text{r}} + R(1 - p)n_{\text{r}}', \tag{3}$$

where $p$ is the fraction of nodes that are master nodes ($0 \le p \le 1$) and $n_r'$ is the number of adjacent readers of the member nodes. Thus, the first term in (2) represents the fraction of messages generated when a tag operates as a master node, which does not hear any blink messages. In addition, the second term represents the number of command messages, $M_{cmd}$, sent to its member nodes. Finally, the third term represents the fraction of messages generated when a tag hears one or more blink messages and becomes a member node.

If the member nodes have the same adjacent readers as their master node, then $n_r$ is equal to $n_r'$. In this case, the maximum number of messages generated by the proposed method, $M_{\text{prop}}^{\max}$, is defined as

$$M_{\text{prop}}^{\max} = 3 - 2p + (p + R) \cdot n_{\text{r}}. \tag{4}$$

Since $(1 - p) \cdot R \ge 0$ and $n_r' \le n_r$, the following inequality holds true:

$$M_{\text{prop}} \le M_{\text{prop}}^{\max}. \tag{5}$$

To compare $M_{\text{prop}}^{\max}$ and $M_{conv}$, their difference is given as

$$\begin{aligned} M_{\text{conv}} - M_{\text{prop}}^{\max} &= 1 + n_{\text{r}} + Rn_{\text{r}} - 3 + 2p - pn_{\text{r}} - Rn_{\text{r}} \\ &= -2 + 2p - pn_{\text{r}} + n_{\text{r}} \\ &= -(1 - p)(2 - n_{\text{r}}). \end{aligned} \tag{6}$$

If $n_r \ge 2$, then $M_{\text{prop}}^{\max} \le M_{\text{conv}}$. Therefore,

$$M_{\text{prop}} \le M_{\text{prop}}^{\max} \le M_{\text{conv}}. \tag{7}$$

Theoretically, this shows that less messages are generated using the proposed method than using the conventional method when a master node secures more than two adjacent readers.

We also evaluate the performance of the proposed method using Castalia, which is a simulator for wireless sensor networks, based on the OMNet++ platform [13], [14]. The simulated area is 70 m × 70 m, in which tags are randomly deployed on the ground, and there are eight readers on the perimeter of the area. There is no obstacle, and the MAC protocol employs a CSMA mechanism for transmissions, which is typically used. TX output power of an RF module is configured to 10 dBm, and the ranging distance is approximately 60 m to 70 m. A simulation study is performed with 1 to 150 tags, and each simulation lasts 100 seconds.

For evaluation purposes, the proposed method is compared with a conventional method using an asynchronous range-based locating system, which is described in Algorithm 1. During simulation, $T_{ACK}$, $T_{TACK}$, and $T_{cmd}$ are set as 0.3 s, 0.5 s, and 0.5 s, respectively, and $T_{sleep}$ and $T_{ev}$ are set as randomized times between 0.5 s and 1 s. For both methods, the operation returns to sleep status if a collection or ranging error occurs or the ranging process completes normally.

Figure 2 shows the number of generated and successfully transmitted messages during 100 seconds of simulation. The conventional method generates many messages and some of the messages fail to transmit as the number of tags increases. In contrast, the proposed method generates only a small number of messages and only a few messages fail to transmit. Thus, the proposed method operates more efficiently.

Figure 3 shows the average number of successful ranging

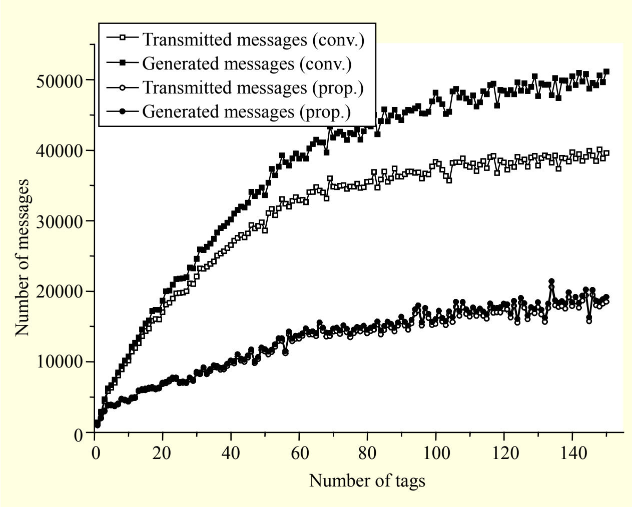



Fig. 2. Generated and transmitted messages in radio layer.

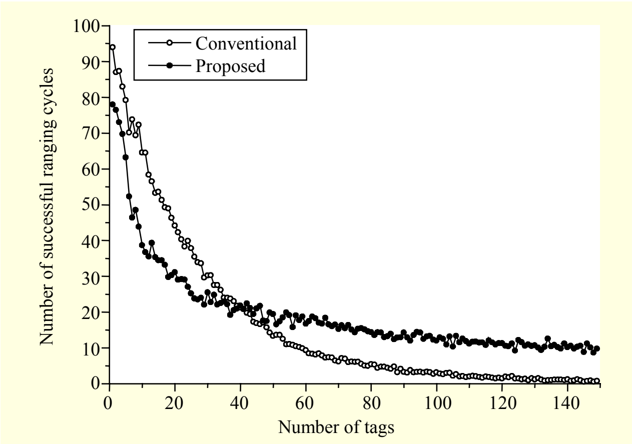



Fig. 3. Number of successful ranging cycles.

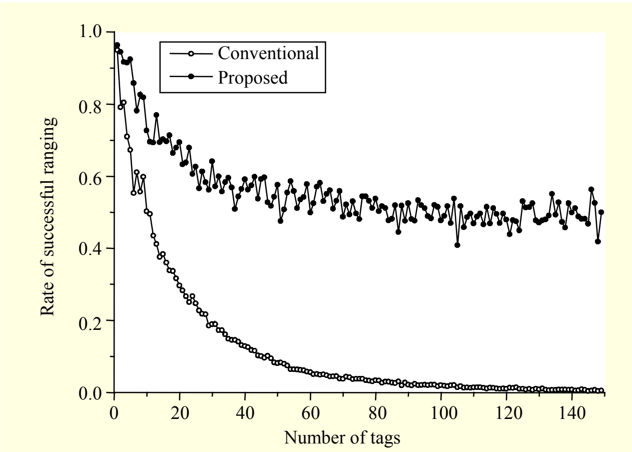



Fig. 4. Rate of successful ranging.

cycles that a tag performs with three or more readers, which leads to accurate estimation of a tag's position. In the

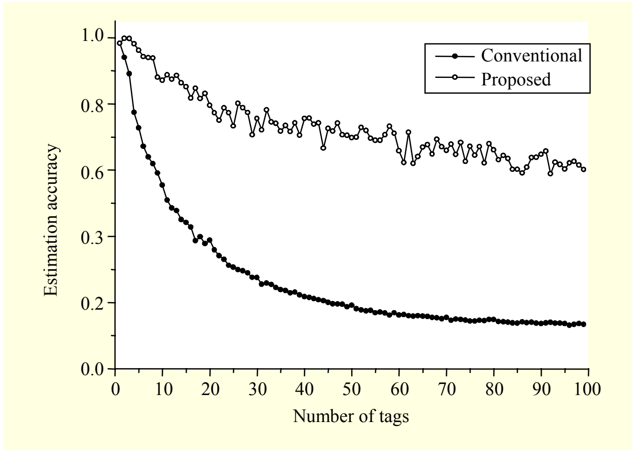



Fig. 5. Weighted accuracy of location estimation.

conventional method, the number of successful ranging cycles decreases significantly as the number of tags increases because each tag tries to collect readers and perform ranging with readers individually. Beyond 100 tags, only a few tags can be successfully ranged.

On the other hand, Fig. 4 shows the effectiveness of the proposed method. As can be seen, the number of successful ranging cycles for the proposed method remains relatively stable even as the number of tags increases.

As another comparison, a weighted accuracy of location estimation is defined, which represents the relative accuracy of location estimation relative to the number of procured reader measurements. If a tag performs ranging with three or more readers, the weighted accuracy is 1.0. If there are two readers, then the weighted accuracy becomes 0.66, and it is 0.33 if there is only one reader [12]. If ranging fails, the weighted accuracy is 0.

Figure 5 shows the respective weighted accuracy for the two methods as a function of the number of tags. The difference between the two methods is significant because the ranging requires several messages to be exchanged without delay. The weighted accuracy of the conventional method rapidly decreases beyond five tags because all the tags try to perform ranging with their adjacent readers, resulting in collisions. On the other hand, the weighted accuracy of the proposed method remains above 0.6 because the master node determines the ranging order of the member nodes, which reduces collision and ranging failure. Therefore, more tags can exist when the proposed method is applied to an asynchronous range-based locating system.

## V. Conclusion

This paper proposed a new protocol for an efficient asynchronous range-based locating system. The novel features of the proposed method are eavesdropping on other tag's reader discovery and sequential ranging operation among tags using a master-member relationship to reduce the number of messages. In addition, the system employs various off-the-shelf products or ranging methods because the proposed method depends on a ranging mechanism [4], [15], [16]. Our evaluation shows that the proposed method results in a significantly smaller number of messages, resulting in more efficient reader discovery and ranging operations. Therefore, more tags with a shorter blink interval can exist than by using the conventional method. In our future work, we plan to improve the system by investigating issues such as large-scale localization, mobile issues of simulation, energy consumption, and dynamic operation depending on network topology and density of targets.

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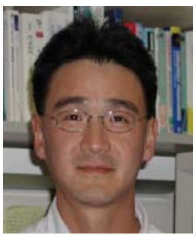
**Hoon Choi** received his BS and MS in computer science from Pusan National University, Busan, Rep. of Korea, in 2005 and 2007, respectively. He is currently pursuing a PhD in computer science and engineering at Pusan National University. His research interests include active RFID systems, port logistics automation, real-time locating systems (RTLSs), and wireless embedded systems.

**Yunju Baek** received a PhD in computer science from KAIST, Daejeon, Rep. of Korea, in 1997. He was an invited professor at KAIST, CTO at NHN Corp., and an assistant professor at Sookmyung Women's University, Seoul, Rep. of Korea. He is a professor in the Department of Computer Science and Engineering at Pusan National University, Busan, Rep. of Korea. His research interests include wireless sensor networks, embedded systems, active RFID systems, and RTLS.



**Ben Lee** received his BE in electrical engineering in 1984 from the Department of Electrical Engineering at the State University of New York (SUNY) at Stony Brook, Stony Brook, NY, USA, and his PhD in computer engineering in 1991 from the Department of Electrical and Computer Engineering at Pennsylvania State University, University Park, PA, USA. He is currently a professor in the School of Electrical Engineering and Computer Science at Oregon State University, Corvallis, OR, USA. His research interests include wireless networks, embedded systems, computer architecture, multithreading and thread-level speculation, and parallel and distributed systems.