

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

Hoon Choi, Yunju Baek and Ben Lee

An 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 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 also 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

I. Introduction

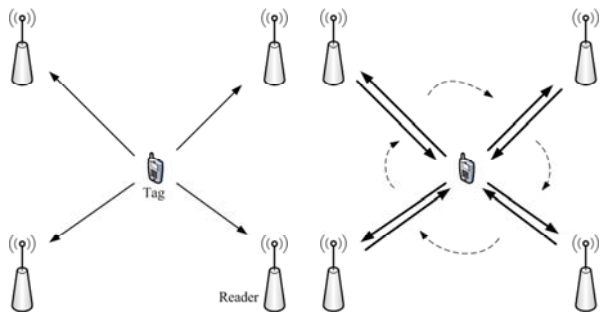
A locating system enables tracking, identifying and managing of target objects, and thus it is an important basis for location-based services. This system generally consists of three components - tags, readers, and a location engine. *Tags* are attached to mobile target objects, while *readers* are installed at stationary structures at known positions in the field. The distances between a tag and readers are measured using wireless communication, referred to as *ranging*. Then, the location engine determines a tag's location using the positions of the readers and the measured values. A *Real Time Locating System (RTLS)* enables tracking, identifying and managing of target objects, and thus it is an important basis for various applications, such as logistics automation, military, and transportation system. An RTLS consists of three components -- tags, readers, and a location engine. *Tags* are attached to mobile objects, while *readers* are installed at stationary structures at known positions in the field. The distances between a tag and readers are measured using wireless communication, 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* ranging 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][2][3], which imposes an 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 synchro-

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(a) Synchronous ranging uses only one message for ranging, but precise time synchronization is needed. (b) Asynchronous ranging uses numerous messages for ranging.

Fig. 1. Ranging in synchronous and asynchronous ranging architecture

nous 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 excessive number of messages leading to transmission delay or failure [7].

Therefore, this paper proposes an operational protocol that uses an efficient congestion control mechanism to reduce the number of messages and collisions during the operations of 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* is reduced by having tags *eavesdrop* on messages between other tags and readers. Second, in the *Measurement phase*, 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 t_p 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 a speed of light.

Because this ranging method is based on 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, while a synchronous ranging needs

Algorithm 1 Pseudocode for the conventional tag-centric method.

```

1: Sleep during  $T_{sleep}$ 
   // Reader Discovery Phase
2: Broadcast  $M_{blink}$ 
3: while  $T_{ACK}$  do
4:   if  $M_{ACK}$  received then
5:     Put  $M_{ACK}.ReaderID$  on  $L_{reader}$ 
   // Measurement Phase
6: for  $ReaderID$  in  $L_{reader}$  do
7:    $r \leftarrow$  Perform ranging with  $ReaderID$ 
8:   Put  $r$  on  $L_{ranging}$ 
9: 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

only one message.

For 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) [5]. In this method, one reader sends a request packet to all the tags. Afterwards, 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 *et al.* suggested a ranging protocol similar to AVSR [6]. 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 of the tags, it sends a ranging message to each tag with its adjacent reader information in sequence. This method uses sleep and waking-up function of a tag in order to avoid collisions among tags as well as save energy.

In these methods, each tag operates during its own time slot assigned by the reader and is able to reduce delay or drop 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 pre-defined 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. Hwang [7] and Choi *et al.* [8] proposed ranging protocol using the tag-centric method. Algorithm 1 shows a

pseudo-code for the conventional tag-centric method (which will be referred to simply as the conventional method). First, in the *Reader Discovery* phase, each tag broadcasts a *blink* message (M_{blink}) to nearby readers, and the readers reply to the tag with *ACK* messages (M_{ACK}). 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 *Measurement phase*, a tag measures round-trip time by exchanging messages with each reader in L_{reader} . Afterwards, the location engine estimates the positions of the tags using measured values as well as other information [13][14].

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 has to 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 would contain errors or even fail. In addition, this operation can minimize the location error caused by difference of 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, where each tag listens to other tag's messages from readers, and ranging occurs sequentially based on the eavesdropped information. Algorithm 2 shows the pseudo-code for the proposed method. In summary, the proposed method works as follows:

- (a) 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.

Algorithm 2 Pseudocode for the proposed method.

```

// Decide Tag's role – master or member node
1: myStatus ← MasterNode
2: while Tev do
3:   if Mblink received then
4:     myStatus ← MemberNode
5:     break
// Reader Discovery phase of Master Node
6: if myStatus = MasterNode then
7:   Broadcast Mblink within communication range
8:   while TTACK do
9:     if MACK received then
10:      put MACK.ReaderID on Lreader
11:    else if MTACK received then
12:      put MTACK.MemberID on Lmember
// Measurement phase of Master Node
13: for ReaderID in Lreader do
14:   r ← Perform ranging with ReaderID
15:   put r on Lranging
16: send Lranging to Location Engine
17: for MemberID in Lmember do
18:   Send Mcmd to MemberID
19:   while Tresult do
20:     if Lranging received then
21:       send Lranging to Location Engine
// Reader Discovery phase of Member Node
22: else if myStatus = MemberNode then
23:   while TACK do
24:     if MACK eavesdropped then
25:       put MACK.ReaderID on Lreader
26:   send MTACK to master node
27:   while Tcmd do
28:     if Mcmd eavesdropped then // not to this tag
29:       reset Tcmd // restart timer of Tcmd
30:     else if Mcmd received then // to this tag
// Measurement phase of Member Node
31: for ReaderID in Lreader do
32:   r ← Perform ranging with ReaderID
33:   put r to Lranging
34:   send Lranging 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 for receiving $L_{ranging}$ from a member node, T_{cmd} : Waiting time for receiving M_{cmd} from a master node, $ReaderID$: Reader, $MemberID$: Member tag r : Ranging value

- (b) If a tag hears one or more ACK messages, it sends a *Tag-ACK* (M_{TACK}) message to the master node, and becomes a *member node*. After this, the member nodes can skip the blink-ACK mechanism of the conventional Reader Discovery phase, 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.
- (c) 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 its eavesdropped readers, 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.

Note that there can be two or more master nodes at the same time 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 significantly less number of messages and failures than the conventional method. This is because, unlike the conventional method where 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 Reader Discovery phase, 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 Measurement phase. 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 *multi-lateration* when three or more ranging values are available [9]. If the trajectory of each mobile object is simple and pre-defined, the location is estimated using only one or two measured distances, but its accuracy would be lower [10].

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:

$$M_{conv} = 1 + n_r + R \cdot n_r \quad (1)$$

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

$$M_{prop} = (1 + n_r + R \cdot n_r) \cdot p + 1 \cdot (1 - p) + (1 + R \cdot n_r' + 1) \cdot (1 - p) \quad (2)$$

$$= 3 - 2p + pn_r + pRn_r + R(1 - p)n_r', \quad (3)$$

where p is the fraction of nodes that are master nodes ($0 \leq p \leq 1$), n_r' is the number of adjacent readers of the member nodes. Thus, the first term in Eq. 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 same adjacent readers as their master node, n_r would be equal to n_r' . In this case, the maximum number of messages generated by the proposed method, M_{prop}^{max} , is defined as follows:

$$M_{prop}^{max} = 3 - 2p + (p + R) \cdot n_r \quad (4)$$

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

$$M_{prop} \leq M_{prop}^{max} \quad (5)$$

In order to compare M_{prop}^{max} and M_{conv} , their difference is given as

$$\begin{aligned} M_{conv} - M_{prop}^{max} &= 1 + n_r + Rn_r - 3 \\ &\quad + 2p - pn_r - Rn_r \\ &= -2 + 2p - pn_r + n_r \\ &= -(1 - p)(2 - n_r). \end{aligned} \quad (6)$$

If $n_r \geq 2$ then $M_{prop}^{max} \leq M_{conv}$. Therefore,

$$M_{prop} \leq M_{prop}^{max} \leq M_{conv} \quad (7)$$

This shows that the number of generated messages in the proposed method is theoretically less than the conventional method when a master node secures more than two adjacent readers.

We also evaluated the performance of the proposed method using Castalia, which is a simulator for Wireless Sensor Networks (WSN), based on the OMNet++ platform [11][12]. The simulated area is 70m \times 70m where tags are randomly deployed on the ground, and there are 8 readers on the perimeter of the area. There's 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 a ranging distance is approximately 60 ~70 meters. Simulation study is performed with 1 to 150 tags, and each simulation is for 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. Dur-

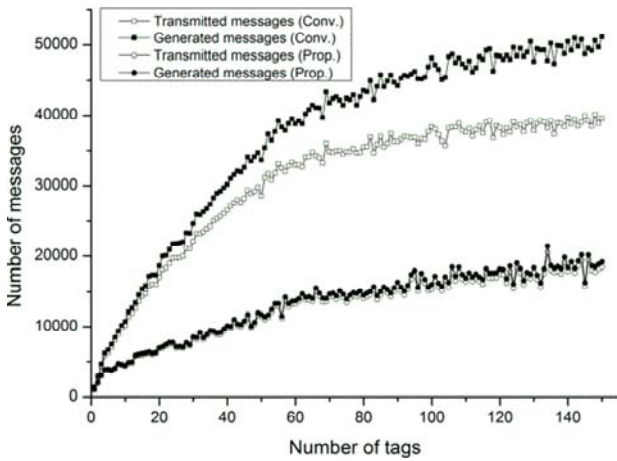


Fig. 2. Generated and transmitted messages in radio layer

ing simulation, T_{ACK} , T_{TACK} , and T_{cmd} are set as 0.3, 0.5, and 0.5 second, respectively, and T_{sleep} and T_{ev} are set as randomized time between 0.5 and 1 second. For both methods, the operation returns to sleep status if collection or ranging error occurred or the ranging process completes normally.

Fig. 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 failed 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 failed to transmit. Thus, the proposed method operates more efficiently.

Fig. 3 shows the average number of successful ranging that a tag performs with three or more readers, which leads to accurate estimation of tag's position. In the conventional method, the number of successful ranging decreases significantly as the number of tags increases because each tag tries to collect and perform ranging with readers individually. Beyond 100 tags,

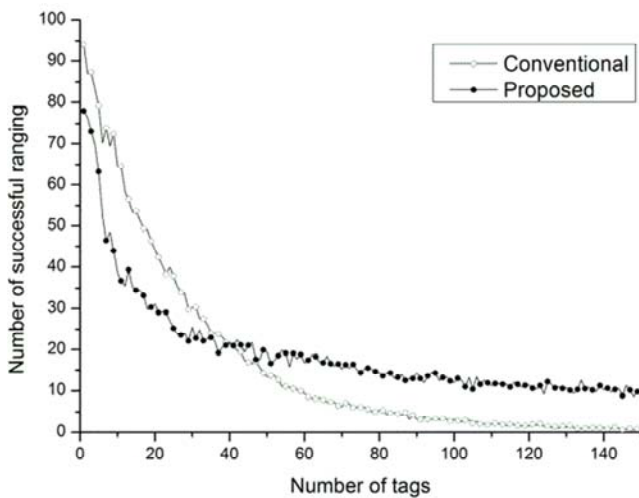


Fig. 3. Number of successful ranging

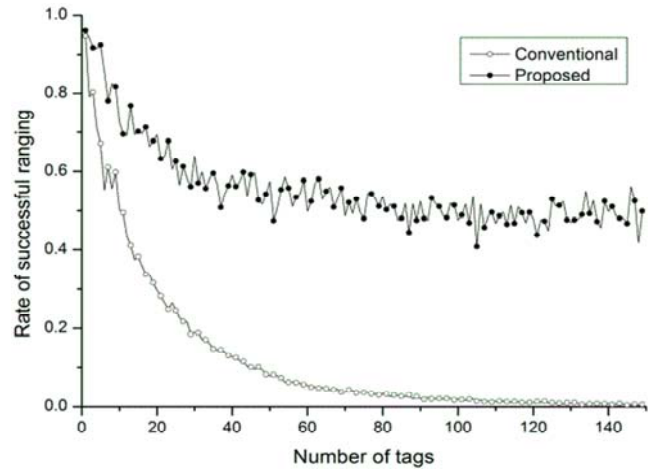


Fig. 4. Rate of successful ranging

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 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 would be 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 [10]. If ranging fails, the weighted accuracy would be 0.

Fig. 5 shows the weight accuracies for the two methods as a function of number of tags. The difference between two methods is significant because the ranging requires several messages to be exchanged without delay. The weight accuracy of the conventional method rapidly decreases beyond 5 tags because

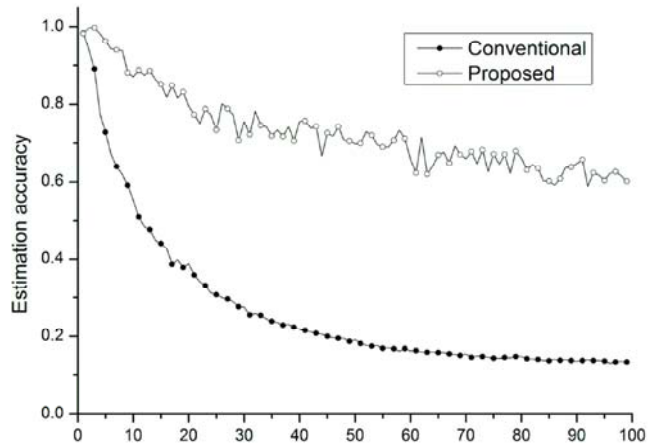


Fig. 5. Weight accuracy of location estimation

all the tags try to perform ranging with their adjacent readers resulting in collisions. On the other hand, the weight 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 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 number of messages. In addition, the system employs various off-the-shelf products or ranging methods because the proposed method depends on ranging mechanism [4][15][16]. Our evaluation shows that the proposed method results in significantly less number of messages resulting in more efficient reader discovery and ranging operations. Therefore, more tags with a shorter blink interval can exist than 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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