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On Distinguishing Relative Locations with Busy Tones for Wireless Sensor Networks

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***Abstract*—Bounding-box mechanism is a well known low-cost localization approach for wireless sensor networks. However, the bounding-box location information can not distinguish the relative locations of neighboring sensors, hence leading to a poor performance for some applications such as location-aware routing. This paper proposes a *Distinguishing Relative Locations* (*DRL*) mechanism which uses a mobile anchor to broadcast tones and beacons aiming at distinguishing the relative locations of any two neighboring nodes. Experimental study reveals that the proposed *DRL* mechanism effectively distinguishes relative locations of any two neighboring nodes and hence significantly improves the performance of location-aware routing in wireless sensor networks (WSNs).**

Keywords—Localization*; *Range-free*; *Relative Locations*; *Mobile Anchor*; *Wireless Sensor Networks

I. INTRODUCTION

Location information has been widely used in applications such as coverage calculation, event detection, object tracking, and location aware routing [1] in WSNs. A number of bounding-box mechanisms [2][3] have been proposed for providing each sensor with a location information. Compared with the DV-hop [4] based and range-based [5] localization mechanisms, the bounding-box approaches do not require any static anchor and has lower hardware requirement. In the bounding-box approaches, a mobile anchor can always be aware of its own location and periodically move and broadcast a beacon containing its up-to-date location for improving the location accuracy of the nearby static sensors. Upon receiving the beacon message, the sensor node learns the fact that it is within the transmission range of the anchor and thus is able to construct a bounding-box region where it is inside.

Though existing bounding-box approaches provide each sensor with bounding-box location information, however, they can not distinguish relative locations between neighboring sensors. When sensors perform some location-aware applications such as routing schemes, a poor performance can be obtained since the relative locations of neighboring sensors are undistinguishable. Figure 1 gives an example for illustrating that distinguishing relative locations of neighboring sensors has a significant impact on routing performance. Let B_i denote the bounding-box of sensor s_i. As shown in Fig. 1, sensor s_a receives a packet and intends to apply the location-aware routing which forwards the packet to the neighbor closest to the sink. In this example, s_a will forward the packet to s_b because that B_b is likely closer to the sink node than B_a. However, the physical location of s_b is located at the southeast direction of s_a. As a result, the packet is forwarded to an improper node, increasing the route length.

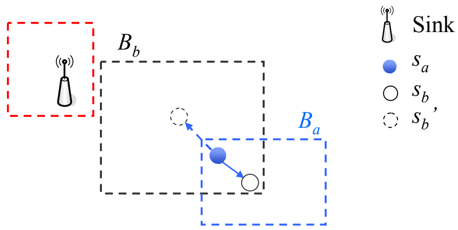


Fig. 1. Distinguishing relative locations of the neighboring sensors has a significant impact on location-aware routing performance.

This paper proposes a *DRL* mechanism which is an extension of the existing bounding-box approaches. The proposed *DRL* not only provides each sensor with an estimated bounding-box location but also help each pair of neighboring sensors distinguishing their relative locations. The *DRL* mechanism employs a mobile anchor broadcasting beacon and tone signals. Similar to the existing bounding-box approaches, the beacon message aims to provide each sensor with bounding-box location information. The key idea of the proposed *DRL* is using tone signals to help any two neighboring sensors distinguish their relative locations.

The remaining part of this paper is organized as follows. Section II illustrates the network environment and the details of *DRL* mechanism. Section III investigates the performance of the proposed *DRL* mechanism. The conclusion and future work are given in Section IV.

II. THE *DRL* MECHANISM

This section initially introduces the network environment and the assumptions of the given WSN. Then the details of the proposed *DRL* mechanism are proposed.

2.1 Network Environment

This paper assumes that n sensor nodes are randomly distributed in an area sized by $L\times W$. Let S denote the set of all sensor nodes in the monitoring region and $N(s_i)$ denote the set of all neighbors of sensor s_i. In the WSN, a mobile anchor that is aware of its own location can broadcast three types of signals, including the beacon message and two types of tone signals. The beacon message contains its current location information while the tone signals does not carry any information and thus consumes smaller energy than beacon message.

The Snake-like path has been widely applied in network deployment and patrolling for WSNs. In this paper, the mobile anchor is assumed to move along the snake-like trajectory. Without loss of generality, we only discuss the horizontal relative locations and therefore we additionally assume that the mobile anchor moves horizontally. More specifically, the mobile anchor moves along east and west directions in turn until the boundaries of the monitoring region is reached. The mobile anchor will broadcast type I and type II tone signals when it moves along east and west directions, respectively. We notice that the vertical relative locations of any two neighboring sensors can also be distinguished if the mobile anchor moves vertically.

2.2 Basic Concept

The basic concept of *DRL* is distinguishing the relative locations of each pair of neighboring sensors based on the order of entering and leaving the tone-single range. To achieve this, each sensor node should maintains table $Entry_E$ in its own cache for recording relative location relations. The following gives an example to show the basic concept of *DRL* mechanism.

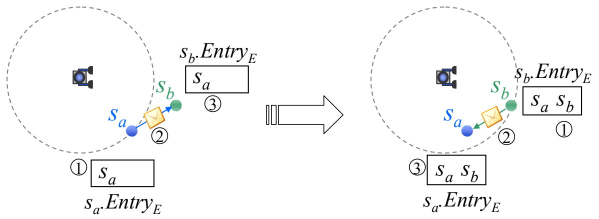


Fig. 2. Sensors s_a and s_b distinguish their relative locations with each other based on the *Entry* table.

Assume that the mobile anchor moves along the east direction. We show the operations what each sensor should perform when it enters or leaves the tone-signal range. In Fig. 2, consider two neighboring sensor s_a and s_b. When sensor s_a enters tone-signal range, it records its ID in its $Entry_E$ table and then broadcasts its ID=s_a to all of its neighbors. Upon receiving the message from sensor s_a, sensor s_b records ID of s_a in its $Entry_E$ table. Afterward, when sensor s_b enters the tone-signal range, it similarly records its ID in the $Entry_E$ table and then broadcasts a message containing its ID. When receiving this message, sensor s_a records the ID of s_b in its $Entry_E$ table. According to the order of IDs recorded in $Entry_E$ table, sensors s_a and s_b know the fact that sensor s_a is located at the west side of sensor s_b.

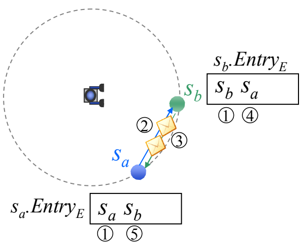


Fig. 3. An example of the *Table Ambiguous Problem*.

Although using the order of entering tone-signal range can generally distinguish the relative locations of neighboring sensors, however, the *Table Ambiguous* and *Mistake Problems* exist. Figure 3 gives an example of the *Table Ambiguous Problem*. In Fig. 3, sensors s_a and s_b enter tone-signal range at the same time and hence they can not distinguish their relative locations. Figure 4 depicts an example of the *Mistake Problem*. In Fig. 4, sensor s_a enters tone-signal range earlier than s_b but it is invalid if we conclude that sensor s_a is located at the west side of s_b. This implies that the relative location can not be correctly determined because that the shape of tone-signal range is a disc.

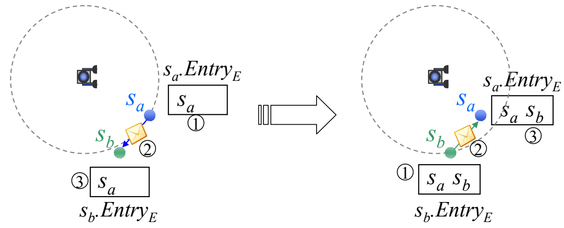


Fig. 4. An example of the *Mistake Problem*.

2.3 Handling the Table Ambiguous Problem

To cope with the *Table Ambiguous Problem*, another tables $Exit_E$ should be additionally constructed to record the order of sensors leaving tone-signal range. The operations for maintaining $Enter_E$ and $Exit_E$ tables are described below. Any sensor, say *s*, that enters (leaves) the tone-signal range should firstly record its ID in its table $Enter_E$ ($Exit_E$) and then broadcasts its ID. Upon receiving the broadcasting message, all neighboring sensors of *s* should record the ID of *s* in their own $Enter_E$ ($Exit_E$) tables.

Herein, we introduce a notation δ to denote the order of two neighboring sensors entering the tone-signal range. Let s_a δ s_b denote the order of two sensors s_a and s_b entering tone-signal range, where $\delta \in \{>_{Ix}, <_{Ix}, =_{Ix}\}$. For instance, $s_a >_{Ix}$ s_b represents that s_a enters tone-signal range earlier than s_b when mobile anchor moves along the east direction. Similarly, let $s_a\, \varepsilon\, s_b$ denote the order of sensors s_a and s_b leaving the tone-signal range, where $\varepsilon \in \{>_{Ox}, <_{Ox}, =_{Ox}\}$. For instance, $s_a >_{Ox} s_b$ represents that s_a leaves tone-signal range earlier than s_b when mobile anchor moves along the east direction.

The following discusses some properties based on the records of $Enter_E$ and $Exit_E$ tables. Three lemmas are therefore developed to help each pair of sensors distinguish their relative locations in a distributed manner.

LEMMA 1. *Sensor s_a is located at the west side of s_b if $s_a >_{Ix} s_b$ and $s_a >_{Ox} s_b$.* □

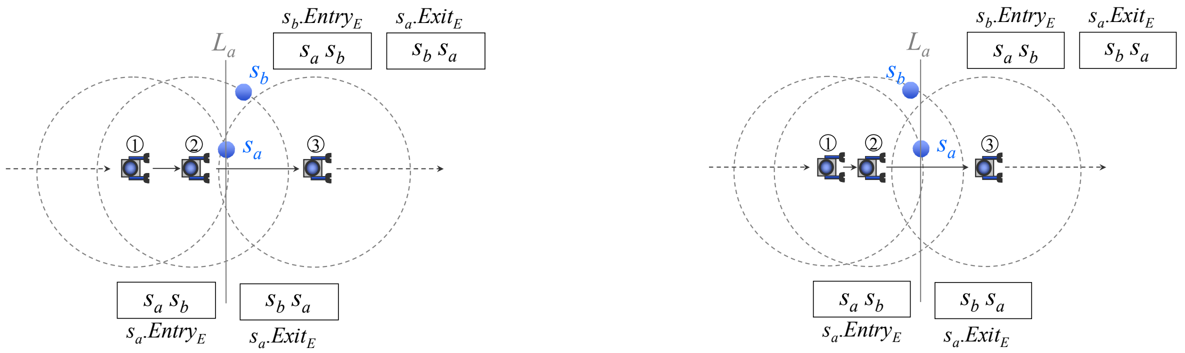
The proof of Lemma 1 is omitted due to limited page length. According to Lemma 1, each pair of sensors s_a and s_b can locally distinguish their relative locations by checking their own $Enter_E$ and $Exit_E$ tables. The following rule is proposed accordingly.

GENERAL RULE. *If the orders of any pair of neighboring sensors s_a and s_b in $Enter_E$ and $Exit_E$ are <s_a, s_b>, sensor s_a is located at the west side of s_b.*

LEMMA 2. *Sensor s_a is located at the west side of s_b if mobile anchor moves in a constant speed v and the conditions $s_a =_{Ix} s_b$ and $s_a >_{Ox} s_b$ hold.* □

LEMMA 3. *Sensor s_a is located at the west side of s_b if $s_a =_{Ox} s_b$ and $s_a >_{Ix} s_b$.* □

The proofs of Lemmas 2 and 3 are omitted due to limited page length. The Lemmas 2 and 3 help each pair of sensors



(a) The first scenario arisen the *Mistake Problem*. (b) The second scenario arisen the *Mistake Problem*.

Fig. 5. The *Mistake Problem.* Assume that s_a enters tone-signal range earlier than s_b, but s_b leaves tone-signal range earlier than s_a.

deal with the *Table Ambiguous Problem*. Sensor s_a selects any of its neighbor s_b and locally checks its *Entry* and *Exit* tables. If their orders in *Entry* or *Exit* tables are different, it represents that s_a and s_b enter or leave tone-signal range at the same time. Sensors s_a and s_b can distinguish their relative locations based on the following two rules.

ENTER-TABLE AMBIGUOUS (ETA) RULE. *Sensor s_a is located at the west side of s_b if the following two criteria are satisfied.*

(1) The orders of sensors s_a and s_b in their $Enter_E$ tables are different.

(2) The order of sensors s_a and s_b in their $Exit_E$ tables is $<s_a, s_b>$.

EXIT-TABLE AMBIGUOUS (XTA) RULE. *Sensor s_a is located at the west side of s_b if the following two criteria are satisfied.*

(1) The orders of sensors s_a and s_b in their $Exit_E$ tables are different.

(2) The order of sensors s_a and s_b in their $Enter_E$ tables is $<s_a, s_b>$.

Herein, we notice that it might cause a collision if sensors s_a and s_b enter or leave tone-signal range at the same time and hence they broadcast *Entering or Leaving* messages simultaneously. To cope with this problem, we additionally introduce random and time-stamp mechanisms. When a sensor enters or leaves tone-signal range, it waits for a random time t and then broadcasts *Entering or Leaving* messages which contain the value of t. As a result, the collision problem can be avoided while a correct record in their *Entry* and *Exit* tables can be maintained.

2.4 Handling the Location Ambiguous Problem

For simplicity and without loss of generality, we discuss the *Mistake Problem* by considering the scenarios that s_a enters tone-signal range earlier than s_b, but s_b leaves tone-signal range earlier than s_a, as shown in Figs. 5(a) and 5(b). Although the *Entry* and *Exit* tables in Fig. 5(a) are identical to those in Fig. 5(b), however, the actually relative locations of s_a and s_b in Figs. 5(a) and 5(b) are totally different. That is, sensor s_a is located at the west side of s_b in Fig. 5(a) but it is located at the east side of s_b in Fig. 5(b). To clearly distinguish the *Mistake Problem* with the *Table Ambiguous Problem*, we further refer the *Mistake Problem* to the *Location Ambiguous Problem*. We observe that the only difference of the two scenarios depicted in Figs. 5(a) and 5(b) is that sensor s_b is located at the different sides of line L_a.

The following Lemma is presented aiming at handling the *Location Ambiguous Problem*.

LEMMA 4. *Assume that relations $s_a >_{Ix} s_b$ and $s_b <_{Ox} s_a$ hold and let*

$$d = dis(loc(s_b), p_{e,p}) - dis(P_{Ly,a,Lx,b}, p_{e,p})$$

Sensor s_a is located at the west or east sides of s_b if d>0 or d<0, respectively. □

Lemma 4 helps each sensor deal with the *Location Ambiguous Problem*. Sensor s_a selects any of its neighbor s_b and locally checks its *Entry* and *Exit* tables. If the *Entry* and *Exit* tables of s_a are identical to those of s_b but the orders of s_a and s_b in *Entry* and *Exit* tables are different, it represents that the *Location Ambiguous Problem* happens. Sensor s_a can distinguish its relative location with any neighbor s_b by applying the following rule.

LOCATION AMBIGUOUS RULE. *If d>0, sensor s_a is located at the west side of sensor s_b. Otherwise, sensor s_a is located at the east side of sensor s_b.*

Based on the proposed *General Rule*, *ETA Rule*, *XTA Rule* and *Location Ambiguous Rule*, each pair of neighboring sensors is able to distinguish their relative locations with respect to each other.

2.5 The DRL Algorithm

The following presents the procedures of the proposed *DRL* mechanism. The *DRL* mechanism consists of several event-driven procedures which will be automatically executed by each sensor when a certain event is triggered. When a sensor s_a enters or leaves the tone signal, the event of *Enter* or *Lost tone* is triggered, respectively. At this moment, sensor s_a will automatically perform the operations defined in *Procedure Enter_Lost_Tone*(*Status*).

```
Procedure Enter_Lost_Tone(Status)
Let TS_x denote the tone signal type
where x ∈ {w,e,s,n}.
for any of sensors s_a do
  switch(Status)
```

Case of *Enter Tone*:
$s_a.EntryTable \leftarrow s_a.id$
$s_a.EntryTable \leftarrow s_a.clock$
$s_a.EntryTable \leftarrow TS_x$
Wait for a random time t_1
Broadcast $Entering(s_a.id, TS_x, t_1)$ message to $N(s_a)$
Case of *Leave Tone*:
$s_a.ExitTable \leftarrow s_a.id$
$s_a.ExitTable \leftarrow s_a.clock$
$s_a.ExitTable \leftarrow TS_x$
Wait for a random time t_2
Broadcast $Leaving((s_a.id, TS_x, t_2)$ message to $N(s_a)$
end for

Another procedure, called *Receiving_Broadcast* procedure, is presented as follows to cope with the event when a sensor s_a receives *Entering* or *Leaving* message from any of its neighbors s_b.

Procedure Receiving_Broadcast(Message)

Let $s_b \in N(s_a)$
for any of sensors s_a **do**
switch(Message)
Case of *Entering Message*
$s_a.EntryTable \leftarrow s_b.id$
$s_a.EntryTable \leftarrow TS_x$
$s_a.EntryTable \leftarrow s_a.clock - t_1$
Case of *Leaving Message*
$s_a.ExitTable \leftarrow s_b.id$
$s_a.ExitTable \leftarrow TS_x$
$s_a.ExitTable \leftarrow s_a.clock - t_2$
end for

III. Simulation Study

This section compares the performance of the proposed *DRL* mechanism against the traditional bounding-box mechanisms *r-DOL* and *s-DOL* [2]. In the *r-DOL* mechanism, the mobile anchor randomly moves and broadcasts its location information to the sensors for localization purpose. Different from the *r-DOL*, the *s-DOL* moves the anchor along the snake-like trajectory.

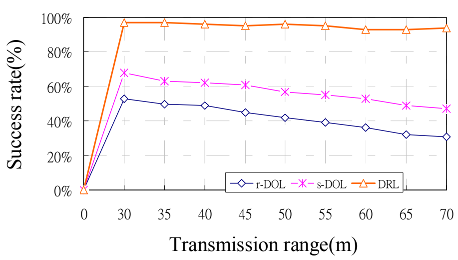


Fig. 6. The comparison of three mechanisms in terms of success rate.

Figure 6 investigates the success rate of distinguishing relative locations of any two neighboring sensors. Three mechanisms are compared by varying the transmission range. The success rates of *r-DOL* and *s-DOL* are decreased with the transmission range. The performance of *s-DOL* is better than *r-DOL*. This is because that all sensors can be visited by the mobile anchor by applying the snake-like movement while some sensors can not be visited if the random movement is applied. On the contrary, the proposed *DRL* mechanism is not impacted by the transmission range. In general, the proposed *DRL* mechanism outperforms the traditional *r-DOL* and *s-DOL* mechanisms in terms of success rate.

Figure 7 investigates the impact of density on success rate of distinguishing relative locations of any two neighboring sensors. The success rates of *r-DOL* and *s-DOL* are decreased with the node density. This is because that the average distance of each neighboring pair decreases with the node density. The *r-DOL* and *s-DOL* mainly apply the bounding-box based techniques which lead to a significant number of overlapped bounding-box when the average distance of neighboring sensors is decreased. As a result, they have a poor performance in distinguishing the relative locations of neighboring sensors. The proposed *DRL* mechanism has similar performance and is not impacted by the node density since tone signals can help neighboring sensors distinguish their relative locations. In general, the proposed *DRL* mechanism outperforms the traditional *r-DOL* and *s-DOL* mechanisms in terms of success rate.

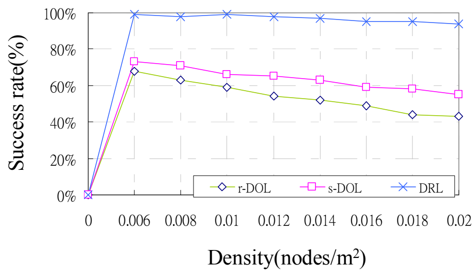
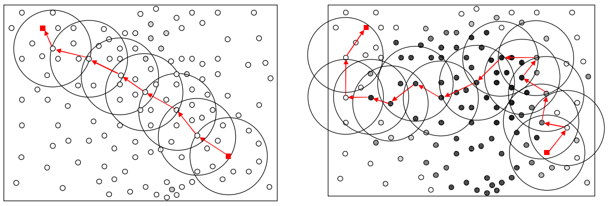


Fig. 7. The comparison of three mechanisms in terms of success rate.

Figures 8 and 9 further verify the impact of relative location information on routing performance. There are 1800 sensor nodes randomly deployed in a 300m × 300m monitoring area. All sensors have a common transmission range of 45m. The location aware routing protocol [6] is applied to construct a route between source and destination sensors that are at least 300m distance away.

Figure 8 gives the screenshots by applying the proposed *DRL* mechanism and the compared *DOL* mechanism. The randomly selected source and destination nodes are marked by the red square. Each sensor is marked with a level of gray color representing the number of neighboring nodes that fail to distinguish the relative locations with their neighbors. A sensor with light (charcoal) gray color denotes that it can (cannot) distinguish the relative locations with most of its neighboring sensors. In particular, a node with white color represents that it and each of its neighbor can successfully distinguish their relative locations. A route from source to destination constructed based on the relative location information is denoted by a sequence of arrows. As shown in Fig. 8(a), most sensors that apply the proposed *DRL* mechanism can successfully distinguish their relative locations with each neighbor and thus they are marked with white or light gray colors. On the contrary, as shown in Fig. 8(b), applying the *DOL* mechanism leads to a number of



(a) (b)

Fig. 8. The impact of relative location information on location-aware routing performance.

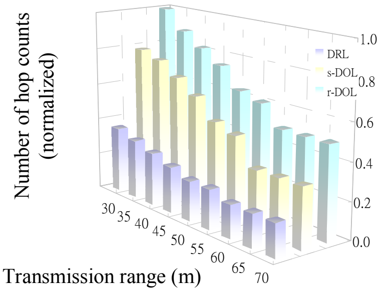


Fig. 9. The comparison of three mechanisms in terms of route length.

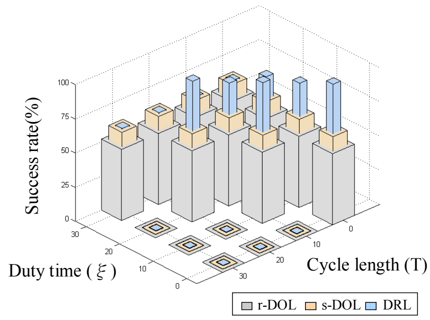


Fig. 10. The impacts of duty time ξ and cycle length T on success rate of distinguishing relative locations.

sensors being failure to distinguish their relative locations with their neighbors and hence most of them are marked with a charcoal gray color. As a result, the route constructed based on the location information supported by *DOL* has a larger path length than that supported by the proposed *DRL* mechanism.

Figure 9 gives the general results of route length comparisons obtained from extensive experiments. In general, the numbers of hop counts of the compared three mechanisms are decreased with the transmission range. This is because that the location-aware routing mechanism always selects the node that is closest to the destination as its next-hop relay node. The proposed *DRL* mechanism outperforms the compared *s-DOL* and *r-DOL* mechanisms in terms of route length. Since the *DRL* mechanism provides more accurate relative location information than the compared two mechanisms, it has better results. The average route lengths by applying the *DRL* mechanism are similar in all cases since *DRL* helps most sensors distinguish the relative locations with each of their neighbors. The *s-DOL* and *r-DOL* lead to a poor situation where a number of sensors can not distinguish the relative locations with their neighbors due to the overlapped bounding-box.

Figure 10 investigates the success rate of distinguishing relative locations of any two neighboring sensors. Three mechanisms are compared by varying the duty time ξ and cycle length T. As a result, the success rates of *r-DOL* and *s-DOL* are not impacted by parameters ξ and T and always keep a constant value. On the contrary, the success rate of the proposed *DRL* mechanism increases with ξ and decreases with T. Given a fix value of T, the number of sensors receiving tone signals is increased with ξ. Based on the received tone signals, each of these sensors and its neighbors can distinguish their relative locations. Similarly, given a fix value of ξ, a larger T leads to fewer sensors receiving tone signals. As a result, the success rate is decreased with T. In particular, when the ξ value is equal to zero, it means that the mobile anchor did not broadcast any tone signal and hence the *s-DOL* and the proposed *DRL* mechanisms have the same success rate.

IV. Conclusions and Future Work

Distinguishing relative locations of each pair of neighboring sensors can help find the best forwarder when applying the location-aware routing, especially in the environment where each sensor has an inaccurate location-information like bounding-box. This paper proposes a *DRL* mechanism, which uses tone signals to distinguish the relative locations of neighboring sensors. Firstly, a *General Rule* is proposed to differentiate the order of entering or leaving the tone-signal range. However, for some special cases, the *Table* and *Location Ambiguous Problems* exist. The *ETA Rule*, *XTA Rule* and *Location-Ambiguous Rule* are further proposed to cope with the special cases. The proposed four rules can be implemented in each sensor for distinguishing relative locations. Theoretical analysis is developed to calculate the impacts of duty time of tone signals in terms of energy conservation and accuracy of relative locations. Simulation results depict that the proposed *DRL* mechanism can significantly improve the performance of routing in terms of the number of hops and the success rate for packet transmission.

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