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A Single Chord Localization Algorithm for Wireless Sensor Networks

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Abstract

This paper presents a novel range-free single chord localization algorithm with low energy consumption and high accuracy for wireless sensor networks. A mobile anchor node and a mobile reference node are employed to periodically broadcast beacon messages and reference messages, respectively. Each sensor node is equipped with a received signal strength indicator for comparing the signal strength. By using the edge function and the result of comparing signal strength, each sensor node only needs one chord on the communication circle for localization. Compared with previous approaches that require multiple chords, less beacon messages are required by the sensor nodes. In the proposed algorithm, the localization error mainly depends on the move distance interval. However, for the other approaches, large localization errors can be observed according to the angle between chords which may descend the localization accuracy dramatically. Analysis results indicate that the proposed algorithm is superior to other approaches in energy consumption and localization accuracy.

Keywords: *Localization, Mobile anchor points, Wireless sensor network*

1. Introduction

Localization is one of the important issues in wireless sensor networks (WSNs). Several approaches have been proposed for dealing with efficient localization. Existing approaches can be categorized as range-based and range-free schemes. In the range-based schemes, the sensor nodes usually employs additional hardware to measure the useful information, such as the time of arrival [1], time difference of arrival [2], angle of arrival [3], distance [4,5], or the communication coverage area [6]. Although such schemes can achieve high localization accuracy, the additional hardware is a burden for economic approaches. In the range-free schemes, simple hardware is employed since the localization information is received from beacon messages. However, large amount of beacon messages are required to determine several chords on the communication circle for localizing, such as the schemes in [7,8,9]. Moreover, localization accuracy becomes critical in recent researches [10,11], the previous range-free schemes are hard to guarantee the accuracy since the localization error is related with the angle of these chords.

For achieving less energy consumption and higher accuracy in localization, this paper presents a novel range-free scheme that uses only one chord on the communication circle for localization. Our analysis indicates that our scheme improves both energy consumption and accuracy.

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2. Double Mobile Anchor Nodes Scheme

The considered sensing field consists of randomly distributed sensor nodes and mobile anchor points. The sensor nodes are static in their positions for sensing tasks and each of them is equipped a timer and a received signal strength indicator (*RSSI*). Two kinds of mobile anchor points are assumed in this paper: mobile anchor node (*AN*) and mobile reference node (*RN*). Both *AN* and *RN* are sufficient with energy for moving and broadcasting messages. Only *AN* is equipped with the device such as GPS to update its position information at anytime. *AN* and *RN* are able to traverse in random waypoint model [3] for assisting sensor nodes to determine their locations. As shown in Figure 1., *AN* and *RN* paralleling traverse in the same direction and *RN* is always in the left side of *AN* following the moving direction. While *AN* changes direction, *RN* automatically adjusts its position. In the obstacle environment, no obstacles or sensor nodes are assumed to locate between the trajectories of *AN* and *RN*.

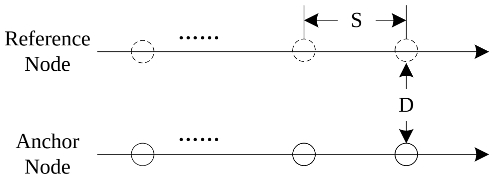

Figure 1. Double Mobile Anchor Nodes Scheme

The notations in this paper are presented in Table 1.:

Table.1 Notations in the Paper

Notations	Description
(x,y)	Current position of *AN*
{AN,(x,y)}	Beacon messages which are broadcasted by *AN*
{RN}	Reference messages which are broadcasted by *RN*
R	The maximum communication range both for *AN* and *RN*
S	Periodical move distance interval
T	Periodical broadcast time interval
D	Distance between *AN* and *RN*
$RSSI_{AN}$	The signal strength of received beacon message from *AN*
$RSSI_{RN}$	The signal strength of received reference message from *RN*
$RSSI_{\varepsilon}$	The threshold signal strength value for the first received *AN*'s message
$Time_{\varepsilon}$	The maximum waiting time between two consecutive received beacon
RgtA	The signal strength comparing result of $RSSI_{AN}$ and $RSSI_{RN}$
Dir	The direction of the chord from *FstBcn* to *SecBcn*
$Side_o$	The side information from the directional chord.

3. The Proposed Algorithm

As shown in Figure 2., the proposed localization algorithm includes two stages: beacon points selecting stage and localization calculating stage.

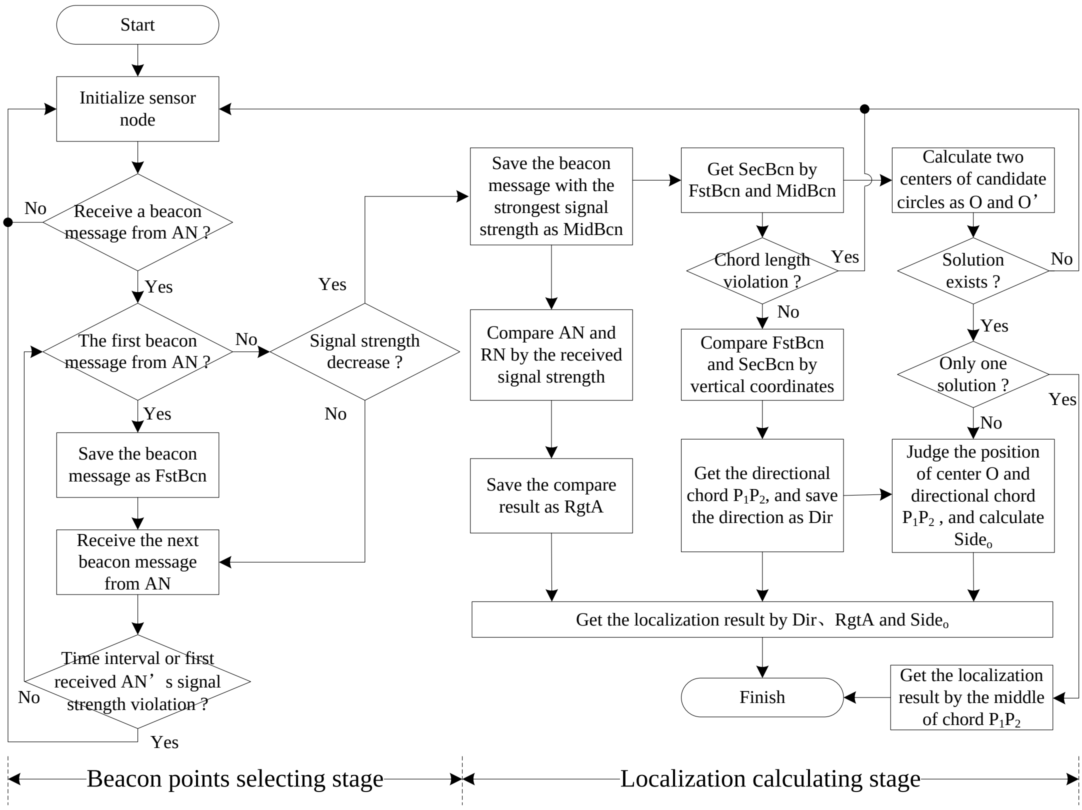

Figure 2. Proposed Localization Algorithm

3.1. Beacon Points Selecting Stage

While *AN* and *RN* traverse in the sensor field with random waypoint model, sensor nodes which are in the communication circle will receive beacon messages *{AN,(x,y)}* from *AN* and reference messages *{RN}* from *RN* simultaneously. If the constraints are satisfied, the position information *(x,y)* will be saved as beacon points by the sensor nodes. The proposed algorithm considers three beacon points: *FstBcn*, *MidBcn* and *SecBcn*, which indicate the start point, the middle point and the end point for a chord on the communication circle, respectively.

When the sensor node receives the first beacon message from *AN*, it saves the position information as *FstBcn*. Under the time interval constraint, the sensor node keeps on temporary saving the successive position information and detects the beacon message's signal strength $RSSI_{AN}$. As *AN* traverses closer to the sensor node, the stronger $RSSI_{AN}$ will be recognized by the sensor node. While $RSSI_{AN}$ begins to decrease, sensor node saves the position information as *MidBcn* which has the strongest signal strength. After recognizing *FstBcn* and *MidBcn*, *SecBcn* can be derived by Eq. (1).

$$SecBcn=2\times MidBcn-FstBcn \qquad (1)$$

3.2. Localization Calculating Stage

In the localization calculation stage, three factors are considered: *RgtA*, *Dir* and $Side_o$. *RgtA* indicates the signal strength comparing result of $RSSI_{AN}$ and $RSSI_{RN}$. *Dir* stands for the direction of the chord from *FstBcn* to *SecBcn*. $Side_o$ presents the side information from the directional chord.

3.2.1. Calculation for *RgtA*: In the beacon points selecting stage, sensor node receives messages beacon message *{AN,(x,y)} and* reference message *{RN}* from *AN* and *RN* simultaneously. Although the exact content in *{RN}* is not considered in the proposed algorithm, the signal strength from *RN* is a critical factor for localization. Since the beacon message is accompany with the reference message, while the sensor node receives beacon message, it compares $RSSI_{AN}$ and $RSSI_{RN}$. In the proposed algorithm, *RgtA* is initialized to 0 and it will be set to 1if $RSSI_{RN}$ is greater than $RSSI_{AN}$ during beacon points selecting stage.

3.2.2. Calculation for *Dir*: According to the *Edge Function* presented in [12], a directional edge P_1P_2 is introduced based on the chord with two ends *FstBcn* and *SecBcn*. As shown in the below operation, the direction is denoted as *Dir* and P_1 is guaranteed to be no higher than P_2.

If *FstBcn* is lower than *SecBcn*, *Dir* is set to 1, P_1 is set to *FstBcn* and P_2 is set to *SecBcn*. If *FstBcn* is higher than *SecBcn*, *Dir* is set to -1, P_1 is set to *SecBcn* and P_2 is set to *FstBcn*. While the chord is horizontal, only *Dir* is set to 0.

```
if(FstBcn is lower than SecBcn)                 // chord is upward
      {P1 = FstBcn; P2 = SecBcn; Dir = 1;}
else if(FstBcn is higher than SecBcn)           //chord is downward
      { P1 = SecBcn; P2 = FstBcn; Dir = -1;}
else                                            //chord is horizontal
      {Dir = 0;}
```

3.2.3. Calculation for $Side_o$: Taking Figure 3.a as an example, according to one shared chord, it is easy to draw two possibly existed circles which have same radius R. The center points of these two possible circles are denoted as *O* and *O*’, respectively. It is obvious that either *O* or *O*’ is the sensor node’s real position.

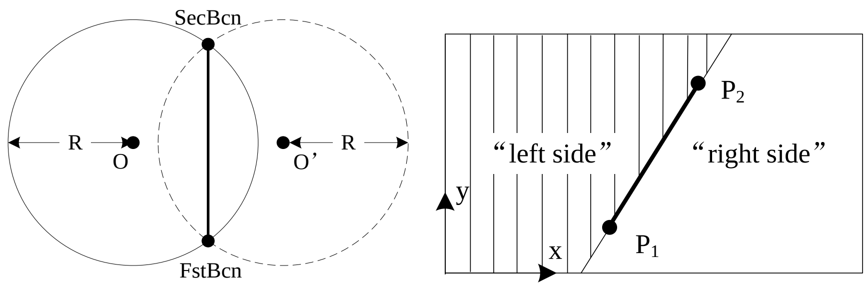

Figure 3.a **Figure 3.b**

Figure 3. Two Circles Share One Chord and “Side” Definition

Assuming the coordinates for *FstBcn* and *SecBcn* are (x_1,y_1) and (x_2,y_2), the two candidate circles' center points *O* and *O*’ can be derived from the following calculation:

$$O_x = x_3 + \frac{(y_1 - y_2)\times\sqrt{R^2-(q/2)^2}}{q}, \qquad O_y = y_3 + \frac{(x_2 - x_1)\times\sqrt{R^2-(q/2)^2}}{q}$$

$$O_x^{'} = x_3 - \frac{(y_1 - y_2)\times\sqrt{R^2-(q/2)^2}}{q}, \qquad O_y^{'} = y_3 - \frac{(x_2 - x_1)\times\sqrt{R^2-(q/2)^2}}{q}$$

where

$$q = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

$$x_3 = (x_1 + x_2)/2, \qquad y_3 = (y_1 + y_2)/2$$

According to the *edge function* introduced in [12], and P_1 is always no higher than P_2, the definition of "*side*" is shown in Figure 3.b. The center *O* locates in which "*side*" of the edge P_1P_2 can be determined by Eq.(2).

$$Side_o=(P_{1y}-P_{2y})(O_x-P_{1x})+(P_{2x}-P_{1x})(O_y-P_{1y}) \qquad (2)$$

If $Side_o$ is negative, the center *O* locates in the right side of edge P_1P_2. Consequently, *O*' should locates in the left side. If $Side_o$ is positive, *O* locates in the left and *O*' locates in the right side of edge P_1P_2. Since the one circle case can be handled during calculating *O* and *O*', $Side_o$ cannot be zero after the calculation in Eq. (2).

3.3. Location Result

Finally, the localization of the sensor node is determined according to *Dir*, $Side_o$ and *RgtA*.

Taking Figure 4.a as an example, the real location of the sensor node locates in the left side of directional chord P_1P_2. Since *RN* is always in the left side of *AN* following the moving direction, when the chord is not horizontal and upward (*Dir*=1), the signal strength of *RN* must be greater than *AN* (*RgtA*=1). If $Side_o$ is positive, *O* is the location result, otherwise *O*' is. Hence, the position of the sensor node can be derived. Table 2. describes all the cases for the final localization results when the chord is not horizontal (*Dir*≠0).

When the chord is horizontal, take Figure 4.b as an example, the real position of the sensor node locates below the directional chord. In this case, *RgtA* is 1 and the direction of the chord is from right to left. It can be observed that the real position of the sensor node is the lower one from *O* and *O*'. Table 3. describes the final localization results when the chord is horizontal (*Dir*=0).

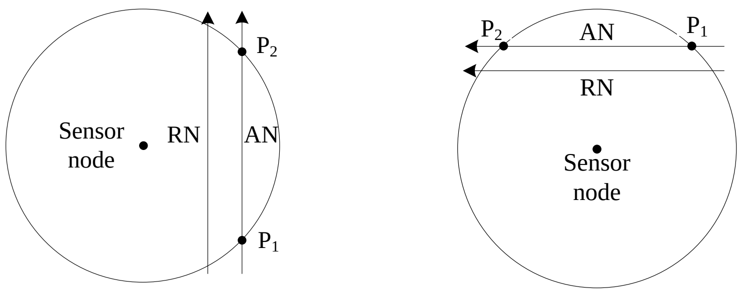

Figure 4.a **Figure 4.b**

Figure 4. Examples of Location

Table 2. Final Localization Results when Dir≠0

Dir	*RgtA*	$Side_o$	Location Result	
			O	*O*'
1	1	>0	√	
		<0		√
	0	>0		√
		<0	√	
-1	1	>0		√
		<0	√	
	0	>0	√	
		<0		√

Table 3. Final Localization Results when Dir=0

RgtA	Direction of P_1P_2	Localization Result
1	Left to right	High point of *O* or *O*'
	Right to left	Low point of *O* or *O*'
0	Right to left	Low point of *O* or *O*'
	Left to right	High point of *O* or *O*'

4. Analysis

4.1. Constrains of Chord Length

Assume the chord length from *FstBcn* to *SecBcn* is notated as *L*, only the chord with valid length can be accepted for localization. The acceptable longest chord and shortest chord are shown in Figure 4.a and Figure4.b, respectively.

In order to guarantee the correct *RgtA* value, the sensor node should be avoid to locate between *AN* and *RN*. Although when *AN* is closer to the sensor node than *RN*, the tolerable chord length could be 2R, more strict constrain should be considered when *RN* is closer to the sensor node than *AN*, as shown in Figure 5.a. Moreover, the critical situation appears when *FstBcn* and *SecBcn* are right on the border of the communication circle. Hence, the longest chord in this case can be derived as $2(\sqrt{R^2 - D^2})$, where R is the communication radius and *D* is the distance between *AN* and *RN*.

During the beacon point selecting, the received signal strength of *AN* must satisfy from increasing to decreasing. Hence, the shortest chord length L should be 2S, as shown in Figure 5.b.

In conclusion, the constraint for chord length is summarized in Eq.(3):

$$2S < L < 2(\sqrt{R^2 - D^2}) \qquad (3)$$

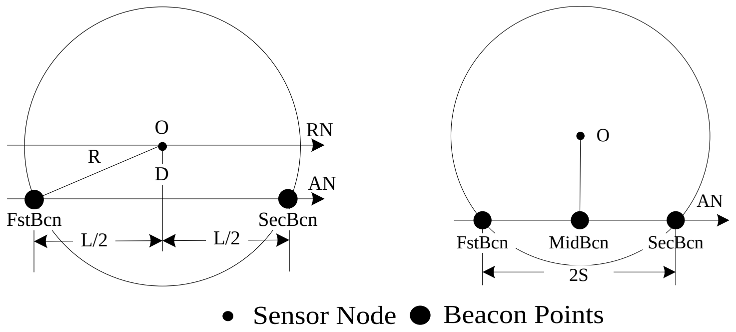

Figure 5.a **Figure 5.b**

Figure 5. Constraints for Chord Length

4.2. Obstacle Tolerance

The obstacle environment is considered in the proposed WSN. We assume that signals can only be received in the line-of-sight propagation. Since there are no obstacles between *AN* and *RN*, it is obviously that we only need to consider when the obstacle is closer to *AN* than *RN*. Hence, two predefined constant values $RSSI_\varepsilon$ and $Time_\varepsilon$ are employed to handle obstacle environment.

When obstacles interfere with selecting *FstBcn*, as shown in Figure 6.a, large localization error may be caused by selecting a wrong *FstBcn* which is too far away from the border of the communication circle. Hence, $RSSI_\varepsilon$ assists to avoid this mistake by comparing $RSSI_\varepsilon$ with the first received $RSSI_{AN}$. Merely when the first received $RSSI_{AN}$ is weaker than $RSSI_\varepsilon$, the received *{AN,(x,y)}* is acceptable. Moreover, the communication circle with signal strength $RSSI_\varepsilon$ guarantees that *FstBcn* should not be over one movement distance interval away from the idea communication circle.

When obstacles interfere with the selecting *MidBcn*, as shown in Figure 6.b, the sensor node cannot discovery *MidBcn* on this chord or selects a wrong *MidBcn* with large error. The strongest $RSSI_{AN}$ should be discovered during certain of time which is notated as $Time_\varepsilon$. So, the timer in the sensor node records the time interval between two consecutive beacon messages and compares with $Time_\varepsilon$. If the consumed time is longer than $Time_\varepsilon$, the sensor node will discard the received *FstBcn* and restart beacon points selecting stage again.

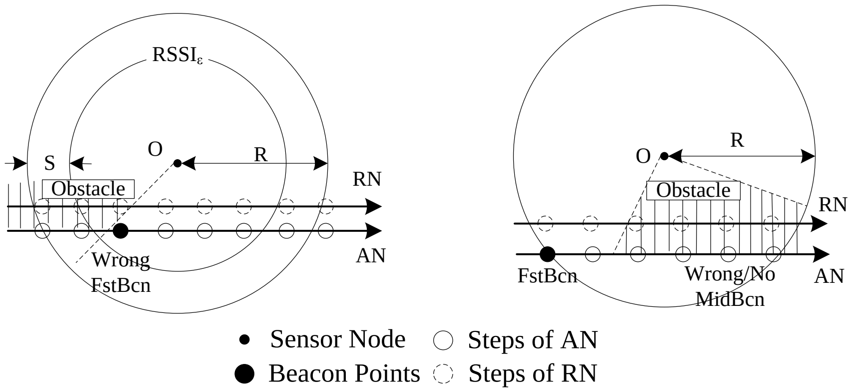

Figure 6.a **Figure 6.b**

Figure 6. Obstacle Environment

4.3. Energy Consumption

The energy consumption is one of the critical factors for the living time of the sensor nodes. In the proposed algorithm, the sensor nodes only need to receive 1/4 and 1/2 number of beacon messages comparing with the Ssu'[7] and Yu's[8] schemes, respectively.

For Ssu's scheme, while discovering beacon points, at least two chords on the communication circle should be considered. Hence, the sensor node needs to receive all the beacon messages when the mobile anchor node moves along these two chords. Yu's scheme reduces the number of received beacon messages to half of Ssu's, however, two chords are still required.

For the proposed algorithm, since we use a single chord scheme and only half chord is required (from *FstBcn* to *MidBcn*), so the sensor nodes receive less beacon messages which decreasing the communication cost of the sensor nodes. Although *RN* broadcasts reference messages, the sensor nodes do not need to save the exact reference messages, they only need to detect the signal strength.

4.4. Localization Accuracy

In the previous range-free localization schemes, such as [7,8], usually employ multiple chords for computation. Since the chords are arbitrary intersected with each other, the localization error is highly related with the intersection angle.

In Ssu's approach [7], an enhanced beacon point selection algorithm was presented for higher precision of localization. It is based on the received signal's strength to select three positions (points A, B and C, as shown in Figure 7.a and Figure 7.b) which have most similar signal strength. However, due to the error caused by the movement distance interval, C_e may be considered as the beacon point instead of C which is shared by two chords. The half length of chord AC_e is notated as L_e and the distance between C and C_e is assumed as S which means one movement distance interval. The ideal location is denoted as O and the wrong location is denoted as O_e. As shown in Figure7.a and Figure7.b, the location error can be derived as $|OO_e| = r - \frac{L_e}{Cos(\alpha)}$ and $|OO_e| = \frac{L_e}{Cos(\alpha)} - r + S$, respectively. Where $r \leq R$ and α is the angle between the error chord AC_e and line OO_e. Large error can be observed according to the angle α. Similar analysis can be derived when wrong selection happens for A or B.

In Yu's scheme [8], the theoretical largest localization error happens when one is ideal and the other beacon point is S distance away from the chord center. As shown in Figure 7.c, the largest localization error is $|OO_e| = S / Sin(\alpha)$, which can become large when is close to 0°

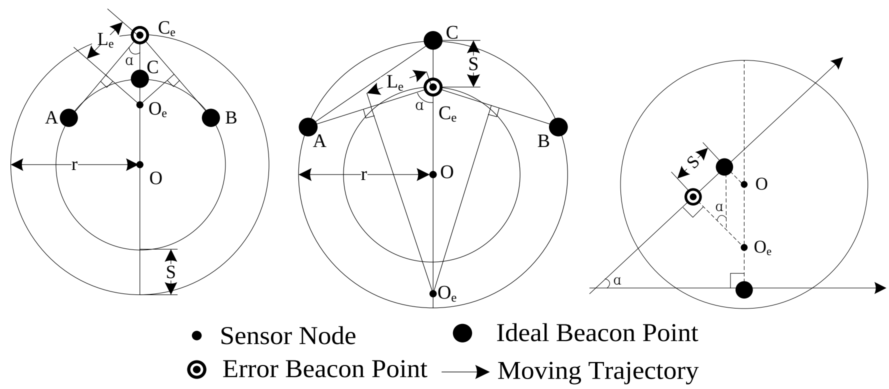

Figure 7.a **Figure 7.b** **Figure 7.c**

Figure 7. Localization Error in Ssu's and Yu's Schemes

However, in the proposed algorithm, the limited localization error can be observed in horizontal and vertical directions. The maximum horizontal direction error happens when *MidBcn* is incorrectly recognized so that away from the middle point of the chord. Since $\left\lfloor \frac{Time_\varepsilon}{T} \right\rfloor - 1$ indicates the maximum number of *AN* steps which may be warded off by obstacles, and *MidBcn* companies the strongest $RSSI_{AN}$, the horizontal location error in $|OO_e|$ is presented as Eq.(4.a). As shown in Figure 8.a, the maxim horizontal location error is only S/2 when all the AN steps are correctly recognized.

$$|OO_e|_{hor} = \left\lfloor \frac{Time_\varepsilon}{T} \right\rfloor \times S / 2 \qquad (4.a)$$

As shown in Figure 8.b, when both *FstBcn* and *SecBcn* are *S* distance away from the communication circle border and *MidBcn* is exact on the perpendicular position of the chord, the maximum vertical error is described as Eq.(4.b), where *S* and *L* indicate the broadcast distance interval and chord length, respectively. Since no sensor nodes locate between *AN* and *RN*, and the signal strength pattern must be recognized from increasing to decreasing, the previous analysis present the constraint for the chord length should be restricted between *2S* and $2(\sqrt{R^2 - D^2})$. Hence, localization error is limited within a certain range for the proposed single chord scheme.

$$\left|OO_e\right|_{ver} = \sqrt{R^2 - (\mathrm{L}/2)^2} - \sqrt{R^2 - ((\mathrm{L}+2\mathrm{S})/2)^2} \qquad (4.b)$$

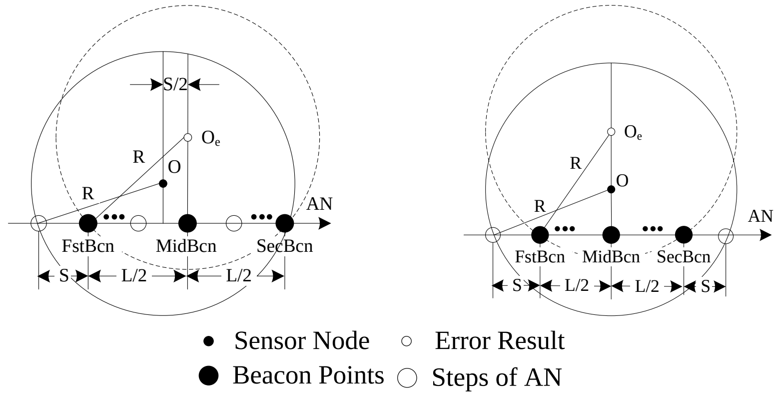

Figure 8.a **Figure 8.b**

Figure 8.Localization Errors in the Proposed Scheme

5. Conclusion

This paper proposes a single chord localization scheme according to a mobile anchor node and a mobile reference node. Each sensor node only requires one chord for localization. Comparing with previous approaches which require multiple chords, less beacon messages are required by the sensor node and limited localization error can be observed. Analysis results indicate that the proposed algorithm is superior to other approaches in energy consumption and localization accuracy.

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