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Abstract—
Sensor localization has become an essential requirement for realistic applications over Wireless Sensor Networks (WSNs). Radio propagation irregularity and the stringent constraint on hardware cost, however, make localization in WSNs very challenging. Compared to range-based localization that depends on received signal strength to estimate absolute point-to-point distance, range-free localization is more appealing since it can achieve higher localization accuracy without introducing extra hardware. In this paper, we perform thorough performance evaluation on two novel range-free localization methods, Approximate Point In Triangle (APIT) [7] and Ring Overlapping based on Comparison of Received Signal Strength Indicator (ROCRSSI) [10]. We disclose the inherent “undetermined node” problem of APIT, and investigate the system configurations that directly influence the performance of both methods, including anchor deployment strategies, which are ignored by most existing papers. We also illustrate the relationship between these configurations and the achievable estimation accuracy. The performance comparison between ROCRSSI and APIT shows that ROCRSSI outperforms APIT in terms of estimation accuracy and energy efficiency under the same system configuration. ROCRSSI also effectively alleviates the “undetermined node” problem of APIT.

Key Words—
Performance Evaluation, Range-Free Localization, Wireless Sensor Networks

I. INTRODUCTION AND BACKGROUND

With recent advances in wireless communication and MEMS (Micro-Electro-Mechanical Systems) technology, it becomes realistic to construct tiny sensor nodes that integrate sensors, processors, memory, wireless communication, and power supply within the size of several cubic millimetres. Large quantities of such sensor nodes can be simply dropped in place to monitor a wide variety of real-world phenomena. Through short-range wireless communication, sensor nodes form Wireless Sensor Networks (WSNs) to coordinate their behaviour, collect and relay measurement data, and process the data in a distributed fashion. Such networks have been used for various applications, such as habitant monitoring, environment monitoring, and target tracking.

Location information plays a crucial role in understanding the application context in WSNs. First, location information is needed to identify the location where an event originates, for instance, the location of a monitored vehicle, or the spot where a thief breaks into a building. Second, location information can assist in a lot of system functionalities such as geographical routing [9], network coverage checking [12], and location-based information querying [6]. Third, location awareness facilitates a lot of application services such as location directory service that provides doctors with the information of nearby medical equipments and personnel in a smart hospital. It is a natural trend that with the advance of WSN technologies, a lot of protocols and applications will depend on location-aware sensing devices.

Because of the above reasons, localization in WSNs has become a very important research direction. Many localization algorithms for WSNs have been proposed to provide per-node location information. They can be divided into two categories: range-based methods and range-free methods. The former ones depend on range information (absolute point-to-point distance information or directional information) to obtain nodes’ locations, while the latter ones do not require any range information at all.

Range-based localization depends on the assumption that the absolute distance between a sender and a receiver can be estimated by received signal strength or by the time-of-flight of communication signal from a sender to a receiver. The accuracy of such estimation, however, is subject to the transmission medium and surrounding environment and usually relies on complex hardware [15]. As the miniaturization of sensor nodes has become an inevitable trend, expensive hardware cost on supporting range-based localization may finally render this method obsolete for wireless sensor networks. In contrast, range-free localization never tries to estimate the absolute point-to-point distance based on received signal strength. As such, the design of hardware can be greatly simplified, making range-free localization very appealing for WSNs.

Among existing range-free localization approaches, Approximate Point In Triangle (APIT) presents a promising solution [7]. Compared with other range-free schemes, such as Centroid localization [2], DV-Hop localization [14], and Amorphous localization [13], APIT is demonstrated to perform best for randomly deployed WSNs [7]. Nevertheless, the performance evaluation of APIT in [7] is not comprehensive. The influence of an important system configuration—anchor deployment strategy—has not been investigated thoroughly. Besides, the inherent “undetermined node” problem of APIT has not been disclosed. Our work on investigating the relationship between different anchor deployment strategies and the achievable localization accuracy, and the severity of the “unde-
termined node” problem under different system configurations complements the performance evaluation of APIT in [7].

Ring Overlapping based on Comparison of Received Signal Strength Indicator (ROCRSSI) is another range-free localization approach proposed recently, aiming at dealing with the “undetermined node” problem of APIT and achieving higher estimation accuracy with lower communication overhead. However, in [10], only a rough comparison on the performance of APIT and ROCRSSI is provided. In this paper, we present more detailed simulation results to demonstrate that ROCRSSI effectively alleviates the “undetermined node” problem and outperforms APIT in terms of achievable estimation accuracy and energy efficiency. Furthermore, system configurations that directly affect the performance of ROCRSSI are investigated thoroughly, and the achievable estimation accuracy under different system configurations is presented as guidelines of deciding system parameters when using ROCRSSI for sensor localization.

II. PERFORMANCE EVALUATION ON APIT
A. Introduction of APIT

Similar to other range-free approaches [2], [13], [14], APIT [7] needs a small fraction of nodes serving as anchors whose locations are supposed to know in advance. Since the number of anchor nodes is small, anchor nodes can use the Global Positioning System (GPS) to obtain their location information and anchor nodes can be equipped with powerful radio transceivers. Using beacon messages from these anchors, APIT divides the neighbourhood area of a sensor node into many overlapped triangles. The vertexes of these triangles are anchors this sensor node can hear. The sensor node can narrow down the area in which it may reside by checking whether it falls within a triangle. Utilizing the combination of all audible anchors’ position information, the size of the intersection area of triangles can be reduced, and the gravity of this intersection area is taken as the sensor’s approximate location. As shown in Fig. 1, the shadowed area is the smallest intersection area of all perceived triangles at sensor node S and the gravity of the shadowed area is considered to be the location of S.

Therefore, a sensor node must have the ability to check whether it falls inside or outside a triangle. As shown in Fig. 2, a proved theorem can be used for such test: in a two-dimensional plane, “if there exists a direction such that a point adjacent to M is further/closer to points A, B, and C simultaneously, then M is outside ΔABC. Otherwise, M is inside ΔABC [7]". However, since a node cannot move around to carry out the above test, APIT lets neighbouring sensor nodes exchange information to perform an approximate test, that is, if a node has no neighbouring nodes further or closer to three anchors simultaneously, this node is assumed to fall within the triangle formed by the three anchors. Otherwise, it is assumed outside the triangle.

B. Further Evaluation of APIT

1) Motivation: We will not repeat the same experiments already done in [7]. Instead, we focus on studying the influence of different deployment strategies on APIT performance. Although two node deployment methods, random deployment and uniform deployment, were used in [7], the authors did not investigate more anchor deployment strategies and did not analyze the influence of different anchor deployment strategies on estimation accuracy. We have observed that with the same number of anchors, different anchor deployment strategies can produce large difference in estimation accuracy. Unfortunately, anchor deployment strategies for range-free localization systems, which may greatly influence the achievable accuracy as well as deployment cost, have not been thoroughly investigated. N. Bulusu et al. [3] propose an incremental adaptive method to deploy anchors. It is required to deploy a large portion of anchors in the terrain at the first step, then the deployment positions of additional anchors are sequentially determined one by one, based on the prediction on estimation error with the available anchors at current time. However, the best way of deploying anchors at the first step has not been addressed in [3].

2) Evaluation Results: We have thoroughly evaluated the accuracy of location estimation of APIT under four different anchor deployment strategies:

1) Even deployment at the edges of terrain. The anchors are deployed evenly at the edges of terrain.
2) Random deployment at the edges of terrain. The anchors are deployed randomly at the edges of the terrain, and the number of anchors at each edge is the same.
3) Uniform deployment inside terrain. The terrain is partitioned into grids with the same size, and anchors are evenly divided amongst these grids. But the locations of anchors in each grid are randomly selected.
4) Random deployment inside terrain. The anchors are distributed randomly inside the whole square terrain.

Within each deployment strategy, we test different system settings such as sensor radio transmission range, Anchor to sensor Node radio range Ratio (ANR), node density, and Anchor Percentage (AP) [7]. To save space, we omit detailed simulation results, which can be referred to [11]. Briefly, our evaluation presents the following key features of APIT that have not been discovered in [7]:
1) When anchors are deployed at the edges of terrain, even deployment of anchors has better estimation accuracy than random deployment of anchors.

2) When anchors are deployed inside the terrain, uniform deployment of anchors has better estimation performance than random deployment.

3) Anchors’ radio transmission range is the key factor to determine the anchor deployment strategy. If anchors’ radio range is large enough, with the same anchor number, deploying anchors at the edges of terrain always yields smaller average location error than deploying anchors inside the terrain. In contrast, when anchors’ radio range is small, deploying anchors inside the terrain outperforms deploying anchors at the edges of terrain.

4) For different anchor deployment strategies, sensor nodes close to the edges of the terrain usually yield large estimation errors, or cannot use APIT to get location estimation because they do not fall within any triangles formed by anchors.

C. The “Undetermined Nodes” Problem of APIT

A sensor is called an “undetermined node” when it cannot estimate its location because it does not fall within any triangle formed by audible anchors. An example is illustrated in Fig. 3. Although sensor node B can hear four anchors 1, 2, 3, and 4, B does not fall within any triangle consisting of these anchors, thus it has no way to determine its own location with APIT.

Through simulation, it is observed that the “undetermined nodes” problem is very hard to eliminate. Fig. 4 to Fig. 7 present the results of percentage of “undetermined nodes” with different anchor deployment strategies. From the figures, we can see that increasing anchor number and anchor radio range can decrease the number of “undetermined nodes” to some extent but is hard to totally eliminate the problem. For instance, when anchors are uniformly deployed inside the terrain, even if anchor percentage is as large as 18% and ANR is up to 7, nearly 20% of sensor nodes are still “undetermined nodes,” because most sensors near the edges of terrain do not fall inside any triangles.

By carefully analyzing simulation traces, we find that most “undetermined nodes” are close to the edges of terrain. With the increase of the size of terrain, the ratio of the number of sensors close to boundary to the number of total sensors will get smaller. Hence the boundary effect for very large network may be negligible. Nevertheless, for small-sized or middle-sized sensor networks, we need consider seriously the fact that certain number of sensor nodes closed to edges of terrain cannot estimate locations with APIT.

One possible solution to the “undetermined nodes” problem is to deploy one anchor at each corner. In this case, the radio range of these anchors must be very large to thoroughly eliminate all “undetermined nodes.” In some situations it’s probably hard to get a good control of the exact position of each anchor. For instance, sensors and anchors are dropped from an airplane. As a result, solving the “undetermined nodes” problem with APIT could be either costly by requiring large power of anchors at corners or impractical for situations where it is difficult to control deployment positions precisely.

III. PERFORMANCE EVALUATION OF ROCRSSI

A. Introduction to ROCRSSI

In order to overcome the deficiency of APIT, paper [10] proposes a method that uses Ring Overlapping based on Comparison of Received Signal Strength Indicator (ROCRSSI). The motivation of ROCRSSI is to get more accurate estimation and reduce the number of “undetermined nodes” with small number of anchors. Since ROCRSSI does not try to map the received signal strength to absolute point-to-point distance, it belongs to range-free localization approaches. Notably, ROCRSSI only compares the relative strength of RSSI and does not depend on absolute RSSI values.

The example in Fig. 8 shows scenarios in which the sensor node S cannot estimate its location with APIT, but can do so with ROCRSSI. In Fig. 8(b), sensor node S is outside ΔABC, where A, B, C are three audible anchors at S. But it can use rings instead of triangles to narrow down the possible area in which it resides. If S can determine that its distance to A is larger than the distance between A and B, but less than the distance between A and C, it can conclude that it falls within the ring centered at A with the inner radius equal to the distance between A and B and the outer radius equal to the distance between A and C.
B. Handling Radio Irregularity

An advantage of ROCRSSI is its ability to accommodate radio irregularity. According to the measurement results over real sensor devices, radio propagation is usually not homogenous in all directions [17], that is, different directions have different radio attenuation rates. So a good localization algorithm should accommodate radio irregularity by not assuming isotropic path losses. ROCRSSI does not exclude wrong rings and thus makes incorrect estimation because of the irregularity of radio propagation. Nevertheless, the grid-scan algorithm that sensor nodes use to calculate the gravity of intersection area helps reduce the influence of wrong rings. The grid-scan algorithm takes the area consisting of grids with maximum counter as the final intersection area. In Fig. 9, suppose more than half of the grids generated by RSSI comparison are correct, and the intersection area of all correct rings is the gray area labeled as A. The gravity of area A will be taken finally as the estimated location of the sensor, because even if all wrong rings happen to have no intersections with area A and even if all wrong rings happen to overlap at one place, the counter value associated with the grids at that (wrong) place must be smaller than that of grids in area A. As a result, wrong rings will not be taken into consideration in the location calculation.

If there are some wrong rings overlap with area A, such as the wrong ring $R_2$ in Fig. 9, then the final intersection area may not contain the sensor node. But the final intersection area is a subset of area A and is thus within the area A. Since the size of area A is usually small if the number of audible anchors is large enough, the gravity of the final intersection area will be very close to the real location of the sensor. As such, even if ROCRSSI may generate some wrong rings, it can still yield fairly accurate location estimation. More detailed discussion on ROCRSSI can be found in [10].

C. Simulation results and analysis

1) Radio Model: As demonstrated in [4, 7, 16, 17], radio propagation exhibits the feature of non-isotropic path losses, that is, radio signal attenuation may be different along different directions. Thus, to get a result close to that in real situation, we do not use the perfect circular radio model in our simulation, even if perfect circular radio model will generate much better performance results.

In [7], a DOI (Degree Of Irregularity) radio model is introduced. In this model, the DOI value is defined as the maximum range variation per unit degree change in the direction of radio propagation. As shown in Fig. 10, large DOI values represent large variation of radio irregularity. We extend the DOI model so that it can calculate the possible received signal strength at any specific point within the maximal radio range of a sender.

The extension is based on two assumptions. First, the received signal strength varies continuously with the incremental degree changes in the direction of radio propagation. This phenomenon has been observed and reported with experiments.
over real sensor networks [17]. Second, unlike the previous DOI model, we do not assume any lower bound of radio irregularity, that is, even in the area very close to the sender, the radio irregularity can still exist. This assumption poses a very harsh radio condition to localization algorithms.

In the extended DOI model, DOI value is still used to adjust the degree of radio irregularity. The signal strength at a receiver can be expressed by the formula below.

Received Signal Strength = $\frac{C \cdot d}{K_i}$

Where $C$ is a constant, $d$ is the distance between the receiver and the sender and is smaller than the maximal radio range of the sender, and $K_i$ is the coefficient representing the radio propagation feature in this specific direction. Thus the radio irregularity is expressed by different $K_i$’s associated with different directions. $K_i$ ($0 \leq i \leq 365$) is calculated by the following formula:

$$K_i = \begin{cases} 
1 & i = 0; \\
K_{i-1} + \text{Rand} \cdot \text{DOI} & i = \text{positive integer}; \\
K_i + (i - s) \cdot (K_i - K_s) & \text{Otherwise}.
\end{cases}$$

In the formula, Rand is a random number uniformly distributed between $(-1, 1)$, $s = \lfloor t \rfloor$, and $t = \lceil \hat{t} \rceil$. We first randomly select a direction as the start direction of a sweep half-line started at the sender, and incrementally rotate this sweep half-line in steps with 1 degree each for all the 360 directions. Each step we get a $K_i$ for the correspondent direction. For directions that do not have an integer value of angle from the start direction, we use interpolation to generate their values.

Note that in very rare cases, $K_i$ might become a negative value if a long sequence of negative random numbers are generated. In this case, we set $K_i$ to zero, meaning that the radio strength is negligible.

2) System Parameters and Performance Measurements: In our simulation, we study several system-wide parameters that directly affect the accuracy of location estimation of ROCRSSI. The system parameters used in this simulation are similar with those used in Section II-B.2 and are listed below:

1) Sensor radio transmission range (R).
2) ANR (Anchor to Node Range Ratio).
3) AN (Anchor Number). It’s the number of anchors deployed. AP (Anchor Percentage, defined as the ratio of the number of anchors to the total number of sensors and anchors) is used in the APIT simulation discussed above. The reason we use AN here, rather than AP, is that ROCRSSI does not depend on the density of sensors, since regular sensor nodes do not need to exchange information in ROCRSSI. It is AN, rather than AP, that directly determines the estimation precision in ROCRSSI.
4) Anchor deployment strategies. We investigate four different anchor deployment strategies within a square area with each edge of length 10R. The four different anchor deployment strategies are exactly the same as in those in Section II-B.2.

We define the location estimation error as the Euclidian distance between the real location of a node and its estimated location. For each simulation scenario, ten runs with different random seeds were executed and the results were averaged. We use average location error as the metric to evaluate the accuracy of location estimation. It is defined as the mean of location estimation errors collected over all determined sensor nodes in ten runs. We also calculated confidence intervals at the level of 95%, which roughly are within 5-10% of the mean value. For legibility reason (as the confidence intervals are too small to see clearly in the figures), we did not plot confidence intervals in this paper. A sensor node is determined if it falls within at least three rings (or circles). Otherwise, it is an “undetermined node.” To demonstrate that ROCRSSI can effectively alleviate the “undetermined nodes” problem in APIT, the number of “undetermined nodes” in each scenario was recorded.

3) Results and Analysis:

a) Varying Deployment Strategy: Fig. 11 and Fig. 12 indicate that no matter how DOI and ANR vary, uniform deployment inside terrain always has the best performance given the same number of anchors. Another phenomenon is that the performance of random deployment inside terrain is very close to that of uniform deployment inside terrain. Therefore, the random deployment has approximately the best performance. This feature is very useful because random deployment inside terrain is the easiest way to carry out in practice.

The phenomenon that deployment of anchors inside terrain has better performance than deployment of anchors at the edges
of terrain can be explained as follows. While APIT permits anchors at the edges of terrain to form more triangles and cover more sensors, ROCRSSI, instead, reduces the coverage of rings since a ring will be cut by the edges and the usable range of a ring with ROCRSSI is only half of the ring at most. In contrast, placing anchors within terrain can fully take advantages of a ring because the whole ring can be used potentially for several sensors’ location estimation.

From Fig. 12, however, the differences of average location errors among different deployment strategies are not significant when ANR value is large. As deployment strategies do affect performance of ROCRSSI, the bad influence of improper deployment strategy can be controlled effectively by increasing radio range of anchors. In the following simulation, we will use uniform deployment inside terrain to obtain the best accuracy in each scenario.

b) Varying DOI: Fig. 13 and Fig. 14 show that with the increase of DOI, the average estimation error increases. This is because with the increase of DOI, radio propagation has large variation along different directions. As a result, a ring generated by the comparison of signal strength may not be able to represent the real area that a sensor resides in. The estimation based on incorrect rings is likely to have errors.

Fortunately, at explained in Section III-B, the grid-scan algorithm used to calculate the gravity of intersection area helps reduce the influence of wrong rings. As a result, ROCRSSI can achieve accurate estimation, even in a very irregular radio propagation circumstance with DOI as large as 0.2. For instance, from Fig. 13 and Fig. 14, when AN=81 and DOI=0.2, ROCRSSI can achieve estimation with average error of 0.4R, which is acceptable for most applications [7].

Comparing Fig. 13 with Fig. 14, the performance with ANR value of 15 is very similar to the performance with ANR value of 7.5, demonstrating that when ANR value is large enough, increasing this values further gains very little benefit. This phenomenon is also confirmed by later simulation as shown in Fig. 16 and Fig. 17.

c) Varying AN: Fig. 15 shows that increasing anchor number can reduce the average estimation error. With the increase of deployed anchors, a sensor node can hear more anchors and generate more rings. Hence, the diameter of the intersection area will become smaller, resulting in more accurate estimation.

d) Varying ANR: Fig. 16 illustrates that in a perfectly circular radio propagation model (DOI=0), increasing ANR will reduce the average estimation error till the best accuracy (The size of grid in our simulation is set to 0.05*R, thus the best accuracy cannot be arbitrarily small). The reason is that increasing ANR will increase the number of audible anchors per sensor node, and thus more rings will be generated. The circular radio propagation model guarantees that each ring will certainly contain the sensor node and can be used to narrow down the final intersection area, resulting in very accurate estimation.

Nevertheless, Fig. 17 shows that when radio propagation is irregular, with the increase of ANR, the average estimation error gets down first and then oscillates around a fixed value. Under irregular radio propagation model, increasing ANR has two effects: on the one hand the number of audible anchors per sensor node increases, and on the other hand more incorrect rings might be generated by possible anchor pairs in different directions. When ANR is small, the first effect plays main roles, and thus the average estimation error can be reduced. When ANR is large enough, however, both factors can influence the final outcome, making the result oscillate.

IV. COMPARISON BETWEEN APIT AND ROCRSSI

APIT is sensitive to node density and requires a fairly high node density to get a good performance [7]. Unlike APIT, however, ROCRSSI does not require message exchanges between neighboring regular sensors, so the sensor radio transmission range and the density of sensors will not affect the performance of ROCRSSI. This is an advantage of ROCRSSI over APIT. However, it makes it impossible to obtain absolutely fair comparison between APIT and ROCRSSI.
Nevertheless, from the results in [7], when sensor density is above 15, APIT performs best and the estimation accuracy is relatively stable. To get a roughly fair comparison between APIT and ROCRSSI, we set sensor density to around 15 by adjusting maximal sensor radio range in the following simulation. We use the same extended DOI radio model to test APIT. Moreover, we set optimal anchor deployment strategy and ANR value for both methods (i.e. ANR=15, deployment strategy = even deployment at the edge of terrain for APIT, and ANR=15, deployment strategy = uniform deployment inside terrain for ROCRSSI) to make two approaches achieve roughly best performance with the same number of anchors.

A. Average Location Error

Fig. 18 demonstrates that ROCRSSI always outperforms APIT in terms of average estimation error, no matter whether the radio propagation is regular or irregular. This is because the intersection of rings usually has smaller size than the intersection of triangles. A simple example can be found in 8(b), where it is easy to see that the size of the shadowed ring intersection area is smaller than the size of \( \triangle ABC \) (if we assume that S falls within \( \triangle ABC \)).

The accuracy of APIT in our simulation is worse than that reported in [7] due to different radio models. In paper [7], the DOI radio model is used. In this model, radio irregularity has influence only on the number of immediate neighbors of each sensor node. If each pair of sensors can symmetrically communicate correctly, APIT assumes that they can always make correct decision on whether one is closer to or further from a certain anchor than the other. In the extended DOI model, however, radio irregularity can influence not only the number of immediate neighbors of each sensor, but also the correctness of their decision of their relative distance to a certain anchor by the comparison of received signal strength. Therefore, in the extended DOI model, APIT will have more errors on the decision of whether a node is inside or outside a certain triangle. This factor can significantly decrease the accuracy of APIT, resulting in worse performance than that claimed in [7].

We also implemented an improved version of APIT, denoted as APIT+ in Fig. 18. Using the grid-scan algorithm, when a triangle is added, only those grid points within the maximum range of all heard anchors are added. This method will improve the performance of APIT in face of radio irregularity with extra checking for each grid point.

B. The “undetermined nodes” Problem

Besides the improvement in accuracy, ROCRSSI can eliminate the inherent “undetermined nodes” problem in APIT, no matter what anchor deployment strategy is used. We verify this statement by considering the worst cases in ROCRSSI.

We have studied all four deployment strategies with ROCRSSI and observed that random deployment of anchors inside terrain can yield more “undetermined nodes” than uniform deployment of anchors inside terrain, and random deployment of anchors at the edges of terrain can yield more “undetermined nodes” than even deployment of anchors at the edges. Therefore, we only present the results for two deployment strategies: random deployment of anchors inside terrain and random deployment of anchors at the edges of terrain.

Fig. 19 and Fig. 20 show the ratio of “undetermined nodes” under the above deployment strategies with different ANR and DOI values. The figures show that if ANR value is larger than a threshold value (for example, 7.5 in the simulation), there will be no “undetermined nodes.” Note that the ANR threshold value of 7.5 is actually small.

C. Communication Overhead

Consider a sensor network with \( N \) anchors and \( M \) sensor nodes. Suppose that each broadcast from sensor nodes costs 1 energy unit. Since the radio range of each anchor nodes is ANR times of that of sensor node, each broadcast from anchors costs roughly \( (ANR)^2 \) energy units if we assume a free-space radio
messages is with the same number of anchors deployed. So the total number of broadcast messages from anchors is $\theta(M)$ and that from sensor nodes is $\theta(N)$. Therefore, the total energy consumption is $\theta(M) * (ANR)^2$ energy units. In ROCRSSI, only anchors need to broadcast and sensor nodes do not need to exchange any information for localization. So the total number of broadcast messages is $\theta(N)$ and the total energy consumption is $\theta(N) * (ANR)^2$ energy units. In cases where $M \gg N$ and ANR is not very large, ROCRSSI consumes much less energy than APIT with the same number of anchors deployed.

Note that in the above analysis we assume collision freedom and we do not take into account the size of messages. We do not delve into those details since currently it is hard to model transmission collision without a commonly accepted MAC protocol.

To summarize, the simulation shows that compared with APIT, ROCRSSI provides a good alternative to range-free localization, with good features such as small calculation and communication overhead, resilience to anchor deployment strategy and sensor node density, elimination of “undetermined nodes,” and acceptable estimation accuracy even in very irregular radio propagation circumstances.

V. CONCLUSION

Range-free localization presents a promising solution for the localization problem in WSNs. In this paper, we perform thorough performance evaluation on two novel range-free localization methods, APIT [7] and ROCRSSI [10]. The inherent “undetermined node” problem of APIT is disclosed. All the system configurations directly influencing the performance of these two methods are investigated and the relationship between these configurations and the achievable estimation accuracy is illustrated. Performance comparison between the two methods is also provided. Evaluation results show that ROCRSSI outperforms APIT in terms of estimation accuracy and communication overhead under the same configuration, and it also greatly alleviates the inherent “undetermined node” problem of APIT.

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REFERENCES