Optimal Sniffers Deployment On Wireless Indoor Localization

Yiming Ji
Computer Science
University of South Carolina Beaufort
Email: yimingji@gwm.sc.edu

Saâd Biaz, Shaoen Wu, Bing Qi
Computer Science and Software Engineering
Auburn University
Email: {sbiaz, wushaoe, qibing}@auburn.edu

***Abstract*— Location determination of indoor mobile users is challenging due the complex and volatile indoor radio propagation signals. A radio-frequency (RF) based indoor localization system, like RADAR or ARIADNE, typically operates by first constructing a lookup table mapping the radio signal strength at different known locations in the building, and then a mobile user's location at an arbitrary point in the building is determined by measuring the signal strength at the location in question and searching the corresponding location from the above lookup table. Usually, the mobile's signal strength is measured by three or more sniffers deployed inside the building. Obviously, the number of sniffers and their positions greatly affect the localization performance. This paper presents a detailed analysis and experimental results that explore the impact of the sniffers deployment on the performance of the indoor localization. The results demonstrate that the best localization performance is obtained when the center of gravity of the equilateral triangular (formed by three sniffers) coincides with that of the floor plan; and in order to provide optimal localization for all positions of a large floor, it is necessary to deploy more than three sniffers in a *semi-mesh* style such that any position in the building is always covered by three nearby sniffers.**

I. Introduction

Location management and mobility management are critical issues for providing seamless interactions and ubiquitous computing for mobile users. For indoor localization, the success and widespread deployment of IEEE 802.11 wireless networks enticed many researchers to exploit the received signal strength indicator (RSSI) of a packet sensed at reference sniffers, and build RF-based indoor localization systems. The sniffer could be an access point (AP) or a computer with signal strength measurement capability.

In order to position a mobile user's location, researchers proposed a two step mechanism [1], [2], [3], [4], [5]: **i)** Map Generation: Establish a signal strength map where the signal strength at known locations is either manually measured or theoretically estimated. A signal strength map is a database table of locations and the signal strength recorded by sniffers at these locations. **ii)** Location Search: Measure signal strength of a mobile and search the signal strength map for the "closest" location using for example the least mean square error (LMSE) criterion.

Based on this two step approach, most existing indoor systems report decent localization performance with particular experimental settings. For example, Ladd *et al.* [4] deployed 14 sniffers over a floor about $65m \times 35m$ and achieved 1.5 meters accuracy with about 70% probability. Haeberlen *et al.* [6] used 33 sniffers for a three-story building of 12,000 square meters and estimated with 95% accuracy over 60% cells; and Bahl and Padmanabhan in [3] used 5 sniffers over a plan of $43.96m \times 21.84m$ and obtained the mean error around 3.0m with 90% probability. Different from these systems, ARIADNE used *estimated* signal strength map, and achieved mean error around 2.5m using only 3 sniffers on a floor of $45.7m \times 36.6m$ [1]. It appears that the number of deployed sniffers affects the performance of the indoor localization.

During the research, we found that in addition to general considerations such as building structure or furniture, the strategy of the sniffers deployment is critical for the indoor localization performance. The impact of the deployment stems from the high variability of the radio signal strength and the weak relationship between signal strength and distance between transmitter and receiver. In general, the deployment must be designed to first provide the maximum overlapping signal coverage on the site, and it should also present the best discrimination of signal strength for different locations in the building.

In this paper, we attempt to formally establish the impact of sniffers deployment on the localization accuracy and to propose guidelines to best position sniffers. This study applies to all approximate range-based localization methods, i.e., methods that rely on inaccurate techniques for measuring distances. We are interested in addressing one single problem: how to optimally deploy the sniffers in order to achieve the best precision in location estimation?

This research is based on the ARIADNE system [1], [2] that was deployed in a basement building at Auburn University. With four months' monitoring, the results show that non aligned sniffers deployment yields better localization performance. And the best localization performance is obtained when: 1) the sniffers form an equilateral triangle, and 2) the center of gravity (COG) of the equilateral deployment triangle coincides with the floor plans own center of gravity. For a large floor plan, more than three sniffers should be deployed in a *semi-mesh* style in order to obtain optimal location estimates.

The remainder of the paper is organized as follows: Section II describes related research in sniffers deployment; Section III defines the problem and assumptions. Section IV ana-

1-4244-1251-X/07/$25.00 2007 IEEE.

lyzes the method of optimal sniffers deployment. In Section V, we introduce the experimental environment and measurement results. Section VI concludes the paper and outlines future research.

II. Related Research

This section surveys previous research with a focus on the deployment strategy in the reported test beds. For a building with limited space, three sniffers are usually used by most researchers in order to evaluate their systems. In order to obtain better location estimation, a simple solution is to increase the number of deployed sniffers [4], [6]. A large number of deployed sniffers masks the pertinence of the sniffers deployment strategy. In addition, the deployment of redundant sniffers cause more interference and impose extra cost on hardware and maintenance. Therefore, it is desirable to deploy just enough sniffers such that a good deployment of minimal sniffers still provides sufficient localization precision.

In reality, most researchers deploy the sniffers around the perimeter of the test building. And an interesting observable fact is that NONE of the existing systems deploys the sniffers along a straight line. It appears intuitively that the straight-line deployment will not provide optimal localization results. To the best of our knowledge, only a few research has formally addressed the intrigue of the sniffers deployment. Battiti et al. [7] applied a set of heuristic search algorithms to determine optimal AP deployment. Chen et al. [8] used the Least Squares algorithm to derive a “closed-form” formula, and focused their research on six deployment configurations formed by triangles and rectangles with up to eight landmarks. Different from previous research, this paper focuses mainly on the fundamental deployment structure with only three sniffers, and with the basic building block we will construct and evaluate a semi-mesh deployment method that fits for large buildings. We present the problem statement in the next section.

III. Problem Statement and Assumptions

In order to assist theoretical analysis of the sniffers deployment strategy, this paper assumes uniform indoor partitions and homogeneous spatial distributions of the floor plan. Moreover, it assumes that the received signal strength SS for a given location at a sniffer is given by:

$$SS \in [SS_{true} \cdot (1 - \delta_s), SS_{true} \cdot (1 + \delta_s)] \tag{1}$$

where SS_{true} is the true signal strength value at that location, and δ_s is the maximum perturbation from measurements (or estimates by the indoor radio propagation model).

In addition, it assumes that the received signal strength SS_{true} at a position uniquely maps to a range r_{true} from the mobile to the sniffer. Let the δ_r be the uncertainty of the radio range corresponding to the perturbation of the signal strength δ_s, then the range r is:

$$r \in [r_{true} \cdot (1 + \delta_r), r_{true} \cdot (1 - \delta_r)] \tag{2}$$

If $r1, r2$, and $r3$ are radii from a position of interest P to three sniffers, then the location P is within the intersecting

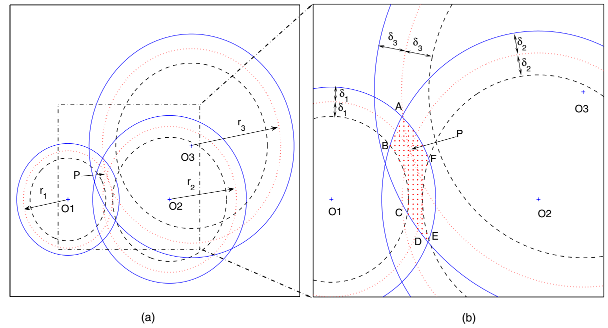

Fig. 1. Uncertainty area

area of three rings (Please, see Figure 1). And thus the intersecting area defines the location estimation *uncertainty* for the position of interest. Note that the radio range for the indoor radio propagation is not *circular* in general [1], however, it is reasonable to simplify the site specific attenuation effects in order to identify the best sniffers deployment strategy that minimizes the localization errors.

Therefore, the research in sniffers deployment can be expressed by the following two problem statements: **Problem a:** for a given position P (or area) of interest, how can we deploy three sniffers with radii of $r1, r2, r3$, such that the coordinates of the given position P (or within an area of interest) could be determined with minimal uncertainty? **Problem b:** for a given floor plan, what is the best deployment strategy for three (or more) sniffers such that the average localization error for the whole floor is minimal?

We use **Uncertainty Area (UA)** to measure the localization performance, and we define it as follows: For a position P covered by three or more sniffers S_i $(i = 1, 2, \ldots, n)$, the uncertainty area (UA) is determined by the intersection area of multiple rings $RS_i,\ (i = 1, 2, \ldots, n)$ that are centered at those sniffers. Suppose a ring surface RS_i is composed by a point set $\{q_{RS,i}\}$, then the UA for the position P is given by:

$$UA_P = \{q_{RS,1}\} \cap \{q_{RS,2}\} \cap \ldots \cap \{q_{RS,n}\} \tag{3}$$

Figure 1 illustrates the deployment for three sniffers O_i $(i = 1, 2, 3)$ and a target position P. If there exists no measurement error, the real radio ranges for the three sniffers would be r_1, r_2, r_3, respectively; consequently, the three circles would cross at location P ideally. Considering the uncertainty of the measurement or estimates, and assuming the range perturbations for the three sniffers are $\delta_i, (i = 1, 2, 3)$, then the possible sensing area for each sniffer at position P would be constrained by a surface of the ring of radii $r_i \cdot (1 \pm \delta_i),\ (i = 1, 2,\ or\ 3)$. In other words, the probable location of position P would be an intersection *area* instead of a single point.

The right chart of the Figure 1 details the *uncertainty area* for the position P, and it is delimited by the surface $ABCDEFA$. It is obvious that different sniffers deployments affect the *uncertainty area* (UA), and smaller UA provides better localization performance.

Similarly, we define the **Average Uncertainty Distance**

d_{AUD} as the average distance of all points in the point set in the *uncertainty area*.

Suppose an *uncertainty area* contains total n discrete points in the set, and d_{ij} is the distance between two points i and j in the area, $(i, j \in [1, n],\ i \neq j)$ in the set, then:

$$d_{AUD} = average\{d_{ij}\} \quad (4)$$

We analyze the sniffers deployment strategy in the next section. We first consider deployment mechanism for a single interested position (or an area), then in Section IV-B, we optimize the deployment strategy for a given floor.

IV. Optimal Sniffers Deployment Method

A. The Impact of Deployment on A Position of Interest

This section analyzes **Problem a** as defined in Section III, i.e., for an interested position (or an area of interest), how to deploy the three sniffers such that the estimation uncertainty for this position or area of interest is minimal.

We first discretize the area into a finite set of uniformly distributed points and consider them as possible positions for three sniffers. In order to reference locations in the plane, we denote the sniffer *O1* as the origin, and we select a second sniffer *O2* to be on the right side of the x-axis. The y-axis is defined such that the third sniffer $O3$ is with positive coordinate in y direction for the coordination system. We denote the angle formed by the line of $O3O1$ and the x-axis α, and distance from the position P to the x-axis is H.

To determine the best deployment configuration, we proceed as follows: **i)** randomly deploy three sniffers with distances $r1, r2, r3$ to the position *P*, and given a perturbation δ for all sniffers (take 10% according to [1]). The effective coverage for each sniffer at the specified radio range is now a ring with space between radii $r_i \cdot (1+\delta)$ and $r_i \cdot (1-\delta)$, $i = 1, 2, 3$; **ii)** Denote the first sniffer $O1$ at the southwest of the position of interest, and we normalize the radius of this first sniffer $r1$ as unit length of 1, i.e., $r1 = 1$. The second sniffer $O2$ is on the southeast of the position *P*, and let it move along the right side of the x-axis, such that the distance H from the point *P* to the x-axis changes between $[0, 1]$; iii) For any configuration of sniffers $O1$ and $O2$ at a given distance H, the third sniffer $O3$ rotates its position around the point *P* (i.e., $alpha \in [0, 180]$). Then we calculate the *uncertainty area* of *P* for each deployment; iv) Repeat the procedure and analyze the relation between *uncertainty area* with $(alpha, H)$.

The normalized *uncertainty area* for the position *P* for all configurations are computed and the typical results are given in Figure 2. In the figure, the x-axis denotes the angle α from 0 to 180, the y-axis represents the distance H, and the z-axis gives the normalized *uncertainty areas*.

The figure indicates three important results: i) when two sniffers $O1, O2$ get closer to each other ($H \rightarrow 1$), the *uncertainty area* gets larger; ii) The linear (or close to linear) deployment of three sniffers $(\alpha \rightarrow 0^o or 180^o)$ always gives the largest uncertainty area; and iii) triangular deployment gives better localization performance, and the best estimation is usually obtained when $\alpha \simeq 60^o$. This shows that best

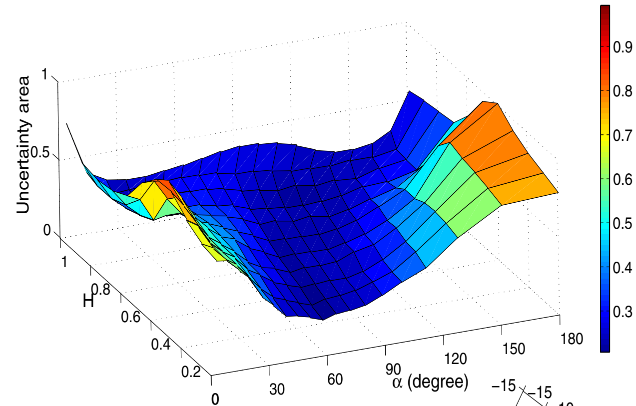

Fig. 2. Uncertainty area at various configuratio

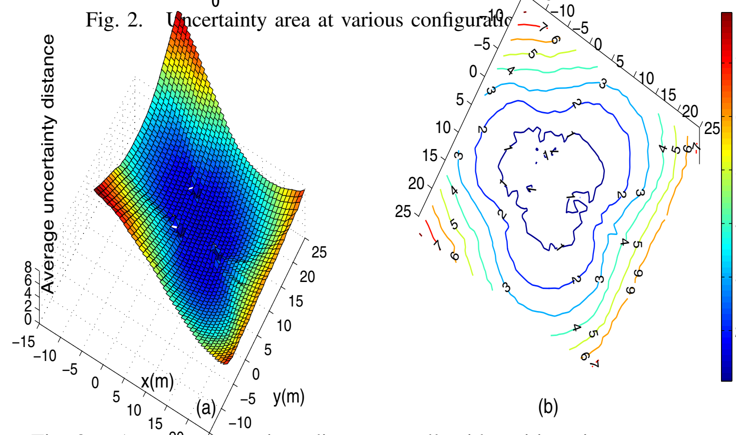

Fig. 3. Average uncertainty distance at all grid positions in a square area

localization performance maybe obtained when three nearby sniffers are deployed in *equilateral triangle* style. We will further analyze this finding in the next section.

B. The Impact of Sniffers Deployment on A Given Floor

This section analyzes the sniffers deployment strategy on a given floor plan. Section IV-B.1 first investigates the effect of the sniffers coverage, and section IV-B.2 studies the essential deployment strategy for the indoor localization.

1) Sniffers Coverage: Similar to the previous section, we deploy three sniffers in a square floor plan. The sniffers form various triangles from the right triangle, general acute triangles, and to the equilateral. For each single deployment, we compute the average *average uncertainty distance* d_{AUD} at all points inside and outside of the triangles. For the analysis in this section, we also assume the range uncertainty to be $\delta_r = 10\%$. [1].

Figure 3 shows a simple scenario where three sniffers are deployed in a small square space of $40m \times 40m$. For both charts, the x- and y-axis represent the dimension of the space. The z-axis in the left chart is the *average uncertainty distance* d_{AUD} at each particular grid position on the space. The right chart is a contour representation of the left chart where the numbers on curves represent the uncertainty distance in meters at that place. It can be seen that the positions inside the triangle obtain much smaller *uncertainty distance*.

Figure 4 compares 6 different deployments where the three

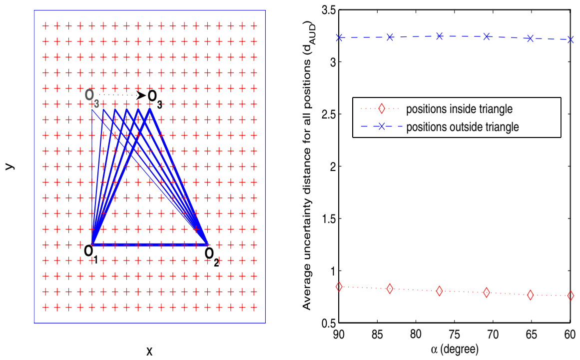

Fig. 4. Average uncertainty distance of all grid positions in-/outside triangles

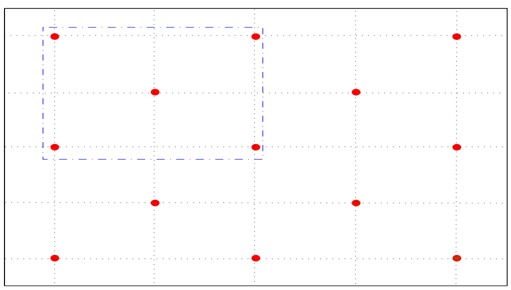

Fig. 5. Ideal sniffers deployment method

sniffers changes from the right triangle to the equilateral, i.e., $\alpha = 90^o \longrightarrow 60^o$. At each single deployment, the space is separated into two sets of positions: the first set includes positions inside the triangle; and the second set is for the positions outside of the triangle. Then for each set of the positions, we sum the *average uncertainty distance* at all positions and make the average distance for the set. The results are given in the right chart, where the x-axis is the degree α, and the y-axis is the *overall average uncertainty distance* for the two point sets.

Figure 3 and Figure 4 indicate that:

1) Different types of triangles for the sniffers deployment do NOT make too much difference for the location estimation of the points inside the triangle
2) The equilateral deployment gives the best performance;
3) For a given space, the localization uncertainty for positions inside & outside of the triangle makes *huge* difference, and the localization for positions that are outside of the triangle is not comparable with those within the triangle.

Therefore, in order to optimally deploy an indoor localization system, it is better to place critical locations (in need of precise localization) inside triangles formed by three nearby sniffers. For a large floor plan, it is necessary to deploy more than three sniffers, and the deployment may take the *semi-mesh* format as shown in Figure 5. The *star* structure (by five sniffers) within the dotted rectangle could be a basic construction unit, and only one such unit may be required for most smaller floor plans in order to provide good location estimation.

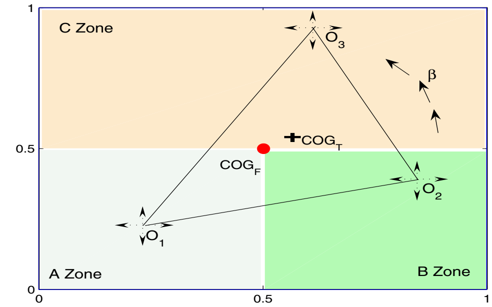

Fig. 6. Random sniffers deployment

2) Essential Strategy: This section researches sniffers deployment strategy for a given floor, in which the optimal sniffers positions will be analyzed. We slice the floor plan into three zones in which each sniffer will be deployed inside only one zone. As depicted in Figure 6, three sniffers (O_1, O_2, and O_3) are deployed in Zone A, B and C, respectively. The cross double-arrows at three sniffers denote that every sniffer is able to *find* its best position in the corresponding zone. COG_F and COG_T denote the Center of Gravity (COG) of the floor plan and the triangle by three sniffers. β is the orientation angle of the triangle around the COG_T that will be discussed next.

To derive the optimal sniffers deployment for the floor, sniffer O_1 is first *randomly* placed in a grid position in Zone A; and sniffer O_2 is placed on one of grid locations in Zone B; then sniffer O_3 searches its place in Zone C such that the overall Uncertainty Area (UA) for the whole floor plan is minimal. We search all position combinations for sniffer O_1 and O_2, and compare each single minimal uncertainty area at each configuration. The configuration corresponds to the smallest minimal is the best deployment.

The simulation reveals an interesting result, i.e., for any position combination of sniffers O_1 in (A Zone) and O_2 (B Zone), the position search of the third sniffer O_3 (C Zone) appears to be determined such that the center of gravities (COG) of the three sniffers (COG_T) needs to close to the COG of the floor plan (COG_F). And the closer the two COGs, the better performance of the deployment (smaller UA) is achieved. Figure 7 presents a scenario of such optimization, where the COG_T (center of gravity of optimal deployment) at each sniffer configuration is given. The simulation is provided on a floor plan of $60m \times 60m$, the radio transmission range is $R = 45m$, and the radio range uncertainty δ_r is 10%. The position $(30, 30)$ is the center of gravity of the floor plan (COG_F).

For the best deployment of all configurations, the COG_T coincides with the COG_F; and the distance between sniffers is approximately the same as the radio transmission range, i.e., the optimal deployment is an equilateral triangle with edge length approximates to the actual radio range inside the building.

In order to analyze the effect of the triangular orientation (β in Figure 6) on the localization performance, the above best deployment is considered, and the triangle is rotated around

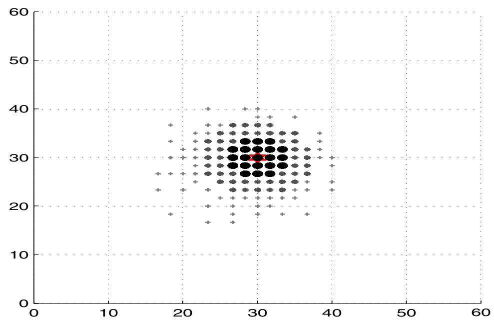

Fig. 7. Center of Gravity (COG) of all optimal deployment triangles

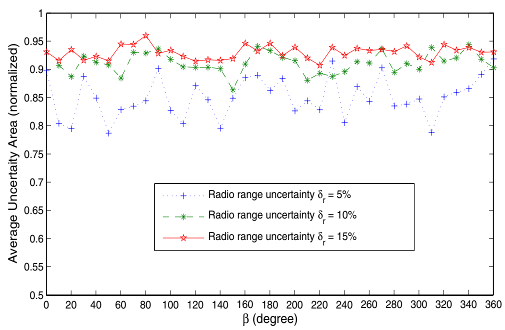

Fig. 8. Normalized Average Uncertainty Area (UA) for the floor plan

the COG_T (which is now also the COG_F). We calculated the average uncertainty area (UA) for the whole floor plan (in Figure 6) and the normalized results are given in Figure 8. In the figure, three different radio range uncertainties δ_r (5%, 10%, and 15%) are considered. To normalize the average uncertainty area (UA), we used the uncertainty circle area that is expressed as follows:

$$S_{norm} = \frac{1}{4}\pi \cdot (\delta_r R)^2 \tag{5}$$

where δ_r is the radio range uncertainty, and R is the radio transmission rage.

In Figure 8, the x-axis is the orientation angle β which rotates from 0 to 360 degree, and the y-axis is the normalized average uncertainty Area (UA) for the whole floor plan. The starred $'\star'$ solid line, the $'*'$ dot-dashed line, and the $'+'$ dotted line represent, respectively, the normalized UA at radio range uncertainty of $5\%, 10\%,$ and 15%. It can be seen that the uncertainty areas remain relatively stable at all three cases when the triangle rotates around the center of gravity (COG_T). This means that the deployment of the optimal triangle is marginally depended on its orientation as long as the COG_T overlaps with the COG_F of the floor plan.

Close inspection of the Figure 8 also indicates that the average uncertainty areas (UA) is slightly less than (or bounded by) the uncertainty circle area (S_{norm} in (5)). In addition, lower radio range uncertainty (smaller δ_r) gives smaller uncertainty area (UA), which corresponds to better localization performance.

In conclusion, to deploy three sniffers for a limited floor plan, the sniffers may be positioned as an equilateral triangle,

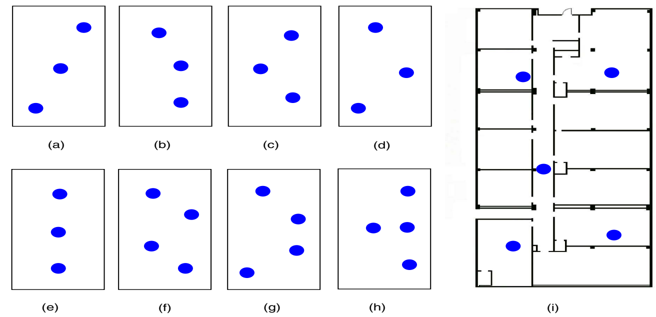

Fig. 9. Sniffer deployment method

and the center of gravity of the triangle should be close to that of the floor plan. For large spacious floor plan, multiple sniffers could be deployed in *semi-mesh* style to provide full coverage.

The next section introduces an experiment that was carried out in a basement building at Auburn University. The experiment considered and compared eight different sniffers deployment strategies.

V. EXPERIMENT

The experiment was carried out in a basement building at Auburn University. The structure of the floor is given in Figure 9, and the floor dimension is $19.16m \times 43.07m$. In the experiment, three to five sniffers are deployed.

Five different deployment configurations in the experiment are considered: i) **Linear**: configuration (a) and (e); ii) **Obtuse triangle**: configuration (b); iii) **Acute triangle**: configuration (c) and (d); iv) **Redundant zigzag**: configuration (f), (g) and (h); and v) **Semi-mesh**: configuration (i).

A. Localization Performance for Different Configurations

Based on the ARIADNE system [1], we built a signal strength map over a grid of positions with the resolution of 0.55m in both x and y directions. Then we simulate the localization process for all configurations and the results are given in Table I, where the second column represents the Average Uncertainty Distance and the third column denotes its standard deviation, and the fourth column is the location estimation error for the corresponding sniffer configuration.

Comparing the localization performance for all configurations with **three** sniffers (a)-(e), the configurations (c) and (d) yield a much better performance than the others. It shows that the *acute triangular* deployment maximizes the discrimination of the signal strength triplet. This outcome confirms the analysis results in Section IV-A.

When **four** (configuration (f) to (h)) or **five** (configuration i) sniffers are deployed, the localization performance improves systematically. The configuration (i) is in *semi-mesh* style, and the experimental results indicate that this mesh deployment method does provide much better localization performance.

Therefore, if higher precision is required, the deployment of extra redundant sniffers could be a reasonable approach.

TABLE I

LOCALIZATION PERFORMANCE FOR ALL SNIFFER CONFIGURATIONS

configurations	(a)	(b)	(c)	(d)	(e)		(f)	(g)	(h)	(i)
err	3.7575	4.1758	2.6986	2.8961	4.2239		2.3781	2.2646	2.4235	1.9176
std	2.1063	3.1056	2.0957	1.6098	2.9542		1.7420	1.4928	2.2844	1.8013

TABLE II

AVERAGE UNCERTAINTY DISTANCE AT ALL CONFIGURATIONS

configuration	d_{AUD}	STD of d_{AUD}	*location estimates*
(a)	4.8907	0.4850	*3.7575*
(b)	3.0809	0.2146	*4.1758*
(c)	2.0694	0.3972	*2.6986*
(d)	1.7815	0.3408	*2.8961*
(e)	6.3066	0.4102	*4.2239*
(f)	1.4752	0.1952	2.3781
(g)	1.4445	0.2625	2.2646
(h)	1.5556	0.4064	2.4235
(i)	1.1319	0.1661	1.9176

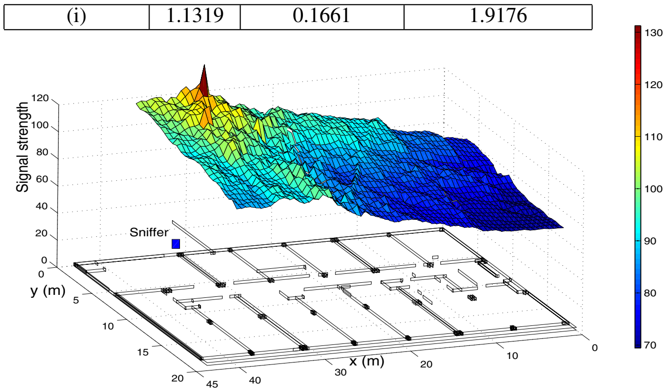

Fig. 10. SS of the Sniffer at southwest corner (config. (d))

And if the sniffers are deployed in the *semi-mesh* style, the location estimation will achieve optimal performance.

B. Estimation Bound for Different Configurations

In order to understand the intricacy of the sniffers configuration on the performance of the indoor localization, we compute the *average uncertainty distance* and average them for all grid points in the space. The results are given in Table II, where the standard deviation and the actual localization results (adopted from Table I) are also provided.

Comparing the values in column 2 and 4, it is clear that the errors of most estimates are larger than the *average uncertainty distance*. The only exceptions are the *linear configuration* (a) and (e) because of the existing of symmetric candidate positions at both side of the lined sniffers. In reality, due to the multipath effect of the indoor radio propagation, the radio shape is not circular, and thus the symmetry may not exist. Therefore the theoretical calculation *over-estimates* the errors for the aligned deployment scheme.

The results in Table II also indicate that the configuration (d) is the optimal deployment strategy when only *three* sniffers are deployed. The configuration (c) ranks the next. However, comparing configurations (c) and (d), the actual localization performance of (d) is a little worse. It shows that while the maximum separation of sniffers is important, the actual *signal strength coverage* is also critical. Figure 10 illustrates the signal strength (z-axis) of a corner-deployed sniffer for configuration (d). It shows the received signal strength at the other side of the building is almost flat (indistinguishable). Therefore, the configuration (d) provides less optimal signal strength coverage.

VI. CONCLUSION

This paper analyzes the impact of the sniffers deployment on the indoor localization performance. The research is based on a new and automated signal strength estimation tool called ARIADNE.

From the research, we found that in order to deploy three sniffers in a limited space, equilateral triangular deployment is the best; and the center of gravity of the triangle should be close to that of the floor plan. This way, the orientation of the triangle provides marginal effect on the localization performance.

Through the experiment with various sniffers configurations, this work supports three major conclusions: (i) acute triangular sniffers deployment (close to equilateral triangle) outperforms other configurations; and the localization performance for positions within the triangle is much better than positions outside. (ii) extra sniffers could improve the localization performance; and the *semi-mesh* sniffers deployment (without other redundant sniffers) is one of the best deployment methods. (iii) sniffers should be maximally separated from each other if each individual sniffer is able to provide effective signal coverage for the plan.

All actual measurements in this paper are based on a complex basement floor in a building at Auburn University. Results from ARIADNE indicate that many site specific parameters contribute to the estimation errors for the indoor localization. Future work will study those problems in more detail.

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