Real-Time RFID Localization Using RSS

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Abstract— **New computing paradigms have underscored the need to locate objects in an environment, motivating several object localization approaches targeting competing technologies and specific applications. While RFID technology recently emerged as a viable platform for locating objects, several unresolved key challenges precluded higher performance and wider applicability. We present an RFID-based real-time location system that uses Received Signal Strength (RSS) to better model the distance-decaying behavior of radio signals in an orientation-agnostic manner. We experimentally leverage the proposed robust models to simultaneously locate several stationary and mobile objects tagged with passive tags in a realistically noisy indoor environment, with an average accuracy of 0.6 meters. A more general conclusion of this work is that contrary to common belief, RSS can indeed serve as reliable metric for a variety of select applications, including localization.**

I. INTRODUCTION

Locating objects is a key requirement in many emerging computing paradigms. Active object localization research has shown that different technologies such as sensors, WiFi, lasers, and GNSS, combined with techniques based on signal arrival time, signal phase, and signal strength can be used to locate objects in an environment [11], [12].

Radio Frequency IDentification (RFID) technology has demonstrated a potential for locating objects, particularly in indoor environments [8]. While standard RFID technology does not provide object localization capabilities, if this was made possible, it would avoid several drawbacks of other localization technologies, including a need for a direct line of sight, a well-lit environment, a lack of occluding obstacles, and radio signal availability [6]. Furthermore, RFID can potentially be combined with GNSS-based location systems to provide wider terrestrial coverage and higher performance [15].

Among previous RFID-based object localization approaches, Received Signal Strength (RSS) -based approaches estimate the tag's location by measuring the variation in the tag's backscattered signal power as the tag-reader distance varies [13]. However, due to ambient noise sources such as environmental interferences, metal-liquid occlusions, multipath propagation, and tag detection variability, RSS-based position estimates can be unreliable and inaccurate [9].

In this paper, we show that tags have significant detection variability which causes interference, and we propose a mitigation technique that selects tags based on their detection performance. The resulting object localization approach utilizes the selected tags to develop several RSS decay models that establish the relationship between the tag-reader distance and the tag's RSS. We then use these models to construct a real-time location system that can simultaneously locate multiple stationary and mobile tags in a 3D indoor environment.

The behavior of a radio signal can vary greatly in a given environment. Assuming the average environment-specific impact on the tag's RSS to be statistically invariant enables the proposed approach to factor out the interfering environment, with improved resilience to the tag's RSS variation caused by the tag's orientation on its axis and around the reader (i.e. axial-radial orientation).

We show, contrary to the common belief that RSS is an unreliable parameter, that by carefully considering the deployment scenario, the tag's radio sensitivity, orientation, and distance from the reader, RSS can be used to establish a reliable empirical power-distance relationship for a variety of select applications, including object localization. Furthermore, we demonstrate that by matching tag-reader pairs, the proposed approach can provide high localization performance without deploying tags at known positions (i.e. reference tags) to help locate the target tags.

Moreover, our approach can perform dynamic in-situ calibrations to correct for possible performance drifts in order to sustain higher localization accuracy and speeds. Thus, by minimizing the tag detection variability and constructing an interference-inclusive localization approach, reliable and high performance object localization can be achieved in select application scenarios (e.g. warehouses).

The remainder of the paper is organized as follows: Section II provides a brief account of the background and related work. In section III we introduce our systematic RFID-based approach to locating objects using robust RSS decay models. Section IV describes the experimental setup and methodology, presents the results, and discusses their implications. We conclude with future research directions in Section V.

II. BACKGROUND AND RELATED WORK

Existing RFID-based object localization approaches already show promise in effectively addressing the problem of locating objects, especially in indoor environments. Numerous approaches based on localization techniques based on signal Angle of Arrival (AoA), signal Time of Arrival (ToA), signal Time Difference of Arrival (TDoA), signal phase, and signal

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strength have been proposed [6]. In this paper, we focus on signal strength -based indoor localization approaches.

Signal strength (and RSS) -based object localization approaches measure the radio signal's propagation distance up to the point where the signal begins to attenuate, in order to estimate the tag-reader distance. Theoretically, tag-reader radio signal strength and distance in the free-space can be defined by the Friis transmission equation as given below [10]:

$$\frac{P_R}{P_T} \propto G_R G_T \left(\frac{\lambda}{4\pi D}\right)^2 \tag{1}$$

where P_R is the power received at the receiver (i.e. a tag) and P_T is the power transmitted by the transmitter (i.e. a reader). G_R and G_T are respectively the antenna gains for the tag and the reader, λ is the radio signal wavelength, and D is the tag-reader distance. Numerous signal strength -based approaches have been proposed [3], [7], [9], [13], as briefly discussed below.

Bekkali et al. [3] utilize two mobile readers, a probabilistic RFID map, reference tags, and a Kalman filter -based technique combined with RSS to estimate tags' positions in indoor environments with a root mean square accuracy in the range of 0.5 to 1 meters. While their probabilistic techniques (i.e. the RFID map and Kalman filter) may enable higher accuracy, the overall approach is computationally expensive and thus precludes real-time localization. Moreover, the overall solution cost of their approach may be prohibitively expensive economically due to its reliance on reference tags.

Brchan et al. [7] propose linear signal strength -based propagation models combined with reference tags and trilateration to locate stationary tags in indoor environments with an accuracy of one meter. However, their approach is not scalable due to the use of expensive active tags, dependence on reference tags, and unrealistic radio signal propagation models.

Choi et al. [9] observe that tags have variable RSS properties (but do not mitigate this), and use a *k*-nearest neighbor algorithm and reference tags to locate the tags with an accuracy in the range of 0.2 to 0.3 meters. Their approach also ignores the fact that a tag's detection probability is strongly dependent on its axial-radial orientation, which in turn dramatically impacts the overall localization performance [4], [5]. Consequently, their approach may not be suitable in real-world applications where tagged objects may have changing orientations.

Ni et al. [13] develop a location system that uses reference tags and *k*-nearest neighbor algorithms to locate tags with an accuracy of less than two meters. Their proposed system is expensive when scaled due to the use of active tags. Moreover, their approach is not real-time as it takes a large amount of time to determine the tag's location. Additionally, the economic cost of their solution is further exacerbated by the use of reference tags, thus making their approach impractical.

In addition to the above limitations, signal strength -based object localization approaches are susceptible not only to ambient interference sources such as environmental noise, occlusions due to the presence of liquids and metals, multipath propagation, tag-reader orientations, but also to the variability inherent in radio-sensitive tags. While the environment's impact on RSS-based object localization has been widely acknowledged, the role of variable tag sensitivity in localization performance has surprisingly received little attention [8], [9].

Furthermore, state-of-the-art RFID readers can report tags' RSS, which can be transformed into a coarse-grained relative position estimates [1]. However, such position estimates are calculated by the RFID reader via integrating the speed and direction of motion of the tag over time with respect to a fixed reference location. Thus, such an approach cannot be used to determine a tag's absolute position with a high degree of accuracy.

To overcome the limitations of existing RSS-based object localization approaches, we start with a large collection of different-type tags, and select from it tags having the longest read range and overall most uniform RSS behavior. We do this for each kind of RFID reader, in order to determine the type of tag that performs optimally with respect to that reader. We next sort all the tags of the type that best suits each reader, based on the measured RSS over different combinations of reader output power levels and tag-reader distances, to ensure their uniform operational behavior. We utilize these sorted/binned tags to develop RSS decay models by characterizing their performance with respect to axial-radial orientation. This methodology effectively pairs readers with select tag types, and enables our real-time location system to simultaneously locate multiple stationary and mobile objects.

III. REAL-TIME RFID OBJECT LOCALIZATION

To develop robust RSS decay models to be used in the proposed RFID-based real-time location system, empirical tag-reader interaction data was collected in a realistic environment having a variety of noise sources such as servo motors, WiFi access points, and metal-liquid containers. We used Alien ALR-9900+ and ThingMagic Mercury6 readers, and Electronic Product Code (EPC) Generation 2 (Gen2) passive tags operating in the ultra high frequency (UHF) band for demonstrating the capabilities of the proposed system.

A. Tag Selection

Characterizing a reliable relationship between a tag's RSS decay and tag-reader distance requires taking into account tag detection variability and orientation. Such characterization-driven RSS decay models are inherently tag and reader dependent. Therefore, to identify tags suitable for developing such RSS decay models, we selected the tags based on their read range and RSS behavior from a collection of 34 EPC Gen2 passive tag types. We focused on the tags having the longest read ranges as this tends to minimize the number of deployable readers for the targeted application scenario. Furthermore, tags that have uniform RSS behavior over distance and reader output power level combinations tend to also have a graceful RSS decay and uniform localization performance.

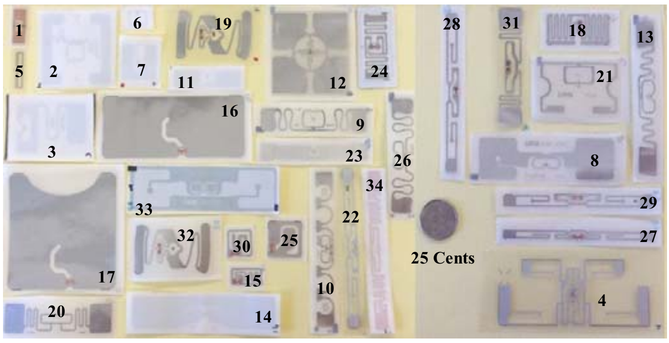

Fig. 1: The 34 EPC Gen2 passive tag types used for selection.

Figure 1 illustrates the collection of tag types (with overlaid tag type IDs) used in the tag selection experiments. We perform two sets of experiments using the ThingMagic and Alien readers, in order to select the most effective tags from the above collection. In the first experiment, we measured the longest tag read distance for each tag in the collection. We found that tag type IDs $\{$2–4, 8–14, 16–23, 26–29, 31–34$\}$ and $\{$2–4, 8–10, 13, 14, 16, 19, 20, 22, 23, 26–29, 33, 34$\}$ were readable at the maximum read distance of 9 meters by the ThingMagic and the Alien reader, respectively.

In the second experiment, we measured the tags' RSS behavior over tag-reader distance and reader output power level combinations using both readers for the tags that have demonstrated the longest read ranges in the previous experiment. To balance the experimental coverage and efficiency, the distance was varied among the set $\{0.61, 1.83, 3.05\}$ meters while the reader output power level iterated over the $\{19.6, 25.6, 31.6\}$ dBm levels. Figures 2 and 3 present the average RSS behavior distribution of the selected tags for different power-distance combinations on the ThingMagic and the Alien readers, respectively.

Note that the RSS values returned by the ThingMagic and the Alien readers are in dBm units and unitless, respectively. Among the tag types having the longest read ranges, Tag-10 and Tag-14 were the only tags that showed consistent RSS behavior over the power-distance combination. For example, Tag-10 and Tag-14 were the only tags that consistently showed RSS activity when kept at a distance of 1.83 meters from both the readers operating at an output power level of 19.6 dBm. The leftover tags either did not have long read ranges and/or did not exhibit uniform RSS behavior over the power-distance combinations.

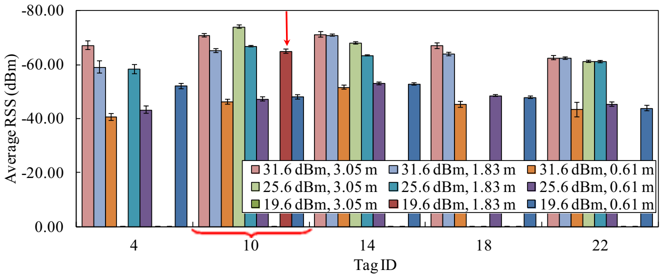

Fig. 2: Average RSS of the selected passive tags using the ThingMagic reader (Red arrow shows the Tag-10's RSS at 19.6 dBm and 1.83 m).

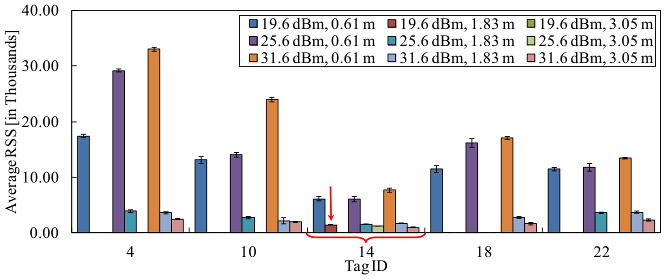

Fig. 3: Average RSS of the selected passive tags using the Alien reader (Red arrow shows the Tag-14's RSS at 19.6 dBm and 1.83 m).

By combining results from both the experiments, it is evident that Tag-10 and Tag-14 are the best candidate tags for the ThingMagic and the Alien reader, respectively. While only one candidate tag per reader was found to be performing optimally in our experiments, it is also possible to identify a larger set of candidate tags per reader.

B. *Tag Binning*

A tag's RSS behavior is not only affected by ambient interference (e.g. multipath propagation, background noise due to motors, etc.) but more importantly also by its variable radio sensitivity. Tag radio sensitivity depends on the tag antenna gain, chip high impedance state, and threshold power sensitivity [14]. Due to manufacturing variability, small changes in the tag's onboard circuit components can cause dramatic variations in the tag's RSS behavior.

To understand the impact of a tag's variable RSS behavior on the object localization performance, consider two tags of the same type but having different RSS behavior. The tag with uniform RSS behavior will have well-defined RSS decay leading to better position estimates than the tag that has variable RSS behavior. Thus, after selecting the candidate tags, we separately characterize the group RSS behavior of both of (i.e. Tag-10 and Tag-14) the tag types.

To identify a uniformly sensitive set of tags from a large group of a given tag type, we observe their RSS behavior over a range of tag-reader distances and reader output power level combinations, and measure the distribution's central tendency. We then sort (or bin) the tags of each type based on their RSS behavior. Figures 4 and 5 illustrate the binning distribution of 500 tags of each tag type using the ThingMagic and the Alien reader, respectively.

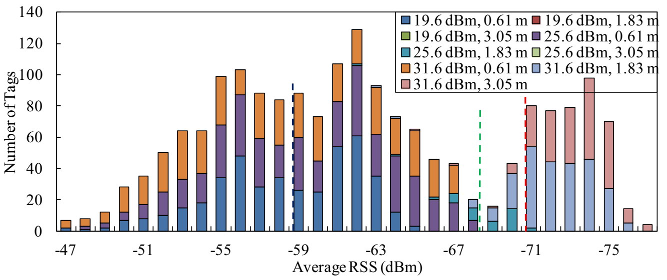

Fig. 4: Tag binning distribution of 500 Tag-10s using the ThingMagic reader.

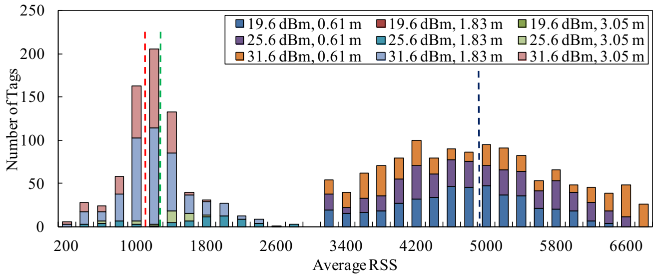

Fig. 5: Tag binning distribution of 500 Tag-14s using the Alien reader.

TABLE I: Group RSS Behavior of Candidate Tag Types.

Mean and Standard Deviation of the Selected Tag-Reader Pairs			
Tag-Reader Pairs	$(\mu_{0.61}, \sigma_{0.61})$	$(\mu_{1.83}, \sigma_{1.83})$	$(\mu_{3.05}, \sigma_{3.05})$
[Tag-10, ThingMagic]	(-59.02, 0.56)	(-68.22, 3.46)	(-70.99, 2.68)
[Tag-14, Alien]	(5076.84, 272.74)	(1256.37, 316.01)	(1109.97, 161.01)

For the tag binning experiment, reader output power level is varied over the values $\{19.6, 25.6, 31.6\}$ dBm while tag-reader distance is gradually increased over the distances $\{0.61, 1.83, 3.05\}$ meters. The intervals used in these sets of experiments were kept consistent with the previous experiments to derive correlated inferences. As illustrated above, tag binning distribution is a collection of distance measurement point -based Gaussian distributions. Table I illustrates the mean (μ) and the standard deviation (σ) for the [Tag-10, ThingMagic] and the [Tag-14, Alien] tag-reader pairs, at tag-reader distances of 0.61, 1.83, and 3.05 meters.

The mean and standard deviation are also shown in the Figures 4 and 5 using the blue (for 0.61 meters), green (for 1.83 meters), and red (for 3.05 meters) dotted-lines. For selecting the uniformly sensitive tags, we use a 2σ filtering window about the mean for each tag binning distribution shown above. For example, considering the Alien reader and the Tag-14 type, the filtering window at 0.61 meters is 545.48 about the mean, thus allowing Tag-14 type tags to be selected from the RSS interval $[4531.36, 5622.32]$. The filtering window can be suitably adjusted to arrive at application-specific tradeoffs between the number of tags available and the quality of their RSS behavior (e.g. relaxing the filtering window to 4σ selects more tags having less uniform RSS behavior, while restricting the filtering window to 1σ selects fewer tags having more uniform RSS behavior).

By counting the tags present within the filtering window at each of the power-distance combinations and eliminating the duplicates we get 66 % tags (i.e. 330 out of 500) of type Tag-10 and 73.8 % tags (i.e. 369 out of 500) of type Tag-14 for the ThingMagic and the Alien reader, respectively, that are uniformly sensitive. All the subsequent experiments were based with these selected uniformly sensitive tags.

C. RSS Decay Models

The goal of the proposed RSS decay models is to reliably characterize and establish the relationship between the tag's RSS behavior and the tag-reader distance.

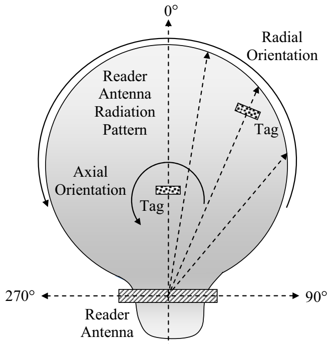

Fig. 6: Measuring RSS using antenna radiation pattern and tag orientation.

A tag's RSS behavior is continually changing due to ambient environmental interference, tag-centric variable radio sensitivity, and orientation [2], [17]. The ambient environment's impact can be minimized by ensuring that the operating environment usually remains unchanged. Thus, such ambient noise can be considered statistically invariant when developing RSS decay models that characterize tag's integral variable radio sensitivity with respect to its axial-radial orientation. Furthermore, knowledge of the reader antenna's radiation pattern helps in determining its shape, which aids in the development of above models (see Figure 6).

In the development of RSS decay models, we initially kept the reader output power level constant at 31.6 dBm and varied the tag-reader distance over the range $[0, 3.30]$ meters in steps of 0.127 meters. We rotated the tag on its axis and around the reader's antenna over the interval $[0°, 90°]$ in steps of $15°$ (for axial measurements) and $30°$ (for radial measurements), respectively. We also measured the tag's RSS at $270°$ to ensure efficient coverage of the reader antenna's radiation pattern. Figures 7, 8, 9, and 10 show Tag-10 and Tag-14 axial-radial orientation based RSS behavior for both readers.

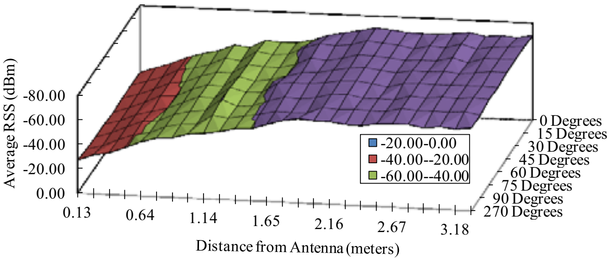

Fig. 7: RSS decay for [Tag-10, ThingMagic Reader] – Axial Orientation.

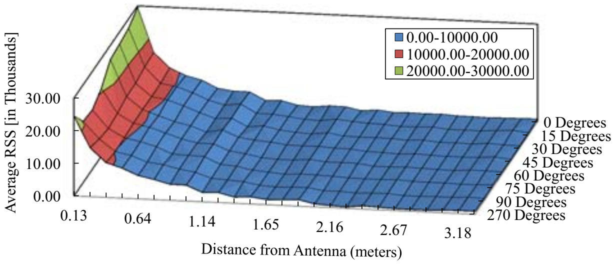

Fig. 8: RSS decay for [Tag-14, Alien Reader] – Axial Orientation.

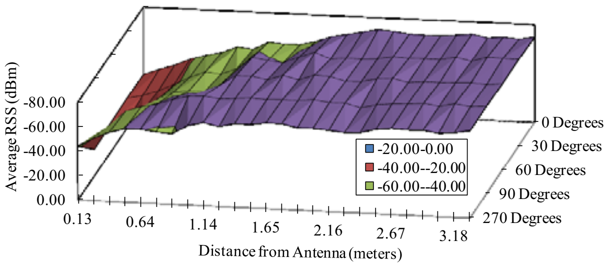

Fig. 9: RSS decay for [Tag-10, ThingMagic Reader] – Radial Orientation.

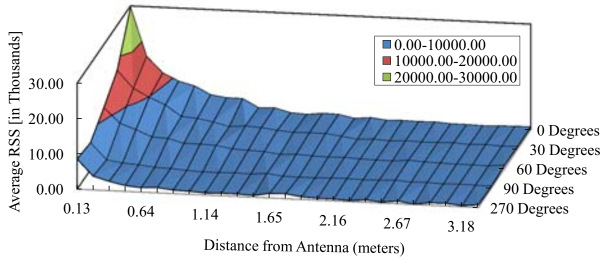

Fig. 10: RSS decay for [Tag-14, Alien Reader] – Radial Orientation.

Peak RSS behavior shown in Figure 10 for the Alien reader is due to the combination of the reader antenna's radiation pattern and the tag's orientation-dependent antenna response. RSS decay models based on the above characterization tend to provide sustained average-case high object localization performance for different application scenario driven deployments. Using the methodology described above, we developed several axial-radial orientation based RSS decay models having the following general expression format:

$$RSS = C \cdot D^{E} \tag{2}$$

where RSS, C, D, and E are the received signal strength value returned by the reader, coefficient, tag-reader distance, and the exponent, respectively. Two separate goodness-of-fit measures, R^2 and normalized root mean square error (NRMSE), were used to select the best possible curves that fit the tag orientation specific RSS behavior. Table II illustrates the average RSS decay models for both the tag-reader pairs.

After the development of the RSS decay models, target tagged stationary and mobile objects are located by measuring the target tag's RSS in real-time and using planar-spatial trilateration combined with Equation 2 [19].

TABLE II: RSS Decay Models

Average RSS Decay Model for the [Tag-10, ThingMagic] Tag-Reader Pair				
Degree$_{\mathrm{a}}$	Coefficent (C)	Exponent (E)	$\mathrm{R}^2_{\mathrm{b}} \in [0.0, 1.0]$	$\mathrm{NRMSE}_{\mathrm{c}} \in [0.0, 1.0]$
$0° - 270°$	-53.17	0.29	0.91	0.07
Average RSS Decay Model for the [Tag-14, Alien] Tag-Reader Pair				
Degree	Coefficent (C)	Exponent (E)	$\mathrm{R}^2 \in [0.0, 1.0]$	$\mathrm{NRMSE} \in [0.0, 1.0]$
$0° - 270°$	3246.76	-0.89	0.96	0.04

[a] inclusive of tag axial-radial orientations
[b] for R^2 value closer to 1 indicates better fit
[c] for $NRMSE$ values closer to 0 indicates better fit

The proposed real-time location system can exhibit some spatio-temporal drifts, which can be mitigated by performing periodic and on-demand in-situ calibration. We outline two calibration methods here to help provide sustained object localization performance. In the first method, uniformly sensitive reference tags combined with k-nearest neighbor algorithms can be used to help calibrate the coefficient and the exponent. In the second method, the RSS decay models can dynamically evolve by using sensor tags that can measure different ambient conditions such as temperature, pressure, and humidity [16].

IV. EXPERIMENTAL EVALUATION

To experimentally evaluate the proposed real-time location system, a realistically noisy environment having 16 cubic-meters volume was set up (see Section III for details on the type of noise sources). Additionally, a Lego Mindstorms based track driven robot system was developed to wirelessly control and move the target tags. RFID readers equipped with four antennas were connected to a host PC (with an AMD Athlon 64 processor running at 2 GHz with 1 GB RAM). The reader-reported real-time RSS values were routed to the host running the models for locating the target objects.

For visualization purposes, the real-time position estimates were wirelessly transmitted to modern tablet computers (an iPad and a Samsung Galaxy). The mobile robots moved along the track at speeds of up to 0.2 meters/second. We designated five different antennas as $(\mathrm{X}_1, \mathrm{Y}_1, \mathrm{X}_2, \mathrm{Y}_2, \mathrm{Z})$ in the 3D space and use four different antenna-pair combinations (i.e. $(\mathrm{X}_1, \mathrm{Y}_1, \mathrm{Z})$, $(\mathrm{X}_2, \mathrm{Y}_2, \mathrm{Z})$, $(\mathrm{X}_1, \mathrm{Y}_2, \mathrm{Z})$, $(\mathrm{X}_2, \mathrm{Y}_1, \mathrm{Z})$) when computing the target tag position estimates. Figure 11 illustrates the experimental setup.

We simultaneously located several stationary and mobile objects in 3D space by placing three objects at several locations while adjusting their heights to three levels. Figure 12 and 13 depict the actual and measured average Euclidean distance for the three stationary and mobile objects from a reference origin using the two tag-reader pairs. The measured average Euclidean distances closely track the corresponding actual distances of the target objects.

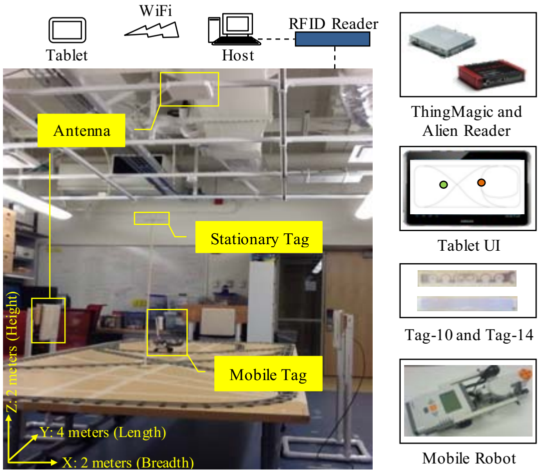

Fig. 11: An overview of the experimental lab setup.

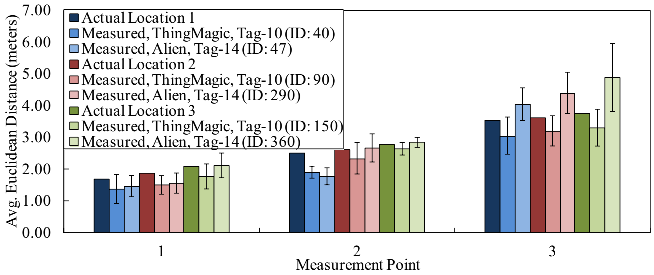

Fig. 12: 3D stationary object localization accuracy.

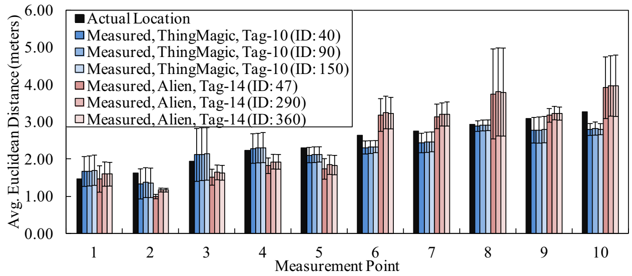

Fig. 13: 3D mobile object localization accuracy.

However, there are a few locations where the localization accuracy variation is slightly larger than the overall localization accuracy distribution (e.g. measurement point 3 in Figure 12 and measurement points 8 and 10 in Figure 13). Such variations are due to the reader antenna's radiation lobe pattern, thus causing some measurement points to be located in radio "blind spots". This phenomenon can be mitigated by using additional antennas with overlapping detection regions.

We found that the combined 3D stationary and mobile object localization accuracy for the [Tag-10, ThingMagic] and the [Tag-14, Alien] tag-reader pairs lies in the interval $[0.3, 1.21]$ and $[0, 1.14]$ meters, respectively. Furthermore, the overall average 3D object localization accuracy for both the tag-reader pairs was determined to be 0.6 meters, comparing favorably with previous works. Considering that the above results were obtained without using any reference tags, the overall object localization performance of the proposed real-time location system can be further improved. The above localization experiments were conducted over a six month period to ensure consistency amidst ambient interference.

V. CONCLUSION AND FUTURE WORK

We presented an RFID-based robust RSS decay model - driven real-time location system that can accurately locate multiple stationary and mobile objects in a 3D space. Our localization performance results compare favorably with other state-of-the-art RFID-based localization systems [3], [7], [9], [13]. We thus dispelled a common misconception, by showing that RSS can indeed be used as a reliable metric for object localization (among other possible applications), by considering select deployment scenarios, the tag's radio sensitivity, orientation, and its pairing with and distance from the reader.

While our system does not use any reference tags, it would still be interesting to investigate the utility and economics of deploying reference tags towards further improving the localization performance. Different combinations of RFID hardware, RSS decay models, automatic calibration procedures, and the economics of scalability should also be investigated. Finally, we should study the efficacy of robust RSS in applications beyond object localization.

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