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Analysis of the variability of RSSI values for active RFID-based indoor applications

Gülben ÇALIŞ,[1,*] Burçin BECERİK-GERBER,[2] Ahmet Burak GÖKTEPE,[1] Shuai LI,[2] Nan LI[2]

[1]Department of Civil Engineering, Ege University, Bornova, İzmir, Turkey

[2]Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA, USA

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Abstract: Radio frequency identification (RFID) technology-based indoor localisation solutions have been widely adapted by many industries. An important factor affecting the performance of RFID applications is the received signal strength indication (RSSI) values. Indoor setting and layout may have direct effects on the RSSI variability, which, in turn, affect the robustness of RFID applications' outcomes. Effects of different environmental factors on RSSI values for RFID tags have been observed and reported in previous literature; however, there is a lack of research that addresses the effects of such parameters on RSSI values in a holistic and quantified manner. In this study, 2 different test scenarios are used to compare and assess the relationships between the RSSI values and system parameters for active RFID tags in indoor applications. These parameters include: 1) type of materials that tags are attached to, 2) obstructions between tags and an antenna, 3) relative elevation between tags and an antenna, and 4) relative orientation of tags and an antenna. The effect of each parameter was evaluated by statistical analyses. The Shapiro–Wilk, Bartlett's, Levene's, Kruskal–Wallis, Mann–Whitney, and Games–Howell tests were conducted. The results show that the data groups for all of the system parameter tests were nonnormally distributed and heterogeneous. Based on the Mann–Whitney test results, U values for comparisons of RSSI values in both test beds were found to be 0.00 for all of the system parameters. The results indicate that different system parameters caused variations in RSSI values as well as the detectability rates. Nevertheless, different test beds changed the influence of each parameter on the RSSI values. It is concluded that testing environment is a prominent parameter that affects the results and fluctuations in the RSSI values, and that the detectability rates cannot be attributed to any specific parameter that has been included in this study.

Key words: Received signal strength indication, radio frequency identification, indoor asset tracking, indoor localisation, hypothesis testing, attached material, obstruction, elevation, orientation, test environment

1. Introduction

Indoor localisation, or determining the position of an object or a person in an indoor environment, is useful for many applications (e.g., tracking, monitoring, or routing) in several industries such as the manufacturing, healthcare, and construction industries (Landt, 2005; Ergen et. al., 2007b; Wang et. al., 2007; Torrent and Caldas, 2009; Yin et al., 2009; Li and Becerik-Gerber, 2011). For example, in the healthcare industry, knowing and tracking the locations of items might be crucial whenever there is an emergency to respond to. Especially in hospitals, where many employees have to share the same assets for work purposes, items can easily get moved and not returned to their original location. In the manufacturing industry, knowing the location of products in

*Correspondence: gulben.calis@ege.edu.tr

a warehouse could support asset management in terms of keeping track of the inventory and reducing the length of time that would be spent for finding assets. Location information could also support facility management activities by providing locations of equipment or building components that need to be maintained or repaired. Occupants unfamiliar with a built environment could be provided with location information to find the routes to their destinations. In addition, high-value assets or critical information devices (e.g., computer hard-drives or objects in museums) might be exposed to theft. Location information could support theft detection and prevention by providing notifications of unauthorised removal of items from a building. This could be done by determining the locations of items. When they are moved outside the boundaries of their location, notifications could be sent to alert the responsible personnel. Wing (2006) summarised the applications of RFID technology as facility access control, inventory management, construction site delivery logistics and materials tracking, document tracking, product life-cycle tracking, and building energy control.

As the importance of indoor location information has been recognised, off-the-shelf technologies have been introduced for localisation infrastructures. Radio frequency identification (RFID) is one of the most widely used technologies and has been developing rapidly, to a global value of US$7.67 billion in 2012; it is expected to grow to $11.3 billion by 2015 (IDTechEx, 2013). Many researchers have focused on the applications of RFID technology and have proven that it has the potential to become pervasive (Domdouzis et al., 2007) for various purposes such as prefabrication control and management (Ergen et al., 2007; Yin et al., 2009), supply chain management (Song et al., 2006b; Kaneko et al., 2007; Wang et al., 2007; Ren et al., 2010), onsite (Song et al., 2006a; Song et al., 2007; Torrent and Caldas, 2009; Chae et al., 2010) or underground (Dziadak et al., 2009) materials management, tool management (Goodrum et al., 2006), safety management (Umetani et al., 2006; Chen et al., 2007; Wang, 2008; Chae and Yoshida, 2010), project process management (Chin et al., 2008), and facility management (Ergen et al., 2007b; Ko, 2009). Li and Becerik-Gerber (2011) provided a comprehensive review and performance analysis of RFID-based indoor location sensing solutions for the built environment.

Radio signal strength indication (RSSI) is a standard feature in most localisation solutions and is defined as the voltage in the received signal strength indicator pin on the radio signal. It is usually expressed in dBm, which is 10 times the logarithm of the ratio of power (P) and the reference power (P_{ref}). The relationship between power and distance is such that power is inversely proportional to the square of the distance travelled (RSSI α log (1/distance^2)). RSSI is considered to be a key parameter to estimate the coordinates of the targets and, thus, is crucial for accurate localisation. RSSI-based algorithms either assume a complete profiling of the deployment area or a specific signal attenuation model that can provide the distance or area information directly or indirectly from the raw RSSI data (Niculescu and Nath, 2003; Patwari and Hero, 2003; Te et al., 2003; Elnahrawy et al., 2004; Stoleru and Stankovic, 2004; Madigan et al., 2005; Yedavalli et al., 2005).

Several researchers have reported that system parameters affect the performance of RFID technology in indoor environments (Bai et al., 2008; Pradhan et al., 2009; Chang et al., 2011; Chen and Shaw, 2011; Huang and Chang, 2011; Luo et al., 2011; Razavi and Haas, 2011; Trappey et al., 2011; Taneja et al., 2012). As indoor radio propagation is more chaotic than in outdoor settings, where signals travel with few obstacles caused by different system parameters, it is crucial to understand whether RSSI values are reliable in indoor environments. Moreover, understanding how different system parameters affect the variability of RSSI values in diverse indoor layouts is useful to further improve the performance of RFID-based indoor localisation solutions. The accuracy of existing RFID-based indoor localisation solutions, such as the ones reported by Pradhan et al. (2009) and Taneja et al. (2012), are impacted by multipath and signal collision issues, which are partly caused by the system parameters. These solutions currently rely on various localisation algorithms to mitigate the impacts. If these impacts and their causes are statistically analysed, it may be possible to further improve the performance of the indoor localisation solutions by altering the system parameters, such as changing the layout and set points, which users have control over. However, although the above prior researchers reported the existence of impacts of system parameters on the performance of RFID technology, no one has explored these impacts in a holistic and quantified manner. In fact, the need for controlling or minimising the impacts observed in the literature calls for a study that examines the statistical effects of system parameters on active RFID tags in indoor environments and how they affect RSSI variability. Active RFID technology is gaining increasing popularity for a wide range of applications, especially in object localisation and tracking, due to its long read range and extendable data storage capacity. Therefore, this study focuses on active RFID technology.

This paper investigates the variability of system parameters on active RFID tags for indoor environments by comparing and assessing RSSI values in 2 test beds. System parameters that are studied in this paper include: 1) type of materials that tags are attached to, 2) obstructions between tags and an antenna, 3) relative orientation of tags and an antenna, and 4) relative elevation (RE) between tags and an antenna. To assess the variability of these system parameters, a total of 39 tests were conducted. The main objective of this study was to understand the variability of RSSI values via statistical analyses. In order to evaluate the variation of RSSI values under different parameters and test beds, detailed statistical analyses were conducted. Shapiro–Wilk tests were carried out to understand whether the data sets represent samples from a normally distributed population or not. After the analyses of normality, scattering of each data set was analysed with Bartlett's and Levene's heterogeneity tests by using the variance deviations of each group. Understanding the distribution and scattering of the data groups enabled the authors to choose the correct significance test that evaluates the variation of RSSI values. Accordingly, Kruskal–Wallis and Mann–Whitney tests were selected. Finally, the magnitude of each system parameter effect was evaluated via Games–Howell post-hoc tests.

The paper is organised as follows: the next section provides the background. The methodology of data analyses, descriptions of the test beds, and results of the statistical analyses are then provided. Finally, discussion and conclusions are presented.

2. Background

Different indoor system parameters can cause different effects on the RSSI values, which result in fluctuations in the received signal envelope and phase. These fluctuations vary depending on the space layout, tags' visibility and mobility, RE of tags and an antenna, and so on (Bridelall and Hande, 2010). Complicated surroundings in an indoor environment could amplify the effect by modifying, altering, or disrupting the radio waves travelling between tags and an antenna (Clarke et al., 2006; Wang et al., 2009). Even if there is a line of sight between tags and an antenna, this effect can randomly decrease or increase the received signal strength (Griffin and Durgin, 2010).

Materials that tags are attached to and obstructions between tags and an antenna can absorb and reflect radio waves and subsequently generate signal interference. The effect of proximity to metal is frequently reported by researchers. This can cause signal detuning and, thus, can degrade the signal-to-noise ratio for active RFID systems (Chen et al., 2009). Attached materials and obstructions can also contribute to these effects, which reduce read rates and read ranges of RFID systems (Bridelall and Hande, 2010). Kim et al. (2011) attached passive RFID tags to a range of construction materials to evaluate tags' performance. RFID tags could be fully detected by the antenna when the tags were attached to wood, porcelain tiles, and marble. The read rates for concrete blocks, polystyrene, and steel were 78%, 89%, and 44%, respectively. RFID tags could barely be detected when tags were attached to steel. Tzeng et al. (2008) investigated the read rate of passive RFID tags attached to interior decorating materials such as sound absorption boards. RSSI values were measured and proved to be significantly affected by metallic materials. UHF passive tags were identified to have performance degradation when placed near metal and water (Aroor and Deavours, 2007). Daily and McCann (2007) found that the read rate for passive tags in the vicinity of metallic surface can be as low as 0%. Empirical tests and simulations proved that the decrease in the electric field with proximity to metals or dielectrics materials leads to the decrease of UHF passive tag read range (Dobkin and Weigand, 2005). The literature supports the idea that the materials that passive tags are attached to can strongly influence the strength of radio signals (Dobkin and Weigand, 2005; Aroor and Deavours, 2007; Daily and McCann, 2007; Tzeng et al., 2008; Kim et al., 2011).

Obstructions between tags and an antenna can affect RSSI values when radio waves pass through obstructions directly since they are absorbed. However, the existence of obstructions between tags and an antenna can also reduce the impact of tag collision. Ergen et al. (2007a) concluded that poor RFID performance in facility management applications was caused by the low read rate of the active tags attached to fire valves, which the authors attributed to the highly metallic environment and the obstructions between readers and tags. Dziadak et al. (2009) evaluated the read range of passive tags in the presence of different soil types. In this research, passive tags were attached to the pipes, which were buried underground. Read range rates were determined based on the distance between the tags and the antenna. Field experiments suggested a significant difference in read range between gravel and sand. In another study, the read range of read-only, passive, and ultrahigh-frequency tags was found to decrease when the tag was immersed in a liquid medium as compared to in air (Ross et al., 2009).

RE between tags and an antenna also has effects on the RSSI values. Whitehouse et al. (2007) proved that small changes in the antenna elevation could generate a large influence on radio signal characteristics. The difference from maximum to minimum strength is about 17 dBm for a drop of 30 cm in the antenna elevation. It should be noted that RSSI values usually range from 0 dBm to –110 dBm as per manufacturers' specifications. Effects of different tag and antennae orientations on radio signals were also assessed in various studies, which mostly focused on the orientations of passive tags (Currie and Marina, 2008; Huang et al., 2008; Mello et al., 2008) and an antenna independently. Clarke et al. (2006) evaluated the read rate of passive tags with different orientations and the materials that they were attached to. The research reported that a 100% read rate could be achieved when tags were facing outward. Stoyanova et al. (2007) discovered that the vertical deployment of a wire monopole antenna, which is a class of radio antenna consisting of a straight rod-shaped conductor, often mounted perpendicularly over some type of conductive surface, could provide more stable RSSI values compared to a horizontal deployment in an outdoor environment. Lymberopoulos et al. (2006) demonstrated that the relative orientation of a monopole antenna is the major parameter in signal strength variability. Dil and Havinga (2010) quantified the influence of the antenna orientation on the signal strength in an indoor environment. Measurements showed that RSSI values could vary by more than 16 dBm between the vertical and horizontal orientations.

Although many researchers pointed out the effects of some of the system parameters on RSSI values, most of these research studies have focused on the passive RFID tags. However, active RFID tags are commonly used for tracking, monitoring, and routing in indoor environments; therefore, the performance of RFID solutions is correlated to the effects that these system parameters have on active RFID tags. There is a lack of comprehensive study with active RFID tags in indoor environments and little has been done in terms of analysing these effects statistically. Predicting how these parameters impact RSSI values may help practitioners to improve the performance of the RFID technology in many applications.

3. Methodology for data analyses

In this study, 2 test beds were designed to evaluate the effects of 4 system parameters on an active RFID system, which are frequently stated in the literature to contribute to RSSI variability. These system parameters are: 1) type of materials that tags are attached to, 2) obstructions between tags and an antenna, 3) relative orientation of tags and an antenna, and 4) RE between tags and an antenna. Equal amounts of experimental data were collected for each test and RSSI values were obtained under different system parameters. The effects of system parameters were derived from the raw RSSI values. It should be noted that RSSI values ranged from –40 dBm to –100 dBm for detected tags in this study and it was assumed that an undetected tag had a –128 dBm RSSI value, a number determined according to the equipment's sensitivity as defined by the manufacturer's specifications. According to the manufacturer's specifications, tags are still detectable at up to –128 dBm; however, RSSI values ranged from –40 dBm to –100 dBm in the tests that were conducted in this study and none of the tags' RSSI values were observed to be between –100 dBm and –128 dBm. The test beds' conditions were maintained the same throughout the tests, and, thus, the effect of other parameters on RSSI values was assumed to remain the same. By conducting statistical analyses, this study aimed to address the need for investigating the variability of RSSI values for 4 selected system parameters. Finally, the significances of selected system parameters were compared for 2 test beds to understand whether the findings were dependent on the testing environment or not. The main objective of this study was determined by investigating the effects of a testing environment on the variability of RSSI values.

Visual observations and basic statistical analyses are important for the evaluation of test data; nevertheless, further statistical breakdowns are also necessary to emphasise the statistical significance among the test groups. First, significance tests are conducted to understand if a difference caused by a system parameter results in statistically meaningful changes in RSSI values. It should be noted that the basic philosophy of the significance tests in statistics is to produce a test statistic, such as t- or F-values, and to calculate a probability value (P-value) using the test statistics. Next, the P-value is compared with a level of confidence (α-level), which is commonly selected as 0.05 in the literature. It should be noted that the α-level is a statistical measure (percentage) of the reliability of an estimate. There are 2 hypotheses valid for statistical significance tests, namely H_0 and H_1. If the null hypothesis (H_0) is false (or rejected), the P-value is below the α-level. The H_0 criterion implies statistical significance, which means that there is no difference between the compared groups. If the H_0 hypothesis is valid (thus, H_1 is false), then the P-value is larger than the α-level, which indicates that test samples are from the same population (Motulsky, 2010; Walpole et al., 2011; IBM, 2012; NIST/SEMATECH, 2012).

On the other hand, there are different significance tests that are used for comparison of 2 or more groups in statistics. The most popular test for the comparison of 3 or more groups is the analysis of variance (ANOVA) method. ANOVA is a parametric test based on several assumptions, namely: 1) data represent samples from a normally distributed population, 2) variances of the groups are similar (data exhibit homogeneous scattering), 3) sizes of the groups are similar, and 4) groups are independent from each other. In other words, as the selection of the significance test completely depends on the results of these data behaviours, distributions of the data groups should initially be assessed in terms of their convenience in normal/nonnormal distribution and their scatting to homogeneous/heterogeneous behaviour. For example, if data are heterogeneous in terms of variance (variances of the groups are significantly different), then the result of ANOVA is suspicious. Specifically, if heteroscedasticity exists (standard deviation or variances are different), even when the population means are same, the probability of getting "false positive" (namely, type 1 error in statistics) results increases. Therefore, even in the case that the null hypothesis is true, groups can be significantly different. This is the reason why ANOVA may fail if the data are heterogeneous. Similarly, if data come from a nonnormal population, parametric tests may fail to evaluate the null hypothesis (H_0), which means that the compared groups are statistically equal. The 3 most common tests for the evaluation of normality are the Kolmogorov–Smirnov, Shapiro–Wilks, and Anderson–Darling tests. Consequently, in the case that these conditions are of normal (Gaussian) distribution and homogeneity conditions are not met, nonparametric test methods, such as the Kruskal–Wallis and Friedman tests, are used (Motulsky, 2010; Walpole et al., 2011; IBM, 2012; NIST/SEMATECH, 2012).

In this study, as data set sizes were smaller than 3000 data points, Shapiro–Wilk tests were performed to evaluate whether the data were normally distributed or not. On the other hand, Bartlett's and Levene's tests were used for the determination of the existence of heteroscedasticity. The major handicap of Bartlett's test is its sensitivity to departures from normality. Levene's test is less sensitive to the departures from normality. Levene's test is based on the trimmed mean concept, and Monte Carlo simulation applied to the data fits Cauchy distribution. In this study, both tests were applied to evaluate the homogeneity (or heteroscedasticity) of data sets. Heteroscedasticity tests are analogous to significance tests to make a decision. Namely, if the probability values corresponding to the test statistics are smaller than the selected α-level, then the H_0 criterion, which implies that the variances are the same, should be rejected (in other words, there is heteroscedasticity). It should also be noted that Bonferroni's method was used to calculate the simultaneous confidence intervals for heteroscedasticity tests. Finally, based on the results of normality and heteroscedasticity tests, Kruskal–Wallis (for the comparison of 3 or more groups) and Mann–Whitney (for the comparison of 2 groups) tests were used for the comparison of data sets in terms of statistical significance as these tests have nonparametric characteristics.

Two different significances were evaluated in the data sets. First, as implied before, the effects of each parameter on RSSI values were characterised with Kruskal–Wallis tests. Second, each data set obtained for different parameters was grouped into 2 classes. Instead of focusing on the variation, each RSSI value was clustered as "measured" or "not measured" in a binary manner. In this context, if the RSSI value is –128 dBm, then the result is considered as "undetected". Analogously, tags with RSSI values other than –128 dBm are accepted as "detected". Therefore, the detectability rate of a tag is analysed with these binary data using Mann–Whitney significance tests. Consequently, all data groups (for each parameter) were analysed in 2 ways: 1) variation of RSSI values and 2) detectability rates of the tags.

Results of significance tests may tell us to reject the null hypothesis (namely, that test groups are statistically different); nevertheless, it is also crucial to know which of the parameters differ. In other words, if there is a meaningful difference among testing variables (parameters), we need to know the magnitude of difference. The way of solving this problem is to perform post-hoc tests. There are several post-hoc analyses, such as the Tukey test or Gabriel's procedure. The Tukey test is a powerful technique; nevertheless, it assumes that the population variances are equal and the group sample sizes are the same. On the other hand, Gabriel's procedure can be applied if a small difference exists in sample sizes, and Hochberg's GT2 test is for data groups that have significantly different sample sizes. Finally, the Games–Howell method does not assume that population variances are equal. In this study, magnitudes of the effect of each system parameter on the RSSI values were analysed using Games–Howell post-hoc tests as the characteristics of data behaviour were found to be nonnormal and heterogeneous.

4. Description of tests

The RFID equipment used for all tests comprised 1 antenna, 1 reader, and 10 active tags, which emitted signals every 1.5 s. UHF active tags operating at the 915 MHz band were utilised throughout the tests as they are commonly used in long-distance operations (Bridelall and Hande, 2010). All active tags were of the same type, were manufactured at the same time, and have been preserved under the same conditions. Therefore, effects of design parameters such as tag shape, size, operating frequency, and transmit power were eliminated. An omnidirectional antenna was selected due to its uniform power radiation and continuous message reception without any disconnection. The radial shape of the omnidirectional antenna is not a perfect sphere and it is polarised in real scenarios; it can cause variance in RSSI with different orientations of an antenna. The antenna received signals from tags and transmitted the data to the reader in real time. A middleware, ILS Explorer, was used to communicate with the reader and to extract data, including tag IDs, RSSI values, and contact time.

Two test beds were designed to assess the effect of 4 system parameters on the RSSI values. The first test bed was an office room in an educational building at the University of Southern California (USC), and the second test bed was a gallery space on the USC campus. The first test bed was selected to represent a scenario in which RFID equipment is used in a daily functioning building. The room was 7 m in width, 6 m in length, and 2.7 m in height with multiple desks, chairs, bookshelves, computers, and occupants (Figure 1a). Test bed 2 was an exhibition gallery 10 m in width, 10 m in length, and 5 m in height, which provided a more spacious indoor area with no furniture inside (Figure 1b). The RFID equipment used in the tests can be seen in Figure 1c.

a b c

Figure 1. Images of the test beds and the RFID equipment.

Tests were conducted with the same test set up to avoid deviations due to the utilisation of different amounts of equipment and layouts. The tests for both test beds 1 and 2 included a total of 10 active RFID tags, which were placed 4 m away from the antenna maintaining the line-of-sight condition. Figure 2a shows the layout of the first test bed layout. All the tags were placed facing the antenna, which was vertically positioned. The elevation of both tags and the antenna was 0.75 m off the floor. A piece of cardboard 0.6 m $\times$ 0.6 m was selected as the attachment material since cardboard itself is free of measurable effects on the read range. The indoor temperature was maintained at 22 $^\circ$C via local HVAC controls. In order to obtain statistically sufficient data, every test was repeated 20 times and a total of 200 RSSI values was measured. For each test, only one environmental variable was changed while all other parameters remained the same.

To assess the effect of materials that tags were attached to, 10 different materials were used. These were aluminium, ceiling board, drywall, foam, glass, carpet, clay, plywood, steel, and cardboard. These materials were selected as they are considered to be the most commonly used building materials in an indoor environment. All materials were of unified size, 0.6 m × 0.6 m. The thickness varied between 0.5 cm and 2 cm depending on the type of the material. The layout of the tests to evaluate the material effects is shown in Figure 2b.

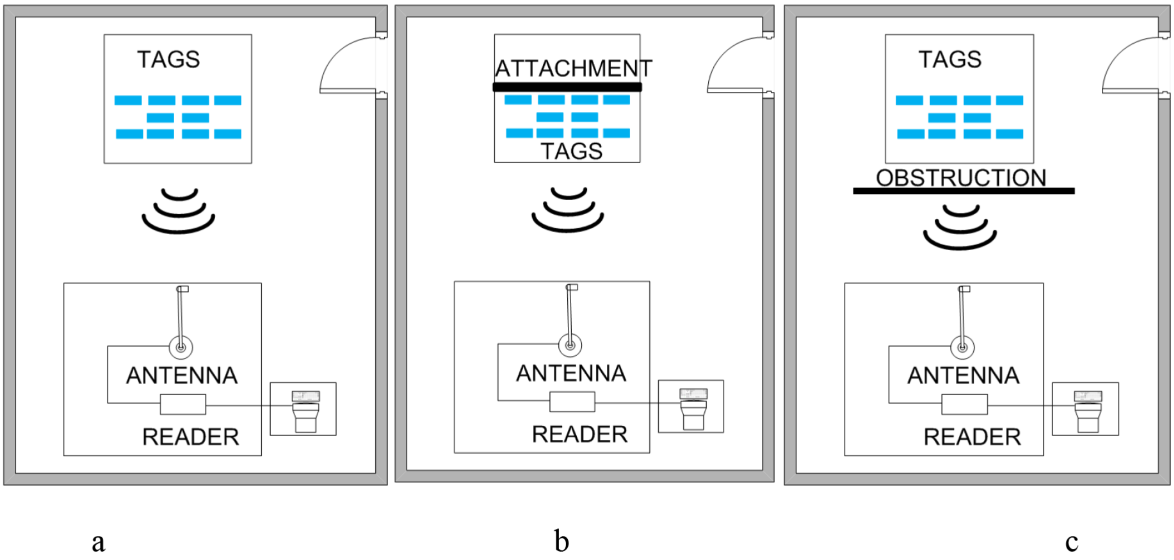


Figure 2. a) Test bed 1 layout, b) layout to evaluate the attached material effect, c) layout to evaluate the obstruction effect.

To assess effects of an obstruction between tags and the antenna, different kinds of obstructions of the same size and similar thickness were utilised in the tests. Figure 2c shows the layout of tests to assess the effects of obstructions. Every obstruction was placed at an elevation of 0.3 m from the floor and a distance of 0.7 m from the antenna. The tested obstruction materials included aluminium, ceiling board, drywall, foam, glass, carpet, clay, plywood, steel, and cardboard, in the same as the test materials explained above.

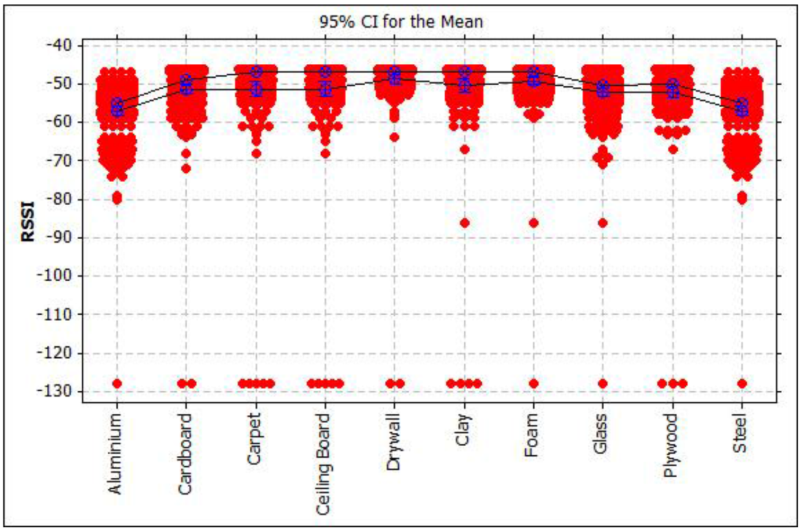
To assess the effect of RE, elevation of all tags was maintained at 0.75 m from the floor, while the antenna was placed at different elevations of 0.75 m, 1.5 m, 2.25 m, and 3 m. REs between tags and the antenna were equal to 0 m, 0.75 m, 1.5 m, and 2.25 m. No higher RE was tested due to the test bed space height limitations.

To assess the effect of relative orientation, the antenna was placed in 2 different positions: horizontal (H) and vertical (V) with respect to the floor. For each position of the antenna, the tag was placed in 5 different positions: 1) horizontal with front side facing the antenna (F); 2) horizontal with front side facing up the ceiling (U); 3) horizontal with back side facing the antenna (B); 4) vertical with front side facing the antenna (Vf); and 5) vertical with back side facing the antenna (Vb). Combining the positions of the antenna and the tag, there were a total of 10 different relative orientations (tag–antenna combinations) assessed in the tests.

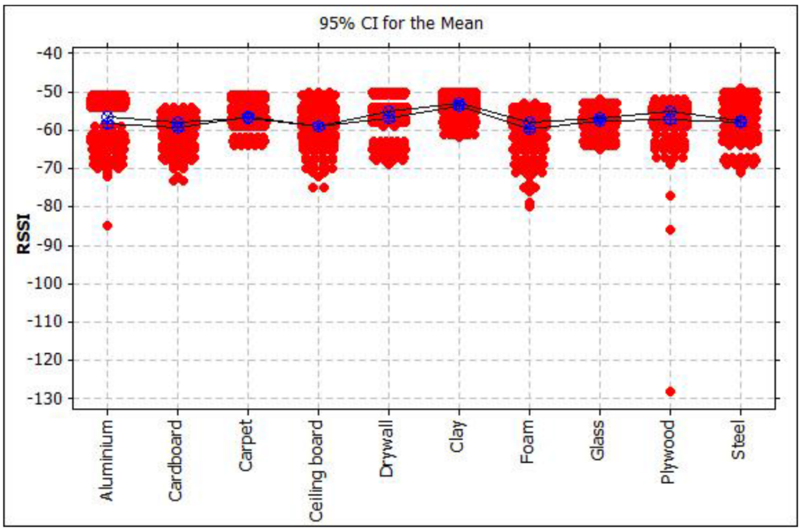
5. Results of the analyses

5.1. Attached materials

Individual value plots, in which the effects on RSSI values of the materials that tags were attached to, were visualised, as shown in Figure 3. Mean and median connection lines can also be seen in Figure 3. Aluminium and steel materials exhibited different RSSI values for test bed 1. The results of the other materials varied within almost the same range for test bed 1. On the other hand, for test bed 2, all materials exhibited similar performances. In all measurements of test bed 2, it is possible to observe that clay yielded different results than did the others. Consequently, it is hard to derive a concrete result via an observation, and different testing environments have different consequences.



(a)



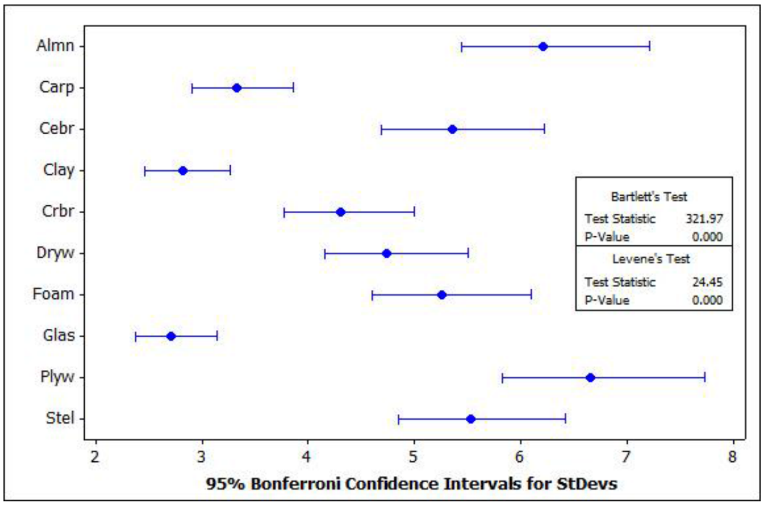
(b)

Figure 3. Individual value plots for types of materials that tags were attached to tests: a) test bed 1, b) test bed 2.

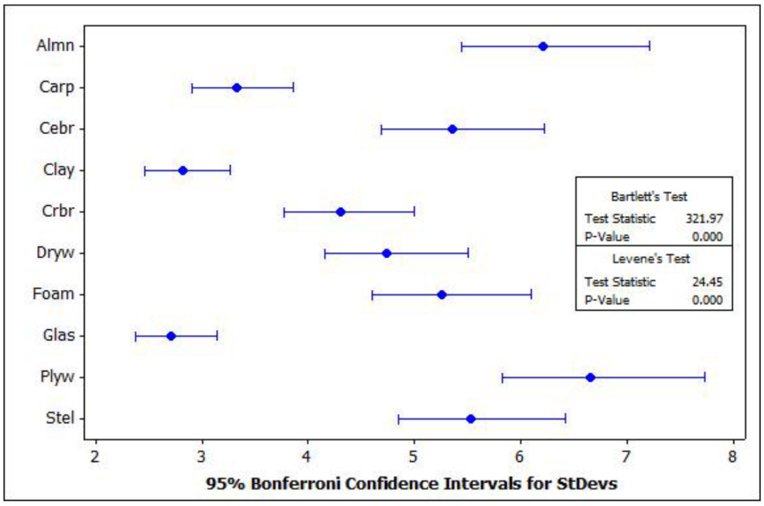
The results of the Shapiro–Wilk tests are presented in Table 1. As the probability values are lower than the selected α-level of 0.05, the H_0 criterion is rejected and it is concluded that none of the data groups obtained from test bed 1 and 2 fit the normal distribution.

Table 1. Results of the Shapiro–Wilk tests for attached materials.

Material	Test bed 1		Test bed 2	
	Test stat.	P-value	Test stat.	P-value
Aluminium	0.743	0.000	0.858	0.000
Cardboard	0.501	0.000	0.873	0.000
Carpet	0.374	0.000	0.916	0.000
Ceiling board	0.374	0.000	0.965	0.000
Clay	0.263	0.000	0.902	0.000
Drywall	0.344	0.000	0.857	0.000
Foam	0.388	0.000	0.847	0.000
Glass	0.634	0.000	0.877	0.000
Plywood	0.743	0.000	0.504	0.000
Steel	0.591	0.000	0.939	0.000



(a)



(b)

Figure 4. Results of heterogeneity tests for types of materials that tags were attached to in data tests: a) test bed 1, b) test bed 2.

In order to characterise the behaviour of the data in terms of heterogeneity, both Bartlett's and Levene's tests were conducted. Since the data groups were nonnormally distributed, Levene's nonparametric tests were preferred to assess existence of heterogeneity in the data scattering. Results of heterogeneity tests, performed on both test beds, are presented in Figure 4. Based on the Levene tests, probability values corresponding to the test statistics are 0 and are smaller than the selected α-level of 0.05; thus, the H_0 criterion, which implies that the variances are the same, should be rejected. As a result, heterogeneity exists in both test bed 1 and 2 data sets due to the variations in the variances. Consequently, the data sets obtained from the type of materials that tags are attached to tests are both nonnormal and heterogeneous.

Based on the Kruskal–Wallis test results, H values (test statistics) were 778.1 and 767.8 for test bed 1 and 2 data sets, respectively. Therefore, the probability values for calculated H values estimated by chi-square distribution with 10 degrees of freedom were 0.00, which are lower than the selected α-level of 0.05. As a result, the H_0 criterion, which implies that samples come from different populations, should be rejected for both data sets, and the conclusion that different attached materials result in different RSSI values could be drawn from the Kruskal–Wallis tests. As expressed before, the comparisons for the detectability rates were carried out for all attached materials individually using Mann–Whitney tests. The corresponding probability values to the calculated test statistics, namely U values, for all comparisons were found as 0.00; therefore, the H_0 criterion, which implies that samples come from different populations, should be rejected and the conclusion that different test beds result in different detectability rates could be drawn from the Mann–Whitney test results.

The results of Games–Howell tests are summarised in Table 2. It should be noted that the upper triangular matrix elements are the results of test bed 2, and the lower triangular matrix is for test bed 1. Furthermore, the bolded values indicate the statistical significance and whether there is a difference between 2 compared variables or not.

Table 2. Results of the Games–Howell tests for attached materials.

Test bed 1/ Test bed 2	Aluminium	Cardboard	Carpet	Ceiling board	Clay	Drywall	Foam	Glass	Plywood	Steel
Aluminium	**X**	0.675	**0.002**	0.984	**0.000**	0.171	0.323	0.560	0.807	1.000
Card board	**0.000**	**X**	**0.000**	0.999	**0.000**	**0.000**	0.999	**0.000**	**0.008**	0.145
Carpet	**0.000**	1.000	**X**	**0.000**	**0.000**	0.957	**0.000**	**0.023**	0.736	**0.012**
Ceiling board	**0.000**	1.000	1.000	**X**	**0.000**	**0.001**	0.925	**0.006**	0.124	0.698
Clay	**0.000**	0.139	0.452	0.452	**X**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
Drywall	**0.000**	0.998	1.000	1.000	0.925	**X**	**0.000**	0.945	0.999	0.462
Foam	**0.000**	0.244	0.637	0.637	1.000	0.985	**X**	**0.000**	**0.002**	**0.040**
Glass	**0.000**	0.993	0.998	0.998	**0.002**	0.733	**0.002**	**X**	1.000	0.922
Plywood	1.000	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**X**	0.978
Steel	0.142	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	0.142	**X**

Based on the post-hoc test results, the following conclusions can be drawn for test bed 1:

- Effects of steel, plywood, and aluminium are dominant on the detectability rates with respect to the others, as most of the Games–Howell test values of these materials are lower than the confidence level of 0.05.
- Significances of remaining materials are almost the same, and considerably less than those of steel, plywood, and aluminium.

On the other hand, conclusions drawn for test bed 2 data are summarised as follows:

- All of the Games–Howell test values of clay are 0.000 and thus are lower than the confidence level of 0.05. This result indicates that the effect of clay is the most distinguishing one for impacting the detectability rate and that there is a significant difference when tags are attached to clay with respect to the other materials.
- Following clay, the effects of carpet on the detectability rates are more notable than the others.
- Effects of the remaining materials are almost the same and considerably less than those of clay and carpet.

5.2. Obstructions

Related individual value plots are presented in Figure 5 to visualise the effect of obstruction types. Based on the visual observations, RSSI values are almost similar for all obstructions for test bed 1; nevertheless, glass resulted in different measurement results and, thus, caused variation in RSSI values. For test bed 2, among all obstructions, aluminium, dry wall, steel, clay, and carpet resulted in different RSSI values. Overall, it is hard to make a precise decision visually, and different testing environments have considerably different consequences in RSSI variability.

The results of the Shapiro–Wilk tests are summarised in Table 3. Based on the test results, the probability values were 0.00, which were lower than the selected α-level of 0.05. Therefore, the H_0 criterion was rejected, which means that none of the test groups were normally distributed.

Table 3. Results of the Shapiro–Wilks tests for obstructions.

Material	Test bed 1		Test bed 2	
	Test stat.	P-value	Test stat.	P-value
Aluminium	0.524	0.000	0.745	0.000
Cardboard	0.623	0.000	0.919	0.000
Carpet	0.422	0.000	0.874	0.000
Ceiling board	0.533	0.000	0.929	0.000
Clay	0.491	0.000	0.896	0.000
Drywall	0.853	0.000	0.582	0.000
Foam	0.643	0.000	0.859	0.000
Glass	0.892	0.000	0.777	0.000
Line of sight	0.884	0.000	0.968	0.000
Plywood	0.613	0.000	0.906	0.000
Steel	0.532	0.000	0.928	0.000

Results of the heterogeneity tests are presented in Figure 6. Based on the Levene's test results, a test preferred due to the nonnormal distribution of the data, probability values corresponding to the test statistics were 0 and thus smaller than the selected α-level of 0.05. Consequently, group variances are different and the data sets exhibit heteroscedasticity.

As a result of nonnormal and heterogeneous distribution of the test groups, the Kruskal–Wallis test was applied to compare the test groups in terms of the statistical significance. Based on the Kruskal–Wallis test results, H values were 76.2 and 301.9 for the test bed 1 and 2 data sets, respectively. Therefore, probability values for calculated H values estimated by the chi-square distribution with 11 degrees of freedom were 0.00, lower than the selected α-level of 0.05. As a result, it is possible to conclude that different obstructions resulted in different

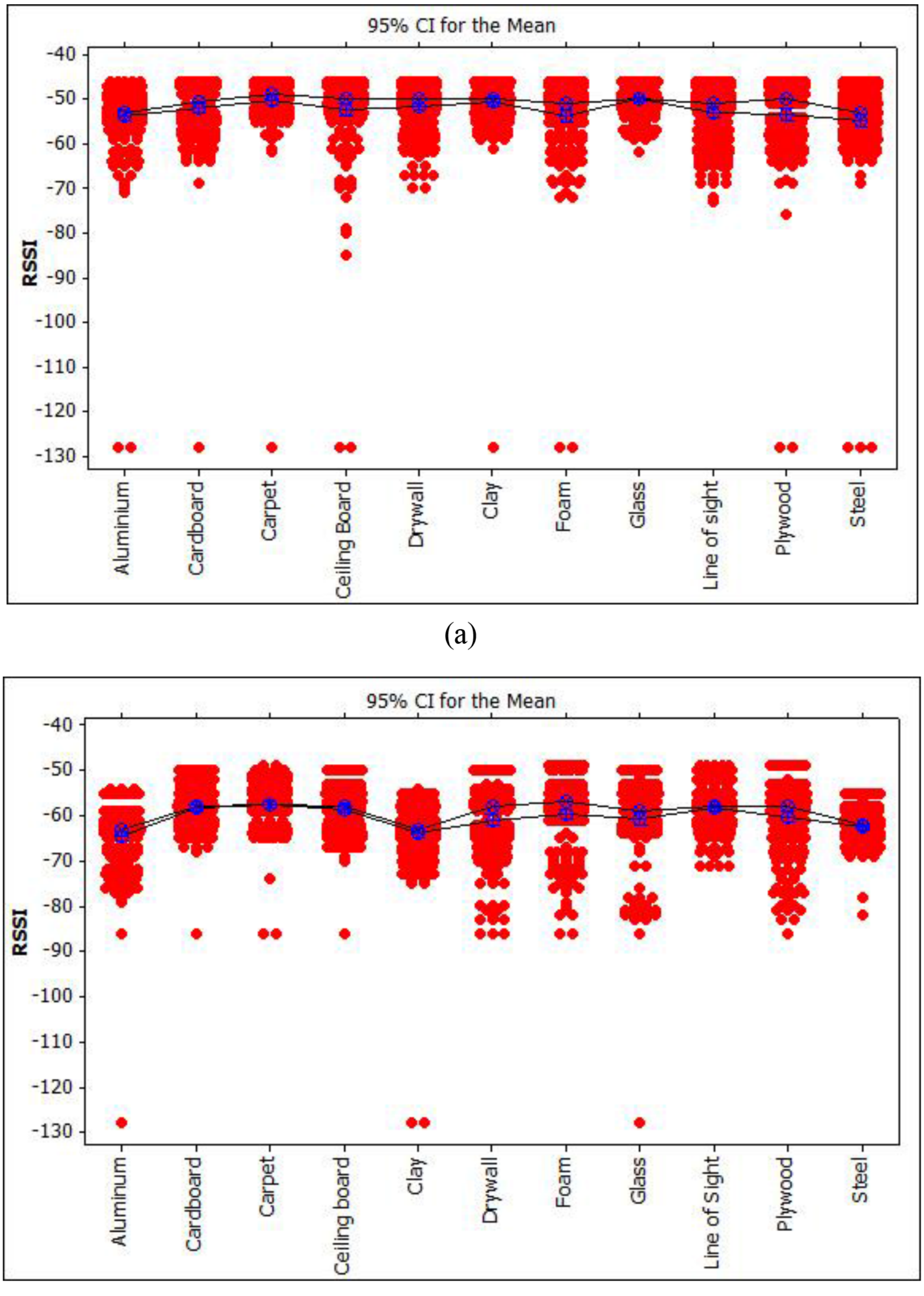
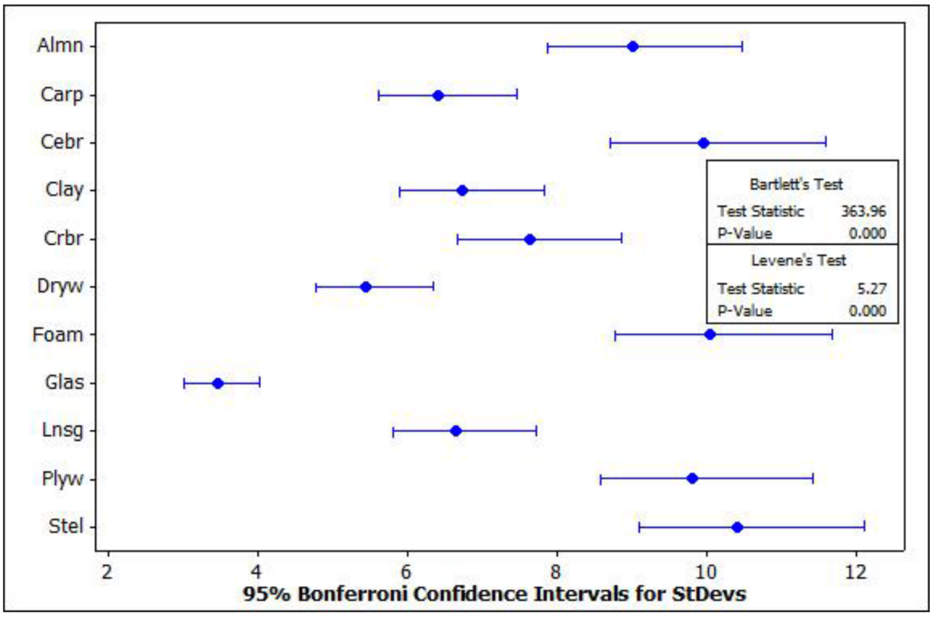


Figure 5. Individual value plots for obstruction tests: a) test bed 1, b) test bed 2.

detectability rates. Furthermore, based on the Mann–Whitney tests conducted for all obstructions individually, corresponding probability values to the calculated test statistics, namely U values, for all comparisons were 0.00. Thus, the result of Mann–Whitney test denoted that different test beds result in different detectability rates when different obstructions exist.



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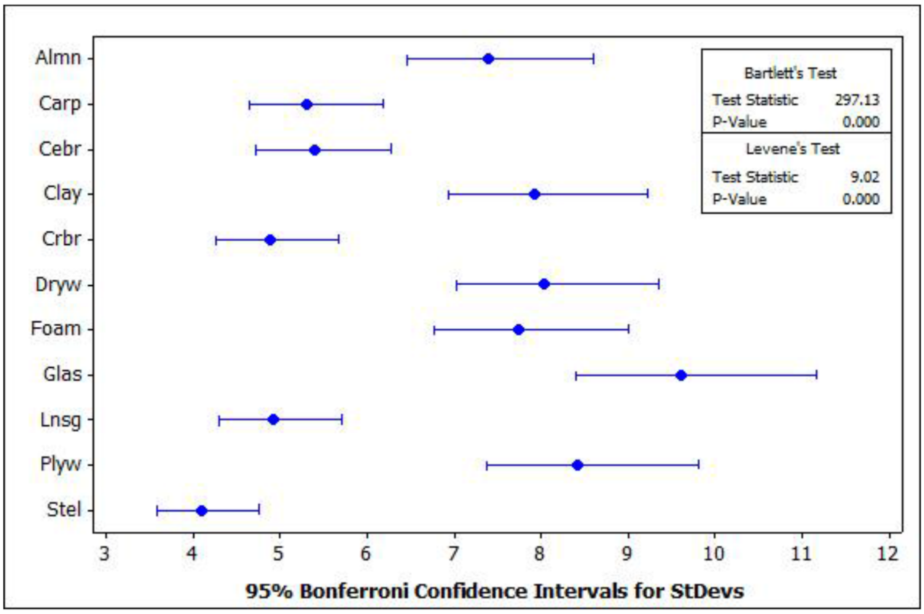


(b)

Figure 6. Results of heterogeneity tests for obstruction data sets: a) test bed 1, b) test bed 2.

The results of the Games–Howell tests are presented in Table 4. The upper triangular matrix shows the results from test bed 2, and the lower triangular matrix presents the results from test bed 1. Based on these results, the following conclusions can be drawn for test bed 1:

- It was seen that 80% of Games–Howell test values for glass were below the confidence level of 0.05. This result shows that the effect of glass is the most dominant on the detectability rates when compared to the others.

- Significances of remaining materials are almost the same, and considerably less than that of glass.

Table 4. Results of the Games–Howell tests for obstructions.

Test bed 1/ Test bed 2	Aluminium	Cardboard	Carpet	Ceiling board	Clay	Drywall	Foam	Glass	Line of sight	Plywood	Steel
Aluminium	**X**	**0.000**	**0.000**	**0.000**	**0.000**	1.000	**0.000**	**0.001**	**0.000**	**0.000**	0.078
Cardboard	0.635	**X**	0.990	0.996	**0.002**	**0.000**	0.434	**0.053**	1.000	0.068	**0.000**
Carpet	**0.001**	0.392	**X**	0.650	**0.000**	**0.000**	0.076	**0.006**	0.967	**0.006**	**0.000**
Ceiling board	0.986	1.000	0.213	**X**	**0.046**	**0.000**	0.927	0.306	1.000	0.409	**0.000**
Clay	**0.007**	0.735	1.000	0.460	**X**	**0.010**	0.888	1.000	**0.004**	1.000	0.243
Drywall	0.328	1.000	0.280	0.998	0.680	**X**	**0.000**	**0.011**	**0.000**	**0.001**	0.595
Foam	1.000	0.506	**0.001**	0.953	**0.006**	0.246	**X**	0.990	0.551	0.999	**0.000**
Glass	**0.000**	**0.042**	1.000	**0.031**	0.988	**0.004**	**0.000**	**X**	0.079	1.000	0.229
Line of sight	1.000	0.898	**0.001**	1.000	**0.012**	0.590	0.996	**0.000**	**X**	0.104	**0.000**
Plywood	1.000	0.790	**0.005**	0.996	**0.025**	0.534	1.000	**0.000**	1.000	**X**	**0.031**
Steel	0.979	0.063	**0.000**	0.464	**0.000**	**0.014**	0.998	**0.000**	0.633	0.968	**X**

The conclusions drawn for test bed 2 are summarised below:

- Obstructions of aluminium and drywall resulted in the most significant effect on the detectability rates of tags, as most of the Games–Howell test values were below the confidence level of 0.05.

- Following obstructions of aluminium and drywall, the effects of obstructions of carpet, clay, and steel were more remarkable than the others.

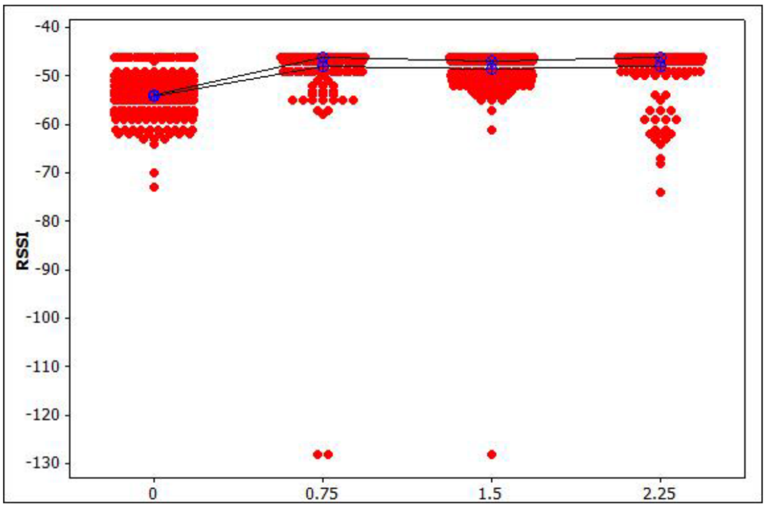
- Different testing environments resulted in fundamentally different detectability rates.

5.3. Relative elevation

In Figure 7, individual value plots are presented to visualise the effects of different REs on the RSSI values. As can be derived from Figure 7, the increase in RE yields different RSSI values, and thus causes variability in RSSI values for both of the test beds. It can be denoted that the elevation difference between tags and the antenna changed the RSSI values in test bed 1; nevertheless, the difference was not significant when the RE was changed from 0.75 m to 2.25 m. The results of the 2 test beds were different and inconsistent. This discrepancy in the results indicates the importance of testing environments on RSSI values.

The results of Shapiro–Wilk tests are presented in Table 5. As can be seen, since probability values were smaller than the selected α-level (0.05), data groups of both test beds did not fit to normal distribution.

Based on the Bartlett's and Levene's test results (Figure 8), the probability values corresponding to the test statistics were 0; therefore, these values were smaller than the selected α-level of 0.05 (H_0 criterion is rejected). As a result, the variances of the data sets were different, and the data sets exhibited heteroscedasticity.



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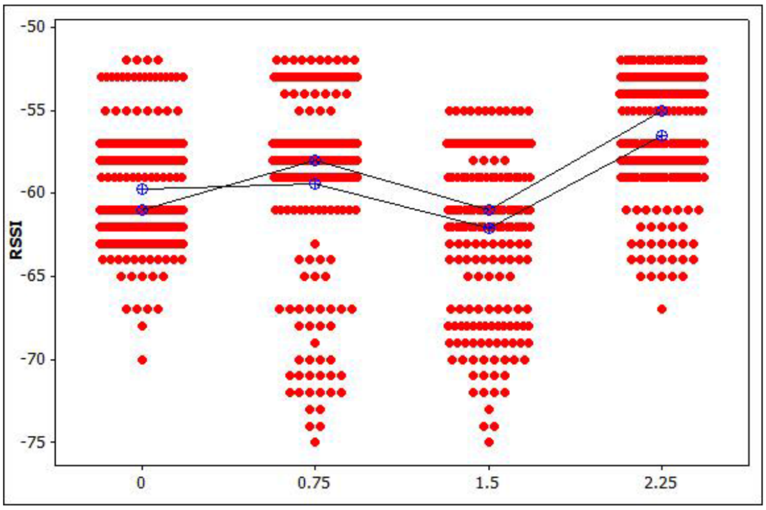

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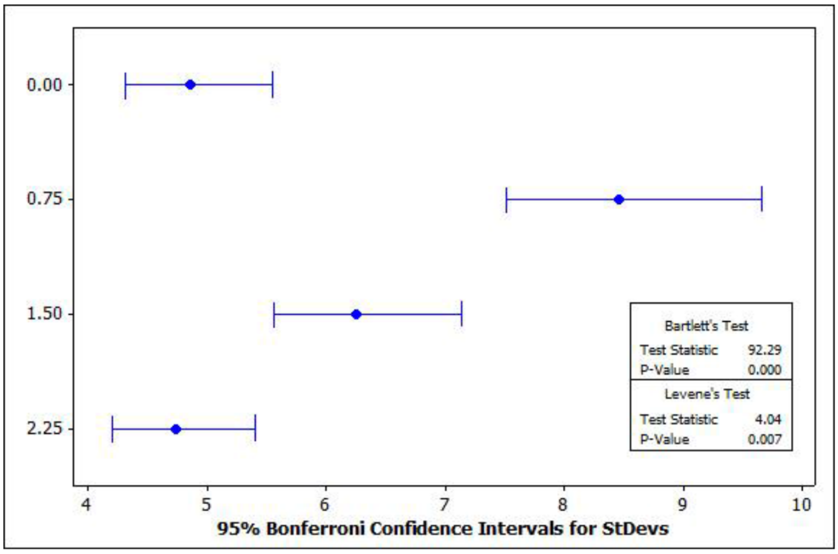
Figure 7. Individual value plots for relative elevation tests: a) test bed 1, b) test bed 2.

Table 5. Results of the Shapiro–Wilks tests for relative elevations.

Relative elevation (m)	Test bed 1		Test bed 2	
	Test stat.	P-value	Test stat.	P-value
0.00	0.965	0.000	0.958	0.000
0.75	0.223	0.000	0.869	0.000
1.50	0.317	0.000	0.922	0.000
2.25	0.507	0.000	0.907	0.000

Based on the Kruskal–Wallis test results, H values were 266.4 and 122.1 for test bed 1 and 2 data sets, respectively. Therefore, the probability values for calculated H values estimated by chi-square distribution with 3 degrees of freedom were 0.00, which is lower than the selected α -level of 0.05. Consequently, it is possible to derive that different REs resulted in different RSSI values. In addition, based on the results of Mann–Whitney tests, corresponding probability values to the calculated test statistics, namely U values, for all comparisons were found to be 0.00. Therefore, the results of Mann–Whitney test denoted that different test beds result in different detectability rates when different REs exist.



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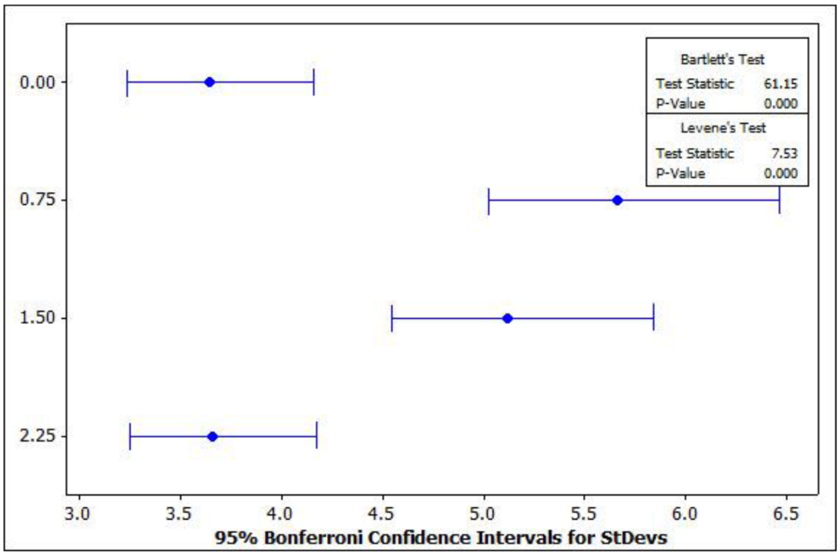


(b)

Figure 8. Results of heterogeneity tests for relative elevation data sets: a) test bed 1, b) test bed 2.

The results of Games–Howell tests are presented in Table 6. The upper triangular matrix elements are the results of test bed 2, and the lower triangular matrix is for test bed 1. In this context, the following conclusions can be drawn for both test beds based on the post-hoc tests:

- For test bed 1, all of the Games–Howell test values are 0.000 and thus below the confidence level of 0.05 for RE = 0.00 m. Therefore, it could be concluded that statistical significance exists in the case of RE = 0.00 m and there is no difference when REs change from 0.75 m to 2.25 m. However, any change in RE causes a change in RSSI values and this is consistent with the individual value plot observations.

- For test bed 2, all of the Games–Howell test results are 0.00 for RE = 1.50 m and 2.25 m. Moreover, only one result is observed below the confidence level for RE = 0.75 m. These results indicate that there is no statistical difference in changing the RE in terms of detectability rates of the tags.

- Importance of the RE is highly dependent on the testing environment.

Table 6. Results of the Games–Howell tests for relative elevations.

Test bed 1 / Test bed 2	RE = 0.00 m	RE = 0.75 m	RE = 1.50 m	RE = 2.25 m
RE = 0.00 m	X	0.915	0.000	0.000
RE = 0.75 m	0.000	X	0.000	0.000
RE = 1.50 m	0.000	0.895	X	0.000
RE = 2.25 m	0.000	1.000	0.827	X

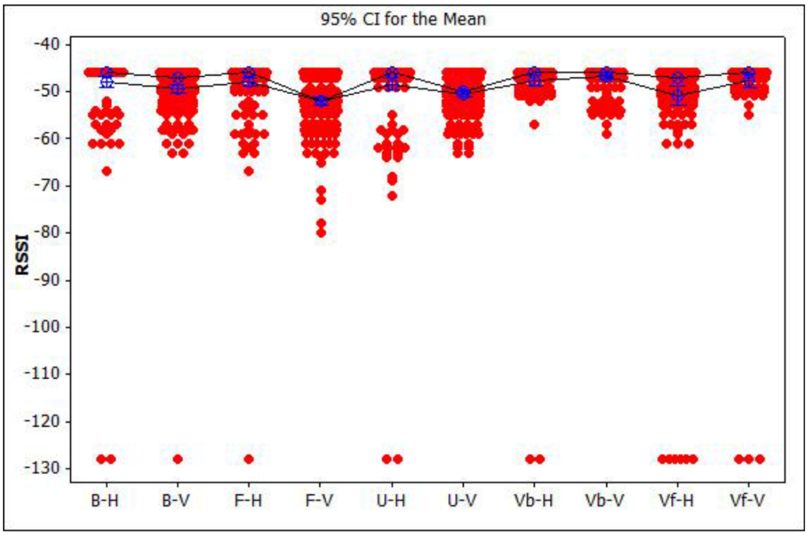
5.4. Relative orientation

The individual value plots of relative orientation tests are presented in Figure 9 for the test beds. For test bed 1, "F-V" and "U-V" orientations exhibited the poorest performances in terms of the tag detectability rates. The other orientation configurations resulted in similar performances. For test bed 2, "F-V", "U-V", "B-V", and "Vf-H" orientations caused the worst detectability rates. There were also variations in the results of remaining orientation configurations. It should be noted that there is a fluctuation in the tag detectability rate as seen in the graph of the test bed 2; thus, the effects of the relative orientation change the outcomes significantly. Changing the testing environment results in different tag detectability rates and the significance of the relative orientation is influenced by the environment. Therefore, testing environment is a crucial factor in the detectability rate. The overall performance of test bed 2 is poorer than that of test bed 1.

The results of the Shapiro–Wilk tests are presented in Table 7. Since the probability values were smaller than the selected α-level (0.05), data groups of both of the test beds did not fit to normal distribution (namely, the H_0 criterion is rejected).

Table 7. Results of the Shapiro–Wilks tests for relative orientation.

Relative orientation	Test bed 1		Test bed 2	
	Test stat.	P-value	Test stat.	P-value
B-H	0.399	0.000	0.273	0.000
B-V	0.155	0.000	0.606	0.000
F-H	0.434	0.000	0.122	0.000
F-V	0.155	0.000	0.858	0.000
U-H	0.477	0.000	0.249	0.000
U-V	0.309	0.000	0.948	0.000
Vb-H	0.426	0.000	0.439	0.000
Vb-V	0.454	0.000	0.476	0.000
Vf-H	0.363	0.000	0.454	0.000
Vf-V	0.433	0.000	0.240	0.000



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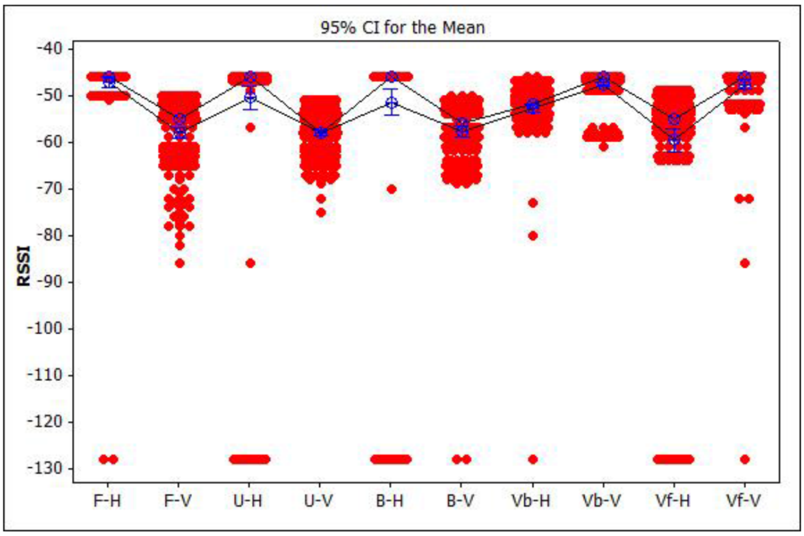

(b)

Figure 9. Individual value plots for relative orientation tests: a) test bed 1, b) test bed 2.

Moreover, the results of heterogeneity tests are presented in Figure 10. Based on the results of Bartlett's and Levene's tests, the probability values corresponding to the test statistics were 0, and, thus, smaller than the selected α-level of 0.05. Therefore, the H_0 criterion was rejected and the data sets exhibited heteroscedasticity.

Based on the Kruskal–Wallis test results, H values were 458.8 and 1327.8 for test bed 1 and 2 data sets, respectively. Therefore, the probability values for calculated H values, which were estimated by chi-square distribution with 9 degrees of freedom, were 0.00, lower than the selected α-level of 0.05. Consequently, it is possible to conclude that different orientations resulted in different RSSI values. Furthermore, probability values calculated from the Mann–Whitney test statistics (namely, U values) for all comparisons were 0.000. Therefore, different relative orientations resulted in different RSSI values.

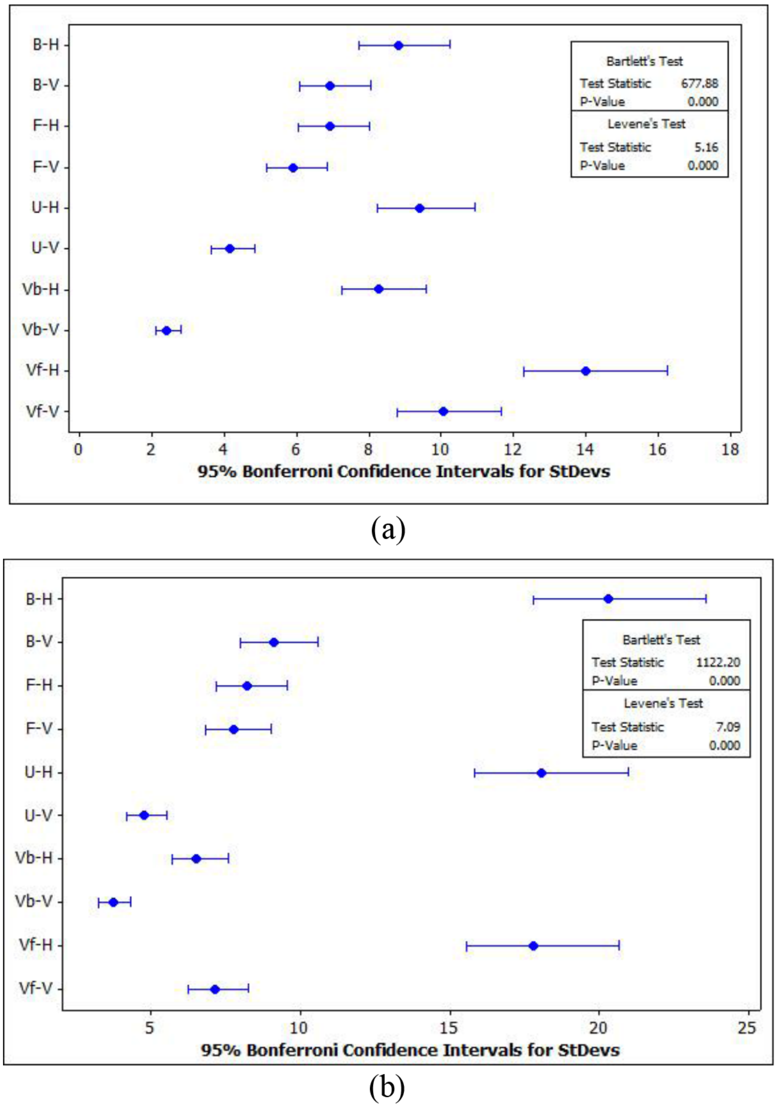

Figure 10. Heterogeneity test results for relative orientation data sets: a) test bed 1, b) test bed 2.

The results of Games–Howell tests are presented in Table 8. The upper triangular matrix elements are the results of test bed 2, and the lower triangular matrix is for test bed 1. In this context, the following conclusions can be drawn for both of the test beds based on the post-hoc tests:

- For test bed 1, "B-V" relative orientation was prominent in terms of affecting the RSSI values as most of the test results for "B-V" are below the confidence level of 0.05. The other configurations seemed not to affect the RSSI values; nevertheless, "F-H" and "Vf-H" relative orientations had the least influence on RSSI values as only 1 test result out of 9 was below the confidence level of 0.05.
- For test bed 2, all orientation configurations resulted in similar RSSI values. In all configurations, "Vb-H" orientation caused slightly different RSSI values than the others.
- Testing environments resulted in major changes in RSSI values. Therefore, the measurement of any tag is much more dependent on the environment than the orientation configuration.

Table 8. Results of the Games–Howell tests for relative orientation.

Test bed 1/ Test bed 2	B-H	B-V	F-H	F-V	U-H	U-V	Vb-H	Vb-V	Vf-H	Vf-V
B-H	X	0.003	0.168	0.001	1.000	0.001	0.999	0.226	0.001	0.301
B-V	0.000	X	0.000	1.000	0.000	1.000	0.000	0.000	0.954	0.000
F-H	0.999	0.001	X	0.000	0.390	0.000	0.000	1.000	0.000	1.000
F-V	0.000	0.102	0.164	X	0.000	1.000	0.000	0.000	0.987	0.000
U-H	1.000	0.000	1.000	0.009	X	0.000	0.842	0.497	0.000	0.604
U-V	0.431	0.004	0.980	0.717	0.653	X	0.000	0.000	0.973	0.000
Vb-H	1.000	0.000	0.985	0.000	1.000	0.266	X	0.000	0.000	0.000
Vb-V	0.660	0.000	0.378	0.000	0.861	0.000	0.990	X	0.000	1.000
Vf-H	0.170	0.992	0.591	1.000	0.248	0.949	0.101	0.004	X	0.000
Vf-V	1.000	0.000	0.998	0.012	1.000	0.569	1.000	0.988	0.202	X

6. Discussion and conclusions

This study investigated the effects of 4 system parameters based on the RSSI values collected from an RFID system deployed in 2 tests beds. The first test bed was a daily functioning building and the second test bed was a spacious indoor space with no furniture inside. These test beds enabled the authors to observe and compare a complex indoor environment to an almost empty indoor environment. The system parameters included in this study were: 1) type of materials that tags are attached to, 2) obstructions between tags and an antenna, 3) RE between tags and an antenna, and 4) relative orientation of tags and an antenna. RSSI was selected as the evaluation criterion as it is considered to be the key metric in most of the indoor localisation algorithms. Even though the parameters were previously noted to affect RSSI values, not many attempts were made to understand the effects of multiple parameters. Moreover, most of the studies in the literature investigated the effect of these parameters on passive RFID tags, whereas this study focused on active RFID tags. The present authors aimed at understanding the variability and reliability of RSSI values of active RFID technology in 2 different test beds. In this context, the following conclusions were drawn from the analyses.

It was observed in this study that all attached materials tested (including aluminium, ceiling board, drywall, foam, glass, carpet, clay, plywood, steel, and cardboard) affected RSSI values to some extent and that these effects could not be ranked. For instance, steel, plywood, and aluminium were found to be the most dominant materials influencing the RSSI values in test bed 1. On the other hand, clay resulted in the most distinguishing effect on the RSSI values in test bed 2.

Similar to the materials that tags are attached to, obstructions were found to have direct effects on the RSSI values by several researchers. Metals (Ergen et al., 2007), soil types (Dziadak et al., 2009), and water and liquids (Bahl and Padmanabhan, 2000; Ross et al., 2009) have been observed to attenuate the RSSI values in the literature; however, materials that are used commonly in buildings have not been studied. In this study, line-of-sight conditions along with 10 different materials (including aluminium, cardboard, carpet, ceiling board, clay, drywall, foam, glass, plywood, and steel) were used to evaluate the variability of RSSI values where different obstructions exist. Referring to the statistical analyses performed on the obstruction tests, the influence of glass was dominant in test bed, 1 while aluminium and drywall resulted in the most dramatic effects in test bed 2. RSSI values were inconsistent between the 2 test beds and the different test beds resulted in different RSSI values even when the same obstruction existed.

Metals were reported to affect the RFID performance significantly in prior research (Aroor and Deavours, 2007; Daily and Cann, 2007; Chen et al., 2009; Bridelall and Hande, 2010). In accordance with prior research, when used as either attached materials or obstructions, metals were observed to have a statistically significant impact on RSSI values in both test beds. However, metals did not always have the most dominant impact, due to the fact that the RFID tags used in the tests had plastic cases that were specifically designed to protect the embedded chips from the effects of metals in the immediate proximity.

Whitehouse et al. (2007) concluded that small changes in the antenna elevation could generate a large influence on radio signal characteristics. Similarly, results of this study indicate that an increase in RE caused significant and consistent changes in the RSSI values and detectability rates in test bed 1. Nevertheless, in test bed 2, no statistical difference was found when RE was changed from 0.00 m to 0.75 m, and all other differences in REs resulted in statistically significant changes in RSSI values and detectability rates.

In the literature, relative orientation has been recognised as one of the parameters that affect RSSI values. Lymberopoulos et al. (2006) stated that the relative orientation of a monopole antenna is the major parameter in signal strength variability and Stoyanova et al. (2007) indicated that the vertical deployment of a wire monopole antenna could provide more stable RSSI values. The results of the statistical tests performed in this study on relative orientation tests showed that relative orientation of tags and antennae resulted in changes in RSSI values. For test bed 1, "B-V" relative orientation was prominent in terms of affecting the RSSI values. Other configurations seemed to be not effective on the RSSI values; nevertheless, "F-H" and "Vf-H" relative orientations had the least influence on RSSI values. On the other hand, for test bed 2, all orientation configurations resulted in similar RSSI values. In all configurations, "Vb-H" orientation caused slightly different RSSI values as compared to the others. Consequently, the results of test bed 1 and 2 were different and the findings were not consistent. Overall detectability rates obtained for test bed 2 are distinctly better than those of test bed 1.

This study provided a systematic approach to compare and assess indoor environmental effects on RSSI variability. RSSI values were analysed via statistical analyses, and it was found that the effects of system parameters could not be ranked and the changes in RSSI values could not be attributed to any specific system parameters. Even though the tests were conducted in steady environments, it was still not possible to find the reliability of RSSI signals and repeatability. It could be concluded that the effects of the system parameters included in this study are not consistent and do not have quantifiable effects on RSSI values and variability. Moreover, the results show that RSSI signals' variance and strength are not directly related to each other, but they are individually dependent on the environment and, thus, the variability of RSSI values could not be attributed to any of the system parameters included in this study. This study could be considered as a first step towards understanding the relative effects of the selected system parameters while other parameters remain the same in an indoor environment, while understanding and controlling all the system parameters was not the focus of this study. On the other hand, since there are several parameters in an indoor environment, it is almost impossible to have ultimate control over every variable. Even if all system parameters (e.g., temperature, layout, or humidity) are controlled, there could still be uncontrollable dynamic parameters in an indoor environment such as number of occupants or digital footprints. These dynamic parameters could also interfere with RSSI values and affect RFID performance. Moreover, sometimes the overall impact of these dynamic parameters could even be more significant compared to the system parameters. Developing more accurate localisation algorithms and applying calibration methods could be a more effective way to mitigate the variability in RSSI values compared to designing and controlling the system parameters in an environment. Luo et al. (2011) and Pradhan et al. (2009) evaluated the effects of different localisation algorithms on accuracy and demonstrated improvements.

In summary, the results of this study are beneficial in terms of providing flexibility in designing and developing RFID deployment strategies since statistical analysis support the idea that RSSI signals' variance and strength are not directly related to each other, but are rather individually dependent on environment complexity. Future studies will focus on understanding the effects of the dynamic parameters as well as different building components, furniture layouts, and testing of the effects of coupling system parameters such as humidity and temperature.

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