Evaluation of Ultra-Wideband Position Localization for an Indoor Office Environment

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EVALUATION OF ULTRA-WIDEBAND POSITION LOCALIZATION FOR AN INDOOR OFFICE ENVIRONMENT

By

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Abstract

Recently, significant improvements have been made in the area of indoor wireless position estimation. Issues of high power consumption and poor accuracy have stifled business and research initiatives to implement this technology to increase efficiency, save money, and obtain critical information. Investigation was done to determine if Decawave's DWM1001 technology is capable of tracking workers within an office environment to desk level accuracy for both a static (immobile) and dynamic (mobile) tag. Evaluation was conducted under sparse and dense deployment conditions of anchors. Sparse deployments held 1 anchor per 30 $meters^2$. Dense deployments held 1 anchor per 15 $meters^2$. It is concluded that the position of an immobile node can be determined to desk-level accuracy (+/- 20cm) using Decawave's Ultra-Wideband wireless position estimation. However, in the case of a tag in motion, a more dense system architecture is needed to achieve desk level accuracy. Due to the robustness of ultra-wideband radio waves and a sleep schedule of tag nodes, it is clear that Decawave DWM1001 technology provides many advantages for managing the tradeoffs between power, accuracy, and range. Finally, the technology needs improvement in acquiring and interfacing with the position data to be fully capable of tracking a large amount of office workers.

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1. Introduction

Real time location systems have made ground-breaking improvements to industries such as healthcare, livestock farming, warehousing, and manufacturing. These systems give people the ability to make informed improvements to their processes. In doing so, businesses save time and money by knowing the exact location of assets at any given time. Alternatively, researchers can eliminate confounding variables related to their hypotheses if it is known for certain when and where occurrences take place. In healthcare, wireless positioning is used for abduction prevention, parent matching, and prevention of medical errors in hospitals [1]. Beyond healthcare, it is useful for maintenance of general animal health and maximizing milk output in herd management [2]. Using location estimation, farmers can determine if animals are showing up for feeding or maintaining healthy movement among the acreage. Wireless nodes are useful in these cases because the position of assets change drastically minute to minute, making the restrictions of wires unacceptable. Utilizing mobile wireless nodes allows for a more robust system capable of adapting to industry or research requirements. To achieve a position estimation, radio waves are used to send signals from nodes of known location (anchors) to nodes of unknown location (tags). The distance between nodes is determined using signal strength or time of flight calculations. When the distance from a tag to three or more anchors is calculated, the position of such tag can be trilaterated.

Pressing issues of lifetime cost of ownership and lack of reliable communication in highly reflective radio frequency environments still challenge the wireless positioning industry [5]. These problems discourage research efforts and ambitious corporations from utilizing the technology in their projects. Recently, ultra-wideband has received attention for its ability to make centimeter accurate distance measurements. Unlike its alternatives it is less susceptible to non-line of sight conditions in wireless ranging. This technology is also capable of reducing power consumption by using a wake/sleep schedule on their devices.

The goal of this project is to evaluate the capability of ultra-wideband technology to determine the position of office workers. This project will enable verified data collection methods for a research initiative. Validating this technology will advance future research efforts that require the knowledge of assets/people in real time indoor environments. It provides a proof of concept for centimeter accurate and low power wireless position estimation with Decawave technology.

This thesis is arranged as follows. Section II examines the background of the technology, reviews the literature, and details the significance of this work. Issues and gaps in the knowledge of real time location systems and ultra-wideband are highlighted. Section III surveys all methods related to the end results. Results and conclusions are made in Section IV and V respectively.

2. Literature Review

Wireless positioning systems are comprised of hardware and software that continuously determine and provide real time position of resources [3]. Software helps control the communication, scheduling, mathematical calculations, and logic of a system. Radio hardware sends and receives the physical signal used to measure distances. Implementation of such a system can be a signal strength or time based scheme. These schemes are used to measure the distance between two nodes. The position of an unknown node (tag) is determined by a trilateration algorithm using distances to three nodes of known location (anchors). The ultimate goal of a real time location system is to manage the complex tradeoff between accuracy, power consumption, and range [3].

As noted earlier, wireless positioning can be implemented in several ways. These methods include: signal strength and time based schemes.

Signal strength methods use the known power of the transmitter, how radio waves behave in air, environmental characteristics, and received power at the receiver to determine a distance. The distance calculation begins with the path-loss model:

$$r^i = P_0 - 10\alpha log_{10}\frac{d_i}{d_0} + n_i \quad i = 1,2,3, \ldots \ldots, N$$

Where

- r_i is the received power from anchor i at a tag averaged over K measurements
- α is the path-loss exponent
- d_0 is a reference distance typically equal to 1
- P_0 is the received power at reference distance d_0
- d_i is the magnitude xyz vector distance between a tag and anchor i
- n_i is a random variable accounting for fading where the signal may rise or fall in amplitude during movement over a period of time

  [4]

Additional variables such as antenna gain may be introduced to the path-loss model as supplementary information. Trilateration algorithms will be used to complete the localization.

Alternatively, project planners may decide that a time of flight based scheme is more appropriate for their process requirements. Decawave categorizes time-based schemes into three main categories: time of flight, time difference of arrival and angle of arrival [5]. Note that “all time of flight based systems work on the basis of determining the time it takes for a radio signal to propagate from a transmitter to a receiver. Once this time is known accurately, then the distance between the transmitter and the receiver can be determined since the speed of propagation of radio waves in air is known" [5]. To begin calculating the distance between a tag and an anchor with time of flight, the two nodes must communicate with each other. This two-way exchange between the nodes is known as two-way ranging. Two-way ranging can differ in the number of messages sent and which node calculates the distance between the nodes. This is largely dependent on process goals. Two simple two-way ranging exchanges are highlighted in the Decawave figure (Figure 1) and Table 1 below:

Table 1: Stages in Simple Two-Way Ranging Scheme [5]

Operation	**Description**	**Symbol**	**Typical Value**
Tag transmits message	Tag transmits message and notes transmit time-stamp	T_{TXTAG}	Depends on the architecture of Anchor, processor used etc.
Message Flight time – Tag to Anchor	Time taken for message to travel from Tag antenna to Anchor antenna	T_t	Depends on the chosen premable length, datarate, message length etc
Anchor receives message, processes it and transmits reply	Anchor receives message, processes it, constructs and transmits reply	T_{TA}	Depends on the architecture of Anchor, processor used etc.
Message Flight time – Anchor to Tag	Time taken for message to travel from Anchor antenna to Tag antenna	T_t	Depends on the chosen premable length, datarate, message length etc
Tag processes received message and calculates distance	Tag receives message, notes time stamp and calculates distance	T_{RXTAG}	Depends on the architecture of Anchor, processor used etc.

Looking at the table, the total time between the two nodes is expressed as:

$$T_T = 2T_t + T_{TA}$$

This simple method can be improved by accounting for processing time in the nodes or sending more messages such as in the figure shown:

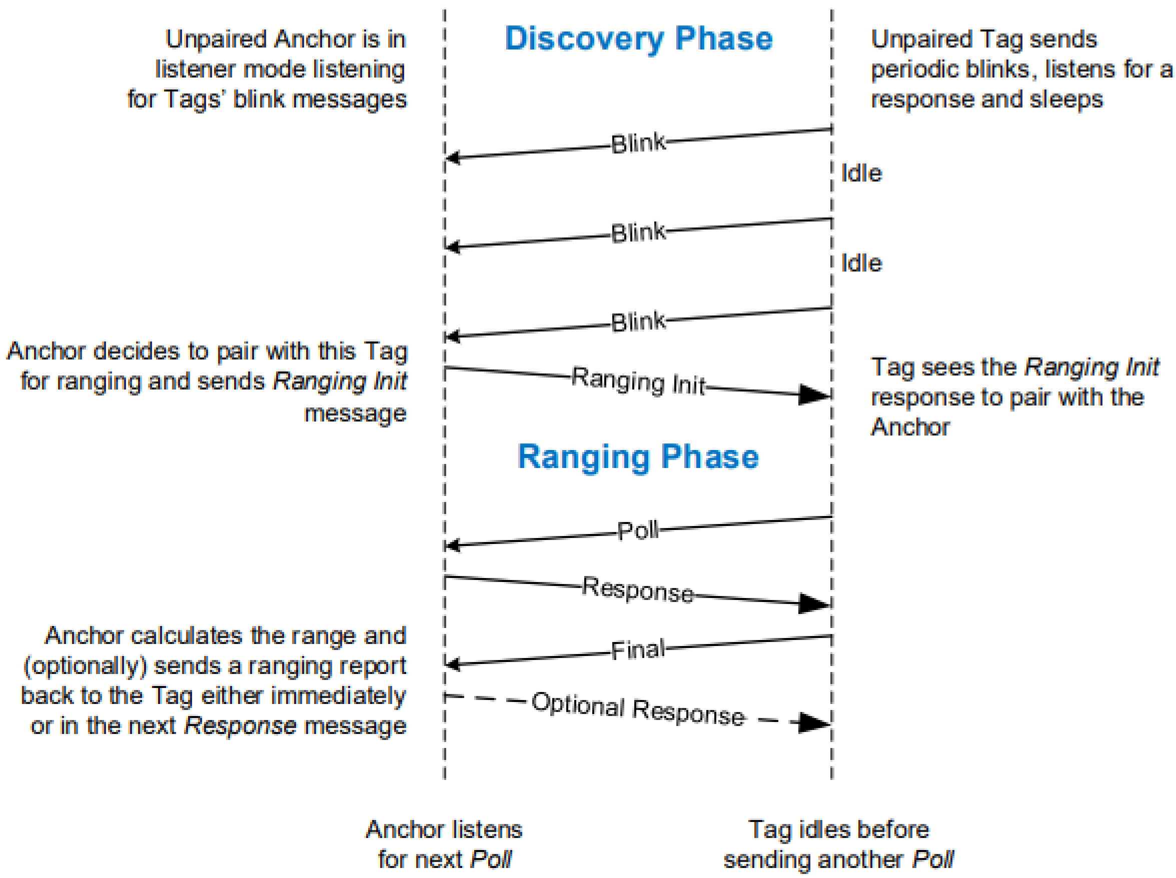

Figure 1: Two-way ranging exchange [5]

The technology evaluated in this thesis utilizes a time of flight based scheme.

In the case of time difference of arrival, all anchors in a deployment must be time synchronized. Using a technique called multi-lateration, the position of a transmitting tag can be determined from the difference in arrival times to surrounding anchors [5]. A one nanosecond difference in clock synchronization will induce a magnitude of error of thirty centimeters; causing this scheme to demand high installation costs for secure, dependable clock management. Finally, angle of arrival "involves determining the angle at which the radio signal from the tag arrives at the anchor relative to a predefined direction" [5]. This technique struggles to remain accurate in non-line-of-sight conditions and multi-path propagation between transmitting tags to a receiver; two very important wireless positioning concepts to be discussed.

Line-of-sight in wireless positioning applications is characterized as the ability of a ranging interaction to travel freely to a target without physical obstruction. This obstruction could be metal objects, people, walls, etc. A situation is considered non-line-of-sight when obstructions are in the path of a radio signal from one node to another. Non-line-of-sight conditions interfere with wireless positioning distance calculations and cause errors in localization. The multi-path propagation problem is when radio signals reach a receiver by more than one path. This occurs when radio waves reach a destination via a direct path, but arrive again at a delay after bouncing off surrounding obstructions. Distance calculating nodes may mistake arriving waves as valid signals leading to ambiguity in perceived power or time of flight. Thus, causing inaccurate estimates.

Ultra-wideband pulses are less susceptible to path loss. "Their wide bandwidth allows most multipath components to be resolved, which allows the direct path to be resolved accurately and with very fine time resolution" [3]. Multipath profiles for ultra-wideband waves were collected in fourteen different locations of an office building. In each room measurements were made in forty-nine different positons in a 3-by-3 foot grid. It was concluded that the ultra-wideband signal is very robust to fading. It suffers its consequences to a minimal extent [6]. Decawave also found that at 10 meters, the worst 10% of narrow band channels have 7dBs more path loss than the worst 10% of ultra-wideband channels [7]. Due to ultra-wideband robustness in non-line of sight environments and its ability to provide centimeter accurate distance measurements via time of flight; commercial ultra-wideband devices have been developed by companies such as Decawave, Zebra, Nanotron, Ubisense, and Apple [8].

In many cases, the addition of more anchors to the environment than required for an estimate can help achieve more accurate wireless positioning. For the purposes of this experiment we will define these deployments as dense. More specifically, a dense deployment will utilize twice as many anchors as needed for a ranging estimate. A "sparse" network is the minimum number of anchors needed to generate an estimate according to Decawave standards. The maximum range of a two-way ranging exchange is characterized using Friis' equation:

$$P_R = P_T + G - L - 20log_{10}\left(\frac{4\pi f_c d}{c}\right) \quad [9]$$

P_R = received signal level [dBm]

P_T = transmitted power [dBm]

G = antenna gains of transmitting and receiving antennas [dB]

L = system signal losses [dB]

f_c = center frequency of channel used [Hz]

d = distance between transmitter and receiver [m]

c = 299,792,458 [m/s]

Readers, be aware this equation is different from the previously used path-loss formula.

For our experiment we assume:

- Negligible antenna gain

- NLOS signal attenuation is limited to the dry wall obstructions

The maximum distance can be found by setting the P_R to the maximum receiver sensitivity of a Decawave UWB radio node. This value of -98 dBm can be found on Table 6 of the DWM1001 datasheet [12]. The transmitting power P_T of -17 dBm can be found on Table 7 of the same document. The channel frequency of the transmissions are set to 6.5Ghz. Finally, the system signal losses are attributed to signal attenuation of dry wall. In our experiment's case the drywall spans 20cm. Signal loss of dry wall at 6.5Ghz in this case equals approximately 6 dB [10].

$$-98 = -17 + 0 - 6 - 20log_{10}\left(\frac{4\pi * (6.5 * 10^9) * d}{299792458}\right)$$

Solving for d yields 20.63m. Thus, the distance between a tag and each of the three closest anchor nodes in the sparse system should NOT exceed 20.63 meters. As a result of this constraint, the experiment run will maintain 1 anchor per 30 $meters^2$ for the sparse conditions.

As interest in the applications of wireless positioning continue to grow, challenges of the system must be considered. Designers of real time location systems still struggle to balance the tradeoff between accuracy, power consumption, and range [3]. For example, high levels of accuracy over a long range would require a tag to broadcast multiple messages at a higher power. This requires high power draw; thus, draining the small battery of a mobile node. Ideally, a tag battery would last for over a year. There also lies difficulty in choosing a channel environment, tag density, and establishing a wireless network. This project seeks to establish a baseline for effective wireless positioning infrastructure in office environments. It will determine if Decawave's DWM1001 technology is capable of tracking workers within an office environment to desk level accuracy. Noting these considerations, it is incredibly difficult to design a one-size-fits-all wireless positioning application. Individuals, businesses, and research teams have different project goals, budgets, and environmental conditions that require consideration. This thesis provides a guideline for evaluating a chosen methodology's effectiveness for a project. After reviewing the literature, it is hypothesized that Decawave's DWM1001 technology is capable of tracking workers within an office environment to desk-level accuracy for both an immobile tag (static) and a tag in motion (dynamic). An evaluation will be conducted under sparse and dense deployment conditions of anchors.

3. Methods

3.1. Validate Static Tag Estimation

An experiment was conducted on the fourth floor of the Seamans Center Annex in Iowa City. Anchors were placed only in accessible rooms. Anchor locations were also constrained by their access to a power source. Figure 2 illustrates the positions of the anchors, where the location of the anchor is at the upper tip of each diamond-shaped marker:

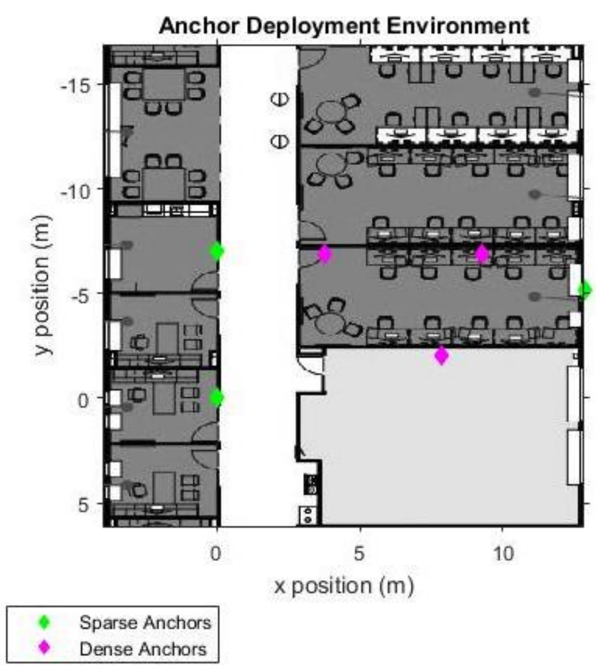

Figure 2: Anchor locations on coordinate grid

The positions of each node on the grid, including the immobile tag, are outlined in tables 2 & 3 below. Node locations are reported in meters.

Table 2: Node locations for Sparse Network

DEV ID	TYPE	X (m)	Y (m)
DW550A	Tag	7.86	2.80
DW0821	Anchor Initiator	0.00	0.00
DW0925	Anchor	12.84	5.16
DW930E	Anchor	0.00	7.00

Table 3: Node Locations for Dense Network

DEV ID	TYPE	X (m)	Y (m)
DW550A	Tag	7.86	2.80
DW0821	Anchor Initiator	0.00	0.00
DW0925	Anchor	12.84	5.16
DW930E	Anchor	0.00	7.00
DWD8B8	Anchor	9.26	6.86
DW97A3	Anchor	7.86	2.04
DWD293	Anchor	3.78	6.86

Initially, an anchor initiator was setup and set as the zero point of the coordinate grid. The relative positions of each anchor were determined using a tape measure and a laser distance measurer. Anchors were mounted on the wall using adhesive strips as shown in the figure below:

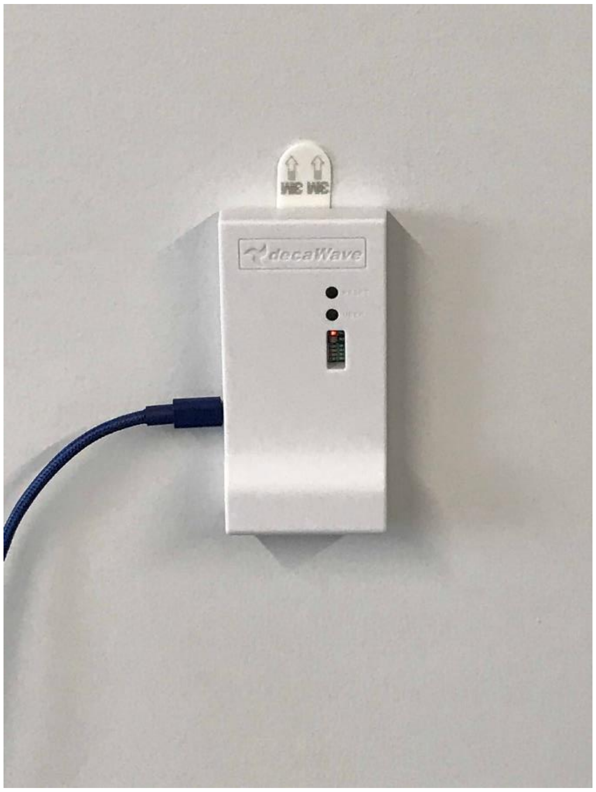

Figure 3: Anchor Wall Mount

The tag was left on a desk and in static equilibrium while data points were collected.

The operation of this system closely follows the two way ranging scheme highlighted in section II. The tag sleeps and periodically wakes up to listen for anchor beacon messages. The tag collects all available anchors to range to and chooses an appropriate slot time to begin a ranging exchange. Two-way ranging is conducted to obtain a distance to each anchor and trilateration algorithms are applied to get location estimates. Once the tag was powered on and in place at the specified coordinates, these position updates were sent to an ASUS Nexus 2012 tablet via blue tooth transmission. Data was collected for approximately three minutes. The raw data logs were parsed using a python script. The first 1100 data points were used for statistical analysis.

3.2. <u>Validate Dynamic Tag Estimation</u>

The dynamic tag experiment used identical anchor positions as the static experiment. These node locations can again be visualized in figure 2 above. Similarly, data was sent to a nexus tablet and parsed with a python script. For this experiment, data was collected as the tag was carried from the west to the east at a steady pace and held waist-high. This path can be clearly seen in the graphical results. The path generated approximately 400 data points.

3.3. <u>Statistical Methods</u>

After experiments were conducted an analysis was done to determine the extent of the accuracy for each deployment type (sparse/dense) and deployment condition (static/dynamic). A 95% confidence interval was calculated for each condition to determine if desk-level accuracy (+/-20 cm) fell within or above the confidence interval. If so, we could conclude with 95% confidence that Decawave technology can track workers with desk-level accuracy under such conditions. Additionally, a one-sided two-sample t-test was done to determine if the mean error of sparse environments was significantly greater than the mean error of dense environments.

4. Results

4.1. <u>Static tag</u>

4.1.1. Sparse Network

Table 4 contains the X and Y errors of each of the 1100 data points in the static condition, along with descriptive statistics, including the cutoffs for the first and third quartiles. It includes the same descriptive statistics for the deviation from the x-plane of 400 data points in the dense condition. Results in table 4 are shown in centimeters. The sparse anchor positions for a static tag can be visualized in Figure 4. Sparse anchor positions are identical for the dynamic tag shown in figure 5, but this figure also includes the positions of the added dense anchors. Both figures include plotted points for each individual estimate made by the Decawave wireless positioning system.

Table 4: Descriptive Statistics for all tests in centimeters.

	N	Mean	SE Mean	StDev	Min	Q1	Median	Q3	Max
Dynamic									
Dense (deviation from x-plane)	400	18.633	0.908	18.16	0.06	5.945	13.14	25.32	109.64
Sparse (deviation from x-plane)	400	51.23	3.18	63.5	0.84	15.14	26.19	50.34	289.04
Static									
Dense (x error)	1100	5.135	0.105	3.467	0	3	4.45	6	23.2
Dense (y error)	1100	10.971	0.235	7.8	0	4.9	9.9	14.8	47.5
Sparse (x error)	1100	12.819	0.166	5.495	0.4	11.4	12.5	13.3	50.9
Sparse (y error)	1100	67.44	0.364	12.066	0.6	67.2	69.6	71.8	103.1

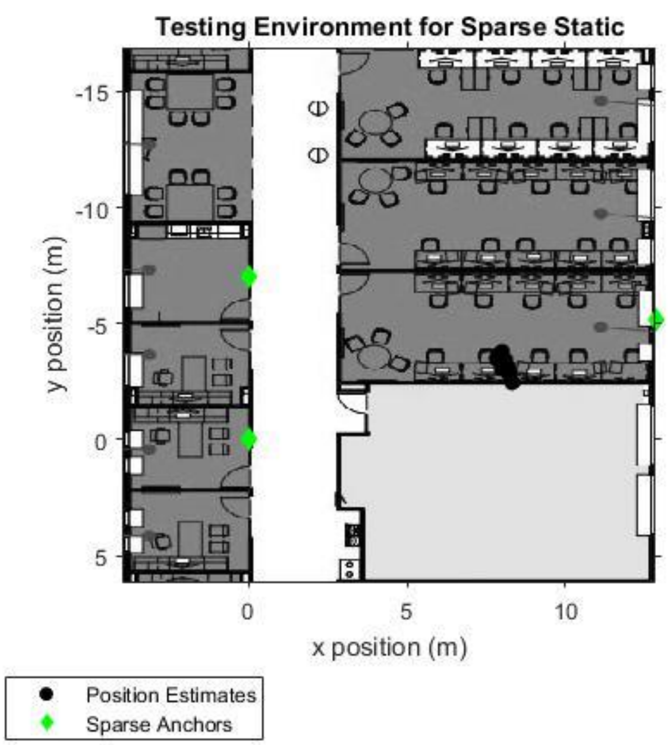

Figure 4: Sparse deployment with a static tag. Grid shown in meters

4.1.2. Dense Network

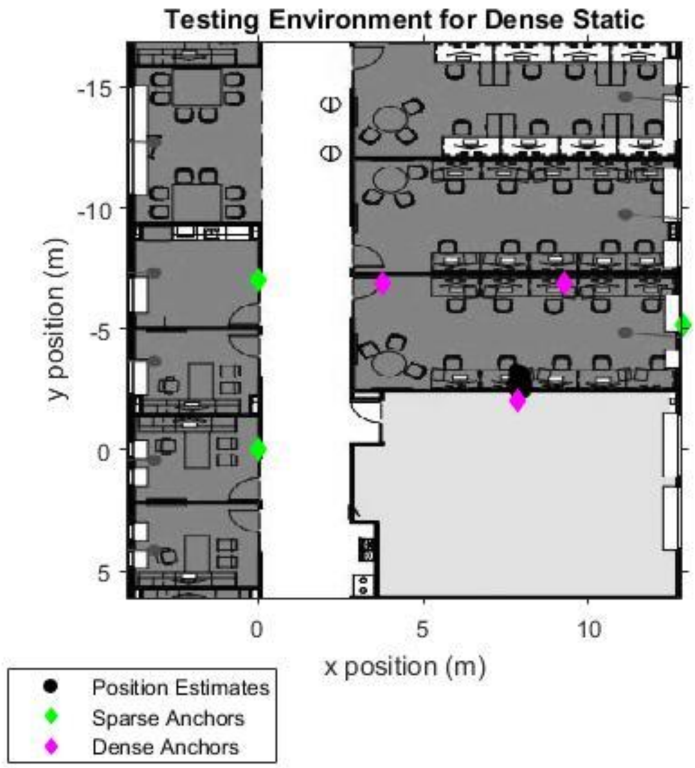

Figure 5: Dense deployment with a static tag. Grid shown in meters

4.2. Dynamic tag

4.2.1. Sparse Network

The sparse anchor positions for a dynamic tag can be visualized in Figure 6. Sparse anchor positions are identical for the dynamic tag shown in figure 7, but this figure also includes the positions of the added dense anchors. Both figures include plotted points for each individual estimate made by the Decawave wireless positioning system in black. The horizontal red line in each figure shows the actual path walked during the experiment.

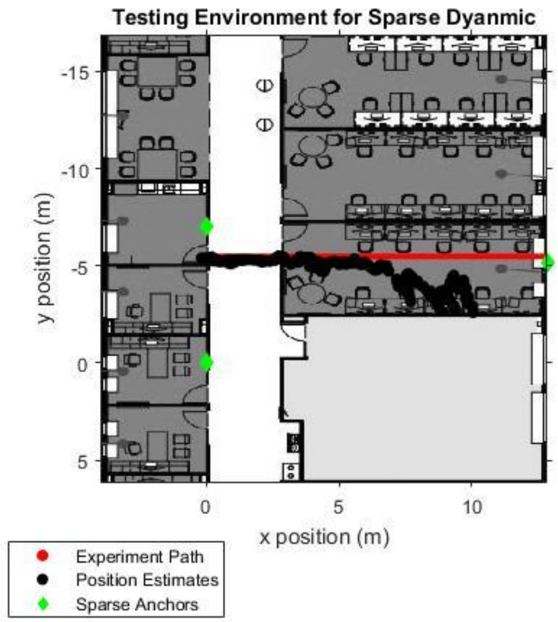

Figure 6: Sparse deployment with a dynamic tag. Grid shown in meters

4.2.2. Dense Network

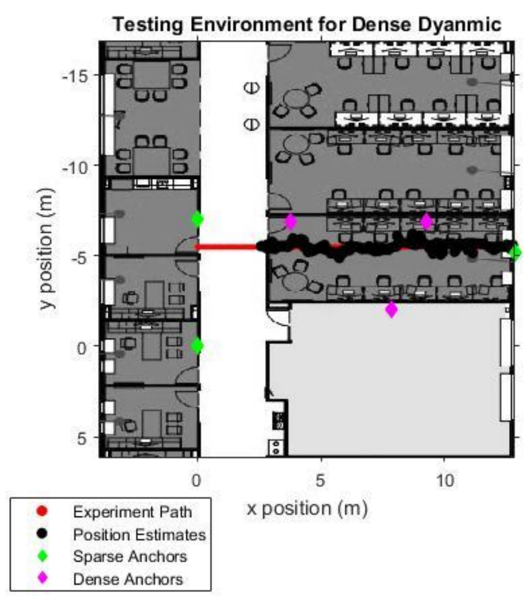

Figure 7: Dense deployment with a dynamic tag. Grid shown in meters

4.3. Statistical Analysis

4.3.1. Static tags

Figures 8-11 show 95% confidence intervals for the mean and median of error in centimeters. These confidence intervals are included for each deployment type (sparse/dense) under the condition of a static tag.

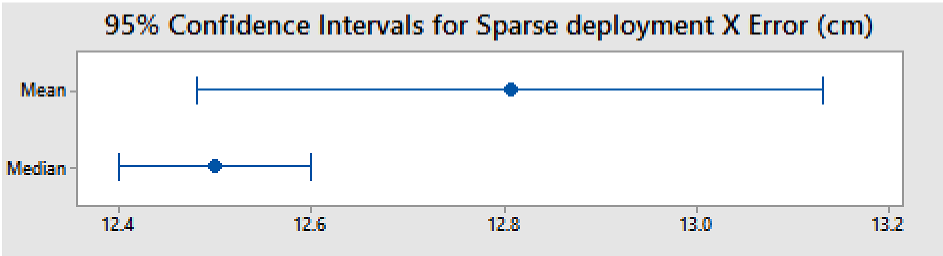

Figure 8: Mean & median confidence intervals for sparse deployment X Error in centimeters

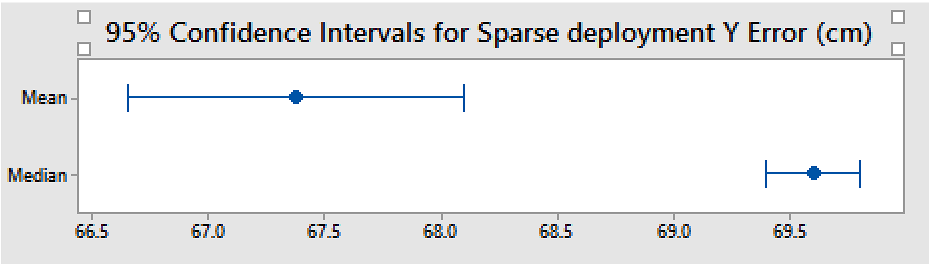

Figure 9: Mean & median confidence intervals for sparse deployment Y Error in centimeters

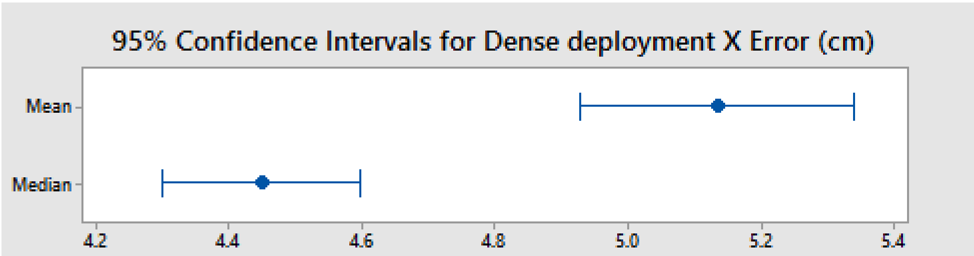

Figure 10: Mean & median confidence intervals for dense deployment X Error in centimeters

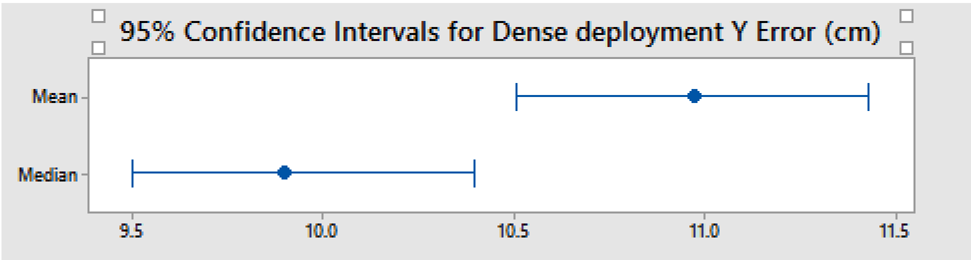

Figure 11: Mean & median confidence intervals for dense deployment Y Error in centimeters

4.3.2. *Dynamic tags*

Due to the drastic x-plane deviation of the sparse deployment, this confidence interval was not considered. However, figure 12 shows the mean and median 95% confidence intervals for the X-plane deviation of the dense deployment under the condition of a dynamic tag.

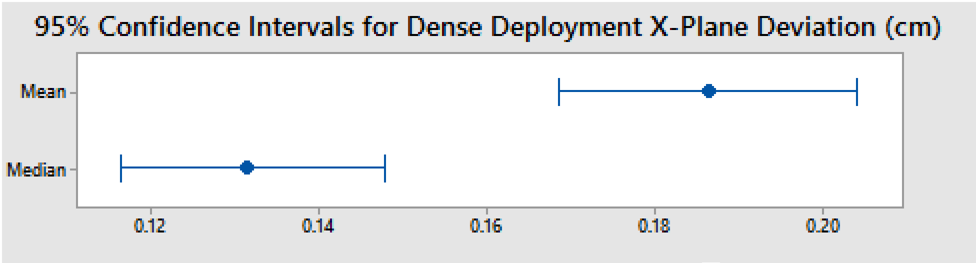

Figure 12: Mean & median confidence intervals for dense deployment X-plane deviation in centimeters

4.3.3. *Sparse Error vs Dense Error*

To statistically prove a greater difference in error from sparse deployment types versus dense deployment types a two-sample t-test was conducted with the hypothesis outline below:

$$H_0: \mu_{sparse\ error} - \mu_{dense\ error} = 0$$

$$H_a: \mu_{sparse\ error} - \mu_{dense\ error} > 0$$

This test was conducted for x and y error of a static tag. It was also conducted for deviation from the x-plane of a dynamic tag.

4.3.3.1. *Static tags*

One- sided two-sample T-test highlights for the given hypothesis of a static in the x-direction.

- T-Value = 39.23
- P-Value = 0.000
- DF = 1854

One- sided two-sample T-test highlights for the given hypothesis of a static tag in the y-direction.

- T-Value = 130.36
- P-Value = 0.000
- DF = 1881

4.3.3.2. *Dynamic tags*

One- sided two-sample T-test highlights for the given hypothesis of a dynamic tag.

- T-Value = 9.87
- P-Value = 0.000
- DF = 463

5. Discussion

5.1. Experimental conclusions

5.1.1. Sparse Network

After conducting the experiment, it is clear that the sparse network with only 1 anchor per 30 $meters^2$ is capable of estimating the position of a static tag to desk level accuracy in the x-direction. It is shown that +/- 20cm falls above both the confidence interval for the mean and median of x-error. Alternatively, the y position error confidence interval exceeds 20cm. Also, the sparse network did not remain accurate across the experiment path of the dynamic tag. Looking at the dynamic tag graph, we can see the location estimates fall off the experiment path dramatically as x position increases. A quarter of all measurements deviate from the plane by more than half a meter (Q3 = 50.34cm). Additionally, the standard deviation (63.5cm) is far too high to label the estimates as reliable for a dynamic tag. As a result of the drastic error, a confidence interval was not calculated for this condition.

5.1.2. Dense Network

The dense network with 1 anchor per 15 $meters^2$ is accurate enough to track both a still and moving worker. For the dynamic data, half of all measurements deviate from the plane by less than 13cm, with a mean deviation of 18cm. There is a lapse in the data in the beginning of the dynamic experiment path. The sparse path position estimates closely followed the path where the lapse exists in the dynamic data. Since the dynamic data consists of the original sparse anchors it is concluded that this isn't a critical issue to the accuracy of the system. We see all confidence intervals for error in a dense deployment either contain or fall below 20cm. So, we can conclude with 95% confidence that this technology can track workers to desk level accuracy for both immobile workers and workers in motion. The data shows a general trend that adding more anchors to the system improves the accuracy of the position estimate. We see for all one-sided two-sample t-tests that dense deployment error is statistically lower than sparse error. For every test we have a p-value of approximately zero. However, diminishing returns apply to the addition of anchors. Eventually, when a sufficient anchor density is reached, adding anchors to the system will no longer improve accuracy. This is a phenomenon to be studied in future work.

5.2. Additional Considerations (Scaling/BLE data acquisition)

5.2.1. Scaling

When deploying a wide scale position estimation system for tracking workers in an office space it is necessary to cover larger areas that demand tens to hundreds of anchors. Therefore it is critical that this technology is capable of robust expansion. Decawave uses a time-division multiple access (TDMA) scheme to manage the system architecture [11]. Each two-way ranging exchange is assigned into dynamic slots. Thus, all anchors are kept synchronized with the timing of an anchor-initiator. Anchors can be added to scale the system with these rules outlined by Decawave [11]:

- Each anchor needs to be assigned a seat number between 0 and 15
- No anchor is allowed to hear 2 anchors with the same seat number
- All nodes must be synchronized with the super frame timing of the initiator

These rules are subject to the following constraints:

- Limitation 1: Maximum number of anchor seats is 16
- Limitation 2: Maximum number of clock level is 127

Additionally, tags can be added to the system with a tradeoff of lower update rates. The Decawave TDMA system is designed to have a 150Hz capacity. The scheduling of tag updates is done in a super frame of fifteen tag slots. Each super frame lasts 100ms. So, the cap of 150Hz indicates that for fifteen tags you can update at 10Hz. One tag of fifteen operating in each available slot in the super frame and ten super frames happening each second equates to10Hz. Tags can reuse seats in a super frame across a wider ranging area where slots are unoccupied.

5.2.2. *Data Acquisition*

With tags calculating their own location, this data needs to reach a central location. In the case of tracking office workers, it is critical that system architecture is capable of extracting the position data at each tagged worker for post-experiment analysis. DWM1001 devices are configurable as routing anchors to send location estimates across the network. Additionally, a raspberry pi can be setup as a gateway to connect the system to the outside network. Here the data can be visualized in end points: web clients, MQTT clients, and local Bluetooth-connected tablets/smartphones.

According to Decawave documentation, much of this functionality will not be available until release two due in the second quarter of 2018.

5.3. *Final conclusions*

In areas where the office worker is to remain stationary for a long period of time, a sparse network could be appropriate. The x-direction accuracy fell well within the definition of desk-level accuracy. The y-direction struggled to meet this definition, but could still be appropriate depending on project goals and with supportive x-direction accuracy. Dense deployments should be utilized in places where workers will move frequently. Ultimately, the data shows that the DWM1001 technology is capable of tracking a worker in an office environment to desk level accuracy. With the addition of the appropriate amount of anchors the position of a worker can be tracked accurately. The accuracy of ultra-wideband radio waves in non-line-of-sight and multipath environments allows for more flexibility in range between nodes. Finally, DWM1001 software mitigates power consumption by setting tags to sleep in between its designated ranging time. The software also leverages an accelerometer to determine if the tag is motion. Users can save additional power by setting the tag to not update location when it is not in motion. It is clear that Decawave DWM1001 technology provides many advantages for managing the tradeoffs between power, accuracy, and range. Still, more work and investigation is needed in the area of data acquisition for this real-time system. This functionality is critical to building a centralized real-time location system for wide-scale deployment.

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