Ecosystem for COllaborative Manufacturing PrOceSses – Intra- and Interfactory Integration and AutomaTION
(Grant Agreement No 723145)

D4.7 Development and Installation of a WSN Physical Security System

Date: 2019-03-25

Version 1.0

Published by the COMPOSITION Consortium

Dissemination Level: Public

Co-funded by the European Union’s Horizon 2020 Framework Programme for Research and Innovation under Grant Agreement No 723145

Document control page

Document file: D4.7 Development and Installation of a WSN Physical Security System.docx
Document version: 1.0
Document owner: TNI-UCC

Work package: WP4 – Secure Data Management and Exchange in Manufacturing
Task: T4.5 – Physical Security for Factories
Deliverable type: Other

Document status: ☒ Approved by the document owner for internal review
☒ Approved for submission to the EC

Document history:

Version	Author(s)	Date	Summary of changes made
0.1	Bobby Bornemann (TNI)	2018-12-18	Strawman
0.2	Bobby Bornemann (TNI)	2019-03-15	First Draft
0.3	Peter Haigh, Bobby Bornemann (TNI)	2019-03-19	Draft for Review
1.0	Peter Haigh (TNI)	2019-03-25	Final version submitted to the European Commission

Internal review history:

Reviewed by	Date	Summary of comments
Vasiliki Charisi (ATL)	2019-03-20	Minor format and spelling comments. There is a need for references throughout the document for what it is reported.
Helene Udsen (IN-JET)	2019-03-21	Approved with comments and suggestions, mainly relating to textual clarity and formatting

Index:

1 Executive Summary

This deliverable presents the work carried out to date on the design, installation and test of a Bluetooth, proximity-based RTLS (Real Time Location System) for use as an ICT physical security layer for use in Boston Scientific's Clonmel facility. Prior Art research had been carried out for this use case in *D4.6 Viability of WSN as ICT Overlay for Physical Security Detection* of which this document is simply a continuation with little cross referencing and so is not covered here. All work has been carried out by Tyndall in collaboration with Boston Scientific (BSL) who facilitated the test environment.

There are a number of wireless tracking systems that can be used in an indoor environment. Previously D4.6 reviewed some of these and found that whilst highest accuracy is found in trilateration/triangulation-based systems, these systems are complex, relatively power hungry and expensive. In a large factory environment where tracking of materials and equipment is required over a very large area, a proximity-based solution is an attractive solution due to its low cost, low power characteristics. Large ware houses today typically use RFID as a proximity-based solution. Compared to using Bluetooth as a proximity solution these tend to be bespoke and higher cost.

Every use case is different and so different technologies all have a place in solving these needs. In many cases it is a combination of technologies that provides the best solution. In the BSL case, tracking equipment and providing security for removed materials was suited to BLE.

This report shows that the chosen off-the-shelf BLE solution selected the correct proximity (beacon) over 90% of the time. As one would expect with a proximity system, as the tag (the thing we are tracking) moves towards the boundary of two or more beacons at similar distance, the system performance degrades. This degradation is highly dependent on the physical environment as constructive and destructive addition of multipath signals can significantly boost the signal level of a more distant beacon over that of the closest beacon. In one experiment it was shown that a region of about 90 cm exists when 2 beacons are placed 4.2 m apart on a planar surface where system performance is degraded. In addition, as this system relies on signal level to determine distance, the absolute output power of all beacons needs to be the same. Further to this, the radiated power is highly dependent on the antenna radiation pattern, and therefore the orientation of the beacon and tags can be a factor in accuracy.

There are options to reduce the region of uncertainty such as the use of historical data, aggregation, inertial measurements, radiated power calibration and fingerprinting. This is all identified as further work.

As we look to scaling up the system to the full manufacturing floor, the maintenance of the system becomes significant. Managing battery replacement is a significant issue, and so this report includes work that has been done to reduce battery replacement in the beacons which are the hardest to reach devices as they are usually located on the ceiling. Currently the work shows a doubling of battery life using photovoltaic cells.

Finally, during the course of the deployment work in BSL there has been significant interest in the technology and how it can help solve problems that exist there, showing the power of providing a live demonstration in a real working environment.

2 Abbreviations and Acronyms

Table 1. Abbreviations and Acronyms

Acronym	Description
AP	Access Point
BLE	Bluetooth Low Energy
BSL	Boston Scientific Limited
EH	Energy Harvesting
ICT	Information Communications Technology
IT	Information Technology
MPPT	Maximum Power Point Tracking
PV	Photo-Voltaic
RF	Radio Frequency
RSS	Received Signal Strength
RTLS	Real Time Location Systems
TEG	Thermal Energy Generator
USB	Universal Serial Bus
WSN	Wireless Sensor Network

3 Introduction

3.1 Purpose, context and scope of this deliverable

Following from work carried out researching and understanding various RTLS technologies which may be used for physical security, documented in *D4.6 Viability of WSN as ICT Overlay for Physical Security Detection*, it was decided that the most viable of the technologies for this application was Bluetooth Low Energy proximity-based tracking. Although not having the greatest accuracy of all available technologies it provided the best balance between all the important metrics on which we focussed. Namely accuracy, battery life, scalability, and ease of implementation.

What this report aims to do is to provide an idea of what kind of performance you may get from a tracking system such as this. Without access to a similar system it is quite hard to find information that demonstrates the capabilities and limitations of Bluetooth tracking in real world scenarios. So, this report will lay out the process by which we determined how to set up the system to provide maximum granularity in the visibility of assets and document the effectiveness of tracking at this level.

As covered in D4.6, there are various whitepapers available online documenting the installation of Bluetooth tracking systems in a number of environments with varying degrees of success. However, the environments that are chosen for deployments are usually close to being ideal spaces in which you would expect RF based tracking to perform. Very regular environments with clear spaces and few objects within the tracking areas which would hamper performance, such as large metal machinery which reflects 2.4 GHz signals. The results seen in these environments, such as in hospitals for tracking medical equipment or in warehouses for stored goods, may not be replicated exactly.

The research in determining the best tracking technology to use for going forward had been carried out prior to this report, and so what this aims to do is simply document the installation carried out and the first stage of testing and to discover the characteristics of this tracking system in a factory floor environment. Due to regulations in place at the Boston Scientific facility, deploying an RF based tracking system on the factory floor would require a lengthy review process before being authorised. To get a proof-of-concept system deployed quickly the Rapid Prototyping Room or Whitespace in BSL is used as an analogue for the conditions on the factory floor.

The targeted use case (UC-BSL-7) involves the tracking of high value test equipment around the BSL facility, and because of this, most of the tests carried out to date involve the positioning of static devices and how they behave over long periods of time. Going forward, more work is planned in tracking moving devices and the precise limitations of this Bluetooth tracking system.

3.2 Content and structure of this deliverable

The main body of this document is divided into three sections. In section 4 the detailed description of the hardware is given. This section first describes the hardware and software of the asset tracking system and then goes on to detail the deployment. In addition this section also describes the work undertaken in relation to implementing Energy Harvesting into the system. Section 5 details the results taken in Boston Scientific and discusses some topics around accuracy and reliability of the system. Finally section 6 presents the conclusions to the work as well as highlighting future work.

4 Description of Physical Security System

4.1 Hardware

Due to the large amount of time and effort which would be required to design a reliable Bluetooth based tracking system from the ground up, it was decided to leverage emerging off-the-shelf technology. This allowed much more time to be spent solely on understanding the characteristics of the system and energy availability aspects in order to demonstrate the utility of energy harvesting for low power sensors such as these.

Tracking was implemented using the Link-Labs AirFinder Bluetooth Low Energy tracking kit (AirFinder) which employs a proximity-based sensing method. Tags listen out for beacons which continuously advertise their signature over BLE. By listening to and comparing the strength of these signals, a tag decides which beacon it is closest to. It then relays that information to an Internet Access Point which talks to the cloud-based application, updating the known location of tags as they move from area to area. The following diagram shows an example of a tag entering the proximity of ‘Location A’ and sensing the signature of the beacon that defines this area, causing a position update event.

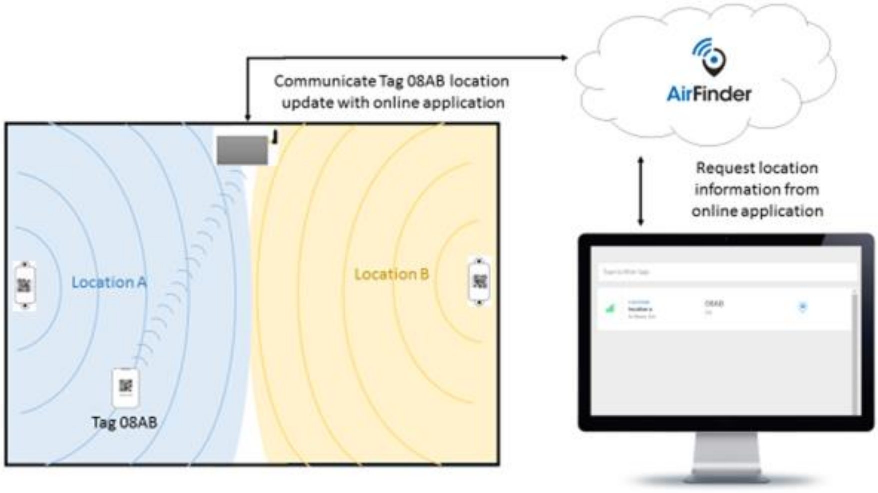

Figure 1. AirFinder Tracking Example (2 Beacons, 1 Tag)

In Figure 1 the three components of the tracking system can be seen; a Tag, Beacons, and an Access Point. The following diagram in Figure 2 shows the two different styles and dimensions of tags that can be used with this system:

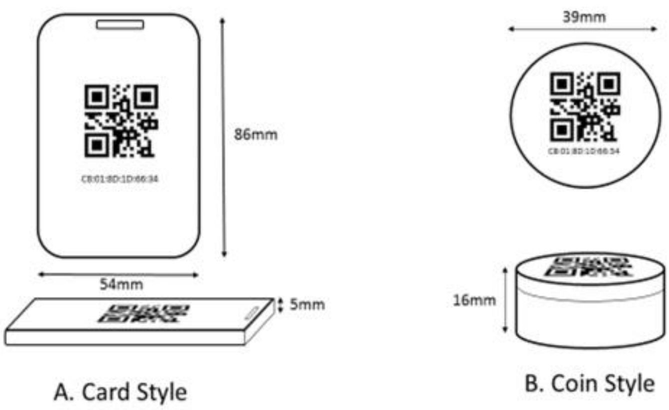

Figure 2. Tracking Tags - Styles & Dimensions

These are attached to assets that it would be desirable to track. Different forms may suit different assets depending on the form factor and conditions faced by the asset. They will usually be attached by strong adhesive tape for long term tracking, and either Velcro strips or zip-ties for shorter term tracking. Again, this depends on the needs of the specific use cases.

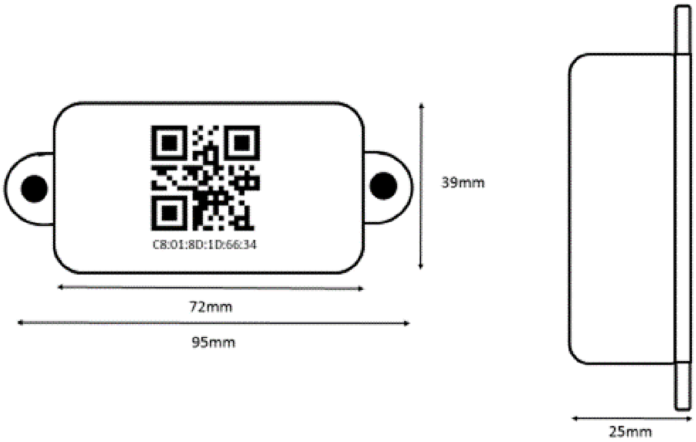

Figure 3. Beacon Form & Dimensions

A tag's position is determined by the Beacon location of the strongest signal it receives. Since the number of beacons defines the number of locations you have in the tracking area, intuitively the higher the beacon density you have the more possible tag locations and the better potential accuracy of the tracking. However as one increases beacon density, this also means that the difference in signal level from each beacon the tag receives reduces. This reduction in differential signal strength, combined with multipath fading, means the tag sees a number of beacons appear as the strongest signal, thus reporting incorrect location more often. If Beacons are less densely populated the difference in signal strength is higher and multipath fading effects the result less. They can be attached at any fixed position through the two loops at either end of the packaging, through screws, zip-ties, or with adhesive tape if either of those are not possible. Determining the optimal placement of the beacons is demonstrated later in this document.

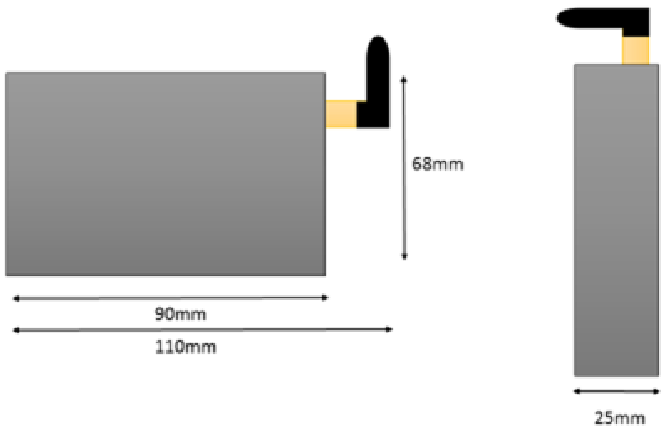

Figure 4. Access Point - Form & Dimensions

The Access Points shown in Figure 4, are placed around the tracking area to communicate with the tags also have a limited range (200-400 m^2), so in most cases some sort of layout needed to be determined to give full coverage of the site. These devices are powered via a micro-USB port, and also need to be connected to the internet using an Ethernet cable, shown in Figure 5. This needs to be considered in the placement.

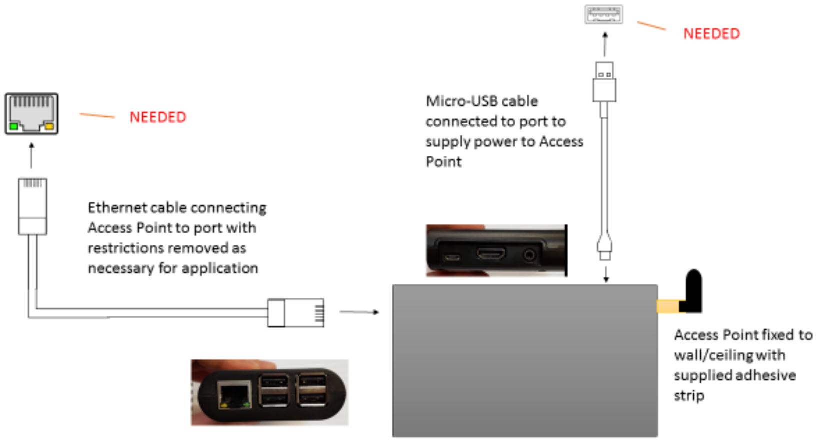

Figure 5. Access Point Required Setup

4.2 Deployment

Since the technology we are using is proximity based we want a layout which minimizes the maximum distance a tag could be from any proximity beacon for a given floor space and number of tags. We also want to make sure that Access Point connectivity is available everywhere in the tracking area. We have been given the Rapid Prototyping room in BSL which has regular dimensions of 18.6 m x 9.6 m.

After discussions with Boston Scientific we agreed an accuracy to track to in this space of 2-3m as this would give a compelling story for tracking equipment. So we need to figure out the optimal layout which will minimize the number of beacons needed. If the room is pictured from above it can be imagined that the beacons' proximity are circles with radius 2.5 m. What we are trying to do is completely cover an 18.6 m x 9.6 m rectangle using the minimum amount of 2.5 m circles. If a standard approach is taken where the beacons are set up in a square grid, Figure 6 shows what we would get with a packing using this method:

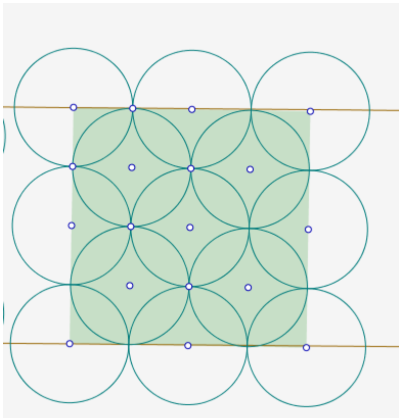

Figure 6. Square Grid Packing

What is obvious here is the large amount of overlap between the circles indicating inefficient packing. And this results in 13 circles being needed to completely cover an area this size. A clever approach would be to use hexagonal packing to cover the area in a more efficient way. The centres of these circles are placed so that if you were to draw the boundaries between each it would result in a grid of regular hexagons.

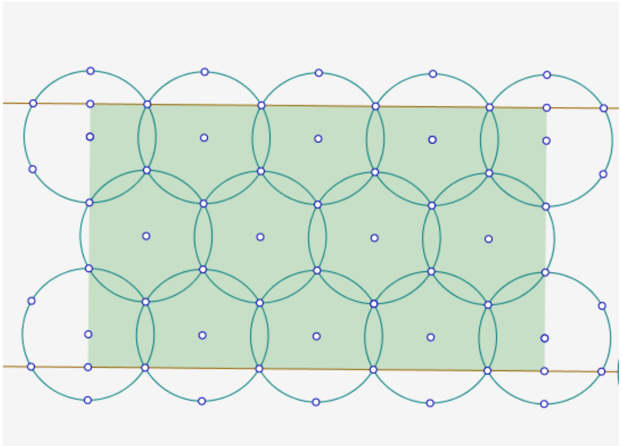

Figure 7. Hexagonal Grid Packing

Figure 7 shows how 14 circles used in this fashion can cover twice the area shown in the first example where a square grid was used. This is the best regular pattern that can be used in this case and so a template was drawn up. We needed to determine the size of these hexagonal areas which would best suit the size room we are working with. Aiming for about 2.5 m accuracy it made sense to tile 3 hexagons across so that they would cover the width of the room (9.6 m). With this setup the grid makes sure that a tag is never more than 2.35 m from a beacon anywhere in the room.

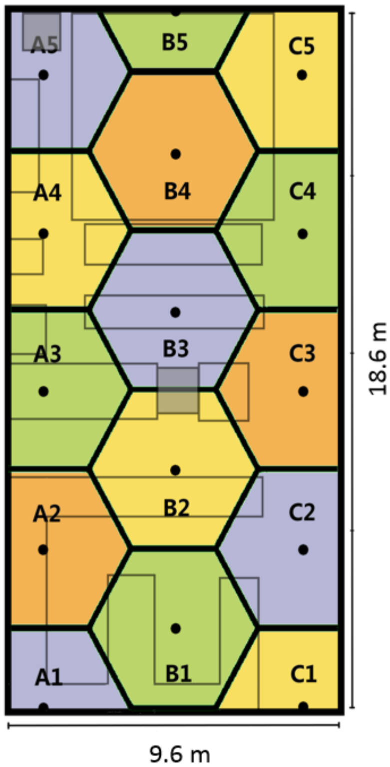

Figure 8. BSL Whitespace Proposed Beacon Placement

Figure 8 shows an overhead map of the BSL Whitespace where desks and other obstacles are outlined and a hexagonal grid of beacon proximities has been overlaid. It has been decided that locations for this prototype will be ordered in rows and columns. The first alphabetic character denotes the column from west to east and the number that follows denotes the row from south to north. This is a first pass design choice, which will be revisited following deployment as a better way of naming locations that is more intuitive may be discovered through long term use.

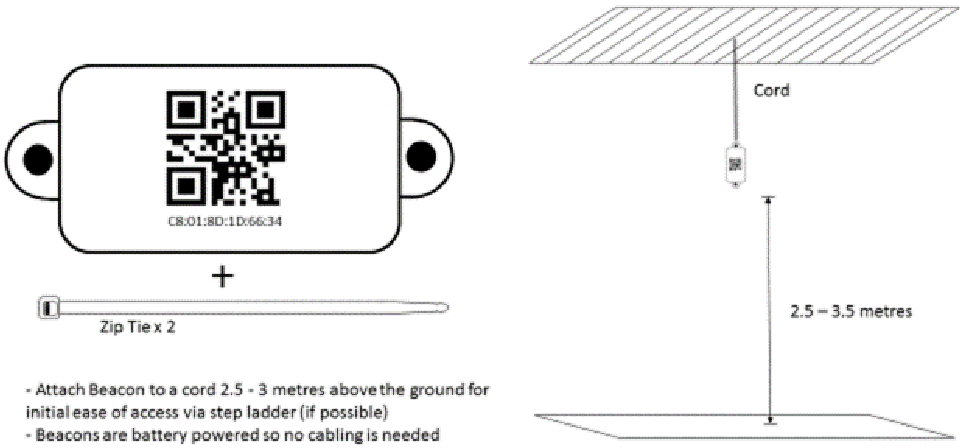

Figure 9. Proposed Beacon Set-up

In the beacon placement grid, we are only looking at a two-dimensional picture of the tracking space where the height aspect is neglected. Taking into account the vertical dimension we notice that if the beacons are placed on the ceiling, then the closer you are to the ground the relative difference in signal strengths between two neighbouring beacons around the border becomes less and less. We need this difference to be great to allow less uncertainty when a tag senses which beacon it is proximate to. Using the Friis equation (Friis) for the propagation of RF signals we estimate that the area of uncertainty between two beacons will be about 3 times as large at the floor compared to the ceiling which is 3.5 m from the floor. This is due to the difference in line of sight distance between beacons being smaller in a 3D arrangement than a 2D planar arrangement. This is a problem but we need to attach the beacons to the ceiling to avoid obstacles, so the ideal solution is to hang the beacons down from the ceiling to a certain extent. To do this we will use a rubber cord to place the beacons 3 m from the ground. The tags should mostly be attached to objects on tables <1 m above the floor. In theory. this should reduce the uncertainty areas by half as well as allowing easier access to the beacons during initial deployment testing.

4.3 Software and Alerts

The AirFinder application is cloud based and hosted by Amazon Web Services, which means that you can easily access the tracking information from anywhere as long as the system is online. Otherwise you lose visibility of the movement of tags. Because of this we have decided to make use of the Ethernet port to provide internet access. The following data flow map in Figure 10 represents how the system communicates with the application and how the tracking data is accessed:

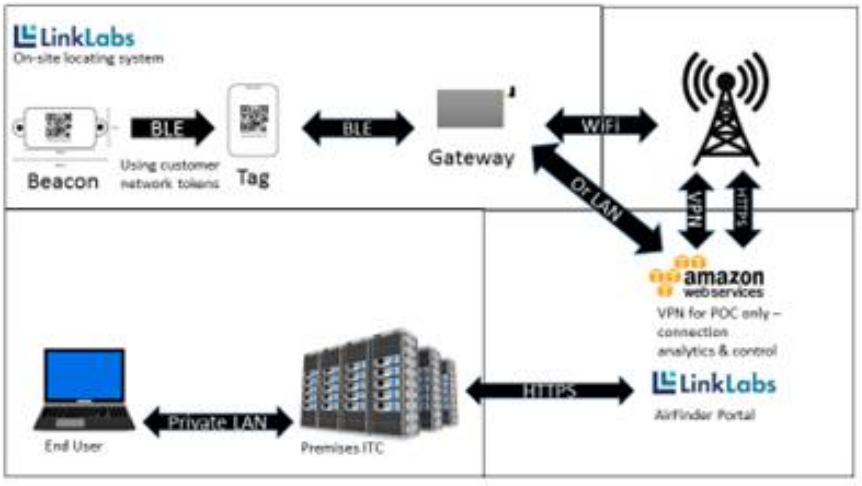

Figure 10. Flow Chart of AirFinder Communication

The application itself is accessed via browser at pro.airfinder.com. Each person who needs access to it may be added as either an admin or user with privileges dictated by the admin setting up the account. These privileges include the ability to add new locations, add tags, download reports, or set/receive activity alerts. The first step to set up the application is to add a new site which would be the facility in which you are setting up. Within this you divide the site into areas and then again divide the areas into locations or zones, both of which are defined by the beacons. Locations are defined by single beacons whereas a zone may be defined by multiple beacons. This is useful in some cases where you only care about whether a tracked asset is in a general area rather than somewhere specifically.

Once the site you want to perform tracking in has been divided up into its respective areas, zones and locations, and beacons have been assigned, you may begin to add tags. The way this application allows classification of tracked assets is by group and category. Because these are loose ways of classifying assets, we will have to define how these tags are used. For our purposes we will say that groups will be general asset descriptors and categories will be more specific. For example, if an oscilloscope which is used for testing is tracked, we would call the group 'Test Equipment' and the category 'Oscilloscopes'. There is also an individual asset description with each tag which may be appended if more specific information is necessary. Adding a tag is as simple as entering the unique hex ID of the tag to be attached as well as all the relevant information about the asset into the application. Once entered, the tag is tracked as long as it remains in the database.

An important application here is physical security, whereby an alarm can be raised when a tagged item lives an area, this is also known as geo fencing. The system has the ability to send out alerts to relevant personnel when tags leave/enter zones, areas or locations. This is entirely configurable, and the alerts can be sent via SMS or email. Furthermore, full reports may be generated of the movement history of any tag from when it was initialised to the present.

4.4 Energy Harvesting Implementation

It has been desired since the start of the project to implement energy harvesting in as many aspects of this system as possible. Investigations were carried out to determine the power consumption of each piece of hardware in the tracking system (Tyn1), (Tyn2). As well as this we needed to determine the available sources and availability of ambient energy which could be captured in each case, compare the two and determine the viability of implementing energy harvesting to increase the life of or replace the battery. Table 2 below shows the available energy sources in BSL's factory floor and the power they could generate.

Table 2. Available Ambient Energy Sources

Energy Source	*Photovoltaic*	*Thermoelectric*	*Piezoelectric*	*RF*
Expected Power	10-30 μW/cm^2 400 - 1000Lux	50-100 μW/cm^2 per °C	10-200 μW/cm^3	<1 μW/cm^2
Availability	600 – 1200 Lux 14 hours per weekday	Some machinery produces temperature differential when active	No consistent source of Hz – kHz vibration	Ambient RF is minimised to prevent interference with production

From the above table we can see that we can eliminate vibrational and RF energy harvesting, as these sources are not present in the environment in a way that would produce consistent power. Between photovoltaic and thermal we have ways of generating decent amounts of power from the surroundings. There is quite high intensity indoor lighting present since this is a production environment where compared to office conditions, brighter lighting is mostly preferred due to improved alertness, safety and productivity of workers. Of the many machines that cover the factory floor there are plenty that produce a temperature differential. They are positioned in a limited number of locations that may not be easily accessible in relation to beacon location. In the end it was decided to go with photovoltaic harvesting due to the greater coverage, potential energy and relative maturity of the technology.

The two pieces of the tracking kit that have a power consumption figure within range of what would be considered energy harvesting compatible would be the tags and the beacons. The main power draw in each component is caused by receiving and transmitting Bluetooth messages. The following graphs in Figure 11 and Figure 12 show the current draw from a 3 Volt source during operation.

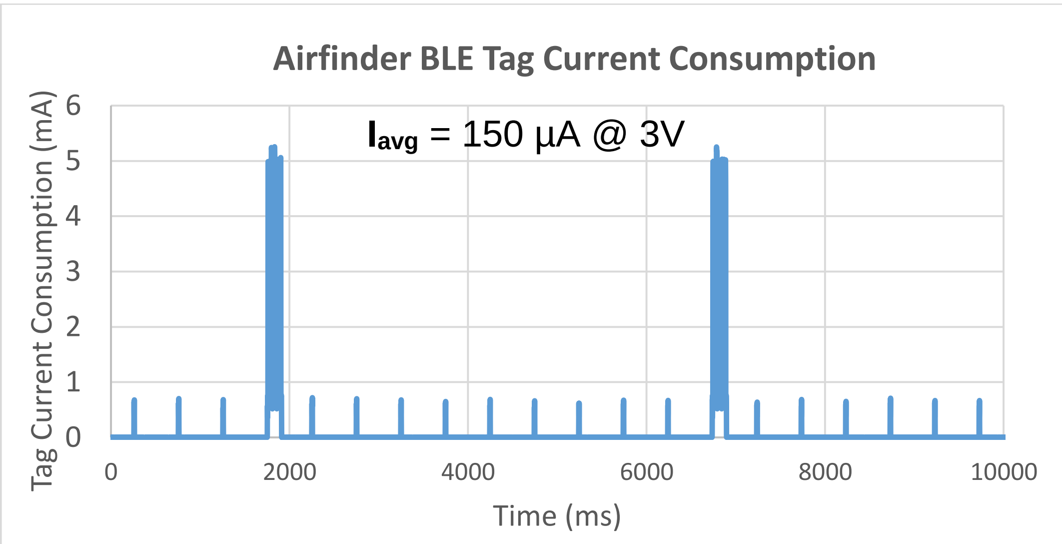

Figure 11. BLE Tag Current Consumption

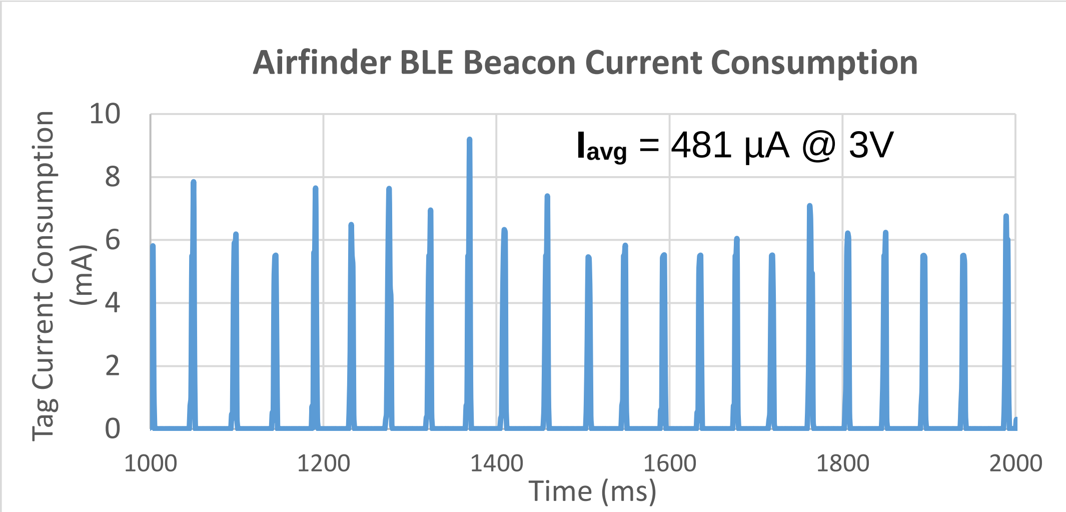

Figure 12. BLE Beacon Current Consumption

The tag consumes on average 450 µW which is well within the bounds for what may be harvested, but the issue arises that since tags are intended to be mobile, we cannot guarantee that tags will be exposed to enough light or any other source of ambient energy to replace or complement the battery as a power source. On the other hand, beacons are meant to be fixed in position, and while the power consumption is three times as high (1.44 mW) we can provide a consistent source of harvested power. The light conditions in the BSL factory floor and whitespace are very good for this, averaging about 1200 Lux at the beacon placement points. Using an AM1816 PV panel which measures 50 cm^2 (53.3 x 94.7 mm) we can generate up to 1.46 mW in full lighting conditions. This figure is based on experimental data using the previously mentioned PV panel with Tyndall's energy harvesting power management board, and considers efficiency of the power management board, MPPT (maximum power point tracking) accuracy, storage and dc/dc conversion losses, etc. Although this can power the device completely during lighting hours, we still want the device to work when the lights are switched off. During these periods, batteries are still needed to provide power, and so the harvesting is to be used to complement and extend the life of the battery.

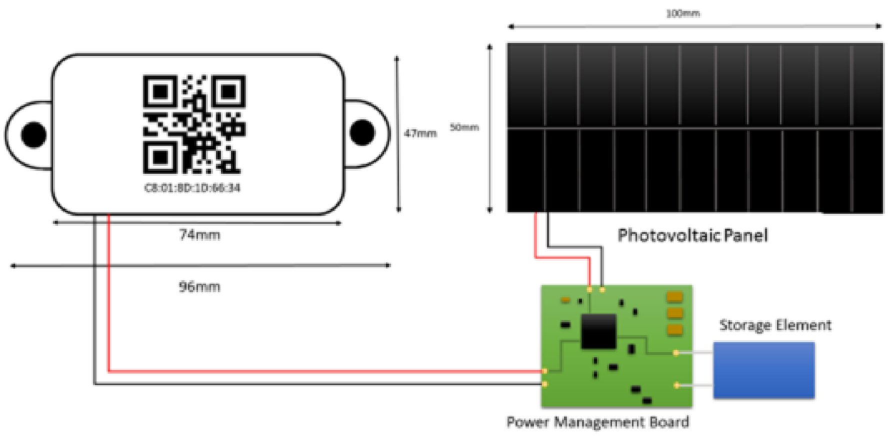

Figure 13. Proposed Energy Harvesting Set-up

The Energy Harvesting Set-up is shown in Figure 13. It was necessary to make predictions about the performance of this device over a long period of time. A script was written in MATLAB which modeled the system's behaviour over weeks at a time for different setups. Based on experimentally determined models of each component, when the script is run it outputs the utilized harvested power, supercap and battery state of charge over a date range, expected battery lifetime, and what contibution energy harvesting has made to this. The following plots in Figure 14 are split into 3 sub-plots, the first showing the power consumption profile of the end device. The second shows the prediced voltage level of the supercap (directly related to how much energy is stored) in blue, and the red line indicates when energy harvested power is being used. The final plot shows the backup battery state of charge, in this case 2 AA batteries in series. The first plot shows the performance of an energy harvested beacon over a 3 week range assuming 1200 Lux, 14 hours of light a day only on weekdays.

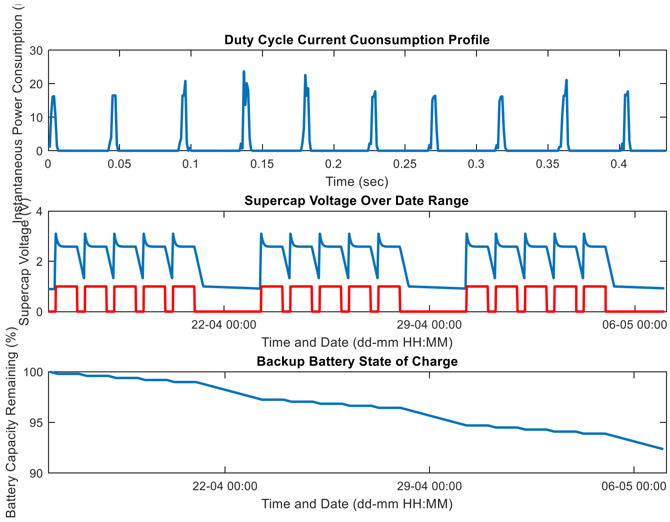

Figure 14. Simulated Energy Availability - 3 weeks, 1200 Lux

It can be seen that during the weekdays the super-capacitor quickly charges and starts providing power to the beacon. There is a small surplus of energy which starts being used when the lights go out but this is quickly drained, and power is once again supplied by the battery. For this set-up we can expect energy harvesting to provide power 52.5% of the time. This extends the battery lifetime by 110% from 260 days to 550 days.

5 Deployment Results

5.1 Deployment

Deployment of the tracking system was carried out as planned with 2 test sites; one full scale test in the BSL Whitespace and one set up in the Tyndall Wireless Sensor Network lab used to debug issues as they arise in the main deployment site. As discussed in the deployment plan, the beacons were suspended from the ceiling using rubber cord to a height of 3 m from the whitespace floor. The precise placement of the beacons along and across the ceiling had been determined and carried out in order to maintain the proximity boundaries as laid out in Figure 8. This was made a great deal easier by the grid-like ceiling where each small square represented 10 cm x 10 cm. Example pictures of the installation can be seen below in Figure 15.

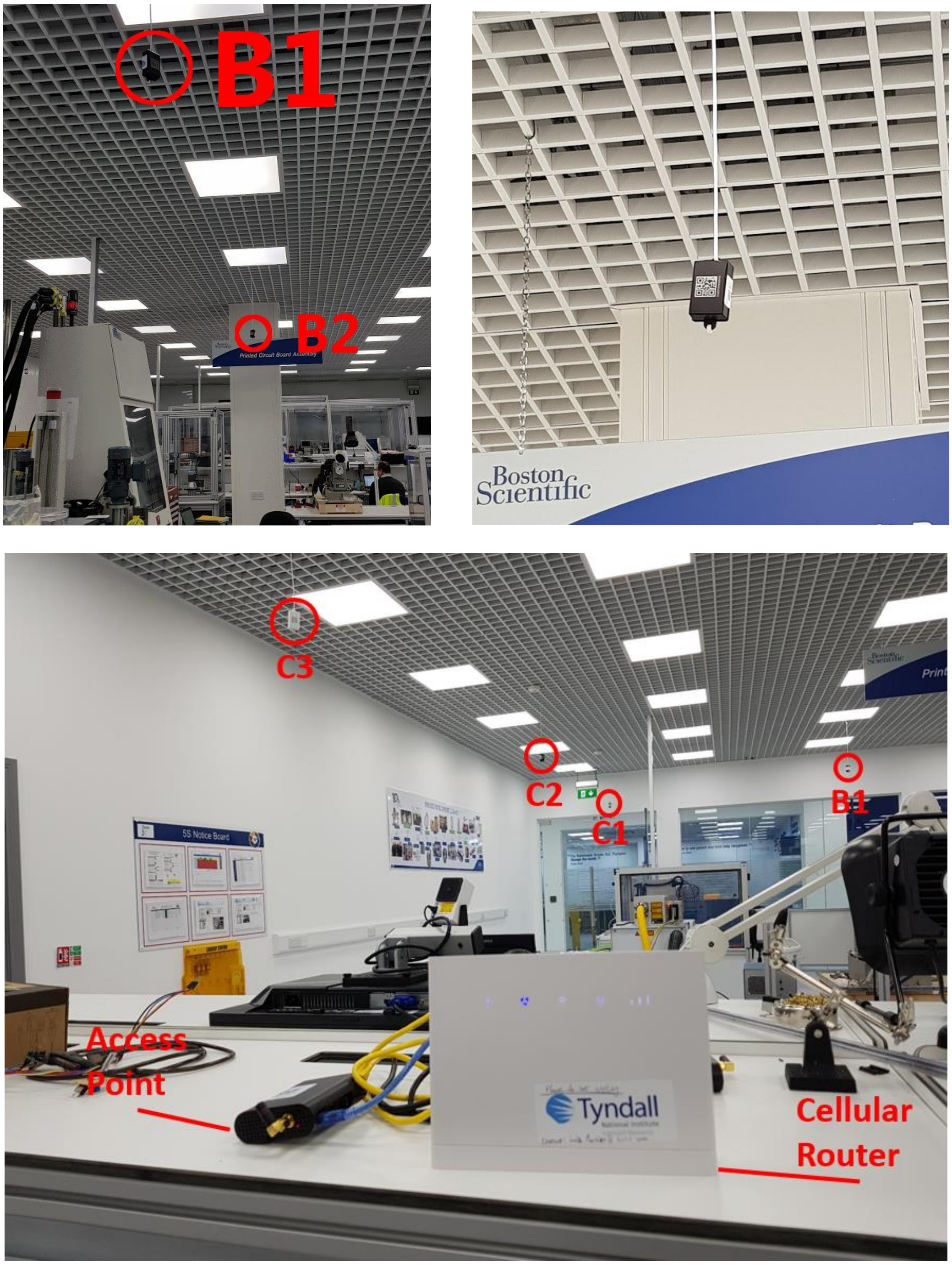

Figure 15. Images of Whitespace Deployment

An issue that came up and impacted the deployment of the system was the need to comply with BSL's internet security policies. There is a network firewall which only permits known and authorised devices access to the internet. This is a good way of preventing malicious attacks, but for our purposes it meant that we either needed to go through a long IT vetting process for each deployed device, or an alternative had to be arranged. In this case to get information back to the online application, a cellular router had to be set up and used. This was useful for our relatively small proof-of-concept set-up, but if it were to be scaled up to a facility-wide system it would not be viable, and IT vetting would be required.

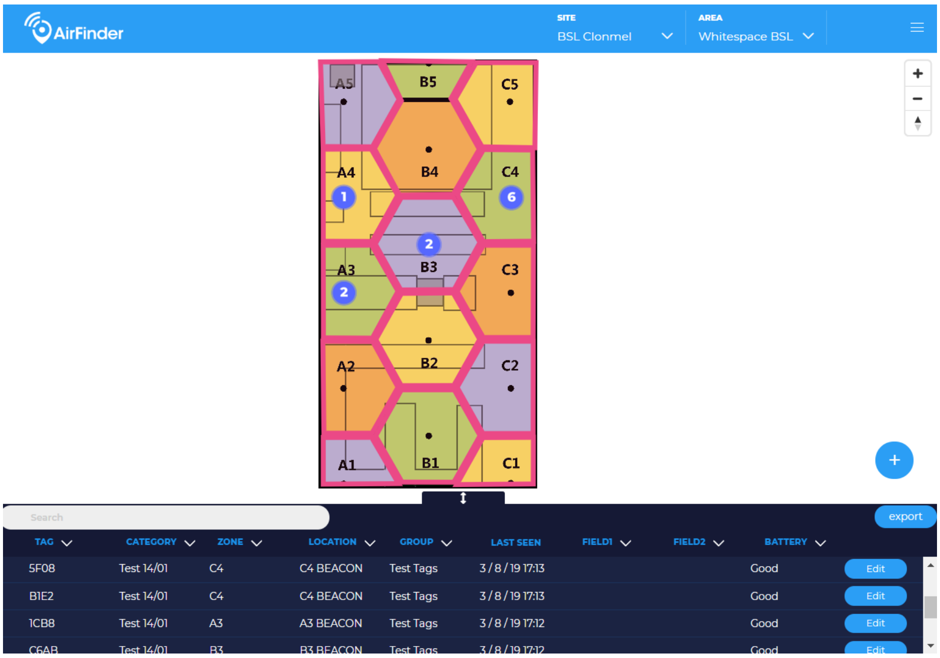

Figure 16. AirFinder GUI

5.2 Test Results

5.2.1 Tracking Accuracy

The most important performance metric for this system is how accurate the tracking is. Since this is a proximity-based system, it is not as simple as comparing the predicted and real positions. What is more important is how well the proximity boundaries are defined. Since we are using the relative strength of RF signals to determine proximity, we can expect a number of factors to make this less than ideal.

- The direction of each device's antenna
- Reflections causing areas of both constructive and destructive interference
- Physical obstructions

What we need to do to get an idea of what kind of performance we can expect is to examine the reported conditions of tags all around the proximity zones, especially in disputed areas midways between 2 or more beacons to see what factors lead to a tag reporting one proximity over another. Also, this will give us an idea of how big these grey areas are, and how trustworthy we can be of our reported location.

In previous work during the evaluation phase, tracking of the tags was verified by taking an active tag and bringing it close to one beacon. This was reported in the online application, and after a few moments the tag was brought toward another beacon several meters away. The position of the tag was updated to that of the location of the second beacon which verified that the system was working as intended.

A series of tests was devised to determine the performance expectations of the system. Some of these were undertaken in the Tyndall labs where we have good control over the environment. Others were undertaken in the deployment site in BSL to get performance data in a real operations environment.

1. ***Test A – Regularly spaced static tags 48 Hour reporting***

   This test was undertaken in the Tyndall Labs which is a controlled environment to determine how tag positions were reported over a 48-hour period when placed between two beacons.

2. ***Test B – Regularly spaced tags in the boundary region***

   This test was also undertaken in the Tyndall Labs to examine more deeply the behaviour in the boundary region between two beacons.

3. ***Test C – Deployment verification of static tags inside Beacon Regions***

   This test was undertaken in the White Space at BSL to determine the performance of the system when tags were placed directly under the beacons, away from any boundary regions

4. ***Test D – Proximity intersection behaviour***

   This test was undertaken in the White Space at BSL to determine the behaviour of tags in the boundary regions between beacons

5.2.1.1 Test A – Regularly spaced static tags 48 Hour reporting

To get an idea of how the beacon proximities interacted with each other and how the tags reported this, the following experiment was conducted within the Labs at Tyndall: Two beacons were placed 4.2 m apart on a long desk with no interfering objects or other beacons in the vicinity. This needed to be done in order to ensure the best-case scenario for the propagation of the RF signal. Seven tags were then placed at regular intervals between the two beacons (52.5 cm) which would report the beacon which it sensed it was nearer to, with tag 9D being at the midway point between the two beacons. These were then left for 48 hours, and the percentage of time which they reported they were closest to each beacon was plotted. The result is shown in Figure 17 below. Please note the tags from here on will be named using either the last 2 or 4 digits of their 12-digit BLE device identifier for simplicity as each identifier is already written on each tag.

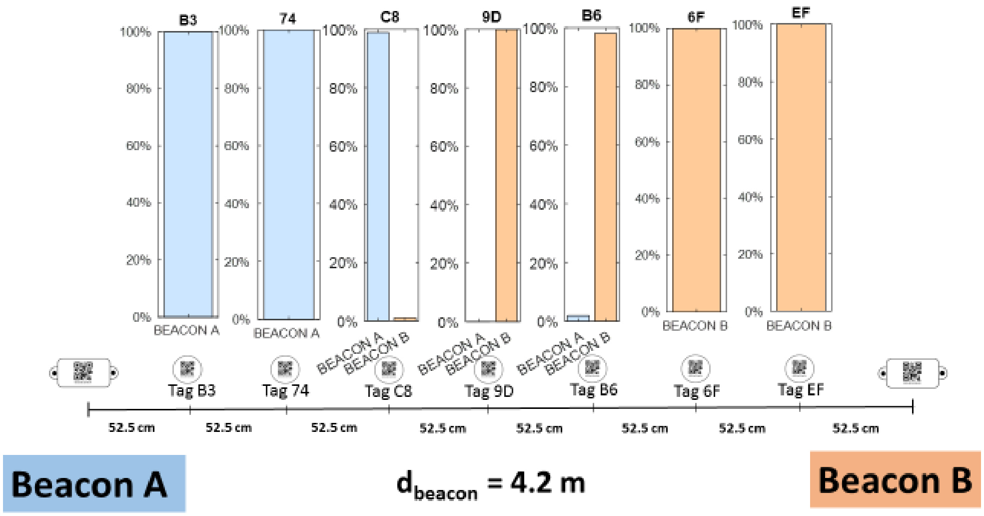

Figure 17. Test A – Regularly Spaced Tags Reported Positions Over 48 Hours

The results were mostly as expected. The nearest two tags to each beacon reported which beacon they were nearest to correctly 100% of the time. What is interesting is the behaviour of tags C8, 9D and B6. The recorded pattern observed for tags C8 and B6 almost exactly mirror each other. Both mostly reported the nearer beacon, but occasionally switched to the further of the two before quickly switching back. It can only be assumed that we are observing the natural fluctuation of the system as the relative difference in received signal strength is small enough that naturally every once in a while, random variations like this happen. From this we would expect that the tag 9D in the middle would constantly be switching between the two beacons. However, tag 9D reported that it was nearer beacon B for the entire 48-hour period which subverted our expectations. The likely cause of this is that the reflected signal from Beacon B being received by tag 9D was adding constructively to the direct path yielding a consistently higher signal level.

5.2.1.2 Test B – Regularly spaced tags in the boundary region

To take a closer look at what is going on in this grey area, the tags were rearranged so that they were equally spaced apart within the middle 2 bands of the previous experiment. They were again left for 48 hours.

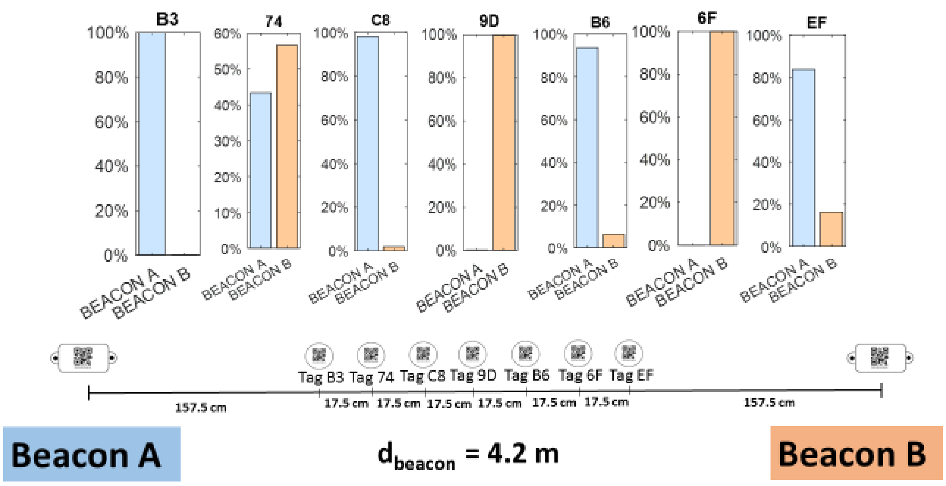

Figure 18. Test B - Boundary Tags Reported Positions Over 48 Hours

In Figure 18 above, what we see is much more random than the previous test with a lot of interesting results. Tag 9D which remains in the same position continues to report its previous assertion that it is closer to Beacon B, whereas C8 while being only 17.5 cm away reports the opposite location. Tags 74 and EF seem to mostly sense the further beacon as being closer, although this is much less confident and there are many switching events where they change their mind. We can also notice that alternating tags for the most part report alternating beacons with varying levels of confidence and with Bluetooth signals having a wavelength of ~12.5 cm self-interference patterns at this scale may be the cause of this result although we can't be certain. The conclusion is that the constructive and deconstructive addition of multipath signals has a greater effect on reporting inaccuracies in regions where the direct path signal levels are at similar levels from each beacon. Therefore, from these results with two beacons placed 4.2 m apart in this specific location, there is a region of approximately 90 cm where the accuracy of the system is unreliable. Note as RF reflections are highly dependent on the physical environment, this region may expand or reduce in other locations. Further work would be required to determine this range with more certainty.

5.2.1.3 Test C – Deployment verification of static tags inside Beacon Regions

With verification of the performance completed in the Lab we can move on to the system as it is deployed in the whitespace. Please refer to Figure 19 below. Taking a sub-section of the layout, 3 tags were placed directly under 3 separate beacons for 48 hours as with the previous tests. Since the beacons are hung from the ceiling and the tags are 1.5-2 m below the beacons, the relative RSS difference between the overhead and neighbouring beacons will be less than if the tags were right next to the beacons. The next nearest beacon to each tag is 4.36-4.51 m for comparison.

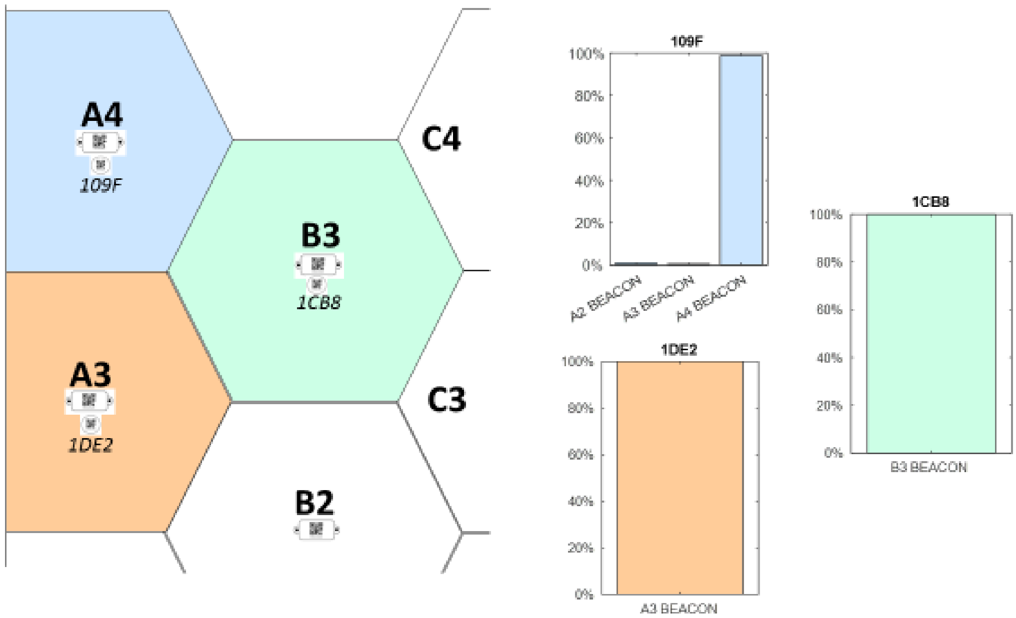

Figure 19. Test C - Deployment Verification of Static Tracking (Reported Positions Over 48 Hours)

This was very much as expected with each tag reporting the correct location in almost all cases over the selected period with the exception of tag 109F under A4 which briefly switched to reporting location A3 and A2, but this was only for a short period and demonstrates again the small amount of random fluctuations that can be seen over a long enough period. In this case there are people working in the area, and this movement will cause reflections with a higher fading content which may give a stronger signal from adjoining beacons from time to time.

5.2.1.4 Test D – Proximity intersection behaviour

Similar to Test B, we wanted to see how the tags behaved while placed at the precise intersection of 3 proximities, but this time within a real deployment scenario. Four tags were placed at the intersection of B3, C3 and C4 as shown in Figure 20, and again the reported location for each was examined. The distance from the tags to each beacon is 2.35 m horizontally, and 2.96 m directly taking height into consideration.

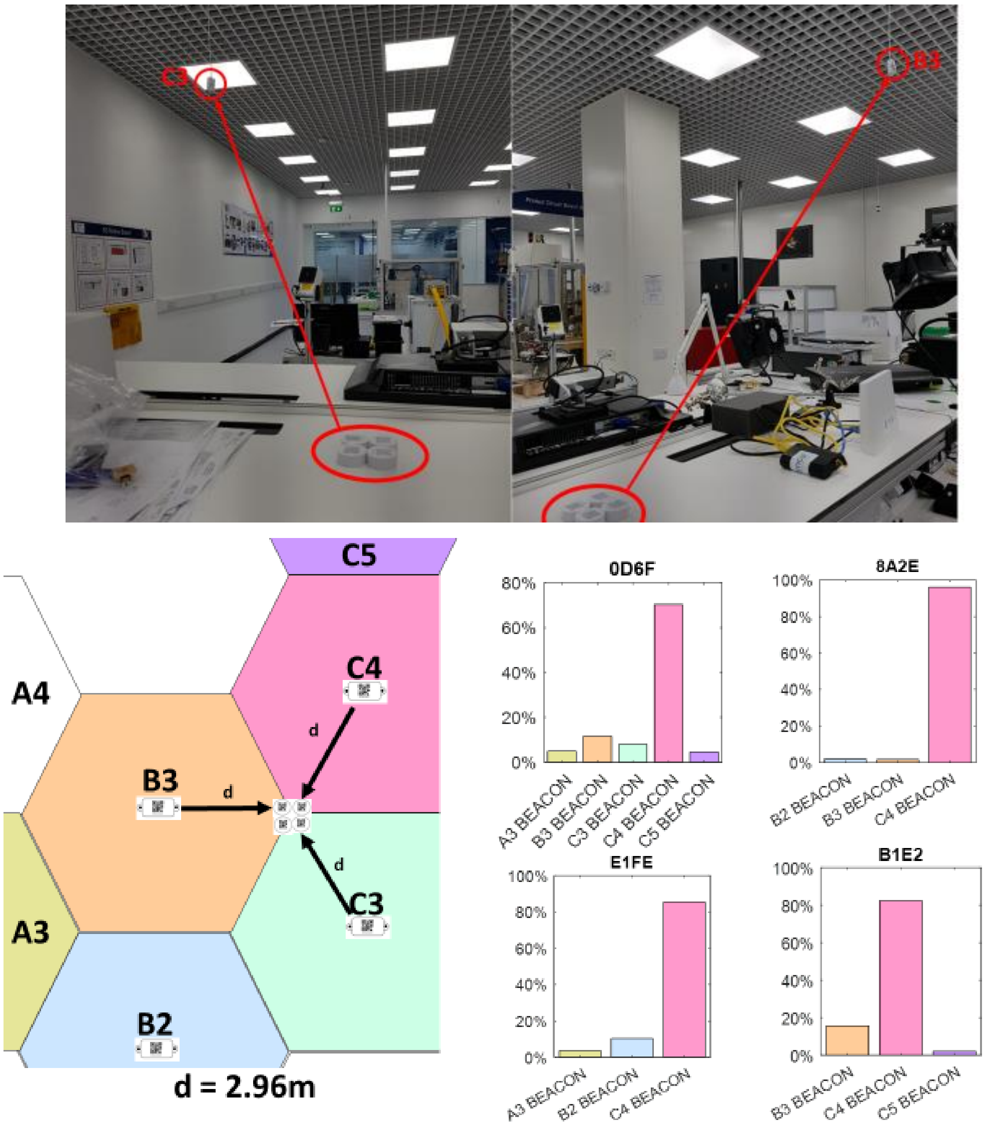

Figure 20. Test D - 3 Proximity Intersection Tag Behaviour

What was learned from this test is that in intersections like this, the relative difference in RSS is so small that beacons much further away than any of the 3 proximate beacons may sometimes appear to be nearer to the tag due to multipath. In general, the system positioned the tag being in region C3, C4, B3 for over 95% of the time. It is interesting that Beacon C4 was sensed by all tags as being the dominant proximate beacon for a significant portion of the time. This could be due to Beacon C4 having a higher power level compared to other beacons or its antenna could be orientated in a more favourable position. It is interesting that the beacons that were otherwise picked up seemed to vary randomly from tag to tag, with each having several particular beacons that it would switch to on occasion. To note the distances to these other beacons from the tags: Beacon B2 is 5.05 m away and beacons A3 and C5 are both 6.63 m away for comparison. We can take from this that in the majority of cases the proximate beacon is sensed. However, there can be a significant error for a small percentage of time, therefore, to help improve accuracy, it is important that the location history is also taken into account when determining position.

It had been expected that as the tags were positioned on the intersection of three beacons, the tag would report each of the three proximate beacons an equal number of times. If this had been the case then as one knows the exact co-ordinates of the three beacons it would have been possible to aggregate the result to determine a more accurate position. However as can be seen from the results above this was not the case.

As an example we show this aggregation calculation with the actual results recorded above using the results from tag E1FE. The x-y room co-ordinates of the 3 beacons (in mm from top left hand corner) it reported seeing are:

- **3.5%** Beacon A3 – [110, 1010] mm

- **10.1%** Beacon B2 – [470, 1210] mm
- **86.4%** Beacon C4 – [820, 590] mm

Since we know how long as a percentage of the test time it reported being at each of these locations, we can average out the reported location to get a new position estimate.

$$POS_{E1FE} = 0.035 \times [110, 1010]\, mm + 0.101 \times [470, 1210]\, mm + 0.864 \times [820, 590]\, mm$$

$$POS_{E1FE} = [754, 668]\, mm$$

This was carried out for each of the previous results to produce these position estimations for the 4 tags plotted in Figure 21 below:

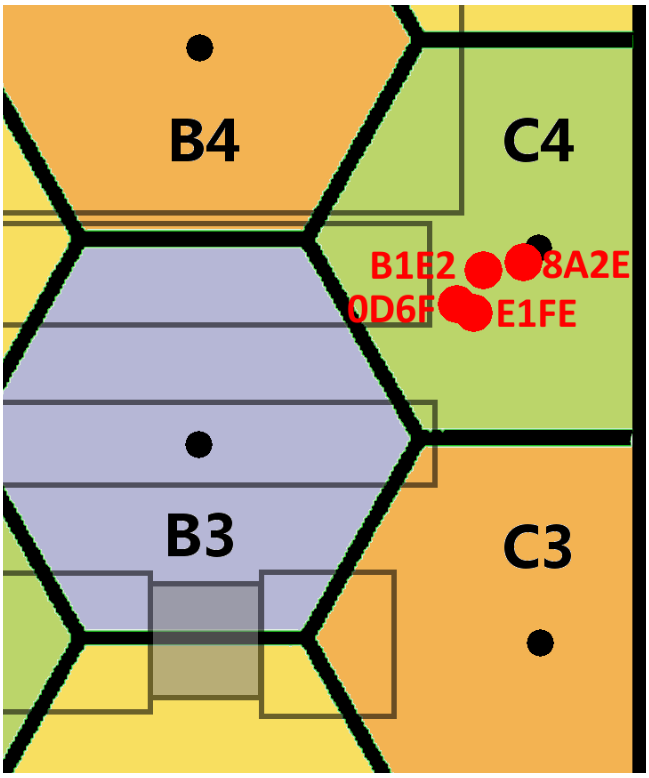

Figure 21. Aggregate Position Location Estimation Test

This looks promising as each of these results produce positions that are closer to the real position of the tags at the intersection than the most commonly reported location C4. However, these results may be skewed by the beacon set-up as was the case during this test. Due to installations in the whitespace it was not possible to install beacons B4 and B5, and so most of the remaining beacons are in the direction to which the estimations are skewed from C4. This test will be revisited soon as it is difficult to determine to what extent the estimations are influenced by the actual tag position or the beacon set-up.

5.2.2 Tracking Reliability & Security

5.2.2.1 Tracking in tough environmental conditions

As a real factory environment provides a lot of equipment made from metallic materials which would block RF signals, it was desired to see how the tags responded to these challenging conditions and what would prevent the tags from communicating. Different enclosures in the whitespace were used for testing, mostly metal cabinets and tool drawers placed throughout the facility pictured below in Figure 22.

Figure 22. Various Secure Enclosures Around BSL

Placing the tags in each of these units it was difficult to reliably prevent the tags from communicating with the access point. Since these are not sealed containers there is still a way for the tags to relay information back. The tags regularly send out 'heartbeat' signals to let the application know they are still there. While some of these messages may be prevented from reaching the access point by the enclosures tested, we saw that at least one managed to reach the access point at regular intervals. On some occasions a position update had not been received by the application for an extended period of time, but the last known position was easily used to track down the enclosure in which the tag(s) had been left.

5.2.2.2 Alert Functionality Test

To test the alert functionality of the application, a workflow was set up to send out an email to a specific email address when a tag left the tracking area. On several occasions a tag was taken out the door of the Whitespace and placed far enough away to prevent the tag communicating with the access point at a precise time. Once the alert email was sent, the timestamp was compared to the time the tag was removed. This gave us an idea how long it would take for an alert to be spread that a tagged asset had left its designated location. The alert delay varied slightly, but there was always less than a minute between the tag being removed and the alert being sent. The shortest delay was 12 seconds and the longest 44 seconds. The workflow alerts are configurable so that you are able to receive alerts for the entry to or exit from any location, zone, or area for any individual asset or category of asset. A sample has been included in Figure 23 below showing the timestamp of when precisely it was determined that the tag was no longer present in the tracking area.

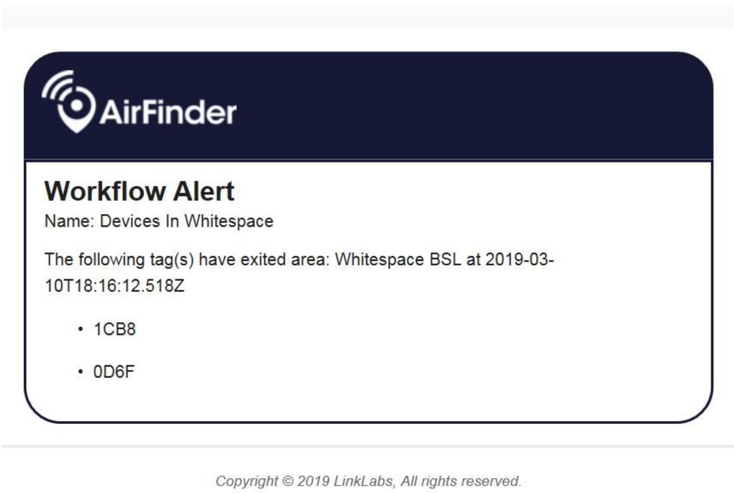

Figure 23. Sample Alert for Missing Tags

6 Conclusions

In this report an off the shelf Bluetooth Low Energy, proximity-based asset tracking system has been designed, verified and tested. For this set-up it was assumed that tracking accuracy would be down to the precise locations designated by each beacon. For most scenarios this seemed to be the case. While a tag was within a moderate distance to a beacon, it reported its location correctly more than 99% of the time. However, due to the density of the beacons, we observe at the boundaries of each location a grey area where tags sometimes found it difficult to tell which beacon was closest, and the reported location did not always reflect the reality. This is due to several factors including small differential in the RSS, fluctuations caused by fluid environments, reflections causing patches of constructive and destructive interference, physical objects in the vicinity, etc. It is quite hard to determine to what extent each of these factors is causing the results we see, but what can be said is that it is impossible to effectively eliminate or manage any of these effects in a real-world scenario. Therefore, a system such as the one which has been installed in Boston Scientific must be used bearing in mind that neither this nor any other such system out there is always tracking perfectly or providing 100% reliable information.

With this consideration, the tracking system can be shown to be a very useful tool for providing visibility and a level of security to assets whose location may be vitally important for operation of the factory. Following the installation of this system in the whitespace, interest has been seen from those in charge of calibrating various pieces of important test equipment in deploying a tracking system. Up to this point they do not have visibility of any of this equipment which may end up in a variety of places across the 4200 m^2 factory floor. It is obvious how a system such as this would provide valuable location information for collecting these devices for calibration, saving time, making sure test equipment is always available for use, and preventing losses associated with unintentional misplacement. This is only one application for which due to the current size of tags this is very well suited to. Going forward there may be other applications for this system if tag size can be reduced.

6.1 Future Work

Scaling this system to a 4200 m^2 factory floor presents a number of challenges. As the resolution of positioning in a proximity system depends on the distance between beacons, this can mean that significant infrastructure has to be installed. This in turn may make maintenance overhead a significant factor. One of these overheads is battery management and replacement. As discussed in section 3.4 work is still ongoing in relation to adding energy harvesting to the system. Work is on-going and we expect to see first results in the coming months.

Another body of work required prior to scaling up is further assessment of positioning accuracy. This report presented a number of experiments suggesting that in a specific scenario, a region of about 90 cm exists where system accuracy is degraded for beacons placed 4.2 m apart. This work needs to be continued to provide more accurate assessments in other environments.

Finally, this report also suggested that using historical data or aggregation may help to improve accuracy of the system. Other techniques such as fingerprinting and inertial movement can also be used to improve performance in proximity-based systems.

7 List of Figures and Tables

7.1 Figures

7.2 Tables

8 References

(Friis) Friis transmission formula for RF transmission http://www.antenna-theory.com/basics/friis.php

(AirFinder) AirFinder Asset Tracking COTS manufacturer https://www.airfinder.com/

(Tyn1) Tyndall Internal Report AirFinder BLE Beacon Power Consumption - 10s at 1kHz.xlsx

(Tyn2) Tyndall Internal Report AirFinder BLE Tag Power Consumption - 10s at 1kHz.xlsx