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Performance Evaluation of State-of-the-Art Commercial UWB RFID Systems for Chain of Custody Process

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I. INTRODUCTION

On demand and real time monitoring and tracking of the stated condition of a nuclear warhead and its components through the dismantlement and disposition process from the point of entry to the point of exit using radio-frequency identification (RFID) tags is a powerful technology for improving chain of custody process. The chain of custody process for on-demand and real-time monitoring may significantly be improved by the use of RFID tags in terms of maintaining the continuity of knowledge for weapons and their components. In addition to tracking of the stated condition of a nuclear warhead and its components through the dismantlement and disposition process from the point of entry to the point of exit may also be aided by use of RFID tags.

Most of the commercially available RFID tags use narrowband signaling to communicate with their readers. RFID systems that use narrowband signaling for tag-reader communications face a myriad of technical challenges related to the physical properties and the propagation characteristics of continuous wave RF signals. These challenges include:

- Susceptibility to detection and tampering
- Poor performance around metals
- Signal blockage
- Low data rate
- Privacy issues
- Inadequate range of passive tags
- Large power requirement of active tags
- Limitations to worldwide operations

In addition to the above mentioned issues, there are also some concerns with the introduction of strong narrowband radio frequency (RF) signals around nuclear explosive assemblies. Many of these problems may be solved through the use of ultra-wide band (UWB) technology in RFID tags.

Although there are no passive UWB RF tags available in the market at this time, several active UWB RFID systems are available in the market that have shown promise for their high performance around metallic objects and accurate positioning capabilities. In this paper, we present the results of LLNL's performance benchmarking of the state-of-the-art commercial "active" UWB RFID systems for their possible use in arms control applications.

II. State-of-the-Art UWB Active RTLS Systems

Shortly after FCC's approval of unlicensed UWB transmission for commercial applications in February of 2002, active UWB RFID systems appeared in the market with Multispectral Solutions Inc. introducing the first UWB real time locating systems (RTLS). Soon after, companies such as Time Domain Inc. and Ubisense Ltd. introduced UWB RTLS to the international markets. Each one of these products has shown great deal of success in solving some of the shortcomings of conventional active RFID systems through the use of UWB signaling. Although UWB active RFID systems are heavily used in healthcare and automotive industries, so far (at the time of preparing this paper) there is no commercial passive UWB RFID system.

In this paper, we present performance benchmark of two of the state-of-the-art COTS active UWB RFID systems developed by Multispectral Solutions Inc and Ubisense Ltd. The performance results presented in this section are based on our recent benchmark study with additional feedback from the vendors. The benchmark is comprised of various application scenarios required for a successful asset tracking system including:

- Long range detection
- RTLS accuracy
- Functionality in the presence of metallic objects
- Functionality in the presence of liquids

This benchmark involved both indoor and outdoor tests to cover the practical scenarios for a true real time tracking and positioning evaluation of the both systems. It's important to emphasize that the purpose of this performance benchmark is not comparing the two systems. It is a report on the capabilities of UWB technology in the currently available RFID systems. Both MSSI and Ubisense systems have unique capabilities and unique design parameters that make each one useful and complementary to each other in various applications. Before we start our discussion on performance benchmarking it is useful to describe some details about each the two systems under evaluation to give the reader some familiarity on how each system operates.

MSSI RTL System

The actual marked name of the system is called "Sapphire DART". For the purposes of this benchmarking report the system will be referred to as the MSSI system. "MSSI Sapphire Solutions Include[1]:

> ***Sapphire DART***
>
> Designed for indoor applications, the DART RTLS system is comprised of a processing hub connected to a set of UWB receivers which span the coverage area. The processing hub provides power, data, and synchronization to all receivers through a dedicated cabling infrastructure. Embedded software on the hub allows for straightforward system configuration and display of real time tag locations. The easy to use, browser based, Graphical User Interface (GUI) utilizes a Java run-time environment. For large scale deployments, RTLS middleware solutions are available from ZES and a variety of vendors. Alternatively, custom middleware solutions can be developed utilizing the Sapphire Application Programming Interface (API).
>
> ***Sapphire VISION***
>
> Designed for demanding indoor RFID applications, VISION fixed readers can be deployed as either a stand alone solution or complement a Sapphire DART system installation. A key feature of the reader is the ability to adjust the read range from inches to hundreds of feet to fit the specific user application. The reader can either stream live tag data or show cumulative tag reports via the easy to use, browser based, Graphical User Interface (GUI) utilizing a Java™ run-time environment.
>
> ***Sapphire Tags***
>
> These indoor transmit-only devices communicate with Sapphire DART and VISION systems wirelessly. Three standard form factors are available: 1x1 Asset Tag, Mini-

[1] Excerpts from Sapphire Technology Datasheet.

Badge Personnel Tag, and Micro Asset Tag. Tags are powered with a 3V coin cell battery producing a battery life typically exceeding seven years even while transmitting updates every second."

Ubisense RTL System

Ubisense Real Time Location system used in our benchmarking report consists of Ubisense tags and Ubisense sensors (readers) with the following features:

Ubisense 7000 Series Compact and Slim Tags

The Ubisense Compact / Slim Tags are designed to provide accurate 3D location in real time. These tags include an LED for easy recognition, for activating a immobile tag, and a button to trigger events. These tags are approved by FCC and ETSI regulations. However, Ubisense offers a higher power system with longer communications range that is intended to be used for military and government applications.

Ubisense tags include a 2.4GHz narrowband control link because they have been certified in both the US and Europe. In Europe (and in other territories, e.g. Singapore), UWB transmitters must cut off after a short time (10s) if their transmissions are not being detected by a receiver. This conservative regulation is in place to ensure that UWB emissions are minimized, thus reducing any potential for interference to other systems. To implement this mechanism the Ubisense tags have a bidirectional communications capability (so they can pick up acknowledgement messages from receivers that have detected their UWB signals). It so happens that (discrete-component-based) UWB receivers are much more complex than UWB transmitters (too expensive, power hungry and large to be placed on tags) and therefore a different radio technology must be used for the communications channel from the UWB receivers (sensors) to the UWB transmitter (tag). The low-rate data which must be handled is well-suited to off-the-shelf 2.4GHz narrowband technologies, which have had a lot of investment for IC integration, and so Ubisense tags use a UWB link (tag->infrastructure) for accurate positioning, and a 2.4GHz link (infrastructure->tag) for command and control.

Ubisense Series 7000 Sensor

The Series 7000 sensor (reader) contains an array of antennas and ultra-wideband radio receivers. These readers utilize a composite data output of AoA and TDoA data to determine the tag's position. Using more than one interrogation scheme increases the fidelity of the tag's position. The other factor of using two communication bands, UWB and the narrowband 2.4GHz, allows the UWB signal to carry less weight in the form of encrypted information so that it may be dedicated to determining a location of a tag.

Table 4-1 shows Ubisense's various positioning system architectures and what each could determine about a tags position based on the number of sensors that were measuring a signal along a line-of-sight (or near-line-of-sight) link. This is of practical interest in environments with a lot of clutter, where the number of line-of-sight paths is often limited:

Number of sensors detecting tag	**Other information required**	**System architecture**	**Result**
4+ 3+	None	TDoA only	3D position 2D position
2+	None	TDoA + AoA	3D position
2+	None	AoA-only	3D position
1	Known height of tag	Single AoA	2D position

Table 1: Ubisense's various positioning system architectures

III. Performance Benchmark Setup

This section describes the system set up and configurations for performance testing of both systems. This section will outline the logistics and physical set-up of the system, the following describes the equipments and hardware used in this performance benchmarking:

MSSI Hardware Components

The actual hardware can easily fit inside a 2'x2' box. For evaluation purposes we have been provided with a substantial set of components that provides for a fully functional system. The components used in our evaluations are summarized in the following Table.

Components	Comments
UWB Reader	4 units needed for accurate RTLS applications Dimensions: 2.5 x 2.5 x 5.5 in. Weight 16 oz.
UWB Tag	Dimensions: 1.16 x 1.16 x 1.0 in Weight: 0.45 oz Operating Frequency: 6-6.5 GHz Transmit power: 1 W
Processor/ Hub	Provides power for up to 64 receivers Dimensions: 14 x 9 x 3.5 in. Weight: 58 oz. Ports: 8-RJ45 (to receivers), RJ45 Ethernet, RS232, Power
Software	Linux with web-based GUI for system configuration. In actuality there is no "software".
Hard-wiring	Shielded Cat-5 cable from receiver to hub (shielded cable guards from overloading the internal circuits in the receivers). There are no other power cables or inputs to the receiver. All power is provided by the hub itself.

Table 2: MSSI's Sapphire Solutions Hardware components

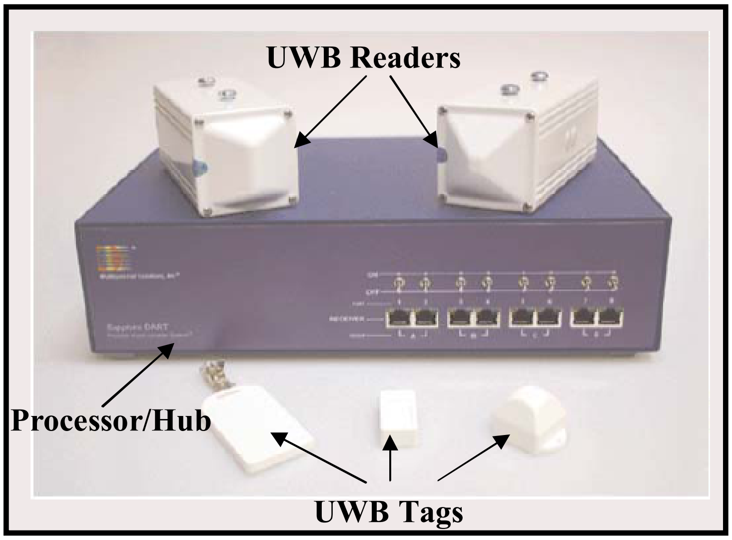

Figure 1: MSSI Sapphire DART system.

Ubisense Hardware Components

The Ubisense RTL system is also very compact, portable and easy to deploy. The components used in our performance benchmarking are summarized in the following Table.

Components	Comments
UWB Reader	4 units needed for accurate RTLS applications Dimensions: 8x 5 x 2.5in. Weight: 23 oz
UWB Tag	Dimensions: 3.25 x 1.65 x 0.4 in. Weight: 1.1 oz Operating Frequency: 6-8 GHz Transmit power: 1 mW Battery: 3 V Coin Cell
Processor/ Hub	A simple power over Ethernet switch is all that is required to feed data into a server.
Software	
Hard-wiring	Shielded Cat-5 cable from receiver to hub (shielded cable guards from overloading the internal circuits in the receivers). There are no other power cables or inputs to the receiver. All power is provided by the hub itself.

Table 3: Ubisense RTLS Hardware components

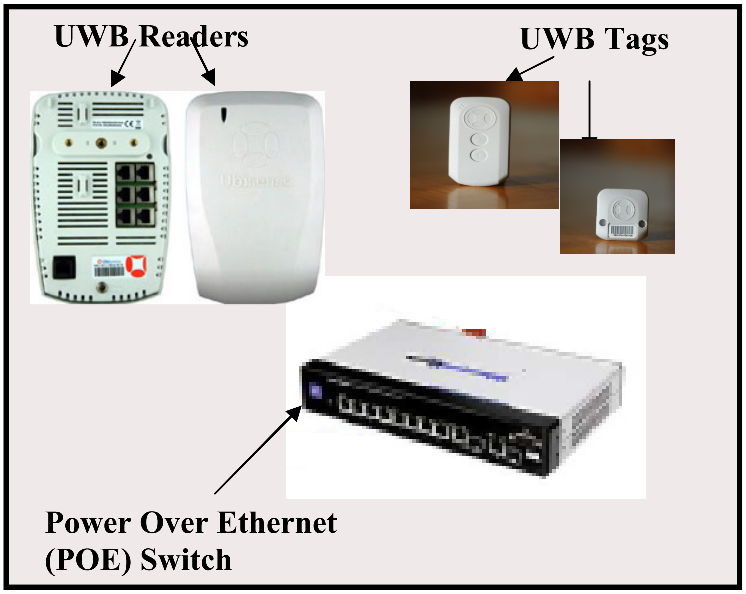

Figure 2: Ubisense RTL System

As described in Tables 2 and 3, both the MSSI and Ubisense readers only require power from the CAT5 cables and no other source. Since UWB systems have simpler transceiver architecture, both RTLS systems provide tag and readers with compact form factor that makes them very portable and easy to deploy.

IV. Performance Benchmark Experiments

In this benchmarking effort each test will be explained first by its parameters and procedure then the generated result as well as the vendor comments for each system under test is presented. One disclaimer to acknowledge is how the data is obtained to conclude to a result.

<u>Test I: Long Range Detection</u>

The parameters for this test are very simple; one reader was situated outside at one end of a corridor separating two three-story buildings shown in Figure 3.

Figure 3: The straight length of the corridor measures 600 feet

This setting proves important to the test of long range detection because it provides an environment that is prone to signal reflection and is moderately metallic while still allowing a clear line of sight detection of the tag. The straight length of the corridor measured 600 ft. As for the procedure, the reader was positioned as stationary at one end of the corridor and the tag moved directly away, continuously, until the detection of the tag stopped.

MSSI Results

In this experiment, real-time graphical information provided by MSSI software was used to identify the tag-under-test with unique identification code, 00010232. Although our team used the graphical information in real-time demo for validating their benchmarking results, it's important to emphasize that the MSSI system is not limited to providing data only in graphical representation. In addition to the real-time demo used in this experiment, the DART systems embedded software offers several other diagnostic tools including:

- Filtering raw output data by tag and data type,
- Enabling the Diagnostic packet feature,
- Enabling the P-data which helps the user assess why location data is not available for a particular tag event.
- The receiver test feature in the Diagnostic tab is another key feature for analyzing tag detection.

In our long range performance benchmarking, the concluded range of detection was measured at 107 meters, equating to 351 ft. Signal degradation for the MSSI tag seemed to have begun at roughly 300 ft with a refresh rate of 2-5 seconds. *However, the discussion with the vendor about range limitation revealed that LLNL team used the mid-gain antenna in this experiment which is one of the three antennas offered with Sapphire DART receivers. According to the vendors engineering team, with additional training on antenna planning distances, the range can be extended to the products advertised range of 600 ft.*

Figure 4 represents the graphical user interface of MSSI software for detecting the tag under test.

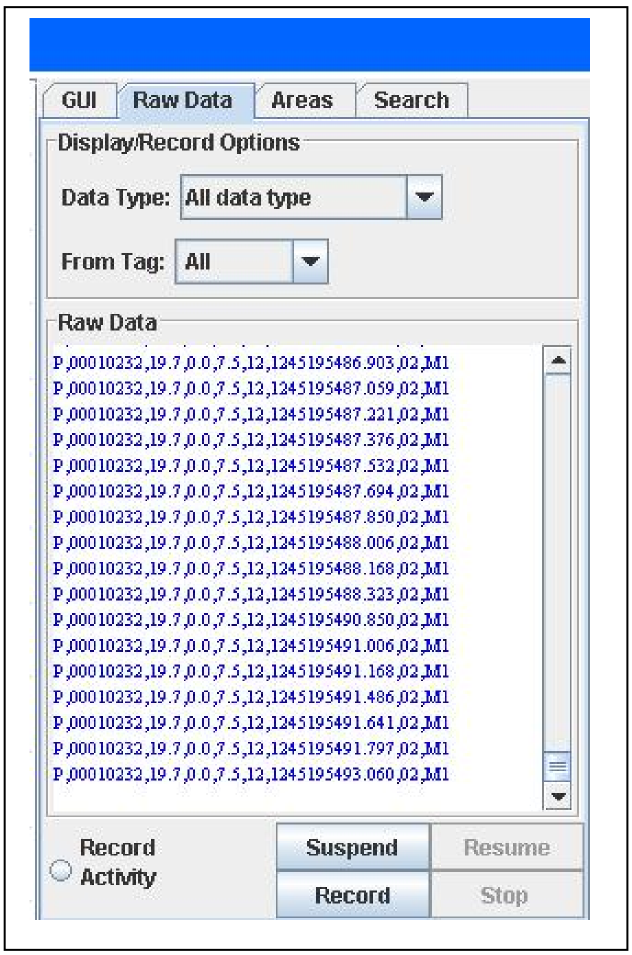

Figure 4: A GUI image of the MSSI firmware detecting tag number 00010232.

Ubisense Results

Similar to the MSSI experiment, in this test we also relied on the real-time graphical information to identify the tag-under-test with unique identification code, -000-079-091. In this case, the concluded range of detection was measured at 64 meters, equating to 210 ft which is a remarkable distance given the tag operates on a maximum power level of *1mW*. During observation, it seemed that the signal detection began to deplete at around 175 feet. After the 175 feet mark the refresh rate displayed on the GUI began to slow down to about 4-7 seconds. Figure 5 represents the GUI from Ubisense RTL system.

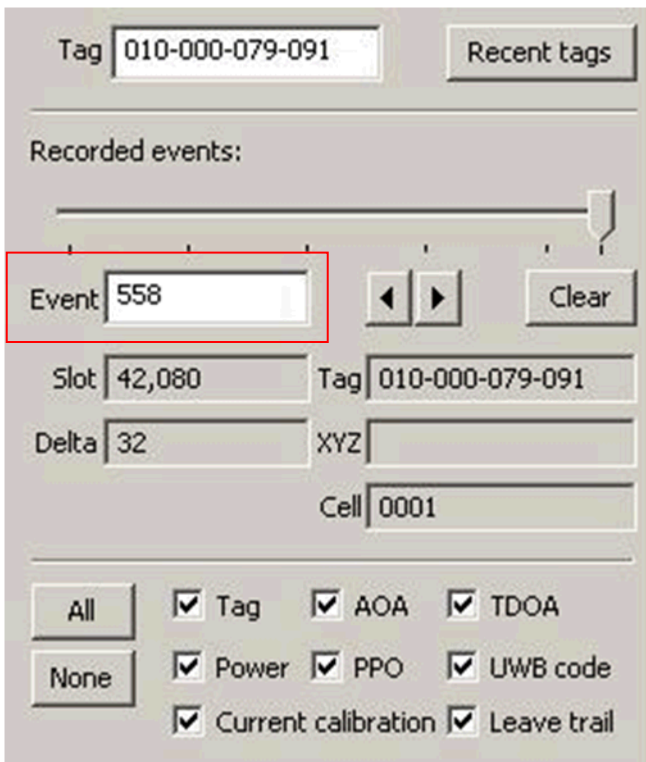

Figure 5: A GUI image of the Ubisense Site Manager detecting tag number 010-000-079-091. This data does not provide hard range data, just detection event logs.

In the above Figure, the GUI displays an “Event” (marked by red box) meaning that a tag signal was detected. When the signal ceases to produce Event logs, then it is understood that the tag is out of range.

Test II: Real Time Location (RTL) Accuracy

Fine resolution in locating objects is highly desirable in almost all asset tracking scenarios. In order to locate a tag, multiple readers have to detect the tags signal and triangulate its position based on received signal strength (RSS), time-of-arrival (TOA) or differential-time-of-arrival (DTOA), or angle-of-arrival (AOA) information. The nature of using short duration UWB signals in RTL systems brings the inherent advantage of fine resolution, since a 1 nanosecond pulse directly translate to 1 foot spatial resolution. Additional signal processing and filtering can add to the precision of UWB RTL systems. The purpose of this test is to evaluate the accuracy of locating objects using Sapphire DART and Ubisense RTL systems.

To illustrate the RTLS capabilities of the systems-under-evaluation, Both of the COTS UWB RTL systems-under-test use four readers, generally each placed in a corner of a rectangular area. In our benchmarking, a specific configuration, called "Star Configuration" (shown in Figure 6), of the readers has been implemented to maximize efficiency with respect to the logistical setup of the readers and the hub.

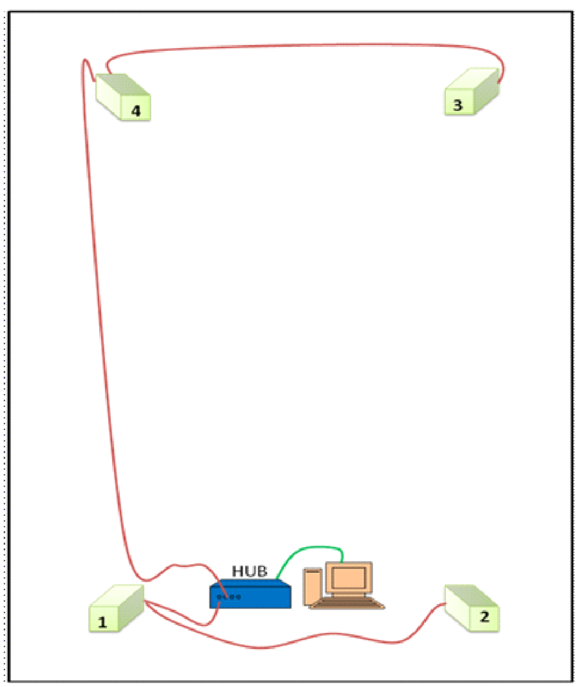

Figure 6: The Star Configuration. Only two readers are directly connected to the hub while the other two are daisy chained to the first two.

In our benchmarking the positioning test emulates a typical indoor asset tracking situation. Four readers were placed in each corner of a room measuring 20x35 ft at 7ft in height occupied with three desks and lab equipment, collectively occupying one third of the room's floor space. The tags were placed in random spots throughout the room, and their positions, shown by the GUI, were verified by their actual positions in the room. Figure 7 illustrates the test setup for indoor experiment.

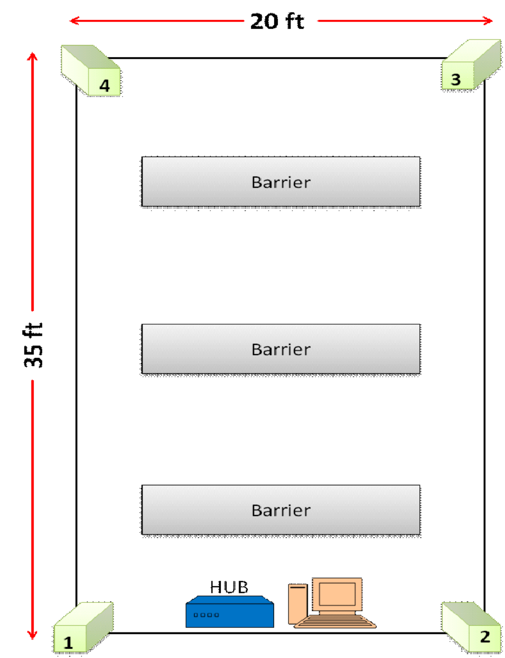

Figure7: Setup for indoor location experiments

MSSI Results

The indoor tag location test proved successful. All present tags were detected with a location resolution of *1* to *2 feet*. This means that the position of the tag determined by the readers deviates one to two feet away from the actual position of the tag. This resolution prevails in comparison to narrowband systems which usually have a resolution of 10 to 20 feet. The only instance when a tag was not located properly occurred when the tag left the plane of detection. Figure 8 shows the MSSI's graphical user interface for locating tags shown with their coordinates.

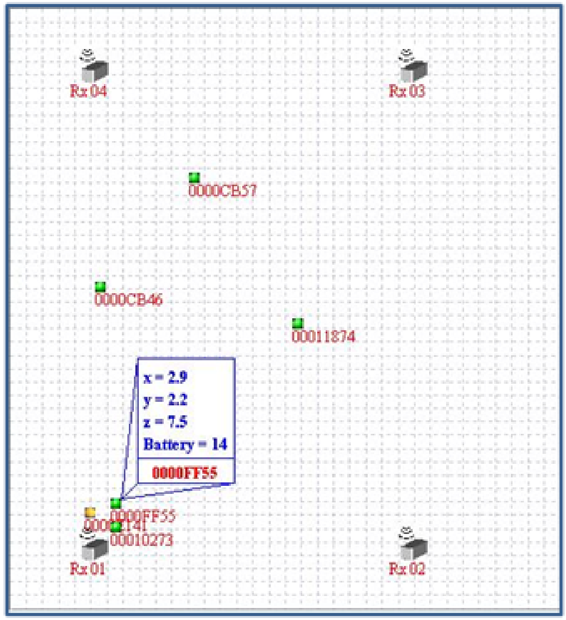

Figure 8: MSSI graphical interface showing the readers and the detected tags.

In this experiment we realized the importance of accurate coordinates entered is an important parameter to consider. A discussion with the vendor on location accuracy results revealed that the testing accuracy of the system with the GUI is difficult to quantify. According to the vendor "*The Sapphire DART Demo GUI displays tags based upon raw output data with the option of a running average but most users who want to run statistical analysis use the MSClient program offered on the technical support website. Tag to receiver line of sight ensures the most accurate TDOA position calculation so any condition that limits this physical configuration will degrade the accuracy of the position calculation but inaccurate coordinate data for the receiver infrastructure and reference tag may contribute as well*".

Ubisense Results

In this experiment, all the tags inside the evaluation area were detected with a location resolution of *6 inches* to *1 foot*. To clarify this result, this means that the position of the tag determined by the readers deviates from one half to one foot away from the actual position of the tag. What might cause a tag's larger resolution may be an improper adherence of the readers to their arbitrary coordinates or deficiencies in the code that calculates the tags' positions, being in real time. What would constitute an improper adherence to the set coordinates could be a small (on the order of inches) deviation of the measured coordinates from the coordinates programmed into the Ubisense Site Manager interface. Mistakes in coordinate calibration will cause the tags to “bounce” in the GUI due to recalculating its position with respect to the set coordinates and the actual coordinates. This bouncing effect is remedied by the software’s filtration feature. The position filter discovers an average position of the tag and “seeds” that position until the tag moves, where a new seeded average is calculated. Figure 9 and 10 are examples of the Ubisense graphical user interface showing the 4 readers and detected tags.

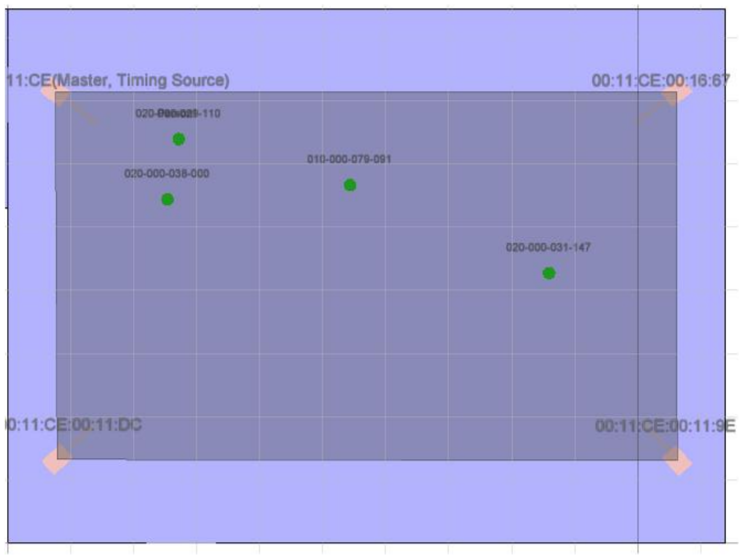

Figure 9: The Ubisense graphical interface showing the readers and the detected tags

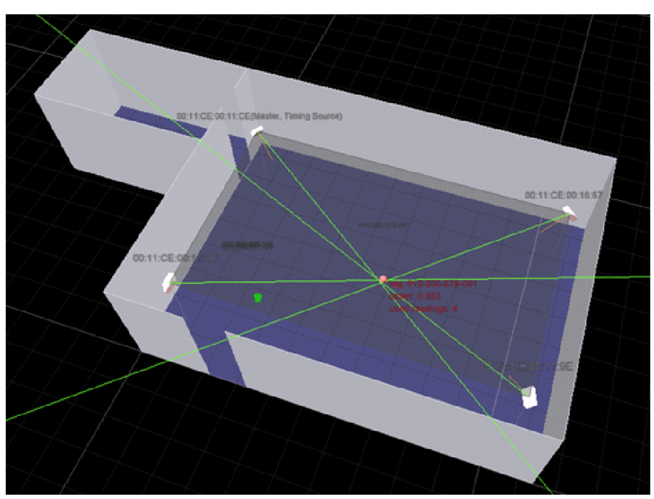

Figure 10: A 3D representation of the tag's location with AoA lines out of each reader

Test III: Tag on Metal

In most of the chain of custody applications, assets tend to be of a metallic construct of reside in metallic containers. However, propagation of narrowband CW radio signals in presence of metallic objects is vulnerable to skin depth attenuation, reflection, multipath interference, and signal coupling. UWB signaling could theoretically be a possible solution to the above mentioned problems due to its frequency diversity. To prove the theory on such promising characteristics of UWB signaling, we evaluated the two COTS UWB RFID systems- under-evaluation in the following scenarios:

1. Tag detection and location on a metallic object
2. Tag wrapped in metal (aluminum foil)

Part One: Tag Detection and Location on Metallic Object

The metallic objects used for this experiment will be a metallic container measuring 2.5x3 ft, shown in Figure 11. The tag is simply placed on the face of the container while readers remained distant, detecting and locating the tag.

Figure 11: UWB tag on metallic container.

MSSI Results

The UWB tag was detected and located as if no metallic object was present. There was no difference in functionality between the tag being on metal and not; the same signal integrity was achieved in locating a tag on a metallic and non-metallic object. Figure 12 shows the GUI display of location of 4 readers and tag detection and location on the metallic container.

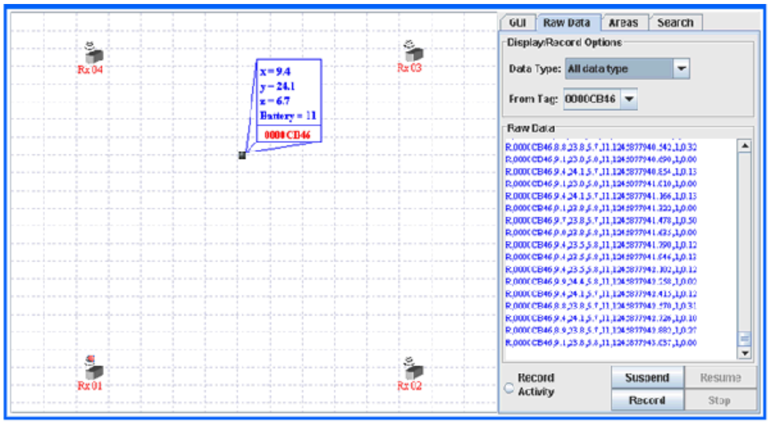

Figure 12: The GUI displaying the tag's detection on metal.

The accuracy of locating the tag was 1 to 2 ft, just like the results achieved form the experiment on non-metallic objects. As explained earlier, GUI is not an optimal method for finding the exact location of a tag. More accurate location information can be achieved by using the statistical analysis option offered by the vendor.

Ubisense Results

Similar to MSSI results there was no difference in detecting and locating a tag on the metallic object and previous experiments for non-metallic items. The reason for such results is that the AoA data for the tag on the metallic showed no difference between the data from the tag being tracked alone, not attached to any items. The UWB tag employed for this test is known as the Ubisense Asset Tag. This tag is to be placed on the horizontal plane of an asset with a fixed antenna position facing away from the material being tracked. The tag's antenna only propagates a signal in one majority direction so that one side of the tag may be attached to an asset while not allowing a structural perturbation against the UWB signal.

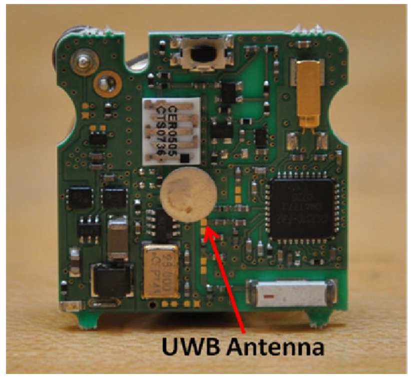

Figure 13: The Ubisense asset tag showing the single sided antenna

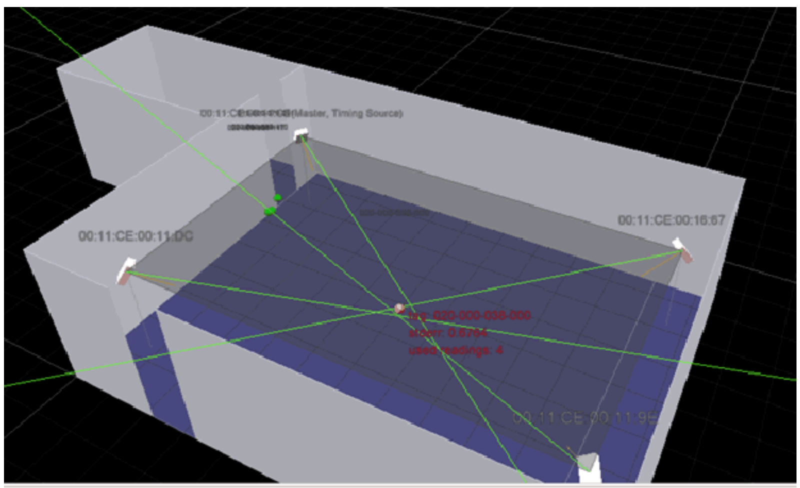

Figure 14: AoA GUI data showing the tag on a metallic object.

Part Two: Tag Wrapped in Foil

This test illustrates the advantages of pulsed UWB signals. When a tag is wrapped in aluminum foil small cracks and openings allow the signal to propagate. One hypothesis is that the cracks and openings could act like waveguides to help UWB signals propagate outside. To demonstrate this theory, a UWB tag was wrapped in a small sheet of foil and remained so until a signal has been detected.

Figure 15: A UWB tag wrapped in aluminum foil.

MSSI Results

The foil test also produced impressive results. The signal was detected as a normal one would be, but with a short delay of one to four seconds of initial signal acquisition. The reason for this delay is not exactly known to the testing team at LLNL, it might've been caused by some variable in the configuration or the manner in which the data was being monitored. Figure 16 represents the tag detection data in monitored in GUI.

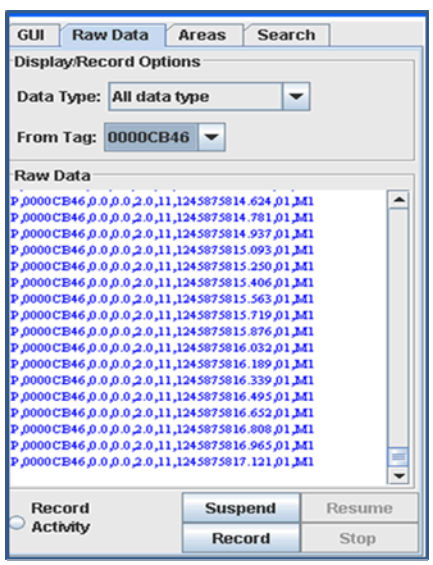

Figure 16: MSSI Tag detected in foil.

Ubisense Results

The Ubisense tag was also detected from inside the aluminum foil still with a short delay of one to four seconds of initial signal acquisition. The reason for the delay is not known at the time of writing this paper.

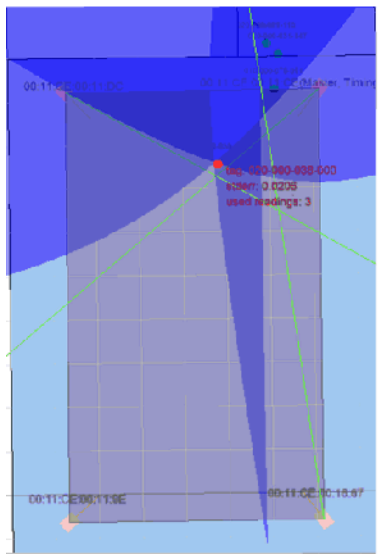

Figure 17: TDoA and AoA data showing the detected tag in foil [red].

It's important to emphasize that in both cases, MSSI and Ubisense, the fact that tags were detected from inside a foil wrap is very impressive and shows a unique capability of UWB signaling versus CW narrowband signaling in RFIDs. The MSSI system in this case could deal with very narrow cracks in the foil, where with Ubisense the tag detection became challenging when the cracks got finer. The reason for this achieved results is the transmit power level in their tags, where MSSI tag transmits 1 Watt, and Ubisense transmits 1 milliwatts.

V. Concluding Remarks

Our limited test cases showed significant success for both MSSI Sapphire DART and Ubisense RTLS systems. Each of the systems proved the advantages of using UWB signaling for detecting and locating objects in long range with fine spatial resolution especially on conductive materials. The impressive result for both systems was their long range detection capability. The first test generated a resultant effective range of 351 ft for MSSI at 1 Watt transmit power and 210 ft for Ubisense at 1 mWatt transmit power. This is a remarkable range factor for both systems considering the level of available transmit power and the overall system form factor. These systems would be very useful for usage scenarios including inventory control where the detection of presence and absence of metallic items (or items stored on metallic racks) with unique identification is required.

Tag location accuracy for the indoor plane with a small location area was successful in both systems. Location accuracy only deviated from 1-2 ft for MSSI and 0.5 to 1 ft for Ubisense. In a larger setting these deviation may be considered negligible and a discussion with the vendors revealed that the deviation could be resolved with accurate mapping of the coordinates as well as using additional features in their software. Again, in comparison with narrowband RTLS RFID systems, this level of accuracy in positioning objects is very impressive.

This success with the commercial UWB active RTLS system can provide an intermediate solution to the chain of custody process, however, for this specific applications longer ranges are required which none of the commercial UWB RFID systems can provide (at this time). Another limitation to the use of these systems in the chain of custody applications is the wiring that needs to connect the 4 readers in both systems. Based on our experience with the state-of-the-art commercial UWB RTLS systems, we conclude that a custom designed solution that offers the advantages of UWB signaling and provides longer detection distances with wireless readers is the ultimate solution for DOE chain of custody applications.

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