2018 ASEE Annual Conference & Exposition
June 24-27, 2018 Salt Palace Convention Center Salt Lake City, UT

Paper ID #22358

Simple, Low-cost IoT/UHF RFID-based Lab Equipment Identification and Tracking System

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Introduction

Radio Frequency Identification (RFID) is considered as the main tool to track and monitor objects identified with RFID tags in real time within local environment and even globally. The tracking and monitoring of objects with unique identifiers and transferring the acquired data over a network without human-to-human or human-to-computer interaction is called the Internet of Things “IoT”. Roselli et al [1] summarizes some of the most important technologies participating in the implementation of the IoT paradigm. These technologies are: Radio Frequency IDentification (RFID), Green Electronics (GE), Wireless Power Transfer (WPT) and Energy Harvesting (EH). Jayavardhana Gubbi et al [3], presented the important role of the RFID systems in enabling the realization IoT as the next revolutionary technology. Ouyamg et al. [4] implemented UHF RFID reader to meet the IoT data acquisition requirements. Chunling [5] promoted the application of RFID for logistics and supply chain managements. Developing the IoT using RFID is also discussed in [6]. Sara Amendola et al. presented the use of IoT utilizing RFID in medical health systems. A survey on the applications of RFID to bodycentric systems and for “gathering information (temperature, humidity, and other gases) about the user’s living environment is investigated” [7]. Design and the future applications of RFID as sensors is thoroughly discussed by Amin Rida et al. [8]

The aforementioned IoT topic was chosen by the course advisor as one of the capstone senior design projects to familiarize the students with state of the art technologies. Laboratory equipment such as function generators, oscilloscopes are often misplaced when moved between the various labs, consequently tracing their locations results in wasted valuable faculty and student time. A team of three senior Electronics Engineering Technology (EET) students were tasked to develop, in one semester and with limited budget, a basic yet smart IoT RFID based tracking system capable of logging the location and time history of any laboratory equipment.

The system was developed by integrating low cost state of the art devices, which includes the Raspberry Pi single board computer, low cost passive UHF (Ultra High Frequency) RFID readers together with industry standard EPC Gen2 passive tags, and a wireless local area network. The final integrated prototype system was tested to autonomously identify and track a number of tagged lab equipment as they were moved into or out the lab laboratory. The information collected was stored in a database and made accessible to the user via a web based graphical user interface. The test results of the prototype system indicated a successful autonomous identification and tracking of equipment movement in simulated scenarios. Several tests were also conducted to determine the system’s reliability, efficiency, and accuracy. These tests identified the overall performance limitations, which are mainly attributed to the low cost hardware, limited resources, and time constraint. However, with the developed skills and experience the system can be further developed and implemented on a larger scale utilizing higher quality hardware and devices.

The paper presents the project findings, their analysis, and the educational outcomes of developing a low cost and challenging state of the art system by undergraduate level EET students with limited practical experience. The involvement of students in such projects is utmost importance. It provides an excellent venue for the student to integrate the theoretical and practical knowledge gained during their educational period to analyze and solve real world problems.

What is IoT?

"Internet of Things (IoT) is a network infrastructure, linking physical and virtual objects through the exploitation of data capture and communication capabilities" [3]. The IoT system must have the ability to autonomously identify objects and relay their information through a wireless network which in turn is connected to the server and to the internet. The IoT system architecture is generally divided into three layers: the perception layer, the network layer, and the service layer (or application layer) [2][3].

- The perception layer, where all physical data is collected by various sensors technologies e.g. RFID systems and tags.
- The network layer, which provides data transfer capability; in this project a local area Wi-Fi network was utilized
- Service or application layer, where all the data are analyzed and the useful information is saved and made accessible e.g. through user interface

In the following sections the development of IoT layers and their integration into a porotype system will be presented as a proof of concept due to time and cost constrain. A team of three students were assigned to develop and integrate the three layers and implement a simple IoT system under the supervision of the advisor. One student was assigned as a team leader and his main task was develop the network layer and analyze the functionality of the reader and its control commands. The second student was assigned the task of implementing and testing the RFID sensors. The third student was assigned to develop the software for the service layers. The final system integration was performed by the team under the supervision of the advisor. Prior to the hardware and software integration of the system the following sub-sections introduce the functionality of the individual layers.

- **RFID Sensor System**

RFID is the perception layer sensor of the developed IoT architecture. The choice of the sensor is important to ensure accurate data collection. The two main system components of an RFID system are the reader, and the tags, which are attached to the items to be identified. The system of choice is the passive Ultra High Frequency (UHF) RFID system, which is characterized by its agility, relatively long range, very high read rates, and low cost passive tags. The passive tag, which is energized by the reader electromagnetic RF (Radio Frequency) field, is composed of an antenna, an integrated silicon chip that includes the basic modulation circuitry and a non-volatile memory. The RF carrier signal is transmitted by the reader (forward link) at the hopping frequency band of 902-922 MHz. When the RF field reaches the tag it couples with the tag's antenna coil and consequently an AC voltage is generated across the coil. This voltage is rectified to supply power to the tag. As the tag is activated it starts to transmit back the coded information stored in its memory (reverse link) to the reader, using backscattered modulation technique, where it is decoded and retrieved [8][9].

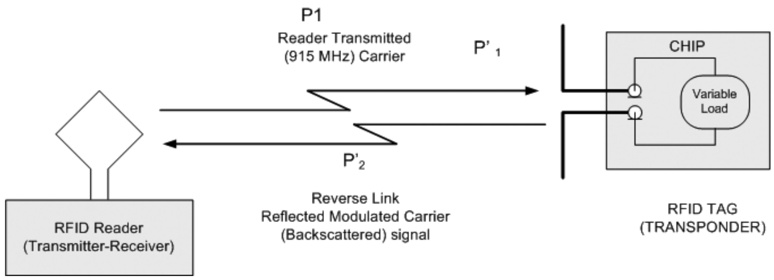

Figure 1, Concept of the passive UHF RFID system

Industrial type RFID readers are expensive, and due to the budget constraints, a cost effective RFID reader is required. However, there are important factors to be considered when choosing a suitable reader. Most importantly, the reader must be able to read and write to tags effectively at high rate and at a range of 1-10 feet. The reader of choice was the low cost LinkSprite Cottonwood UHF RFID reader, which is capable of powering one antenna only and adequate for the purposes of a low cost project. The Cottonwood RFID reader complies with ISO-180006C standards and is rated for a read range of 1-6 meters with a read time of less than 6 milliseconds. This prototyping style RFID reader, shown below in Figure 2, fulfills the project requirements and costs much less than commercial readers, which can range between $1,000 and $3,000.

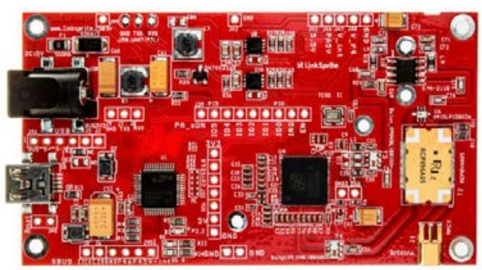

Figure 2, Cottonwood UHF RFID reader

Figure 3 Solid State Antenna

Figure 4, ALR-9611-CR antenna

Two other major components of an RFID sensor system are the reader antennas and the RFID tags. Two types of antennas were used, the first is a low cost ($10) antenna manufactured by Solid model SD_Ant_001 shown in Figure 3. The second type the Alien ALR-9611-CR antennas; a high quality 6 dBi antennas that cost $155 each, see Figure 4.

- **The Service System**

The service level system was developed by the first student. He made the choice of using single board Raspberry Pi computer, shown in Figure 5, based on his familiarity with the computer and the Linux operating system. The Raspberry Pi 3 has a 64BIT quad core processor with a 1.2 GHz clock speed and 1 GB of SDRAM clocked at 400 MHz. It has 40 general input/output pins, onboard Wi-Fi, onboard Bluetooth LE, utilizes a Linux based operating system, and costs $35. Its main role is to control the RFID readers, log equipment data when passes through a detection area, and host a web based user interface for tracking the current time and location of the equipment.

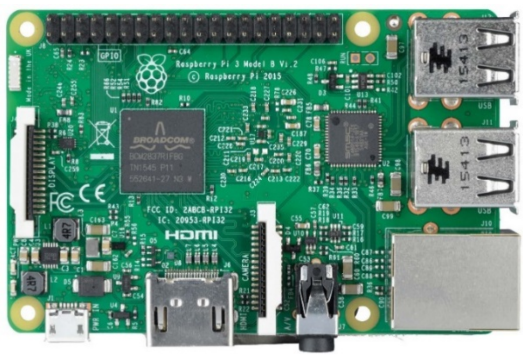

Figure 5, Raspberry Pi 3 Single Board Computer

The Network System

To avoid the required IT security measures placed on the University's wireless network a local area wireless network, using a single access point, was set up within the laboratory by the students. Each RFID reader is interfaced to a Raspberry Pi single board computer. The developed software on each Raspberry Pi controls the operation of each RFID reader and sends collected data to a database setup on the master Raspberry Pi. The master Raspberry Pi also has built in Apache web server used to host a web based graphical user interface. This allows users to access equipment location and other important information from any device connected to the local area network. Further details on the system is presented in later sections.

System development

The initial task was to control and monitor the RFID system, which was a developed as a team. To gain an insight into how the reader operates, an XCTU application software was utilized by the students. This is a free multi-platform application designed to enable developers to interact with RF modules through a simple-to-use graphical interface. The XCTU enabled verification of Cottonwood RFID reader operation including the send and receive commands, acquire reader information such as the firmware version and hardware version, and change its operating settings such as frequency and read time. In addition, the vital RFID reader control commands were determined, which include the power level control commands, the read/write tag commands, select tags, and set reader operating carrier frequency.

Based on the above, the second task was to control the cottonwood RFID reader using the Raspberry Pi 3 single board computer and establish a gateway where the Raspberry Pi can control the RFID reader. To achieve this the Cottonwood RFID reader was interfaced to the Raspberry Pi to establish serial communication between the two devices, see Figure 6. Application Program Interface (API) written by GuyLewin was utilized to test the ability of the Raspberry Pi to control the Cottonwood RFID reader [10]. Acquiring the ability to control, write to and read tags through the established the communication gateway between the Cottonwood RFID and Raspberry Pi facilitated the development of the fundamental system structure.

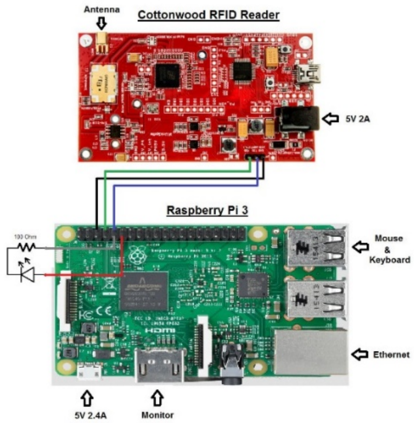

Figure 6, Raspberry Pi and Cottonwood RFID interconnections

IoT System Integration

At the service level the Raspberry Pi 3 single board computer was used, a powerful yet affordable standalone Linux based computer. As a proof of concept, a prototype system was developed by the students to track equipment movement within a single laboratory; Figure *7* below, shows the proposed integration of the constituent parts of the system. Each RFID reader is directly connected to a Raspberry Pi single board computer and communicates to a central hub via a wireless local area network. Software developed on Raspberry Pi controls the operation of each RFID reader and sends collected data to a database setup using the master Raspberry Pi. The master Raspberry Pi contains an Apache web server used to host a web based graphical user interface. This allowed the users to access equipment location and other important information from any computer linked to the local area network.

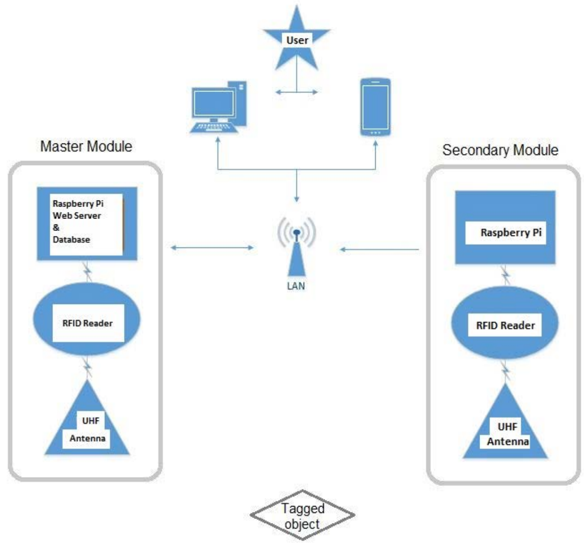

Figure 7, System Hardware Integration

Design Challenges

Concurrently with the senior design project the students attended the Radio Frequency (RF) Effects and Measurements course. The course helped them to understand the fundamentals of RF and introduced the various RF antennas and the radiation measurements techniques. They were instructed by the advisor on RFID concepts and the problems associated with their real world applications. Various operating conditions can affect UHF RFID system performance. For the passive tag to activate and successfully send its message back to the RFID reader, it must first receive enough power from the RFID reader transmitted signal. Other conditions that can interfere the communication link between the reader and a tag and impede its performance include:

- Distance between RFID reader antenna location and the passive tag
- Angular orientation of passive tag with respect to RFID reader antenna
- RF noise interference
- RF signal reflections from ground or walls
- RF signal reflection of metal surfaces to which the RFID tags attached

Tag Performance Evaluation

The following RFID tags were tested by the students under guidance of the advisor to determine the most suitable tag to be used: The Alien Technology Squiggle Tag, The Alien Technology ALN-9540-WR 2x2, the Alien Technology ALM-9554-WR Inlay, Omni-ID, and Omni-ID Max Rigid, a metal tag coated in silicon, Key Fob Tag, and Mango Key Fob tag. Three tests were performed to validate the tags' performance, their limitation and suitability for the intended application. [9]

- **Read vs. Distance**

It is vital that the reader antenna transmit its signal with adequate power level to activate the tag to retransmit. The tag backscattered signal power must be at a level detectable by the reader antenna to interpret the tag data. Since the electromagnetic (EM) wave power density is inversely proportional to the square of the distance traveled, it is expected that the rate of reads will decrease as the distance between the tag and the reader antenna increases. To evaluate the performance of the above-mentioned tags, the reader antenna and the tag were mounted on test fixture developed by the students, as shown in Figure 8. Using the integrated Raspberry Pi/RFID reader modules, a Python script was written by the students to measure and record the accumulated number of reads during 10 seconds intervals. For each type of tag, a set of reads/sec were recorded at incrementally varying distance between the tag and the reader antenna, see Figure 9. The reads/second data gave an indication of the Received Signal Strength Intensity (RSSI) each time a tag is scanned by the reader. It was determined that he squiggle tag was the best choice for the project since it had the longest range (120 cm) even it has less sensitivity than the rectangle tag (100 cm).

Figure 8 Distance test setup

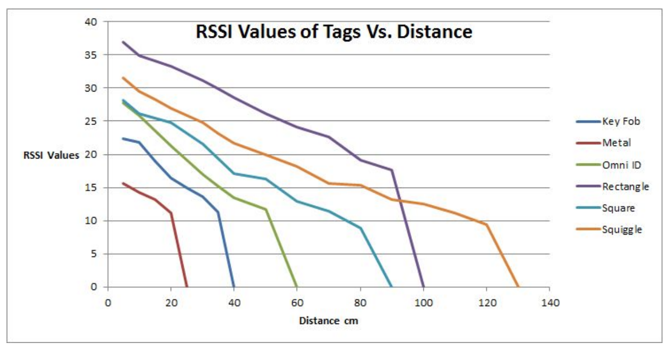

Figure 9 Distance test graphs

- **Tags Performance on Metal Surfaces**

The tag under test was attached to the equipment conductive metal surface and the previous experimental set up “RSSI vs. distance” was utilized to determine the tag’s RSSI sensitivity. From the results shown in Figure 10, it was concluded that the metal tag (5 cm range) and the Omni-ID tag (10 cm range) were the only activated tags when attached to a metal surface. These two tags are expensive and their ranges are too small, consequently a work around was necessary to modify a low cost tag to increase its read range performance when used on a metal surface. A similar work around technique discussed in [9], utilizing the squiggle tag with modified dielectric layer, was used.

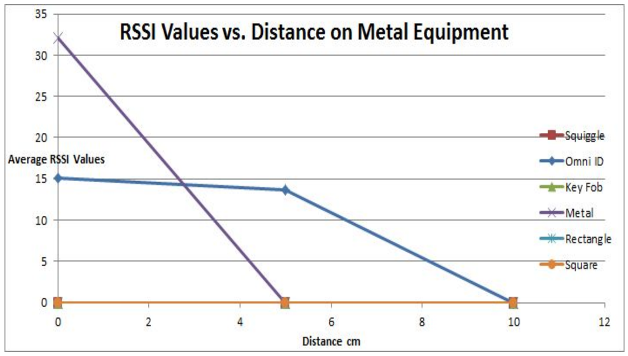

Figure 10, Tag on metal performance test

- **Modified Tag Technique**

The squiggle tag has the best range, but will not operate when attached to a metal surface. When placed on a conductive surface the RF signal power is attenuated causing the backscattered signal power to be considerably reduced. However, with proper spacing between the tag and the metal conducting surface the RF signal power in the vicinity of the tag can be preserved and harnessed by the tag. The spacer material choice and its thickness are important. Its dielectric properties can affect the propagation speed of the incident UHF RF signal thereby changing its wavelength and causing a mismatch at the tag antenna. Similar to what is suggested in reference [9] a spacer made from a chalkboard eraser (acrylic felt material), was attached to the squiggle tag as shown in Figure 11 below. The results shown in Figure 12 indicate a considerable improvement in squiggle tag sensitivity, 50 to 70 cm range as compared to no activity without a spacer, when using varying dielectric spacer thickness.

Figure 11, Squiggle Tag with a spacer

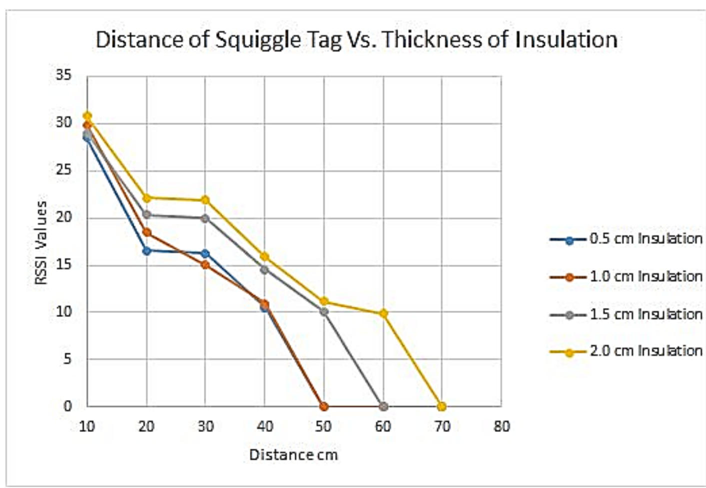

Figure 12, Squiggle tag RSSI with different spacer thicknesses

- **Tag radiation Pattern and Polarization Tests**

Analysis of reader and tag radiation patterns properties are vital for determining the positional orientation of the reader and tag antennas to achieve an efficient detection. The Squiggle tag radiation pattern and its polarization sensitivity were determined by the students, see Figure 13 and Figure 14.

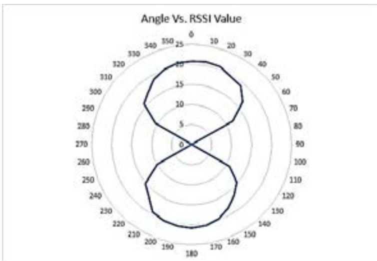

Figure 13, Squiggle Tag Radiation pattern

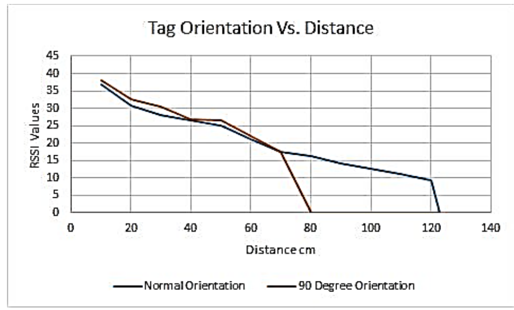

Figure 14, Squiggle Tag Polarization Test

Reader Antenna Testing

Two antennas were tested; both were set up to determine the maximum range that it could read the squiggle tag. The Alien antenna was selected since it was able to read the tag at a distance of over 120 cm, and the Solid antenna was able to read the tag up to a distance of 45 cm.

The proper in-lab placement and orientation of the RFID antenna is vital to avoid distortion of its radiation pattern. Consequently, the Alien Antenna in-lab radiation pattern was determined by the students using a LABVOLT antenna test system they were trained to use in the RF course. The radiation pattern of the antennas is shown in Figure 15 and Figure 16. The effectiveness of the radiation pattern was determined by two parameters, the hall-power beam width and its directivity.

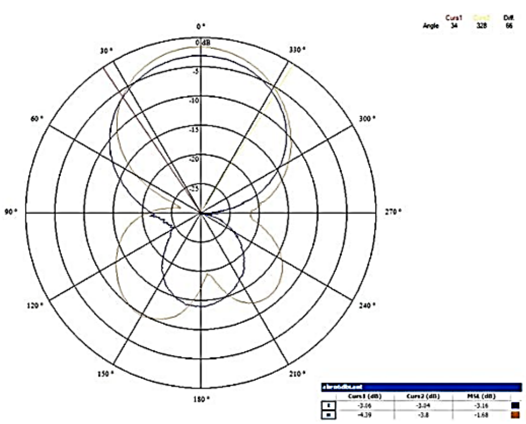

Figure 15, E & H field radiation pattern

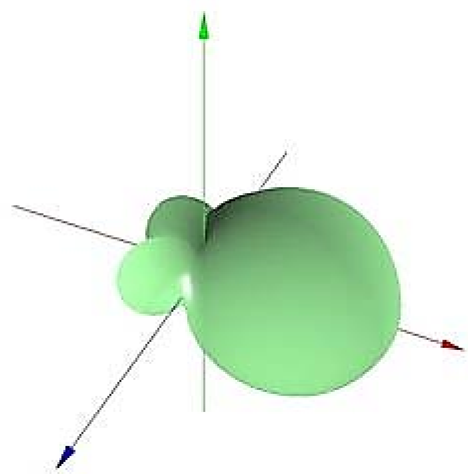

Figure 16, 3D Radiation Pattern

From figure 14, the half power beam width was calculated:

$$HPBW = 34° - (-32°) = 66°.$$

The directivity D of the antenna radiation pattern was calculated:

$$D = 26000/ (HPBW_E * HPBW_{H)} = 26000/ (66*66) = 5.97$$

Experimental System Model

The experimental model was developed by the students after consultation and discussion as a team together with advisor. A typical model to track an equipment within a lab requires at least two reader antennas be placed at the lab entrance; each antenna is controlled by a Raspberry Pi/Cottonwood Reader. With one antenna located inside and one outside the entrance, the tagged equipment will be identified twice when passing through the entranceway. The order in which each antenna reads the tag determines whether the equipment has entered or exited the room, see Figure 17. As a proof of concept an experiment, using the two Raspberry Pi/RFID readers and antennas, was set up within the lab to replicate the equipment tracking requirements as shown Figure 18. When Antenna 2 (named inside antenna) in Figure 18 reads the tagged equipment after being detected by Antenna 1 (named outside antenna), then the equipment is logged as having entered the room. If Antenna 1 identifies the tagged equipment after Antenna 2, then the equipment is logged as having left the room.

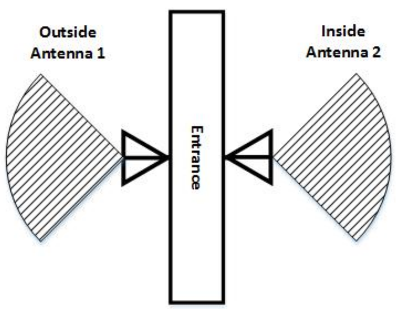

Figure 17, Two Room Setup

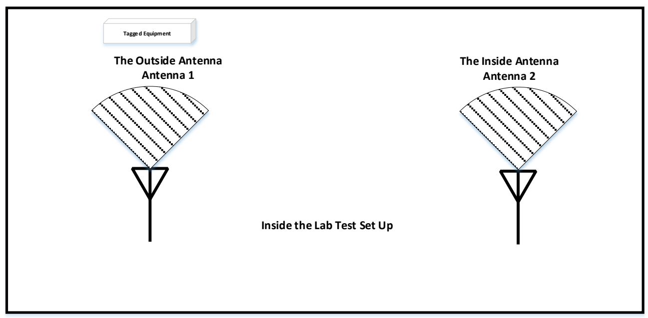

Figure 18, One Room Set-up

System Software Development

The system software was developed by the students using Python. Their basic knowledge of Python was important; they have already attended a Python language course during their program of study. They further developed their skills utilizing Python for system monitoring, control, and database management during their senior design project development. The developed system is designed to be modular and expandable. At the core of the design is a central hub consisting of a master Raspberry Pi which stores all data logged by each RFID reader connected to the system, and also hosts the web based graphical user interface. Each additional Raspberry Pi will simply control additional Cottonwood RFID readers and relay equipment location and time information to the master Raspberry Pi. To accomplish these tasks, the master Raspberry Pi was set up as a basic web server and the website was built using Django, a web framework software module written in Python. A table, “location_roster”, was developed using Django to store the tagged lab equipment information; Figure 19 below shows the structure of the table “location_roster”. Some fields are static, but “location”, “direction” and “timestamp” are dynamic and updated in real time when equipment passes through a detection area while entering or leaving a room. In addition, a table named “location_history” was developed to keep track of past location and time of previously detected equipment.

id	epc	model_type	kind	bloom_id	description	entry_date	location	direction	timestamp	assigned_location
4	e2003411b802011029333303	GPC-3030D	Power Supply	12345	Currently used to power master Raspberry Pi	2016-11-17 22:05:58	G-31	Exiting G-31	1480978893	G-31
5	10011002100310041005l870	Agilent E4420B	Oscilloscope	20126	Oscilloscope at lab bench in G-20	2016-11-17 22:39:52	G-31	Leaving G-31	1481143194	G-20
6	deadbeefcadefeed12347892	Agilent E4420B	Oscilloscope	20154	Oscilloscope at lab bench in RF lab	2016-11-18 21:02:08	G-20	Exiting G-31	1481153177	G-31
7	e2003411b802010953314083	HP EliteDesk 800 G1TWR	Computer	109408	HP desktop in back of the RF Lab	2016-11-19 23:51:35	G-31	Exiting G-31	1481045568	G-31
8	e2003411b802010953314084	HP Laptop	Computer	110031	n/a	2016-12-06 17:31:35	G-31	Entering G-31	1481148919	G-20
9	e2003411b802011029333376	Agilent 33220A	Function Generator	93	20MHz Function/Arbitrary Waveform Generator	2016-12-06 17:57:31	G-31	Entering G-31	1481047526	G-31

Figure 19, Location Roster Table Structure

Each Raspberry Pi controlling a Cottonwood RFID reader communicates to the database using a Python script. As a proof of concept, two separate Python scripts were developed; one script was written to test the system's ability to monitor equipment as it moved from one lab to another. Each time the equipment is scanned at a particular location, the "location" field in the database is updated with that current time and location. One script was written to test the system's ability to monitor equipment as it transported from one lab to another. Each time an equipment is scanned at a particular location, the "location" field in the database is updated with that location information. When the equipment leaves the location, the database information will not be updated until scanned by another RFID reader as it enters its destination. The second Python script was written to monitor if equipment is entering or leaving a lab by updating the database field "direction". Both scripts do essentially the same task. The only difference lies within which fields in the database are updated when a tag is scanned. Figure 20 below shows the process flow of the Python scripts.

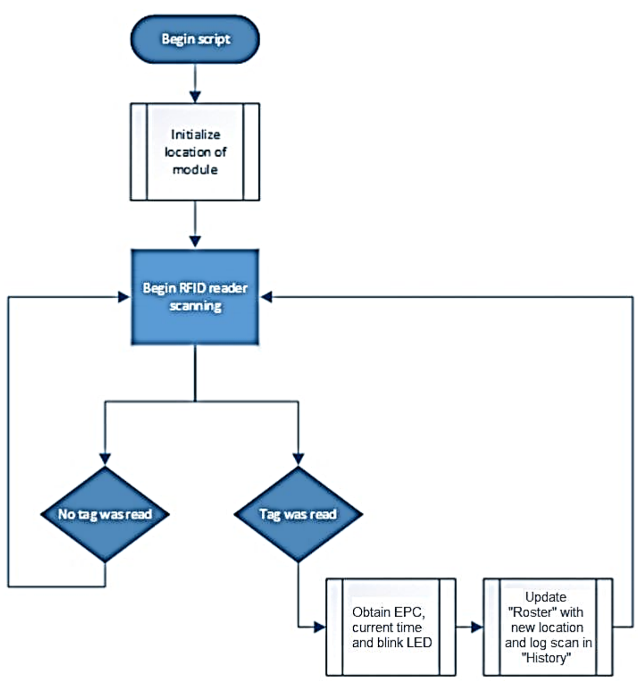

Figure 20, Python Script Process Flowchart

As the script starts, a few parameters are initialized to denote the location of the equipment monitoring modules, “Raspberry/RFID”, and then decide whether the reader recognizes an RFID tag or not. First, a function within the API is called to initiate an inventory scan. At this time the RFID reader starts briefly scanning for tags. If nothing is read, another inventory scan is initiated. If a tag is read its EPC code is recorded, the current time is set, and a connection to the MySQL database is opened. The script then updates the location and timestamp fields in the table “location_roster” associated with the unique EPC code of the scanned equipment. It also logs an entry in the table “location_history” with the EPC code, time and location of the scan. Finally, the database connection is closed, and the while-loop restarts scanning for another RFID tag to read.

User Interface Development

The graphical user interface was developed using the Django Framework, see Figure 21. Django is a free and open source high-level Python Web framework that encourages rapid development and neat, pragmatic design.

Figure 21, Django Admin Login

The entire web site was created using basic HTML scripts. The use of HTML in most of the templates extended to basic tags such as headings, paragraph, divisions, unordered lists, anchors and href links, forms, inputs, buttons, and select. Despite the students’ limited experience as graphic designers they managed to give the website a little graphical upgrade and made use of the Django CSS template file and incorporated it into the site as the main template.
Overall the students were pleased with the final web design and most importantly with how the data was displayed.

System Evaluation

The advisor required the students to test and evaluate the integrated system performance. A scenario, shown in Figure 18, was approved and implemented by the students utilizing two antennas placed across the lab from each other. To determine the percentage of successful reads, a tagged equipment was transported five times pass the two reader antennas’ line of sight. The number of times the equipment was detected was determined from the data base log. A 100% success rate means that the equipment was successfully logged every time it changed location, the results of these tests are shown in Table 1. The tracking of three types of equipment were tested using a one layered tag; a function generator, a laptop, and an oscilloscope. The tracking of the function generator was tested again using four layered tags attached on each side. Each test was performed with a clear path i.e. the equipment tags are within the Line of Sight (LoS)of the antenna radiation field, and an obstructed path i.e. equipment tags are not in the LoS.

Table 1, System Level Analysis

	Location:	Conditions:	% Success
Function Generator (1 insulated tag)	Next to Antenna	Clear Path	100
	Center of Door	Clear Path	100
	Center of Door	Obstruction	10
	Away from Antenna	Clear Path	30
	Away from Antenna	Obstruction	0
Function Generator (4 insulated tag)	Next to Antenna	Clear Path	100
	Center of Door	Clear Path	100
	Center of Door	Obstruction	20
	Away from Antenna	Clear Path	40
	Away from Antenna	Obstruction	0
Labtop (1 insulated tag)	Next to Antenna	Clear Path	100
	Center of Door	Clear Path	100
	Center of Door	Obstruction	0
	Away from Antenna	Clear Path	20
	Away from Antenna	Obstruction	0
Oscilloscope (1 insulated tag)	Next to Antenna	Clear Path	100
	Center of Door	Clear Path	100
	Center of Door	Obstruction	20
	Away from Antenna	Clear Path	100
	Away from Antenna	Obstruction	0

A table similar to the one shown in Figure 19 was successfully generated while tracking the equipment as they were moved between antenna 1 and antenna 2 (Figure 18). Based on the test results analysis, the following important procedures need to be followed to ensure a reliable tracking of equipment:

- The tag of choice is the modified squiggle Alien UHF RFID tag with the layered material, which is the most suitable for equipment with metal chassis.
- Multiple tags may be required for one equipment to ensure 100% detection
- While transporting the tagged equipment the user must ensure that the tags are within the LoS of the RFID antenna radiation field when they leave or enter a room.
- To increase the system reliability 4 antennas can be used, 2 on each side (the entrance and the exit) of the lab door.

A suggestion for future implementation of the system within the department is shown in Figure 22

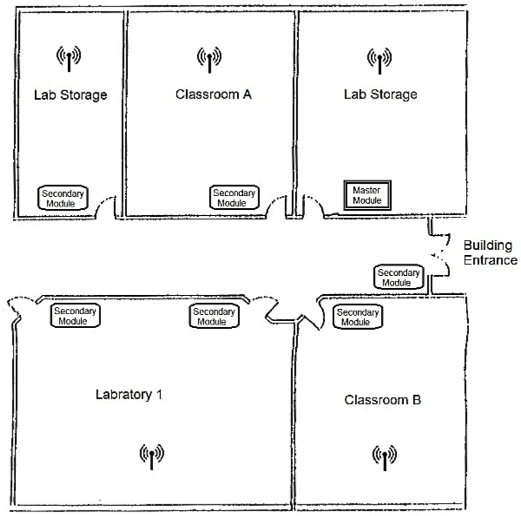

Figure 22, Suggested future system deployment diagram

Educational Outcome

The involvement of students in developing a state of the art technology system is of utmost importance. It provided an excellent venue for the students to integrate the theoretical and practical knowledge gained during their educational period to analyze and solve real world problems. In this project:

- The students utilized an evolving state of the art technology to develop and implement an IoT system.
- They were confronted with the practical complexity of RF signal propagation, and used their knowledge to provide a successful solution.
- They learned the theory of RFID system, gained hands-on experience on its practical applications, and realized how a seemingly simple operational configuration can have considerable effects on the reliability of the system.
- Learning the theory of UHF RFID tags and how they operate they innovated effective solutions using a low cost RFID reader and tags that parallels the efficiency of an industrial relatively systems.
- Involving in a state of the art project made the student think like an engineering technologists, they did not only learn how a sophisticated system operated but also learned how to analyze the problems associated with RF systems operations, signals, and their effects.
- Utilizing their computer programming and mathematical knowledge, they further sharpened their skills in developing various programming and data base techniques, which not only acquired and analyzed the data but also controlled the process and provided vital information through a simple informative user interface.
- They developed a decision based method and provided a simple yet effective reliability analysis method to justify the outcome.
- They learned that a well-planned project management and distribution of tasks between the team members are vital to the success of any project. The tasks were divided between three

students, one tasked with RF analysis, one with software development, and the leader was in involved in both to ensure successful coordination and system integration.

Conclusive Remarks

A basic autonomous IoT/UHF RFID Tracking System was developed, the design process was challenging and the development of the initial stages of the project was particularly difficult for the students. They had no previous experience working with RF systems or RFID technology and had no prior knowledge of any of the hardware components. Their Python programming and database software skills were limited. Despite the challenges, the students persevered and overcame almost all the encountered problems. Throughout the process the students utilized a variety of engineering skills that ranged from testing and analyzing to developing new ideas to accomplish their objectives. They broadened their knowledge, gained during their undergraduate years, by teaching themselves new skills, especially in the areas of RF communication, and computer science. As a result, this project provided the students with a valuable opportunity to test their skill sets to analyze and solve real-world problems. They were proud of their accomplishment and satisfied with the final outcome. One of the students' final comments was: "As we move forward we are encouraged by the outcome of this project. We believe it will serve as a reminder that we were capable of solving complex problems and validate one semester's worth of hard work".

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