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16. Abstract

The purpose of the augmented Speed Enforcement (aSE) project was to detect and warn speeding vehicles in a work zone and provide warnings to work zone workers. The system developed by Montana State University consists of 28 orange traffic drums (called smart drums or sDrums) that were positioned adjacent to the orange cones marking the work zone lane closure. When the system detects a speeding vehicle approaching, it synchronously flashes the orange lights on top of the drums, warning the driver to slow down and the workers of a speeding vehicle. If the vehicle speed is above a set trigger speed, the system activates a pager system that warns the workers of the speeding vehicle. The sDrum system used a Digi XBee adaptor mesh radio for communications which is the focus of this report. Basic antenna pattern and range measurement were performed to validate the published range. The outdoor range was measured as 200 feet. That is much less than the 1 mile outdoor range published by the manufacturer and even less than the 300 feet indoor published range. This report contains the full results of the radio tests performed.

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Radio Communications for the Western Transportation Institute's augmented Speed Enforcement Project

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A report prepared for the

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Washington, DC

Final Report

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Executive Summary

The purpose of this project, augmented Speed Enforcement (aSE), was to detect and warn speeding vehicles in a work zone as well as providing warnings to work zone workers. The project consisted of two systems, one provided by California PATH at UC Berkeley and the other developed by the Western Transportation Institute (WTI) of Montana State University. Either can be deployed independently or they can be deployed together.

The purpose of the WTI project was to design, assemble, and real world test a deployable smart drum system for rural area work zones. The original concept was to develop a warning system for work zones that would detect vehicle speeds and track a speeding vehicle using warning lights mounted on traffic cones. The warning lights would warn the work zone workers and the speeding driver. Due to the project schedule being compressed and the difficulty of the task, the tracking requirement was postponed; the warning lights were designed to simply flash synchronously upon detection of a speeding vehicle.

With the assistance of the California Department of Transportation (Caltrans), the pilot system was deployed for four weeks near Los Banos, CA to evaluate the effectiveness and deployability of the sDrum system.

The sDrum system used a Digi XBee adaptor mesh radio for communications which is the focus of this report.

The XBee radio specification did not include an antenna pattern so a basic pattern measurement was performed. A range measurement was also performed to check the validity of the published range. Since limitations of the mesh radio determine the complexity of light patterns that can be performed reliably a few simple light patterns were tested.

Measuring the antenna pattern showed an irregular oval shape with two opposing shallow nulls. The oval shape is advantageous since its long axis was in line with the drums, improving range.

Measuring the radio range at 10 and 20 feet drum spacing showed it to be approximately 200 feet. That is much less than the 1 mile outdoor range published by the manufacturer and even less than the 300 feet indoor published range.

Finally there are similarities between the outdoor and the lab light pattern test results. In both the outdoor and lab results, lighting pattern quality decreased significantly with the size of the XBee network. In addition, shorter delays between commands caused the number of successful patterns to diminish. This particular factor had a greater effect on the outdoor XBee network than the lab network. A possible explanation could be that the mesh delays receipt of the packet by the XBee; consequently there must be longer delays for successful lighting patterns with mesh networks.

1. Background

Speeding is a primary factor contributing to major injury and fatality crashes in rural area highway work zones. Automated Speed Enforcement (ASE) detects speed violators and automatically processes speeding citations, but there can be legal barriers for some jurisdictions to implement ASE. Augmented Speed Enforcement (aSE) which is based on similar technologies utilizes the information about detected violators to notify an onsite California Highway Patrol (CHP) officer to manually identify and stop the speeder. The development of aSE was conducted with funding from the Research and Innovative Technology Administration (RITA) in the United States Department of Transportation.

As shown in Figure 1, the aSE system consists of two systems developed by two research teams with both systems operating in the same work zone. One system developed by California PATH at UC Berkeley has a camera with built in radar to detect and photograph the license plates of speeding vehicles. Upon detecting a speeding vehicle the vehicle's license number and speed are recorded and displayed on a changeable message sign. The same data is transmitted to a CHP Officer located in the work zone. The CHP Officer will use his radar system to verify the vehicle speed and determine whether or not to issue a citation.

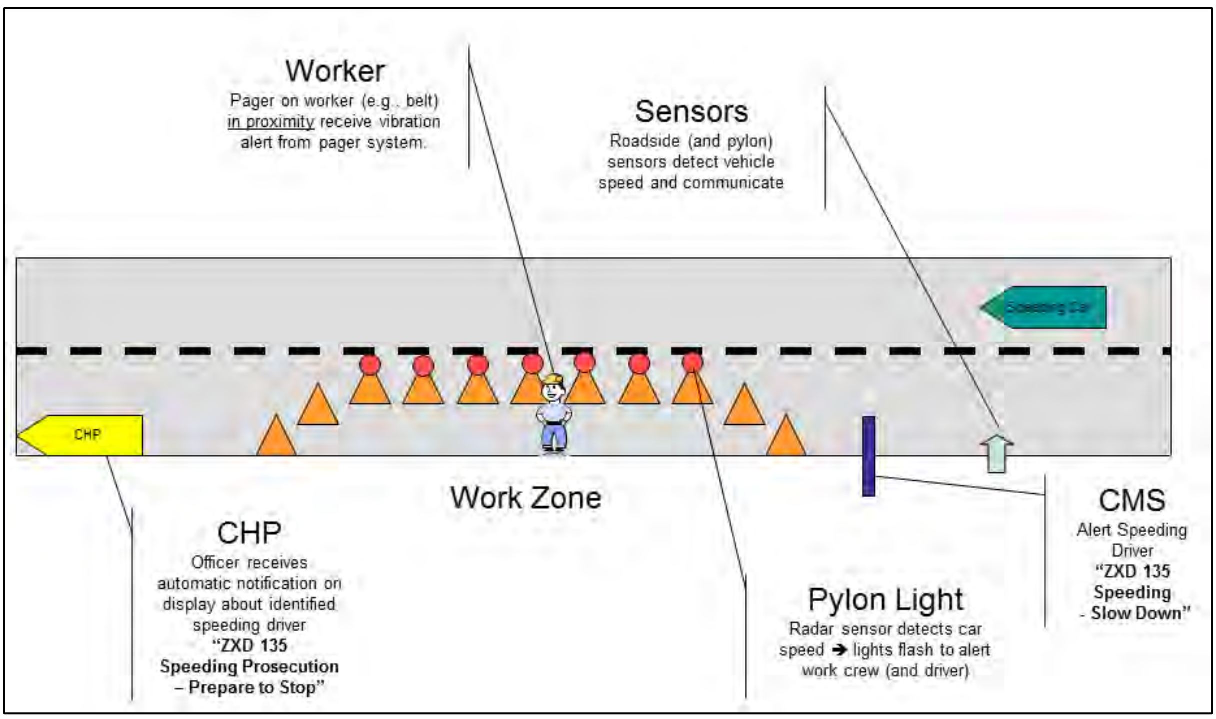

Figure 1: aSE System Diagram

The second system was developed by the Western Transportation Institute (WTI) of Montana State University. It consists of 28 orange traffic drums that are positioned adjacent to the orange cones marking the work zone lane closure. When the system detects a speeding vehicle approaching, it synchronously flashes the orange lights on top of the drums, warning the driver to slow down and the workers of a speeding vehicle. Also, if the vehicle speed is above a pager set speed, the system triggers a pager system that warns the workers of the speeding vehicle. The WTI system was dubbed the smart drum (sDrum) system.

The sDrum system architecture is shown in Figure 2. The master drum is the control center of the system and receives vehicle speeds from its internal radar and flashes the lights and triggers the pagers depending on the vehicles speed and the controller's configuration. The master drum communicates with slave, logger, and pager drums through a XBee (ZigBee) mesh radio network. Logger drums solely log vehicle speeds although they contain the same components as the master drum. The repeater drum repeats transmissions received from the pager transmitter, extending the range of the pager system.

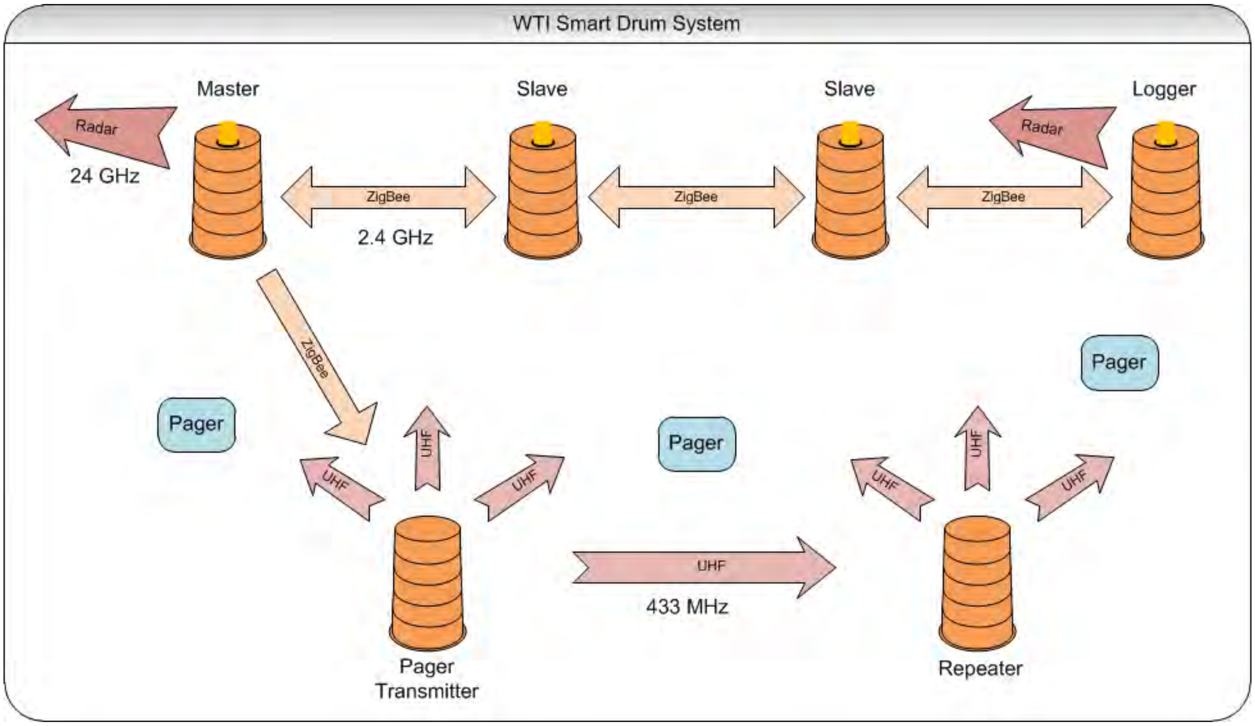

Figure 2: sDrum System Architecture

The full sDrum system includes one master, 24 slaves, three loggers, one pager and one repeater drum. The master is at the beginning of the line and a logger is at the end of the line. The other two logger drums are equally spaced between the master and the last logger drum. Eight slaves are deployed between the master and logger drums and between the other logger drums. The pager and repeater drums are deployed on the shoulder of the roadway, positioned to provide the best work zone coverage.

2. Introduction

This report focuses on the Digi International XBee-Pro adaptor radio chosen for the sDrum system communications. The radio is small, lightweight, and inexpensive. Other key specifications are RS-232 serial communication, low power consumption, 12V dc powered, mesh protocol capable, short range, and a wide operating temperature range. The radio's range performance is listed as 1 mile outdoor line-of-sight but no antenna pattern is provided.

Initially WTI measured the XBee radio's basic antenna pattern and the radio's range but delayed testing the radio's latency with complex light patterns until after deployment.

For deployment the sDrum warning lights were synchronously flashed because it was the simplest pattern to implement and time was short. After returning from California the feasibility and applicability of various light patterns was explored. Testing was conducted to determine the ability of the sDrum system to produce various light patterns which, as expected, is mainly limited by the XBee radios.

This document details WTI's XBee mesh radio testing, including the additional light pattern test results. Note this material is included in WTI's aSE Final Report.

3. Design/Development

For the initial system design cone spacing was 10 feet to enable three lights to track individual speeding vehicles. Precise and continuous tracking of individual vehicles was determined to not be technically feasible within the project timeline prior to testing and deployment. Moreover, it was recognized that there may be an advantage to flashing all lights at the same time as it increased awareness of all drivers and also increased the conspicuity of the alert to workers (and officers) in the work zone that a speeding vehicle was present in the traffic stream. Thus, the prototype was developed with a strategy of flashing all lights (synchronized) when any speeding vehicle was detected. The issue of technically feasible lighting patterns was revisited after the deployment phase of the project. See section 4.3.

3.1. Radio

The Digi International XBee-Pro radio shown in Figure 3 is small, lightweight, and inexpensive. Other key specifications are RS-232 serial communication, low power consumption, 12V dc powered, mesh protocol capable, short range, and a wide operating temperature range.

Figure 3: Digi International XBee - Pro Radio – WTI Photo

The RS-232 serial communication provides a common computer interface. Since 10 foot cone spacing had been initially specified a short range radio would minimize interference issues and power consumption.

Mesh radios were desirable for their self-forming and self-healing ability. If a cone failed or was replaced it would not require the system to be manually reconfigured; the system would heal itself.

The radio is configured with a 9-pin serial cable and the manufacturer's X-CTU software. A screen shot of the software is shown in Figure 4.

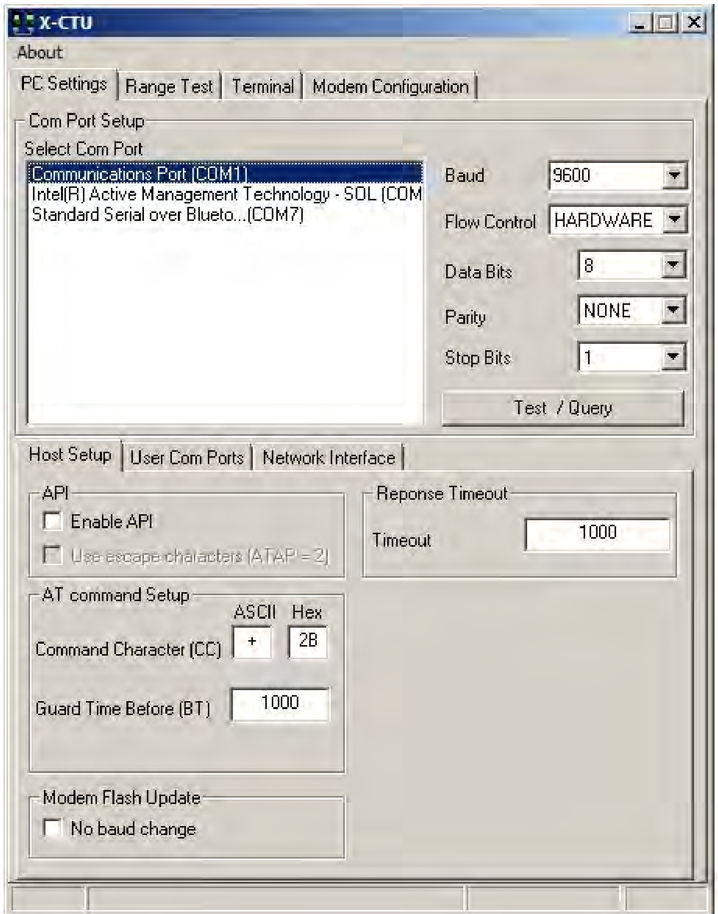

Figure 4: Digi X-CTU Software Start Screen

3.2. Software Suite

The sDrum system requires two types of software:

- Linux control software that operates the system and runs on the Moxa controller,
- Management software for system configuration and testing which runs on a Windows laptop/desktop computer.

The software suite was programmed by WTI's systems group.

3.2.1. Control Software

The control software is installed on the Moxa computers located in the master and logger drums. It controls the data collection, paging and light states.

3.2.2. Administration Software

The aSE administrative software is a Graphical User Interface for administrating the various functions of the sDrum system. The software can be used to connect to any master or logger although only set time, radar device and signal device can be accessed on a logger controller.

The aSE Administration software opening screen is shown in Figure 5.

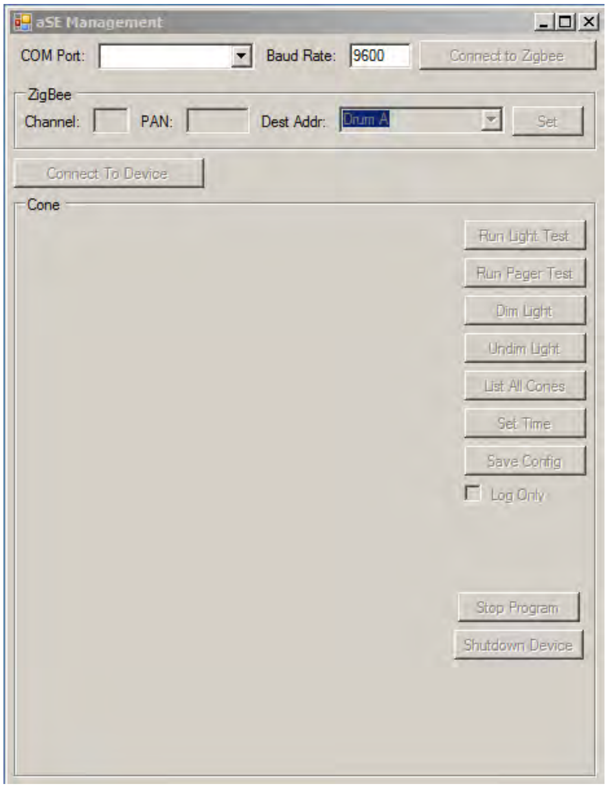

Figure 5: aSE Management Opening Screen – WTI Image

The appropriate COM port must be selected and the 9600 baud rate verified. The "Connect to Zigbee" button initializes the XStick, which is an XBee radio in a USB stick form for use with a laptop. Note the XBee radio is a proprietary implementation of a ZigBee radio.

When the XStick is connected to the management software the screen will look like Figure 6.

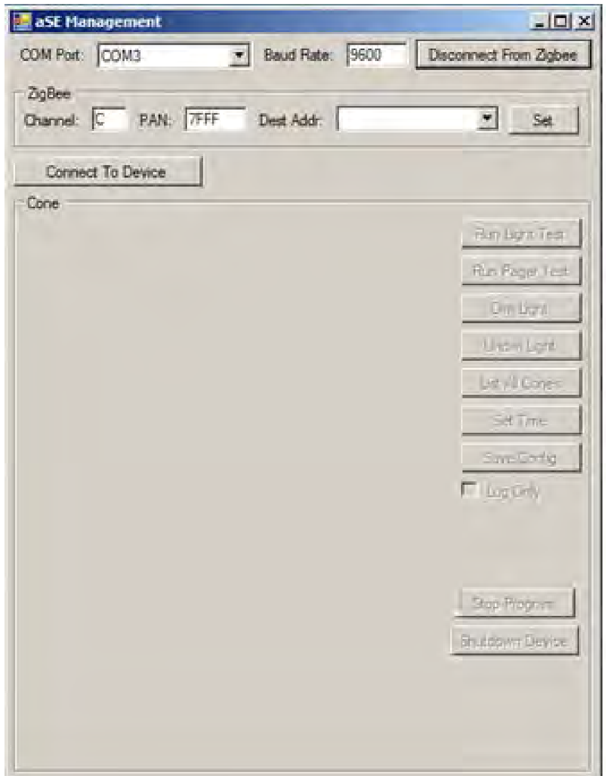

Figure 6: XStick Connected – WTI Image

By default, the Channel and PAN are set to "C" and "7FFF" respectively. Note all of the radios in the system must be set to the same Channel and PAN to communicate.

The "Dest Addr" is the address of the ZigBee radio for the drum the XStick is connecting to. The first time the aSE Administration software is run the 16 digit alpha-numeric Dest Addr must be entered. "Set" saves the communication settings. The XStick remembers the address from the previous session; however, to change the settings of another drum the new address must be entered.

The "Connect to Device" button initializes communication with the drum and will populate the interface with the drum's settings. See Figure 7.

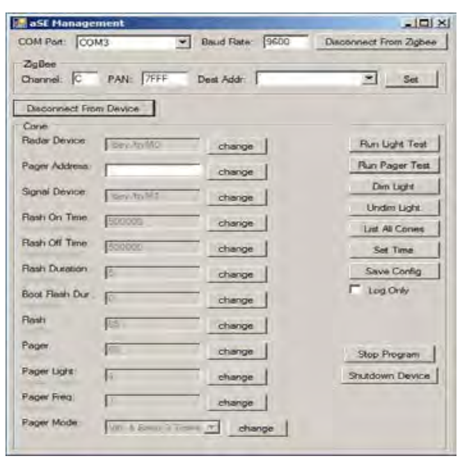

Figure 7: Connected to sDrum Screen – WTI Image

At this point, communication with the drum has been established and the functions of the drum can be configured. The following descriptions refer to Figure 7.

Adjustable Parameters:

- Radar Device - identifies the Moxa serial port the software expects the radar to be connected to. If by chance the RJ-45 connections for the radar and the light become switched, this setting enables the ports in the Moxa software to be changed, restoring proper function.
- Pager Address - the radio address of the pager drum's ZigBee radio.
- Signal Device - the same function as the "Radar Device" function, described above.
- Flash On Time - the time that the light is illuminated, in microseconds. Currently set at 500000µs, or 0.5s.
- Flash Off Time - the time that the light is not illuminated, in microseconds. Currently set at 500000µs, or 0.5s.
- Flash Duration - the length of time that the lights flash after the radar confirms a speed above the trigger speed. It is currently set for 5 seconds.
- Boot Flash Duration - length of time in seconds that the light flash routine runs at power on. This is used to synchronize the radios upon initialization. Currently set at 0 seconds.
- Flash - speed in mph that the Moxa needs to receive from the radar for it to begin the light flashing routine. This is currently set at 65mph.
- Pager - threshold speed in mph that the Moxa needs to receive from the radar for it to send a command to the pager transmitter. This is currently set to 65mph.
- Pager Light - sets the number of pager lights to illuminate. This is set at 4.
- Pager Freq - tells the pager transmitter how long to delay between pages. Currently set to 3 seconds.
- Pager Mode - changes the options of how the pager behaves when it receives a page from the pager transmitter. Currently the pager will vibrate and beep 3 times.

Button Functions:

- Run Light Test - sends a command to the master drum to turn the lights on and off for all drums in the master's network. This routine runs for the time specified by Flash Duration. This is useful for verifying that all of the drums in the network are functioning normally.
- Run Pager Test - sends a command to the master drum to transmit a single page. This test is useful for verifying pager operation.
- Dim Light - reduces the light's output by approximately 50% enabling the system to be used at night.
- Undim Light - reverses the Dim Light function and returns the light to 100% brightness.
- List All Cones - Opens a popup screen which lists the radio address of all drums connected to the master's network; initially the popup will be blank but when "Find Additional Cones" button is clicked, the address and ID of the connected drums will populate. In addition to the address, there is RSSI (Received Signal Strength Indicator) which is a snapshot of the connection quality of the last hop to the address specified. The "Done" button closes the popup window shown in Figure 8.

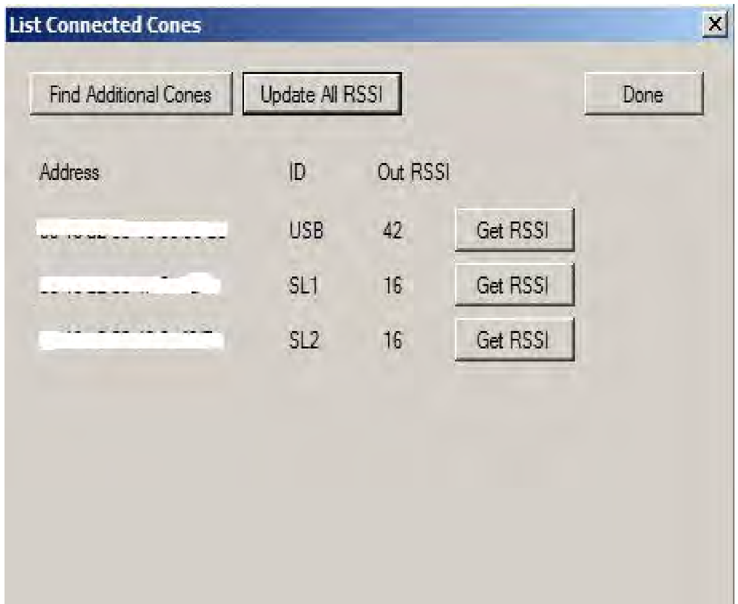

Figure 8: List Connected Cones Screen – WTI Image

Note: The XStick's ID is "USB" and since there are two other drums currently in the network, there are three addresses. The drum the XStick is "connected to" does not show up because it is doing the interrogation. The listed drums are connected TO the drum being configured.

- <u>Set Time</u> - synchronizes the Moxa clock in the master with the clock of the laptop or desktop running the aSE Administration software.
- <u>Save Config</u> - saves all of the changes made during a session in the aSE Administration program to the memory in the master drum. If the Save Config button is not pushed, any changes made will be lost when the master is turned off; configuration will revert back to the last saved configuration upon restart.
- <u>Log Only</u> - ceases sending light flash commands to the drums in the network; it will continue to record the speeds sent by the radar. It is useful for operating the system incognito.
- <u>Stop Program</u> - stops the software program running on the Moxa. The master will not send light flashing commands or pager commands and will not record the speeds measured by the radar.
- <u>Shutdown Device</u> - turns the master's Moxa computer off. No further communication with the master drum is possible until the drum's power switch is turned off, then on again to reboot the system.

The "Disconnect from Device" severs communications with the drum; and "Disconnect from ZigBee" shuts off the XStick.

4. Test

Since the XBee radio specification did not include an antenna pattern a basic pattern measurement was performed. A range measurement was also performed to check the validity of the published range..

A few simple light patterns were tested to determine the limitations of mesh radios to reliably preformed complex light patterns. Details of the radio testing follow.

4.1. Radio Antenna Pattern

XBee antenna pattern tests were conducted in 2011 in WTIs parking lot.

4.1.1. Test Setup

To better understand the performance characteristics of the Digi XBee radios a basic antenna pattern measurement was performed. The radio was placed on the end of a PVC pipe at the same height and orientation as a cone installation. A master cone was placed 50 feet way and a laptop running the admin software accessed the master cone for received signal strength indicator (RSSI) testing.

RSSI is a power measurement of the received signal strength; in this case it is measured in -dBm by the receiving Digi radio. RSSI is not a standard; as such it is not necessarily an accurate value but is useful for comparisons. For the Digi mesh radios it is a measurement of the last hop to the radio being measured.

4.1.2. Test Procedure

RSSI of the radio under test was measured with the master's XBee radio. The radio under test was rotated in 22.5 degree increments with RSSI measured by clicking the "Get RSSI" button five times at each angle and the five values averaged.

4.1.3. Test Results

A plot of three different radio antenna patterns is shown in Figure 9. Note the nulls at approximately 20 degrees and 202 degrees.

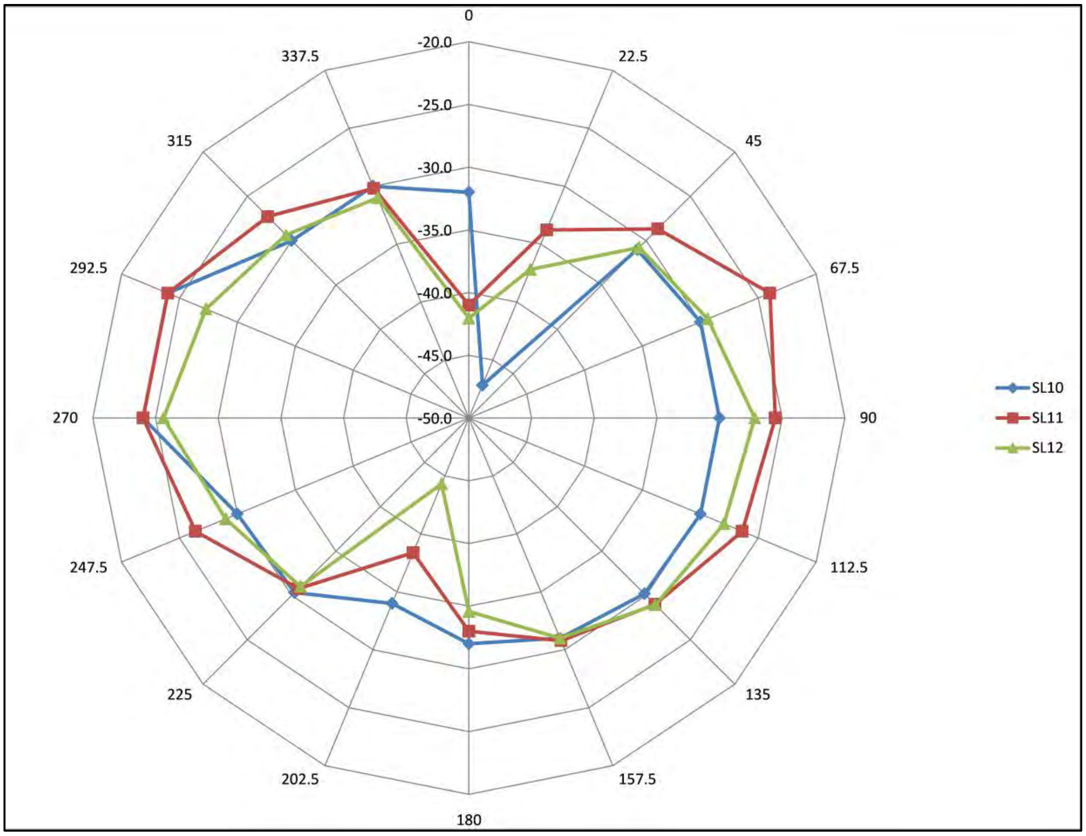

Figure 9: XBee Radio Antenna Patterns

The nulls may be caused by the antenna's orientation in the radio. See Figure 10. The radio antennas are the short black tipped wire near the bottom of the blue circuit board (XBee module). The wire is bent at approximately 90 degrees, so the cover can be installed, and pushed down and/or to the left to avoid the foam block in the cover, which can be seen directly above the radios. The ground plane on the back of the printed circuit board along with the antenna bending possibly causes the pattern nulls.

Figure 10: Digi Adaptor Antennas – WTI Photo

Note that when the radios were tested inside cones, the nulls where much shallower or not present. That may be an effect of the metal frame.

4.2. Radio Range

The radio range tests were conducted in 2011 along 11th street near WTI.

4.2.1. Test Setup

All 28 cones were placed in line along 11th street near WTI. Radio range was evaluated first at 10 feet spacing then at 20 feet spacing, by recording the RSSI value measured by the radio in master 1 (M1), which was at the beginning of the line.

4.2.2. Test Procedures

Only M1 and the cone to be measured were powered up. The List all Cones routine was run three times, if three RSSI values were received that cone was turned off and the next cone turned on; the procedure repeated. This continued for all 27 cones. If three RSSI values were not received, List all Cones was repeated until three values were received.

4.2.3. Test Results

For the ten feet spacing, more than half of the radios required one to four retries before responding the first time; the farthest radio required eight tries before responding. Interestingly, no radio failed to respond after responding the first time. Figure 11 shows the results for the 10 feet spacing measurements.

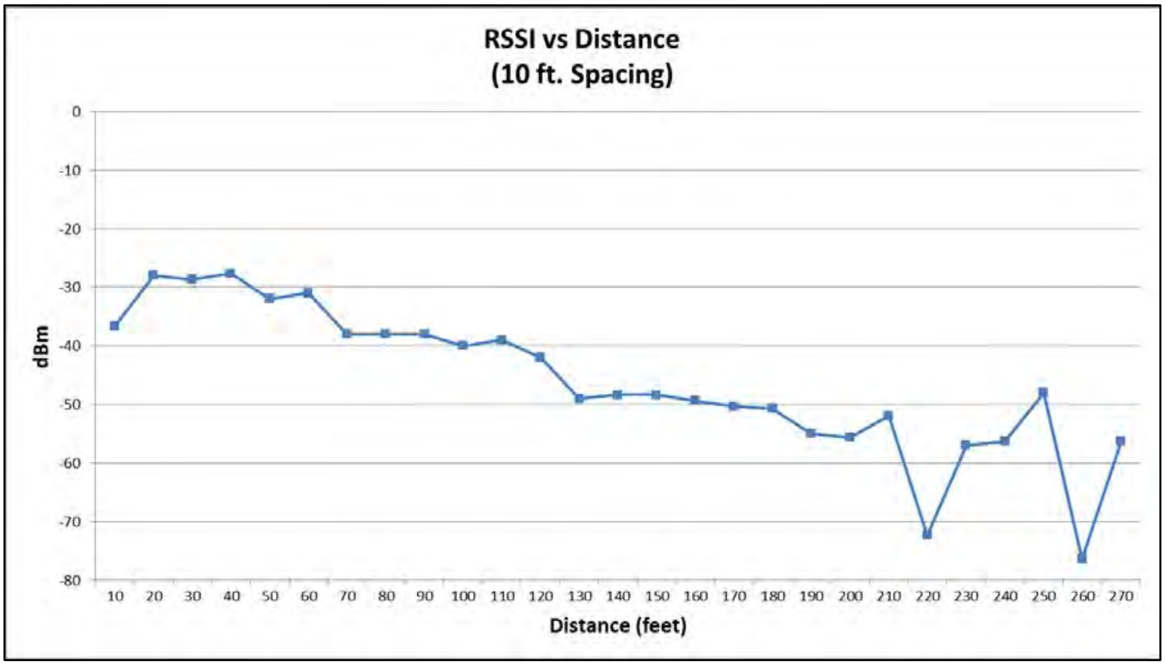

Figure 11: RSSI Values for 10 feet Spacing

Note the values decrease consistently up to 200 feet then become erratic indicating the limit of the useful range. The 200 feet limit repeated for 20 feet spacing although the radios abruptly quit communicating at 200 feet with only four of the remaining 17 radios responding at longer distances. See Figure 12. The random responses at longer distances were omitted for clarity.

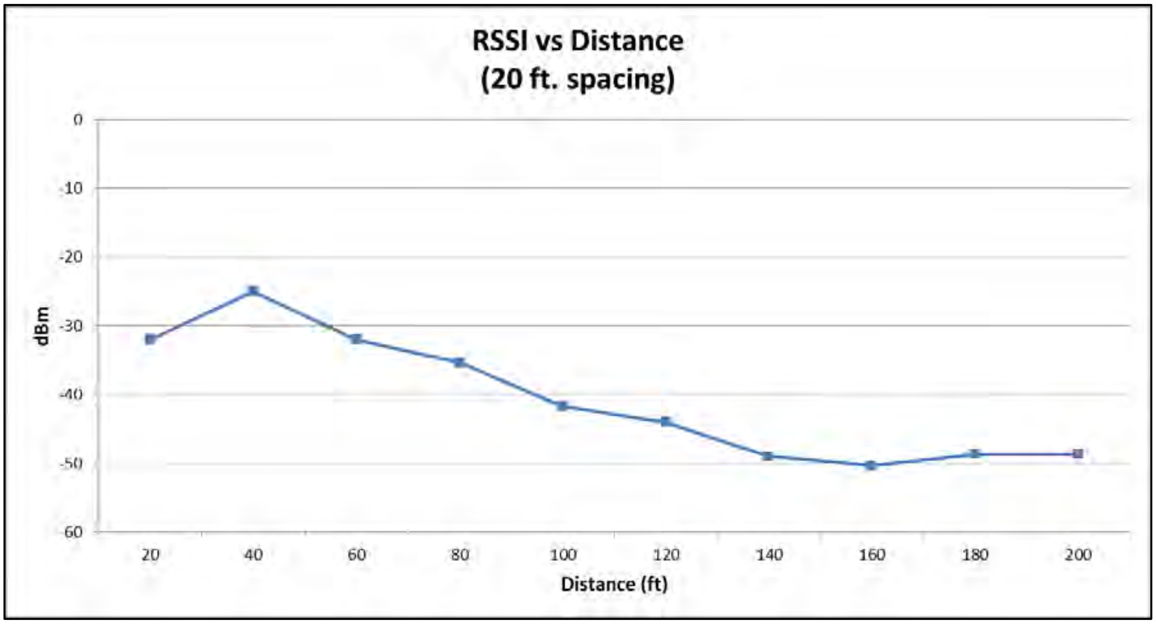

Figure 12: RSSI Values for 20 feet Spacing

The tests were not a definitive measurement of the Digi's adaptor's communication range, which would entail measuring the same radio at each distance, but it did provide an indication of the radio's average range.

4.3. Light Patterns

Following the Los Banos deployment time and personnel were available to research the radio networks ability to handle complicated light patterns. The following section documents WTIs research to determine the XBee Networks communication capability relative to complex light patterns; showing that latency is a significant issue even for relatively small networks.

Custom software was written for the light pattern testing. Note the prototype cones were used for the light pattern testing because they are easier to handle than the drums.

4.3.1. Test Setup

Laboratory tests were setup with the lights arranged linearly in groups of five with spacing between the groups averaging five feet. See Figure 13. The tests were run utilizing a laptop with an XStick dongle located close enough to the light groups that all/nearly all XBee communication was direct, with little or no meshing. Note light number 1 is against the wall in the upper right corner of the image.

Figure 13: Laboratory Light Pattern Testing - WTI Photo

For outdoor tests the lights were setup linearly with 50 feet spacing. Tests were run using a laptop and an XStick dongle located near light number one. See Figure 14. Due to the large spacing between lights, the XStick only communicated with the first two or three lights, therefore primary communication between lights used mesh networking.

Figure 14: Outdoor Light Pattern Testing - WTI Photo

4.3.2. Test Procedures

Four light patterns were tested:

- Two light metronome (lights 1 and 10 alternately illuminating, similar to the operation of a metronome).
- Turn lights on sequentially with unicast packets then broadcast packets to turn all lights off.
- Light triplets forward (move a group of three illuminated lights down the line of lights).
- All lights on and off using broadcast packets.

A broadcast message is meant for all lights in the network and every light that receives the message repeats it a set number of times. A unicast message is sent from one light to another light based on the lights addresses (*1*). For any light pattern other than broadcast on and off, individual light addressing (unicast) is required. The lights can be configured to resend a unicast message if no acknowledge (ACK) is received. If this parameter is set and an ACK is not received within the default 200ms time delay, the message is resent.

Initial testing showed that slowing down the light pattern, i.e. adding delay between illuminations, improved pattern execution in most cases. As a result, delays ranging from 1000ms to 12ms were tested. The delays used for each pattern were dependent upon the complexity of the pattern. Each delay had 10 trials where each trial consisted of five loops of the pattern. Consequently each test pattern was repeated 50 times. An individual trial was considered successful if the pattern visually met the requirements of the pattern (lights illuminate in order and on time) for each of the 5 loops of the trial.

Note: Before any test of a light pattern was initiated, the pattern was executed once and not recorded. This preliminary pattern run was to allow the network to establish connections and routing tables required by the pattern for the test. This enabled more accurate results from the actual pattern test, rather than include data from generation of the network.

4.3.3. Test Results

The following charts show lab and outdoor success rates of various delays for the four light patterns tested. The main difference between the lab setup and the outdoor setup was the spacing between lights. Spacing outdoors was 50 feet where in the lab it was 5 feet or less.

An 80% success rate indicates 8 of the 10 trials ran successfully. An individual trial was considered successful if the pattern visually met the requirements of the pattern for each of the 5 loops of the trial.

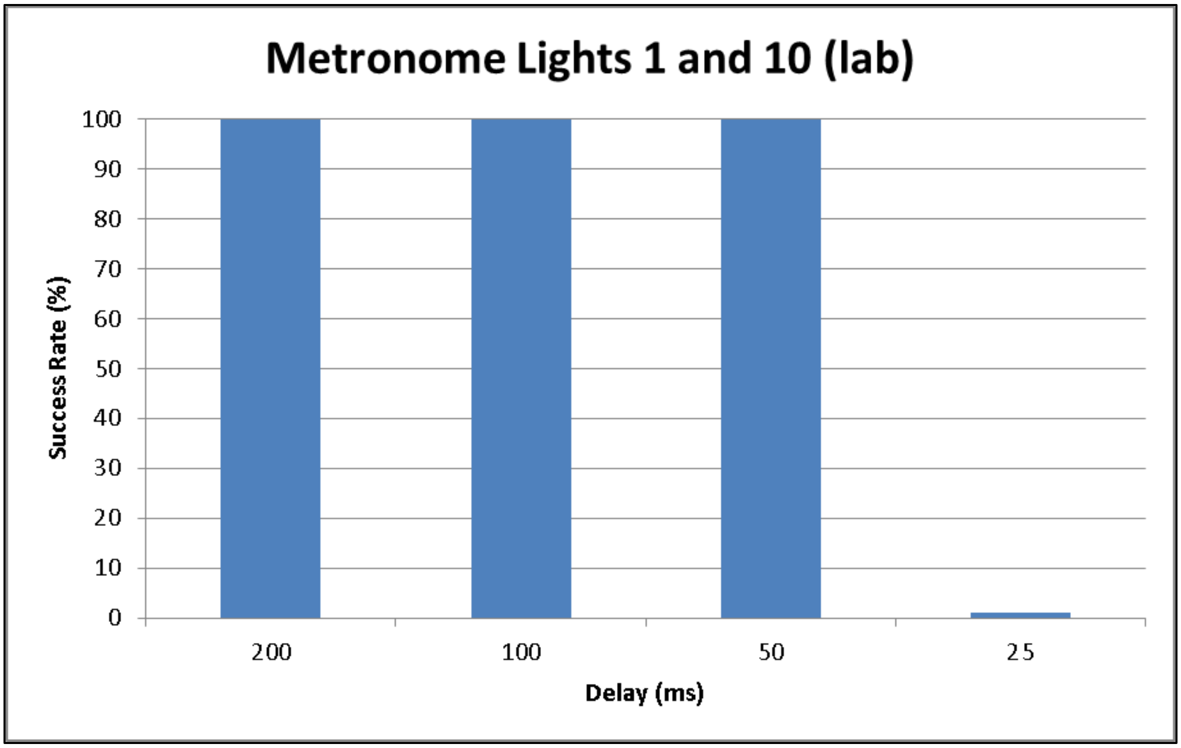

Figure 15: Laboratory Metronome Test Results

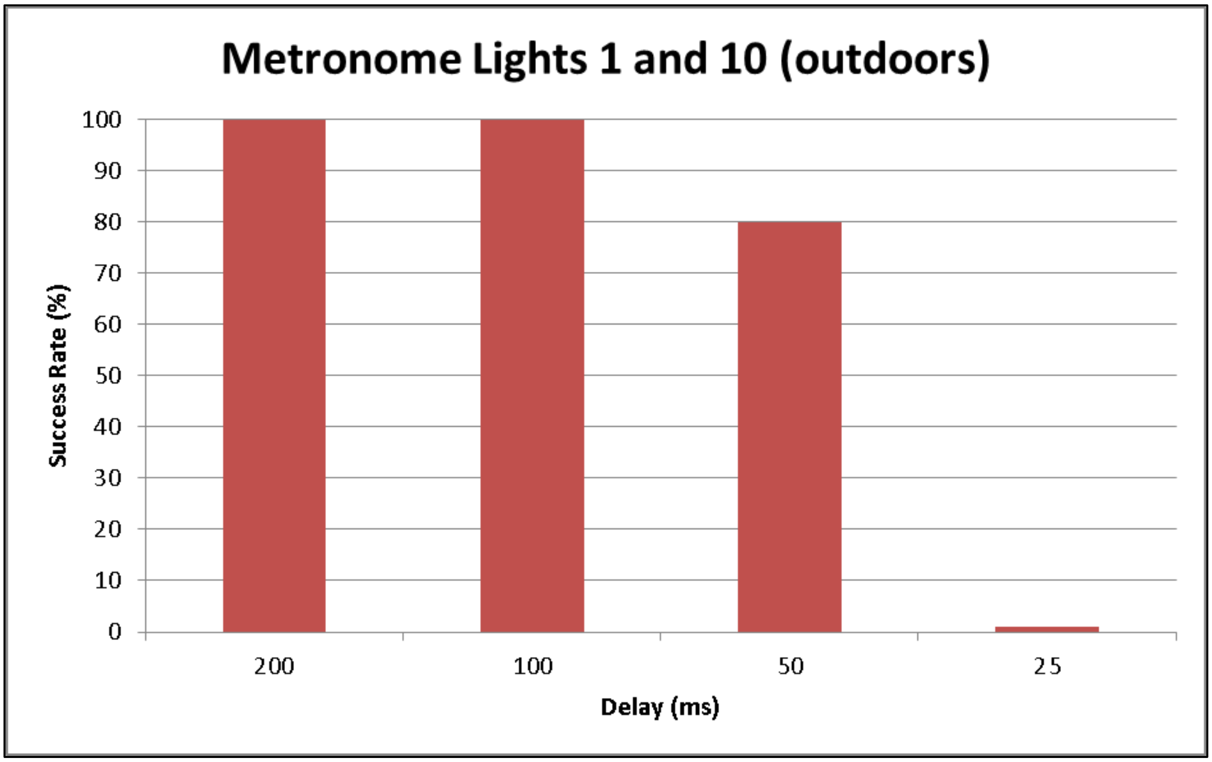

Figure 16: Outdoor Metronome Test Results

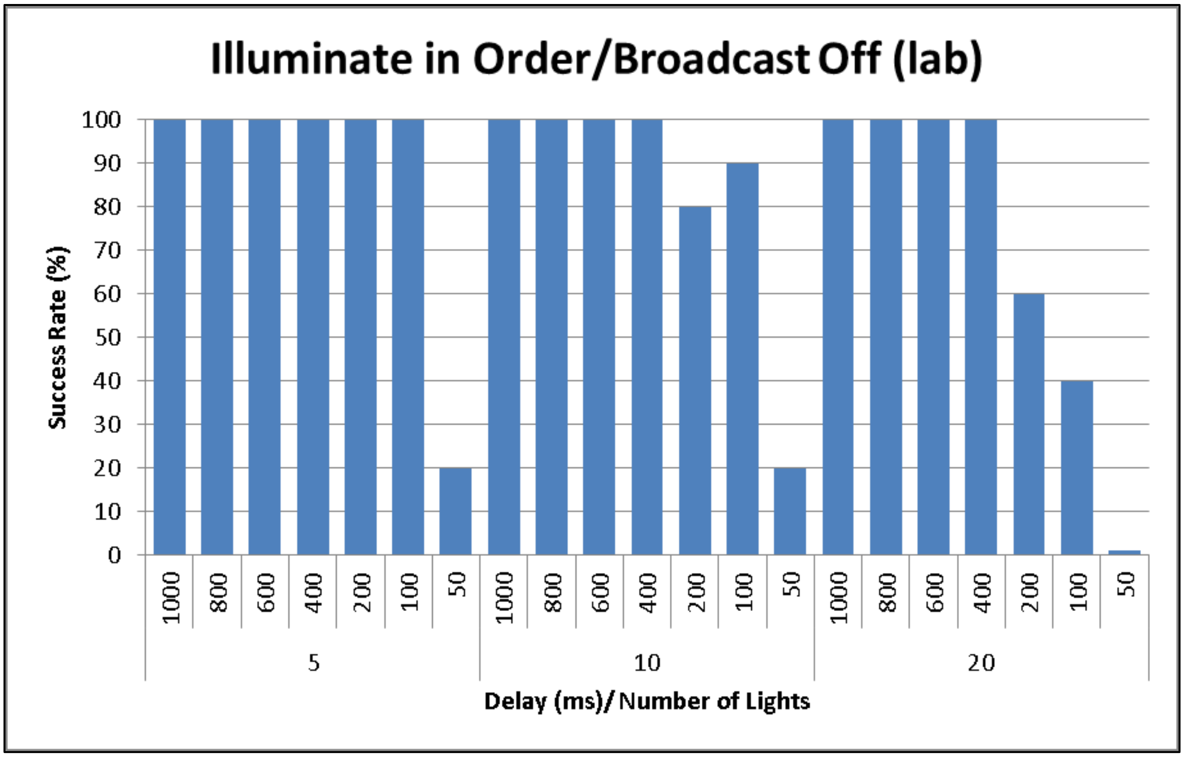

Figure 17: Laboratory Sequential Illumination Results

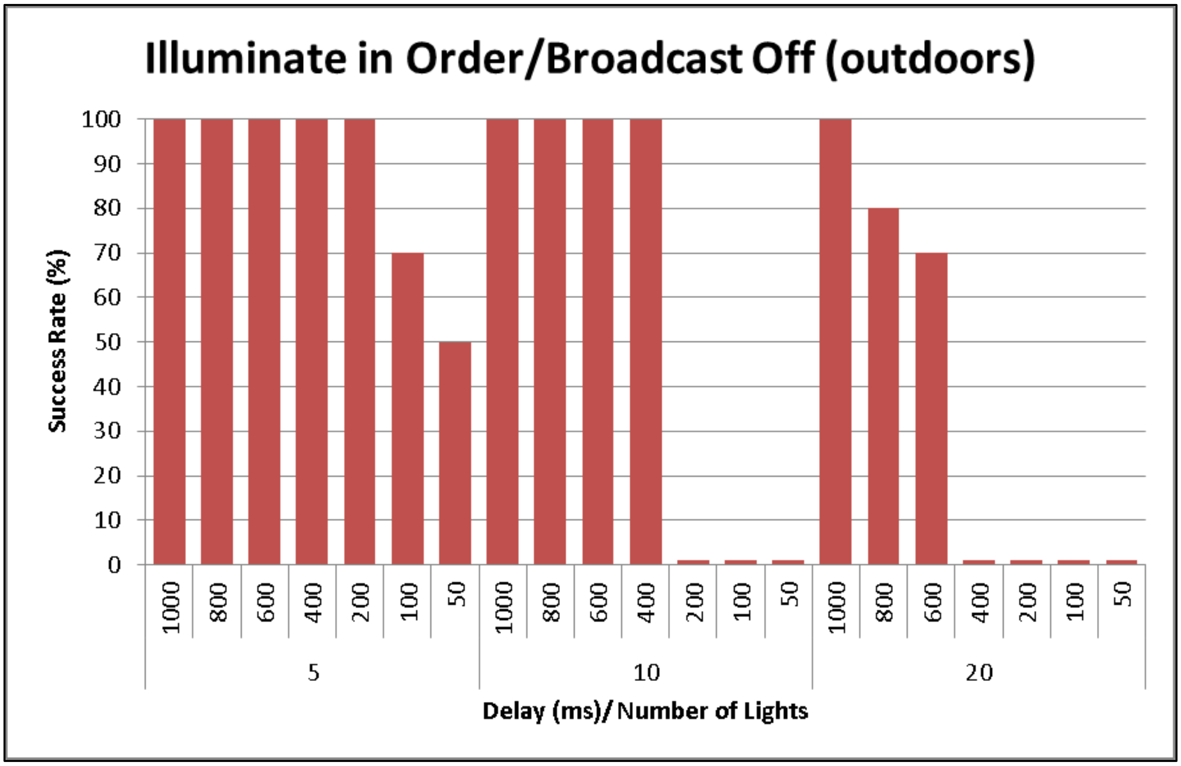

Figure 18: Outdoor Sequential Illumination Results

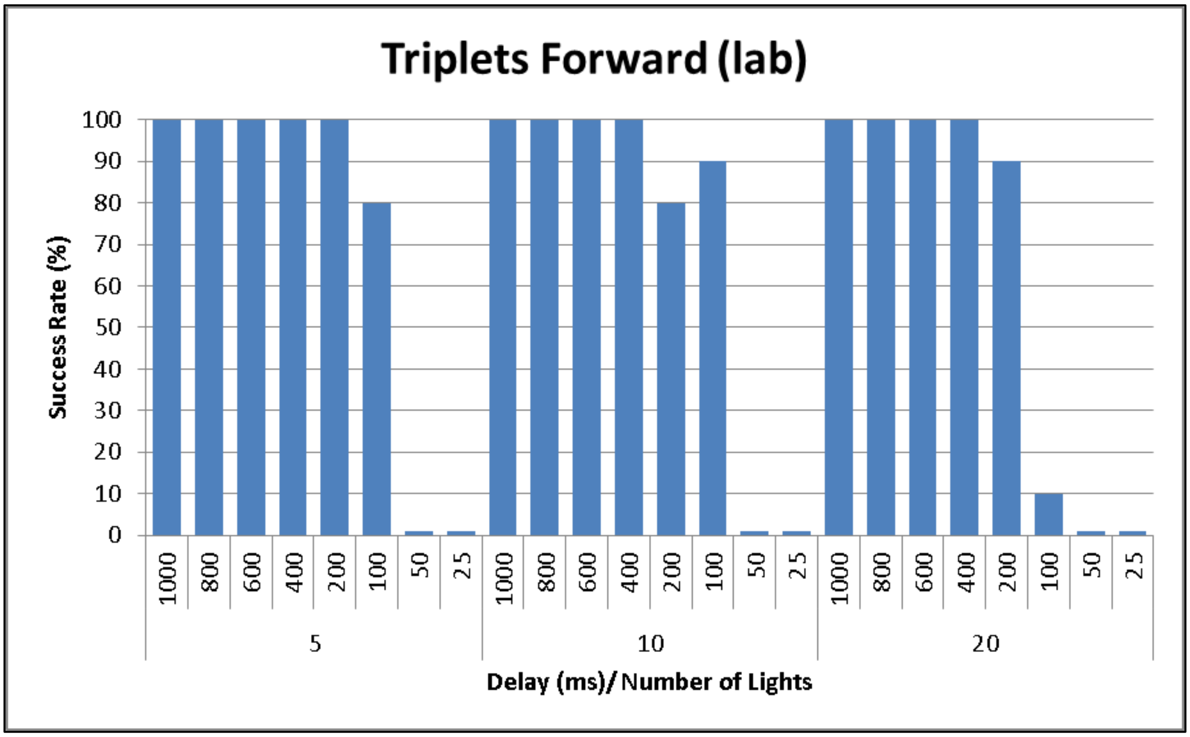

Figure 19: Laboratory Forward Triplets Results

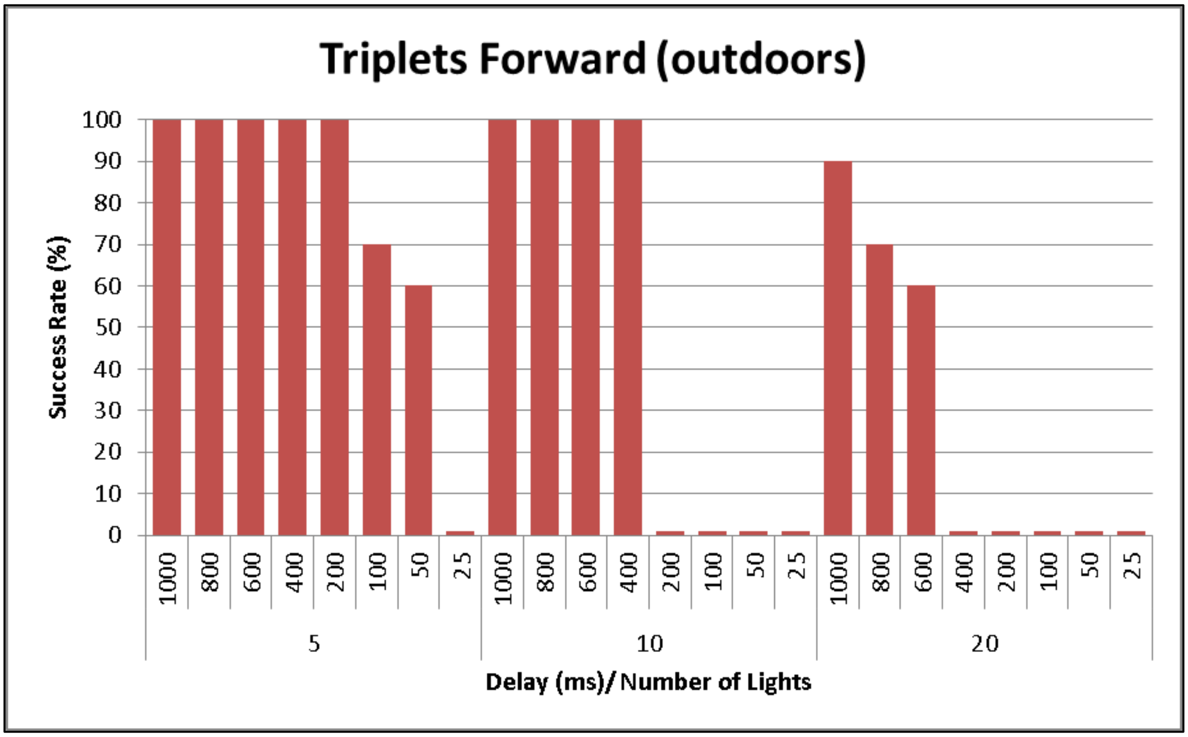

Figure 20: Outdoor Forward Triplets Results

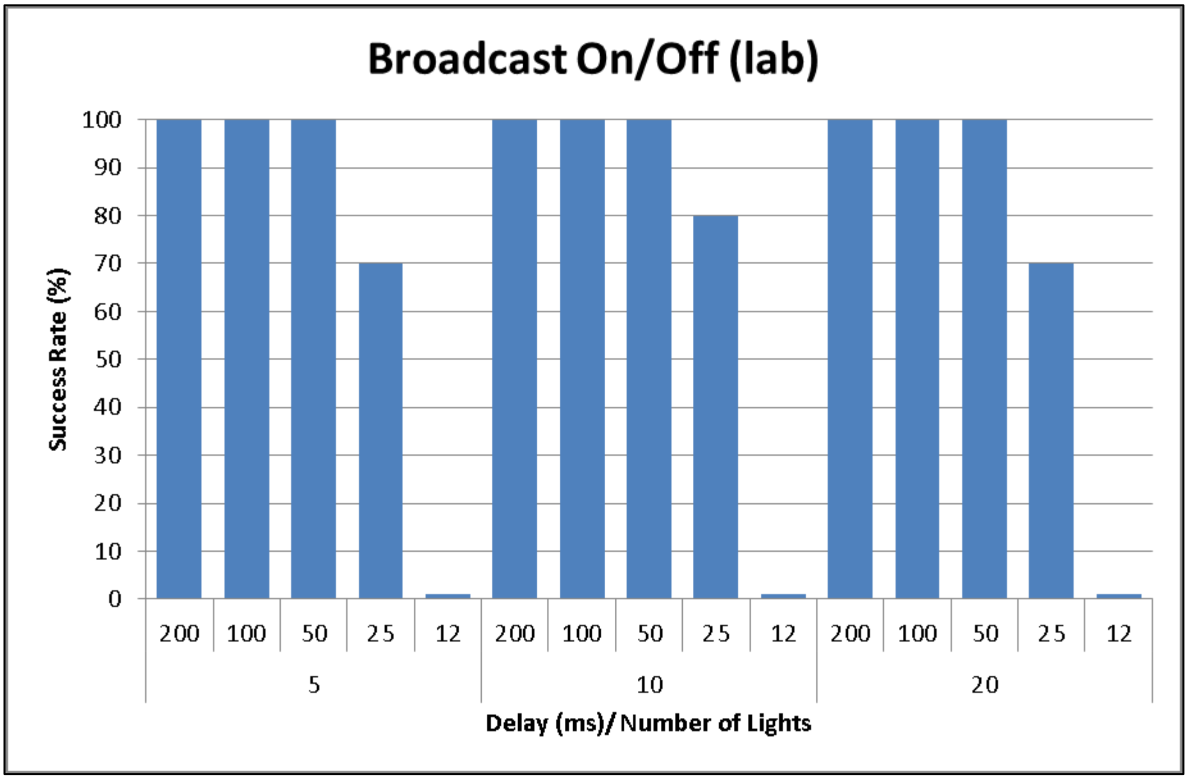

Figure 21: Laboratory Broadcast On/Off Results

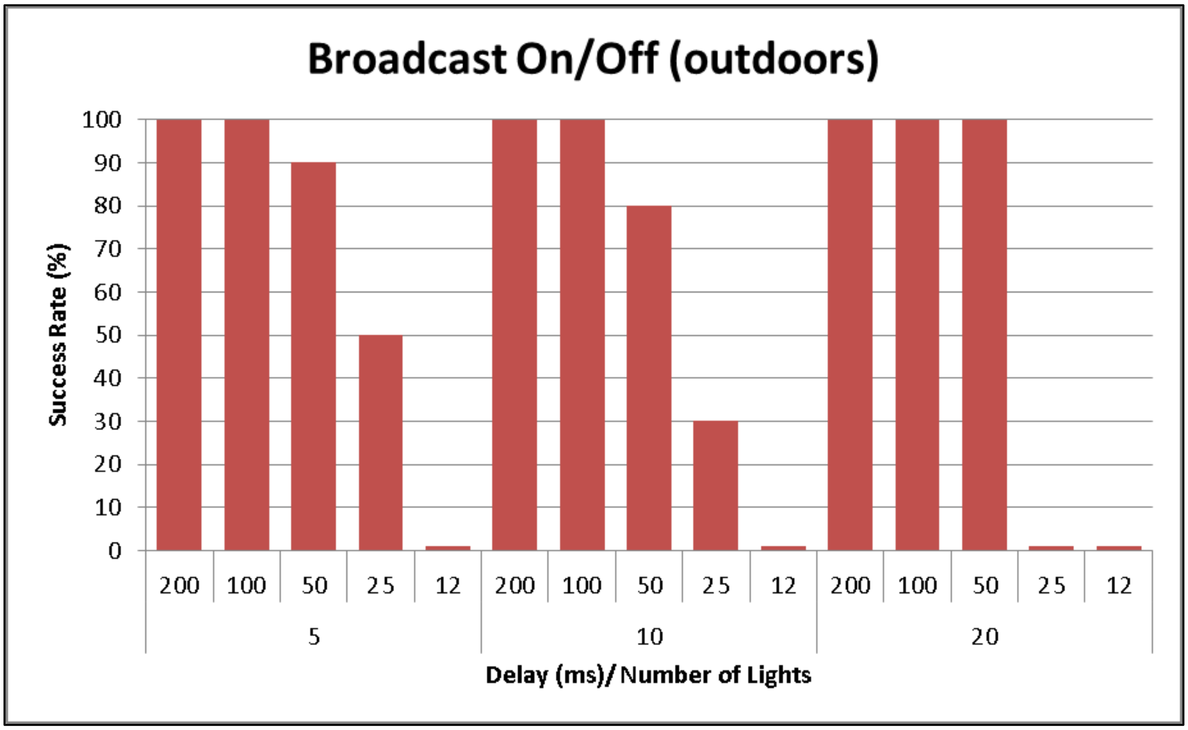

Figure 22: Outdoor Broadcast On/Off Result

While unicast packets are more versatile in the creation of lighting patterns, broadcast packets are far more reliable and can operate with significantly shorter delays. Of the unicast patterns, the less complex patterns run more consistently but only on small networks of 2 to 4 nodes where the delays were comparable to broadcast packets.

Broadcast patterns worked consistently at 50ms delays and only occasionally at 25ms. In comparison, unicast packet patterns were consistent at delays of 200ms or longer, with a few of the simpler patterns functioning with 80% or greater success rates with delays as short as 100ms. This means that patterns implemented with broadcast packets can run up to 4 times faster than unicast packets in addition to completing the patterns more consistently. Another interesting property of the broadcast packets is that their success rate did not diminish with an increase in the number of lights in the pattern although further testing would be needed to establish its limit.

Outdoor testing success rates were lower for all light patterns, but the severity varied greatly between broadcast patterns and unicast patterns. Outdoors the broadcast patterns had limited success with the delays that proved successful in the lab and unicast packets required up to 400 milliseconds more delay than the lab test to complete with marginal success rates. The exception to this was the 2-light metronome.

5. Conclusion

The XBee adaptor antenna pattern is not ideal for a linear array of drums but it is acceptable for the short ranges used. If cone spacing exceeds 100 feet a longer range radio should be explored.

Finally there are similarities between the outdoor and the lab test results. In both the outdoor and lab results, lighting pattern quality decreased significantly with the size of the XBee network. In addition, shorter delays caused the number of successful patterns to diminish. This particular factor had a greater effect on the outdoor XBee network than the lab network. A possible explanation could be that the mesh network delays the receipt of the packet by the XBee; consequently there must be longer delays for successful lighting patterns with mesh networks.

6. References

1 http://www.digi.com/support/kbase/kbaseresultdetl?id=2187 (As of January 2, 2013).