Optimization of Single-Hop SAMAC Network and Characterization of Antenna Effects for Multi-Hop Network

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Abstract

Wireless sensor networks are becoming more prevalent in today's world and being used for such tasks as monitoring borders, intrusion detection and even to control different switches/controls in vehicles. With any wireless system, several issues exist, which can affect the performance of the network such as power level, receiver thresholds, environment the nodes are in and objects/obstructions near the network. The main problems with wireless sensor networks are dropped packets, noise, power consumption and lack of reliability. The goal of the project is to study networks in different environments and look at how the network performance changes.

The first goal is to optimize the network for low power consumption, and minimal data transmit time. To achieve these optimal conditions, the timeslot duration, power level, and inter-arrival time are modified in several combinations. The tests are run on a single-hop, contention-based wireless network with one to eight nodes competing for transmission depending on the given test. The nodes are separated at a distance of five feet from the sink node.

The antennas on the wireless sensor network nodes are stated as being almost omni-directional [5]. Since the power pattern of the antenna will affect quality of network communications if not perfect, the orientation of the nodes is examined to see how a change in orientation affects how the network is created in a multi-hop setting. The second goal is to analyze the effects of three different node orientations on how the

network is formed. The SAMAC code is run for each orientation and the network topology is recorded. This topology will be examined to see if a difference exists in how the nodes communicate when oriented differently.

Lastly, using the results from testing, guidelines for optimization of the networks will be created. Recommendations will be given on how to set up both the single-hop and multi-hop networks for ideal communications. Future research topics related to current research will also be suggested.

Acknowledgements

First I would like to acknowledge the people I have worked with over the past two years. Prof. Ekici brought me onto his research team in the fall of 2007. He has been very helpful to me over the past two years, and offered me several opportunities to help his masters and PhD students with their research. I have learned a lot from him and appreciate his help and guidance as my advisor for my undergraduate thesis. Second I would like to thank Emad Felemban for all of his help getting me acquainted with the new software and hardware I would be using for my research. Third I would like to thank Robert Murawski. Robert has worked with me for a year and a half explicitly with wireless sensor network performance. Robert was especially helpful getting the software and hardware to work with my computer and took a significant amount of his time weekly to help me set up a research plan, troubleshoot problems I encountered, and analyzing my results. Without his help I would not have been able to successfully complete this project.

Last, I would like to thank all of my friends and family for their support. My friends were understanding of the time commitment of my research and helped me out when needed. My family has been my support system throughout my college experience; I partially owe my success in college to my parents and other family members. Without their love, support, and guidance, I would not be the person I am today and not have been able to accomplish so much in the five years I was at Ohio State.

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Chapter 1

Introduction

1.1 Motivation for Present Work

Everything in today's world is leaning towards a wireless structure. Some examples include: cell phones, laptops with Wi-Fi and car door unlock mechanisms. In particular, wireless sensor networks are used for many purposes including use by the military for environmental monitoring and intrusion detection, as well as general environmental modeling. As the amount of devices that operate wirelessly increases, there becomes greater noise and stress in the environment during device communication. It is important to be able to model the structure of these networks to know how they perform in different environments and with different settings. Two very important factors in a successful network, both single and multi-hop, are power conservation and the elimination of un-necessary network connections.

The following terminology will be used throughout this paper. A 'node' refers to the Tmote device used for testing [5]. It is a small transmitter/receiver with an attached battery pack used for wireless sensor networks. A 'parent node' will refer to the node from which the particular node received its data from. A ‘sink node’ will refer to the node controlling the network. It sends out the information for neighborhood discovery and is where all data is sent back to once it is transmitted over the network. Unless otherwise noted, ‘environment’ will stand for the different settings each node was programmed with. The ‘physical environment’ will refer to the physical environment of the system.

One of the key settings to monitor with wireless networks is power consumption. Since the devices are wireless, they can only communicate as long as they have power. Some systems use a wireless transmitter and receiver to send information back and forth, but each end is connected to something stationary with its own power supply. With a multi-hop wireless network, the sensors are usually independent from a system and thus must have their own power source. Batteries are used to power these devices that are not hooked up to a system with a traditional power supply. Depending on the function of these nodes, it may or may not be easy to replace the batteries for continued operation. For example, if these nodes were used in a battle-field setting, they would most likely be dropped off at a given location and never retrieved, and just allowed to communicate for as long as the batteries last. However, if it was for something more heavily used, like a device in a vehicle, it could be made in a location as to simplify the changing of batteries.

Another key setting with multi-hop networks is simplifying network communications. If the power level is too strong, instead of creating a multi-hop network, several nodes at varying distances may all talk to the same parent node, eliminating the multi-hop nature of the network, and creating contention for communication. When an increasing amount of nodes try to talk to the parent device at a given time, more stress is put on the network This increased communications volume can reduce the effectiveness of the network.

Lastly, antennas that are not true “omni-directional” antennas do not radiate equally in all directions. In some directions nulls are expected, and thus the signal will be weaker in certain directions as compared to others depending on the antenna’s orientation. If these nulls exist for a given transmit and receive antenna, it is important for the user to understand this and to ensure the network will perform optimally without being affected by these nulls.

1.2 Outline of Thesis

The motivation for present work was described at the beginning of this chapter. Chapter two will discuss related research to both this project and the applications of wireless sensor networks in general. Chapter three will discuss the background investigation and experiment setup. The network protocol, hardware, software, and design process will also be discussed. Chapter four will use the information established in chapter three as a basis for guidelines for optimizing multi-hop networks. The experiment outline will be discussed as well as the actual results and analysis. Chapter five will summarize the results. Chapter six discusses future research opportunities related to this project. Chapter seven is the final chapter and will provide a conclusion and real world applications. The references and appendices A through E are at the end of this document.

Chapter 2

Background

2.1 Related Works for Wireless Sensor Network Optimization

Studying packet loss and performing research with the goal of reducing these packet losses during transmission is not a new concept. Many of these tests were run with the idea of changing code in the MAC level in regards to how many times a message would be sent, and ways to better ensure more reliable performance [1], [6]. Examples of this include re-sending data that was lost during transmission, including relay nodes to shorten data transmission distance, and increasing power level.

SAMAC [3] is a relatively new MAC protocol developed at Ohio State and will be formally introduced in section 3.2. Since SAMAC is unique to Ohio State and relatively new, very little research has been conducted to study how different combinations of environmental parameters can reduce packet loss and conserve power within a wireless sensor network (WSN). The Ohio State research group, under the guidance of adviser Eylem Ekici, has studied network performance with different power levels and changes in environmental variables in terms of meeting specific network performance goals. These were usually performed changing one variable at a time, and not studying the combination of variables.

In research outside of Ohio State, it appeared as if a network was seen as only being able to perform to a certain level, and 'fall-backs' were put in to place to help reduce the numbers of packets lost. There has not been very specific research done on combining parameters in the SAMAC layer of the network to optimize power consumption and packet losses. No prior research has been performed for setups outlined in sections 3.6.1 and 3.6.2 to characterize networks as efficient based on power consumption and packet losses.

2.1.1 Node Placement

In [6], problems with placement of nodes are discussed as well as how potential solutions could be formed to fix the given network problems. The proposed solution to help reduce packet losses during transmission is to add relay points in the network. Instead of studying parameters of networks as this paper explores, [6] tries to increase the successfulness of the network by adding more support in terms of these relay nodes. Relay nodes are extra nodes that are not taking measurements or creating/sending new information out, but are simply relaying messages from one node to another. Adding these nodes lets the WSN designer to alter the network topology, hopefully reducing the number of nodes communicating simultaneously. This is similar to the use of repeaters for cell and radio applications.

While this work presents new concepts on how to strengthen the communications in a multi-hop network, two main problems arise with this type of solution. One, with an increased amount of nodes in the network, there is an inherent increased potential for error in the form of dropped packets. Secondly, if the network is being used to gather physical environmental data or to monitor conditions, having these relay nodes will not be effective. In this type of situation it is important that all nodes are collecting data and sending it back to the sink node via their parent nodes. Relay nodes would be useful in such applications as sending data from point A to point B, with a large distance in between that numerous nodes are sending data across.

2.1.2 Repetition of Data Transmissions

In [1], data loss during transmission is shown to be reduced if commands can be re-sent if the data was not initially received correctly. In order to do this, the commands are stored in memory on the node so the missing data can be re-sent. The sacrifice for this method is primarily power but also the network performance time is increased. [6] supports the claim that retransmission of lost packets increases power consumption and lowers the network lifetime.

2.2 Related Work with Tmotes and Wireless Sensor Networks

A majority of the foundational knowledge for this project came from interaction with other team members, PhD students and experts in this area. Two students in particular had done extensive research with a specific MAC layer protocol to optimize the performance of the network, called the SAMAC layer [3]. Different protocol was established to determine how the network connections were made, and how the nodes would communicate in a given timeslot. For the research in this paper, the Bellman Ford method was used. This method allows the nodes to perform neighborhood discovery, and once this is done, the number of hops back to the sink node for each possible path are analyzed, and the path with the shortest hop count back to the sink node is chosen. This is done to eliminate unnecessary transmissions in the network, allowing it to save power and transmit less data for the duration of the experiment. These researchers also created "groups" of nodes so that instead of individual nodes being assigned timeslots, the group of nodes would be assigned a timeslot. This reduction in communication time greatly reduces the overall superframe length, which is made up of the individual timeslots. A group of nodes would include a parent node and its children nodes. These students continue to work on furthering the success of the SAMAC protocol with ETRI boards, currently using both sectored antennas and omni-directional antennas in hopes of creating a more efficient and reliable network with the sectored/directional antennas.

Chapter 3

Background Investigation and Experiment Setup

3.1 Background Investigation

Initial investigation with wireless sensor networks began with observation and assistance to PhD students with great expertise in this area. The focus of their research was SAMAC layer programming for the nodes to create multi-hop networks. Most of the initial work involved assistance with test completion and trouble-shooting and no back-end work with the code. A hallway floor plan was then developed with measurements taken between positions of nodes under test. These layouts were used as a standard for tests, and allowed consistency over time. Use of this drawing allowed visualization of the developing networks in both topology and how the network was established. The PhD Students did the initial software modifications and began teaching how the different settings worked together to create a successful, or in some cases, unsuccessful network. Once the initial testing phase was complete, individual tests were developed and run separately under the advice and help of one of the PhD Students. The main goal of these experiments was to characterize the nodes and how they perform in different environments. Work was done with these students for over a year running experiments with the Tmotes, learning how to troubleshoot problems, creating test setups, and changing the environment to successful impact the network performance. The research in this paper fits into their larger research area by expanding the knowledge base about the Tmote nodes, adding to existing knowledge of effects of environmental changes on network behavior and by adding new knowledge in areas previously unexplored.

3.2 SAMAC Protocol

The protocol used on the wireless sensor networks is SAMAC protocol, Sectored Antenna-Based Medium Access Control. This protocol was developed by researchers in Prof. Ekici's research group specifically for use with wireless sensor networks. The following are the three objectives outlined by the group in [3]:

1) To obtain a high packet delivery ratio by minimizing channel contention and packet collisions in the shared wireless communication media

2) To enhance the throughput characteristics of the sensor network by exploiting the spatial reuse capability of directional antennas.

3) To extend sensor battery lifetime by minimizing transmission and reception power and idle listening.

This is believed to be the first protocol of its kind to be used with directional antennas.

When running on the Tmotes, the SAMAC code executes in the following manner:

1) The sink node receives a signal telling it to begin data transmission process.

2) Neighborhood discovery starts.

3) Once neighbors are discovered a time schedule is computed by the SAMAC protocol and distributed by the sink node to the entire network.

4) Nodes follow this time schedule and transmit and receive data until complete.

5) Sink node receives information back from children nodes.

6) Results can be displayed on a computer screen when the sink node is hooked into a computer.

The second step, neighborhood discovery, is where the environmental properties in the SAMAC layer are important. If the power level is too high for the network, two things happen. Once, power is wasted and battery life of the nodes is drastically reduced. Two, if they are transmitting a large amount of power, individual nodes might see all other nodes in the network, and turn what is supposed to be a multi-hop network into a single hop network. This can also happen if the threshold of which signals to receive and which to ignore is too low. Neighborhood discovery works in the following manner. The sink node sends a signal out looking for other nodes within its communication limits. Once it establishes communications with these nodes, a signal is sent giving them the “right” to perform neighborhood discovery. Only one node can have the token at a time. These nodes are the children of the sink node, and the sink node is the parent to the discovered nodes. Each of the discovered nodes will then repeat the same process of finding neighbors, and creating a parent/child relationship among the network. Once this process is complete, the time schedule of when nodes can communicate and when they are silent is computed by the SAMAC protocol as mentioned above.

When the time schedule is being distributed to the network, a token-passing approach is used. This means that a token is sent with the time schedule, and only the node that has the token can communicate. This allows for accurate transmissions with the reduction of packet collisions in the network. A group of nodes is classified as a parent node and its children. In many protocols, time slots are assigned to individual nodes, which lead to a large amount of time required for the network to communicate. The SAMAC protocol assigns a time slot to each group of nodes, which greatly reduces the overall length of the superframe. To save power, the SAMAC protocol establishes that nodes "sleep" when they are not communicating in their assigned time slot. Also, when no communication activity is required from the network, they are also in "sleep" mode to conserve power.

3.3 Hardware

The wireless sensor networks under test are a compilation of nine Tmote Sky, ultra low power, wireless sensor modules [5]. They are compliant with the IEEE 802.15.4 standard and have an operating frequency of 2.4GHz. While not used in this testing, these modules feature on-board humidity, temperature and light sensors. Each module uses an 8MHz Texas Instruments MSP430 microcontroller with 10k of RAM and 48k flash memory. At a maximum transmitted power level, these modules can transmit up to 50 meters indoors and up to 125 meters outdoors in ideal settings. Along with ideal power consumption, these nodes also do not draw much current during use. A USB port on the module allows for easy data uploading to the unit and easy data downloading during testing. They can be powered with both batteries and via the USB port when plugged into a computer.

3.4 Software

The program was edited using X-Emacs and the nodes were loaded with the SAMAC program using Cygwin. Each time changes were made in the code, the nodes would need to be re-programmed and reset before running the next test. The nodes were running the Nano-Q-Plus operating system which is proprietary software from ETRI, the project sponsor.

3.5 Design Process

The goal of this project was to create a test procedure to characterize and optimize wireless sensor networks with. This procedure can be used for both single-hop and multi-hop networks and consists of the following steps. First, the goals of the research are lined out. Several environmental changes are suggested, new values brainstormed, and then tested. Each environmental change is studied to learn of its effects on the network performance. During testing, conclusions are made from the data collected whether the testing procedure was properly outlined. If no data can be collected, or data is not following an expected pattern, the procedure is re-examined. If need be, levels can be changed, for example power, if the network cannot send data through. Once the data is collected, and problems worked out with initial test plan, if any existed, observations of the data are made and data analysis is performed. Trends are identified, and capability limits are applied to the appropriate data showing the viewer where the network can perform ideally and where the cutoff point exists. This cutoff point signifies the number of nodes that are in contention to talk to the sink node concurrently while still classifying a network as efficient.

3.6 Experiment Setup

3.6.1 Single-Hop Contention Network

Characterization of contention in single-hop networks is important to understand. There are several factors that affect the success of a network, measured by its' accuracy and efficiency. For this project, contention in an 8-node, single-hop network, was analyzed for a separation distance of approximately five feet between the sink node and children nodes, shown in Figure 1. It is important that the distance between the children nodes and the parent/sink node is constant to allow equal opportunity for data transmission between the two levels. For all contention testing, nodes were left attached to a computer via USB cables to allow data to be downloaded to a PC for analysis after each test is complete. There were no metal objects or other sources that could potentially shield/absorb the transmitted signal within a 10 foot radius of the testing setup. All other wireless devices were removed from the testing room except for the laptop used for collecting data, and the wireless card was disabled for testing. The environment was made as low-noise as possible for an indoors testing area not in a shielded room. Address filtering was turned off for testing. This allows the user to specify the addresses of nodes to which others can communicate with. This is most commonly used in multi-hop networks to create the network configuration the user wants. In this case with the single-hop, all nodes were given the opportunity to talk to the parent/sink node. The directions of the nodes were all parallel so that the antennas were all facing in the same direction.

This allows for ideal transmission and reception and reduces the possibility of losses due to polarization mismatching between the antennas. The USB port was facing towards the user on all nodes. It is important to keep these directions constant due to the directional effects of the antenna on the Tmote.

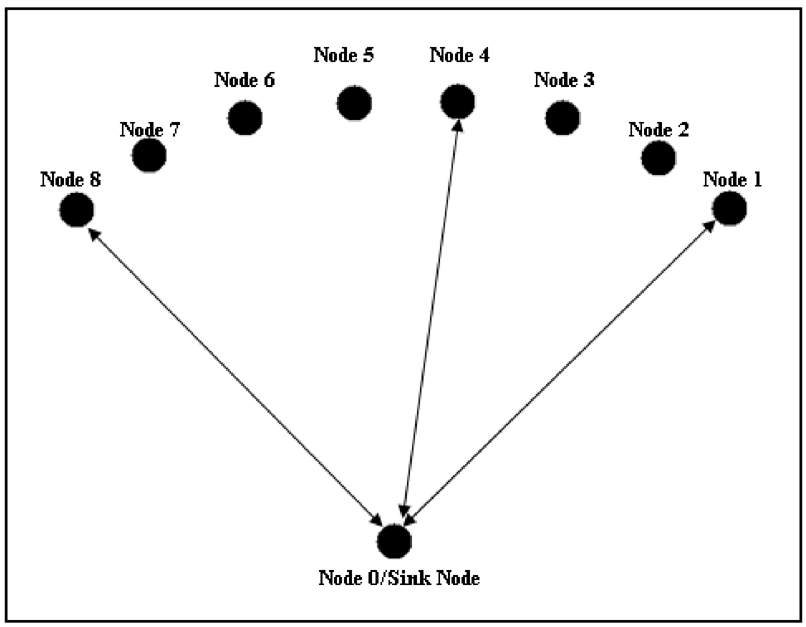

Figure 1: "Desktop" Setup for Single-Hop Network Testing

3.6.2 Antenna Orientation Within a Multi-Hop Network

The goal of the second portion of the project is to characterize multi-hop network data collected in a hallway. For this portion of testing, nodes were programmed then placed in a hallway at specific spots. These spots had been measured out and drawn out on a floor plan shown in Figure 2.

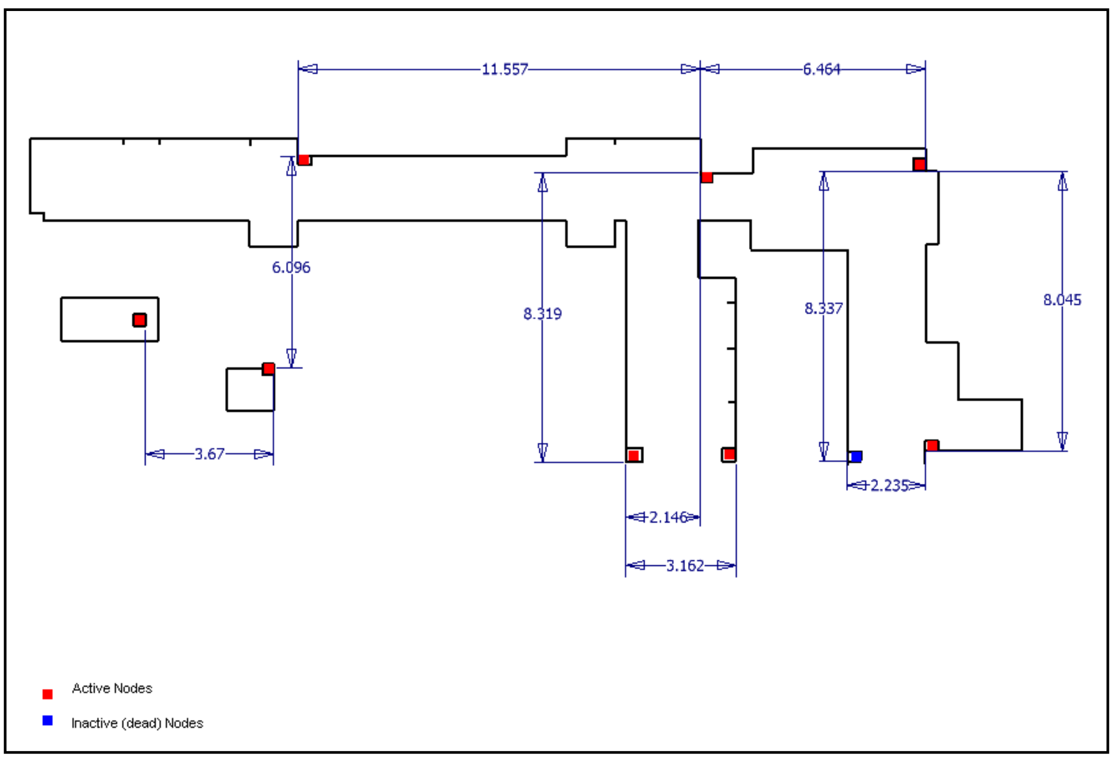

Figure 2: Hallway Setup for Multi-Hop Network Testing

This particular image shows reporting of a test where one node was not communicating with the network, as labeled. This is important to see distances between node placements. The actual test setup and node placement is shown in Figure 3.

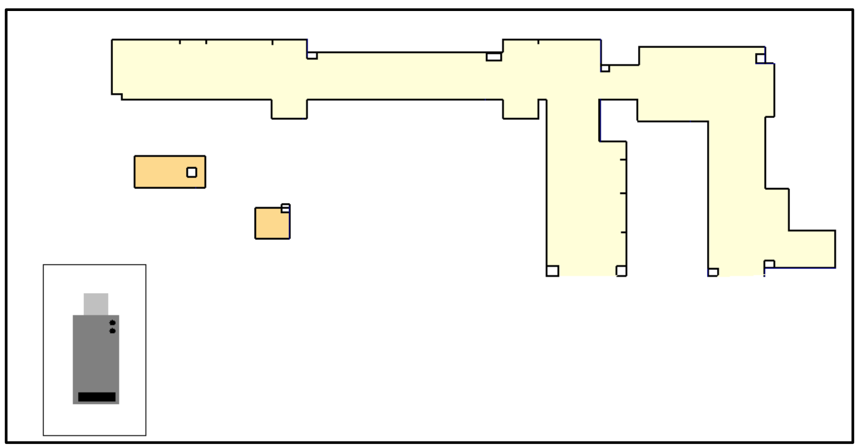

Figure 3: Initial Node Orientation and Placement

For each hallway test that was run, a sheet with the floor plan and node location was used to record testing results. This was done to keep node placement consistent, keeping distances between nodes consistent, allowing for more accurate data to be collected, and more consistent analysis. The data taken for these tests was in an empty hallway with no human traffic in the hallways during testing. The positioning of the nodes on the wall varied for each test, as the directionality of the antenna was being examined for multi-hop communications. For each test setup, the orientation of the nodes will be described along with the corresponding results. Once the nodes were programmed they remained in the same spot except for the rotation for each test. This meant that each test had the same program loaded onto the nodes, and were in the same location in the hallway so distances between nodes did not change throughout testing.

The Tmote sky nodes have an integrated antenna. While there is an expansion slot to attach an external antenna, only the on-board antenna was utilized for testing. The antenna is an Inverted-F microstrip design and is a wire monopole with the end folding over the edge of the node so it creates a plane parallel to the ground plane on the node. This antenna sticks out from the end of the board, away from the battery pack. When these are placed in the hallways, the battery pack is against the wall and thus the antenna would be coming out from the wall. The antenna radiates differently if turned vertical or horizontal. According to [5], the data sheet for the Tmote, it achieves a near-omni-directional pattern.

Chapter 4

Experiment Outline and Goals, Results and Analysis

4.1 SAMAC Layer of Protocol

Two files were used to manipulate the environmental parameters. This code is the base code used in the research group. In the two main files, Samac.c and Samac.h, the information to characterize the network and set parameter values were entered. Table 1 shows the lines of code changed in the Samac.h file which controlled the timeslot duration and inter-arrival time. The timeslot duration tick had to be changed with the timeslot duration and was always 1/5 of the duration.

Table 1: Program Statements For Timeslot Duration and Inter-Arrival Time Testing

Location in Code	***Line of Code***
Application Definitions	#define SAMAC_APPLICATION_UPLINK_INTERARRIVAL_MS (250)
TDMA Timeslot Definitions	#define SAMAC_TIMESLOT_DURATION_MS (180)
	#define SAMAC_TIMESLOT_DURATION_TICK (36)

Table 2 shows the code modified to determine power settings. In the Samac.c file, one of two setups had to be selected for a given test. The first is tabletop setup, indicating all nodes are connected to the computer via USB. This mode was used for the contention testing. The second is hallway testing setup; it is used for multi-hop network analysis and was used for the network topology creating with different antenna orientations.

Table 2: Program Statements for Power Level Testing

Location in Code	*Line of Code*
Nano-MAC Initialization	nmac_set_tx_power(3);

Each time the code was modified the code was re-made then loaded onto the nodes. Resetting the nodes allowed the new code to execute next time they received a command to communicate within the network.

4.2 Experiment Goals

4.2.1 Contention Testing

Three variables were altered throughout testing including: transmit power level, time-slot duration, and inter-arrival time (related to how many packets are sent per second).

Table 3 shows the three power levels used for testing and the corresponding power in dBm as referenced in [2].

Table 3: Power Level Settings for Tmotes

Power Level (SAMAC)	**Output Power [dBm]**
11	-10
7	-15
3	-25

Table 4 shows the different levels of timeslot duration and inter-arrival time (inversely proportionate to packets per second) used in testing.

Table 4: Independent Variables Under Test

Timeslot Duration [ms]	**Inter-Arrival Time [ms]**	***Packets per Second [#/1 sec.]***
200	**1000**	*1*
150	**500**	*2*
100	**250**	*4*
75		

The experiment was split up into three main sections according to the transmit power level. For each power level both the timeslot duration and inter-arrival time were varied. For each specific power level and timeslot, a group of testing was run for each inter-arrival time. Once all the inter-arrival times were tested, the timeslot duration was changed and each was tested. Once all combinations of timeslot duration and inter-arrival times were complete, the power level was changed and the entire process was run again. This process was repeated three times for all combinations of power level, timeslot duration and inter-arrival time. The average value of the three tests was recorded. This resulted in a total of thirty-six separate experiments conducted. The values recorded for each combination of variables is the average of three runs of the identical test. This was done to account for any outliers in a given test, and to stabilize results and get a more representative model of how the network performs with different environmental settings.

In practical applications, the inter-arrival time is specified for a given system and is not changeable by the user. For this research, the inter-arrival time is available for the user to change in order to test the strength of the network. Inter-arrival time is equal to 1/(packets sent per second). As the inter-arrival time is deceased, the number of packets sent per second increases. A network can only handle so much traffic and data trying to be communicated between nodes. The goal is to increase the number of packets per second sent and stress out the system until it breaks. This is executed to see how robust the network is, and to see how it would react in different situations given the set value for inter-arrival time in practical applications. As inter-arrival time decreases and the amount of packets sent each second increases, it is expected that since the load on the network is increasing it will reach a breaking point where the network is not being efficient. As power and inter-arrival time are held constant, the time-slot duration will be varied to determine the packet delivery ratio, PDR. The PDR is calculated as follows.

$$PDR = \frac{Packets\ Received}{Packets\ Generated}$$

This ratio is used to evaluate the reliability of the network. A goal of 90% PDR is expected to be characterized as a reliable network. This value is used to find the capability region for the network under different environmental conditions.

The other two variables under test have expected behaviors; as power decreases, so should the packet delivery ratio and as the inter-arrival time gets smaller, the PDR should decrease. The PDR should not fluctuate as much when the time-slot duration is decreased because the data is still being transmitted at the same power level and the same amount of data is being sent. If this becomes too small, there will be some drop-off in network performance as there is not enough time for communication within the designated timeslot.

4.2.2 Multi-Hop Network Characterization

The main goal of this portion is to characterize how the nodes form networks when oriented in different directions. Ideally, if the antennas on the modules were actually omni-directional, it should not matter the orientation, and the same network should be established consistently. Since these antennas do not radiate in this perfect pattern, there are nulls in its radiation/power pattern, meaning there are some places that do not receive as strong of a signal as others as you change placement with respect to making a circle around the antenna in its same plane. If there is a significant difference the nulls create when the network topology is being generated, this experiment will show that weakness and system users can decide if the difference in the system performance in regards to orientation is important for the application or if it does not make a difference.

Depending on the orientation of the nodes, the network will create a different network based on the antennas inconsistent radiation pattern. The nodes were placed around the hallway in specified locations and the test was performed three times for each node orientation. The layout/topology of the multi-hop networks was recorded. The nodes were turned three different ways: antenna pointing up, antenna pointing left [pointing towards sink node] or antenna pointing right [pointing away from sink node]. Figures 4 and 5 show the on-board antenna's power pattern when oriented in both a horizontal and vertical fashion.

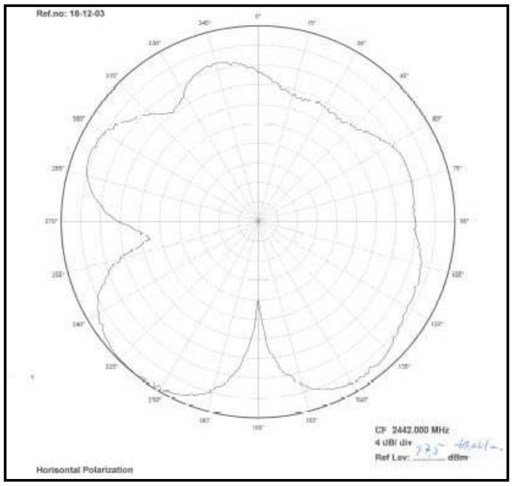

Figure 4: Power Pattern for Horizontal Orientation [5]

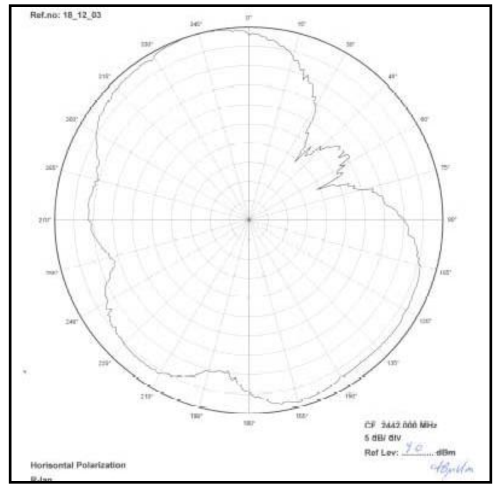

Figure 5: Power Pattern for Vertical Orientation [5]

The two radiation patterns corresponding to the direction the node is mounted are not identical. Depending on the orientation of the node, the antenna may not be radiating equally in all directions, and in particular, in the direction of neighboring nodes. Usually a change in this orientation would rotate the pattern but as one can observe there is a slight variation in the two patterns. For the horizontal orientation (USB port on the left end), the nulls come from the direction of the on-board USB port, theta=180°, and perpendicular from the long side of the module where the antenna makes the bend, at theta=-90°. Another null would be expected at theta=90°, opposite the other null from the antenna, but this did not appear. For the vertical orientation (USB port pointing down), the null appears in the same location as the second null for the horizontal orientation; appearing perpendicular to the long side of the module, where the antenna makes the bend. For this orientation the null seems to consume angles of theta=30° to theta=60°. Talking with an expert in the electromagnetics field [4], these power patterns are most likely not reproducible, and the takeaway from these plots is that the pattern is not consistent. The best way to characterize the antennas would be to measure a new power pattern for each orientation or just turn the nodes in the network and analyze the results. Due to budget constraints, only the second suggestion was an option.

The differences in the patterns and irregularity of the patterns is most likely due to the circuitry on the module, the addition of the battery pack underneath the board, and also the effects from the USB port on the opposite end from the antenna. The VSWR plot for the module when the battery pack is attached is shown in Figure 6. From examining the return loss on the right graph, as frequency is varied so is the return loss. This means that if the transmitted signal frequency has some error component or noise or interference changes the appearance of the signal, its strength could change by a small amount. At the center frequency of the device, the return loss is -5dB.

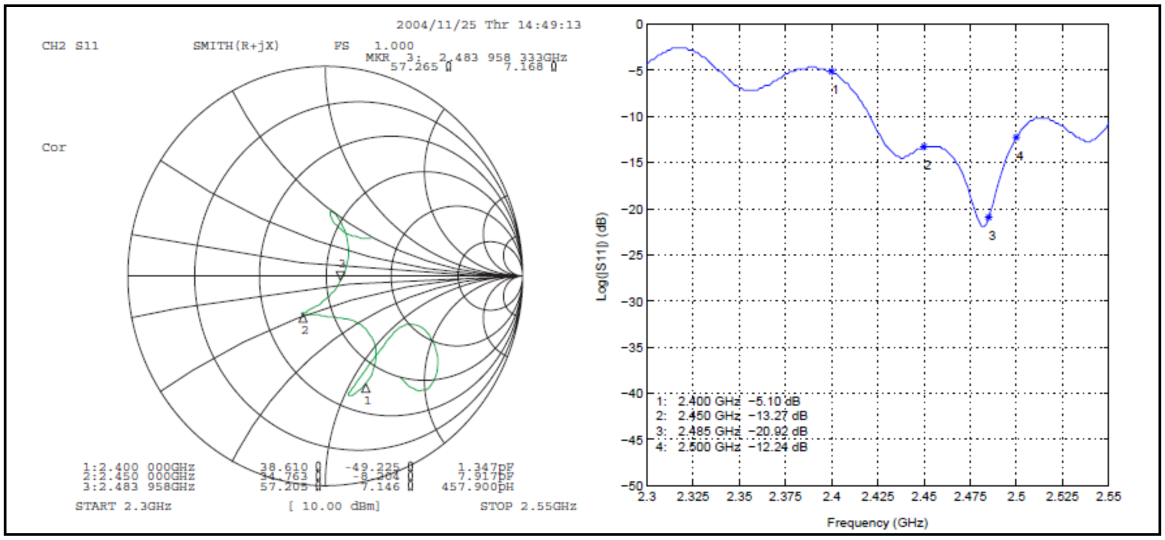

Figure 6: VSWR for Module with Attached Battery Pack [5]

For this test the power level was set at 11, the inter-arrival time was set at 1000ms, and the timeslot duration was 200ms. Tests were repeated three times.

4.3 Experimental Value Effects and Experiment Results

4.3.1 Transmit Power

Three transmit power levels were used for testing, levels of 3,7,11, corresponding to -25dB, -15dB, -10dB. The network performed best at the higher power level which was expected. The lowest power level of 3 caused problems when the number of packets-per-second transmitted was at its peak and the time slot duration was below 200ms. Power falls off at $1/r^2$, where r is the distance between the transmitter and receiver, and thus as the power level is lowered or distance between nodes is increased, the power received is not linearly proportional. While a power level of 11 was successful for all transmissions of testing even with lower packet delivery ratios with a higher number of nodes, it is important to examine lower power settings to see if one could obtain similar network performance results while consuming less power.

At a power level of 3, there are problems with communications at the lower time-slot durations, and with a higher packet generation rate. This seems impractical for a variety of situations. Lastly, since this testing was done with a distance of 5 feet between the sink node and child nodes, as distance is changed the power received by the children nodes will reduce at a higher rate due to the correlation of the two variables. This is important to note as there is a threshold setting in the SAMAC layer that determines at what power level the node will stop accepting communications and only look for data at higher power levels. If the distance between nodes will be significant it is important to look at the threshold for communication so that nodes would still have the opportunity to talk to several others, further away than initially possible.

Figure 12 through Figure 14 in the Appendix A show how when inter-arrival time (i.e. Number of packets per second transmitted) is kept constant and multiple timeslot duration times are tested, how the different power levels affect the corresponding PDR.

These graphs are shown in order for an inter-arrival time of 1000ms. The other graphs for inter-arrival times of 500ms are shown in Figure 16, Figure 19, Figure 22 and the results for inter-arrival time of 250ms are shown in Figure 17, Figure 20, Figure 23 in Appendices B, C and D, respectively. After the graphs for an inter-arrival time of 1000ms are presented, the following graphs are shown in a different order since each change in inter-arrival time showed the same pattern of a power level of seven yielding the best performance based on capability limit. The capability limit is chosen when all graphs for timeslot duration meet the 90% PDR requirement.

Table 5 shows the capability limit, rounded down to the closest integer value for node count, corresponding to a given timeslot duration and power level. This table sums up what the series of graphs following the initial order would show. The graphs in Appendix B, C and D, as previously mentioned, use a different pattern to display the data. In these appendices, the power is kept constant for each set of three graphs, and the inter-arrival time is changed. On each graph, four sets of timeslot duration data are shown.

Table 5: Capability Limits for All Timeslot Durations Combined

Inter-Arrival Time (ms)	***Power Level***	***Capability Limit (no. of nodes)***
1000	11	4
1000	7	7
1000	3	5
500	11	4
500	7	5
500	3	3
250	11	3
250	7	3
250	3	2

A power level of 7 yields the highest capability limit for each inter-arrival time. The same trend appears in all sets of timeslot durations as power is varied. For the lowest inter-arrival time, the highest capability limit is achieved at both a power level of 11 and 7, but for all three inter-arrival times, the power level of 7 obtains the best network performance.

4.3.2 Inter-Arrival Time

Inter-arrival time is the amount of time between packet transmissions. As the inter-arrival time becomes lower, the packets-per-second being transmitted increases. Three transmission rates were tested: 1 packet-per-second, 2 packets-per-second and 4 packets-per second. In general, the inter-arrival time/packet generation rate, is not something the user can specify. The application or specific system usually has constraints that determine this value. This variable was added to the SAMAC layer by the OSU Research Group to test its effects on different network topologies to gain a better understanding of the networks. A distinct pattern appears across each power level, as the inter-arrival time is decreased. The point at which communication falls off, which can be measured as the point at which the PDR falls drastically below the 90% goal, decreases as the inter-arrival time is decreased. This is expected due to the fact that the faster packets are being sent, the more likely a packet will get dropped during transmission. Also, as more nodes are communicating on the network and trying to simultaneously send more date, the load increases more than with just one factor, further explaining this behavior. Depending on the number of nodes that will be contending for data exchange with the sink node, a combination of inter-arrival time and timeslot durations could be used to meet system performance requirements.

Looking at the graphs for a power level of seven in Appendix C, then looking at the inter-arrival time, values of 1000ms and 500ms for inter-arrival times yield the most reliable networks. When the inter-arrival time is 250ms, only three nodes can be used to have an optimum network and meet the 90% PDR goal. For an inter-arrival time of 500ms, five nodes can be used to create an optimum network, and for an inter-arrival time of 1000ms, seven nodes can be used. For this type of network, the two inter-arrival times of 1000ms and 500ms are chosen as ideal settings for the network to be optimized.

4.3.3 Time Slot Duration

Four time-slot durations were tested including 200ms, 150ms, 100ms and 75ms. Initially the smallest time-slot duration was set at 50ms, so there would be a 50ms interval between all durations, but reception was hard at this small of a time-slot duration and the packet loss rate was extraordinarily high, so the lowest duration used for testing was changed to 75ms to obtain data that would be more useable than that of a 50ms time-slot duration. This variable should have the least effect on the network performance due to its definition. The timeslot is made up of four main areas in the following chronological order: guard time, sync time, contention time, and guard time. The guard time is set in the SAMAC layer at 5ms and is there for padding in transmission. If the nodes get off-synch with each other this extra time in the timeslot should allow for transmission of previous data to end before the next node in line begins communication. The second part of the time slot is the sync time. During the sync time the node is communicating and synchronizing with its parent node to get any required information about transmission including which nodes it talks to and when it can talk and how long it can talk for. Like the guard time, this time is set to duration of 5ms in the SAMAC layer. The third and most time consuming portion of the timeslot is the contention time. During contention the node is communicating with its parent and children nodes to execute transmission of the message. This portion of the timeslot is actually broken down further into back-off time and transmission time. The back-off time is assigned randomly from the SAMAC layer, and is a period of time (between 0-15ms) where the node does not communicate and waits to make sure the channel is free before communicating. The node with the shortest back-off time, which was assigned randomly, will be the one that can communicate first in the channel during contention. The final portion of the timeslot is the guard which is in place to make sure communications are complete before the next round of communication begins; its duration is 5ms. Ideally the timeslot duration would have minimal effects on the network, but as the timeslot gets closer, there is a smaller window of time for the nodes to communicate within. Figure 7 shows the setup of an individual timeslot.

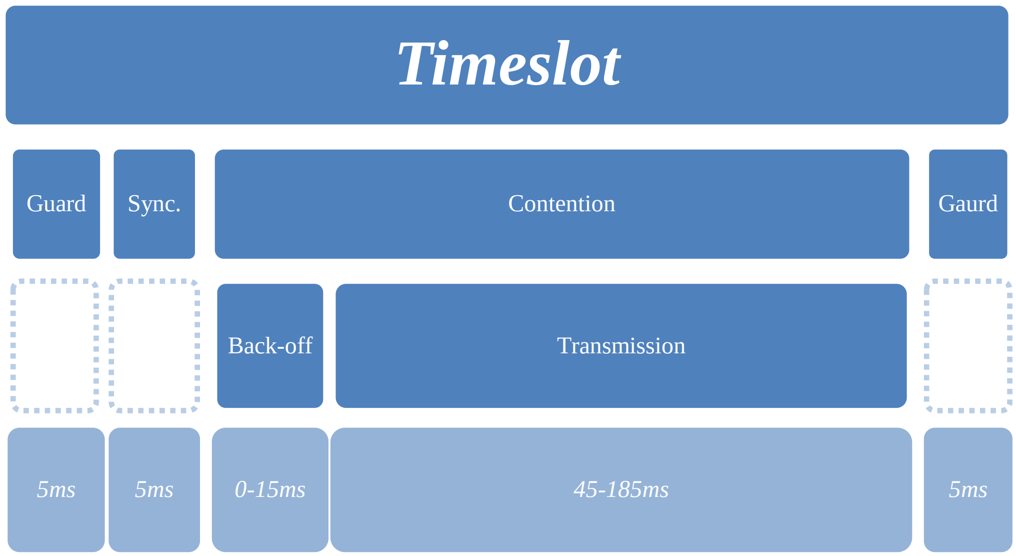

Figure 7: Timeslot Dichotomy

For the timeslot durations under test, the actual transmission time can last anywhere from 45-185ms. When the timeslot was at 50ms, the shortest possible duration for transmission was 20ms, which is a very small time period to transmit the packets and allows for greater error. This allows for a greater possibility of no data transfer which was the case in initial testing and thus why the lowest timeslot duration being studied was 75ms. Because of the great span of possible data transmission, the timeslot duration did have an effect on the performance of the network. The smaller timeslot durations consistently had the average lowest packet delivery ratio. In some cases the PDR was still above the 90% PDR goal, but was lowest compared to the longer timeslots. Depending on the system configuration and what inter-arrival time is specified, a corresponding timeslot duration could be chosen to have optimal performance but while saving power and time. For an inter-arrival time of 250ms at a power level of 3, only the signal with a timeslot duration of 200ms worked successfully. For all other values of timeslot duration, no data was successfully transmitted and received.

The ideal inter-arrival time was found to be 500ms or 1000ms and the ideal power level was found to be set at a level of 7, as determined in the previous sections. Figure 18 and Figure 19 in Appendix C were analyzed for all timeslot durations at the given ideal inter-arrival times and power levels. To have six nodes all achieving the 90% PDR goal, a timeslot duration of 200ms or 150ms should be used. Expanding this to five nodes achieving the 90% PDR goal, all timeslot durations could be used. These conclusions can be obtained from the referenced graphs.

4.3.4 Tmote Orientation

The setup for each node orientation test was identical except for the orientation of the node. The network topology achieved from the different orientations is shown in the figure with the corresponding achieved networks.

4.3.4.1 Vertical Orientation, Antenna Down

Figure 8 shows the network topologies created when the software was run on the nodes. The orientation of each module on the wall is shown in the figure. Two paths were created; one that follows the blue bath including the purple branch, and the other branching off at node 3, where the red line is shown and continuing to the purple line.

Node 5 shows where that node was the child node for two different parent nodes, nodes 2 and 3, depending on the test. This is the only variation found among the two paths that were created for network communications.

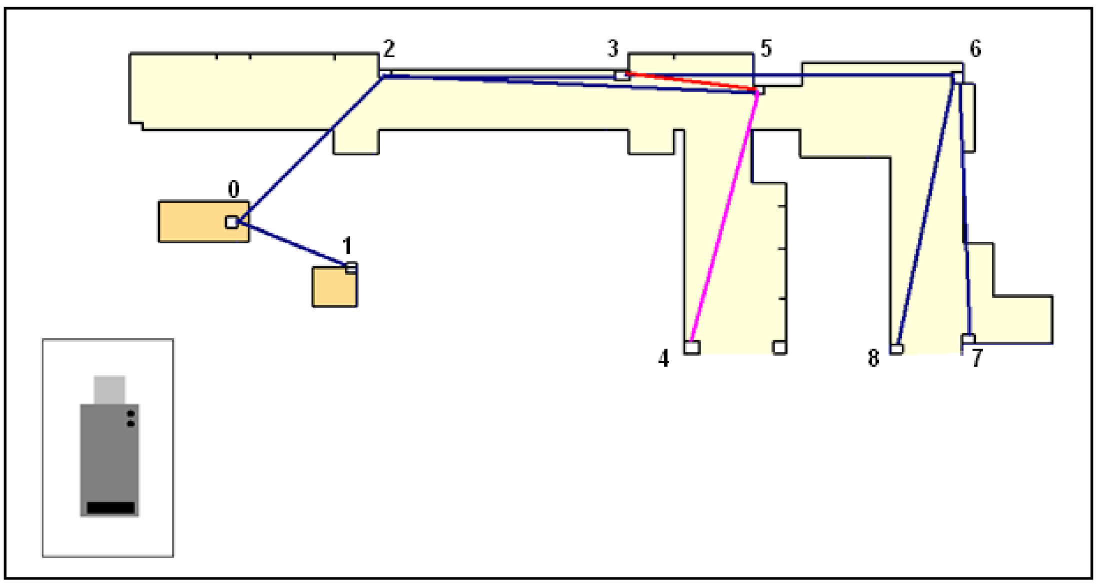

Figure 8: Network Topology for Vertical Orientation

For this orientation, only two paths were chosen. As previously discussed, the routes each node takes when choosing child/parent nodes is determined by the Bellman Ford method and chooses the least number of hop counts back to the sink node. Part of the time, node 5 had the parent closest to it, node 3, and part of the time its parent was the one furthest to the left in the hallway, node 2. The routes established in this orientation all appear to be the assumed route the nodes would take when forming the network.

4.3.4.2 Horizontal Orientation, Antenna to the Left

Figure 9 shows the network topology created when the node was rotated 90° clockwise. When all nodes were in this orientation, and the test was run three times, only one network was created. The routes each node used to communicate back to the sink node are shown in red. There are two strange observations from looking at this figure.

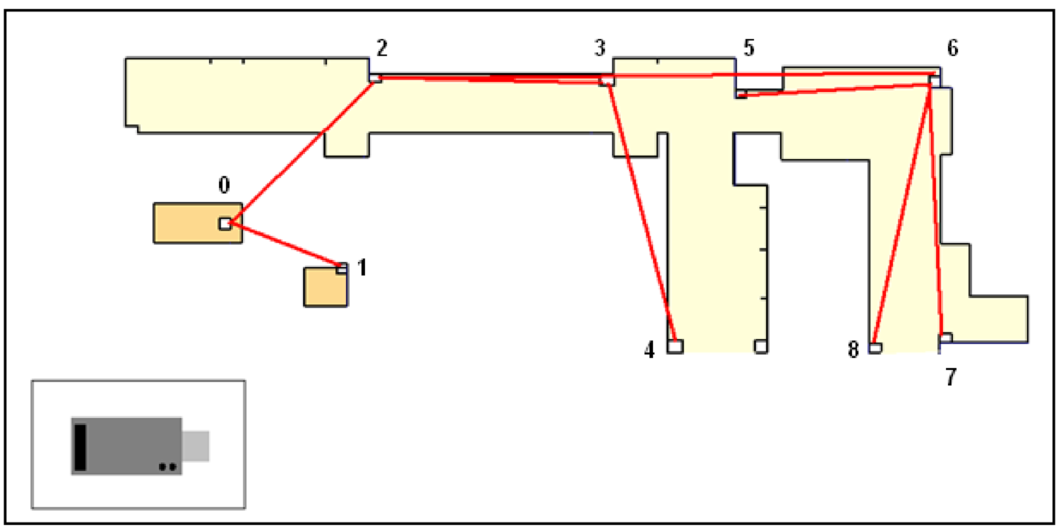

Figure 9: Network Topology for Horizontal Orientation, Antenna to Left

The first is that node 2 has a child at the furthest right end of the hallway, node 6, skipping over two other nodes, nodes 3 and 5. Also nodes 3 and 5 in the center do not connect. Node 5 has a parent to its right, node 6 which is an unpredicted connection. While these are strange observations, the network always creates the same topology which is reliable. It appears to have strong signal strength due to the distance of some of the parent/child node pairs. Even though the same network is laid out each time the test is run, if something were to get in the way of these paths, the entire network might be interrupted and not be able to communicate in its established network. Some diversity in paths would yield more reliability in an uncontrolled environment.

4.3.4.3 Horizontal Orientation, Antenna to the Right

Figure 10 shows the network topology when the node was rotated 180°.

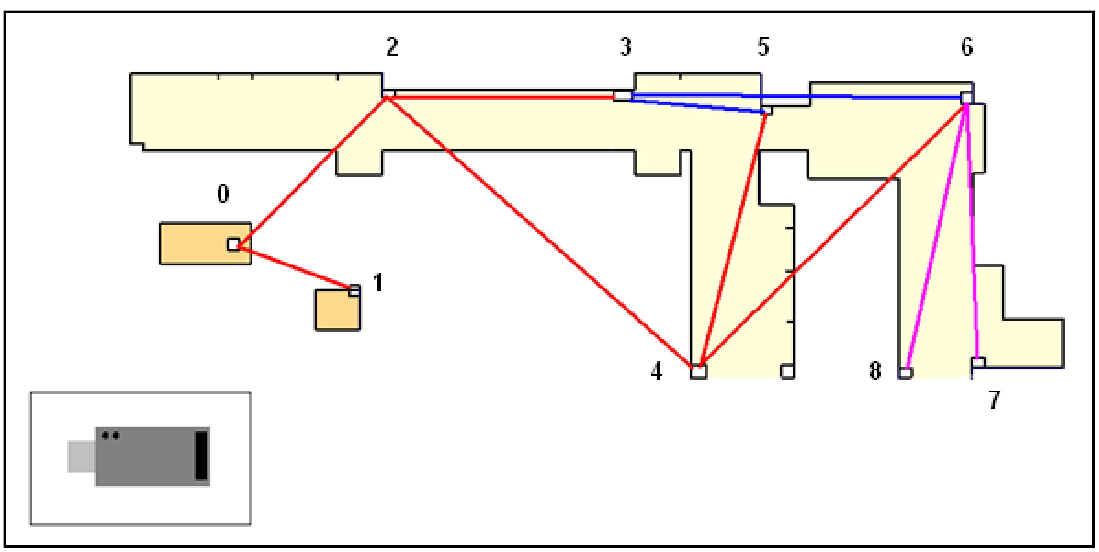

Figure 10: Network Topology for Horizontal Orientation, Antenna to Right

Throughout the three tests, two distinct routes were created. The first is the red path connecting with the purple path. The second path starts with the red path, then branches out at node 3 where the blue path is shown, then connects with the purple path at node 6. Nodes 5 and 6 have different parent nodes for a given test. This can be observed by tracing the lines back for both the red and blue routes.

What is interesting about this orientation is that the nodes connect across large distances that do not seem intuitive. For example, the one connection appears to be going through the wall from node 2 to 4. Whether or not the signal bounces through the hallway to make the connection or goes through the wall, either indicate strong signal strength. Also, the strength of the signal can be seen again on the right hand side where the signal appears to bounce through the hallways again from node 4 to 6, or goes through the elevator shafts. The elevators are located between the hallways where containing node 4 is and nodes 7 and 8. Node 3 connects with the furthest right node, node 6, skipping its neighbor, node 5, which is not intuitive. Also note this orientation yields two different paths that are separated by approximately eight meters, the approximate distance between nodes 4 and 5.

This orientation is said to be the most robust and yield the most reliable network. The two paths this network creates are very diverse towards the middle. In an uncontrolled environment, if something entered the environment that caused a disruption in transmission of data or would not let nodes finish their presumed path, this orientation allows for two routes separated by a significant distance. If something disrupted the signal in the top hallway in the figure, the network could still be created with the red to purple path. Again, the elevators are the right inlet on the right side of the drawing between node 4 and nodes 7 and 8. If the area by the elevators became crowded or if a delivery had been made and items were sitting near the elevator, the red to purple path might not be possible and then the red to blue to purple path would be utilized. Because of the apparent signal strength and diverse routes, this is stated to be the most reliable orientation for all nodes to be when placed on the wall in this type of configuration.

4.3.5 Reporting Results

Graphs were made in two groupings. The packet delivery ratio was plotted for each combination of unique power level and inter-arrival time while the time-slot duration was varied on each of these combinations. An example of data reporting format is shown in Figure 11 for an inter-arrival time of 500ms [2 packets/second] and a power level of 7 [-15dB].

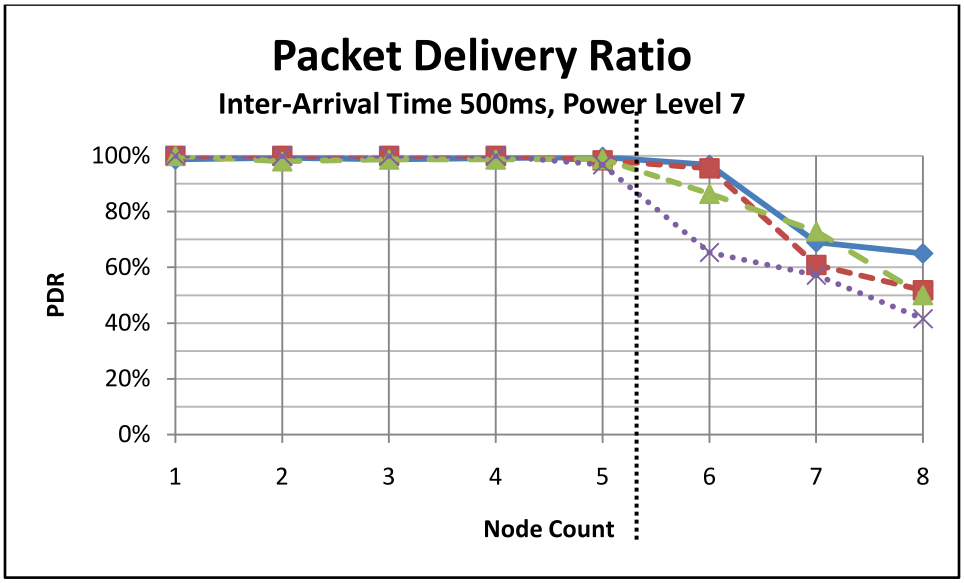

Figure 11: Example of Graph Layout

All graphs for each combination of power level and inter-arrival time are shown in the Appendices are previously referenced.

Chapter 5

Summary of Results

5.1 Single-Hop Network

When looking at environmental constraints in a single-hop network a few protocol become apparent. First, it is important to realize there is an ideal power level for a given distance. Through this testing it showed that for this setup, with five feet separating the children node from the parent/sink node, the ideal power level of the three tested was the middle level, a setting of 7. While logically one would assume the larger power level would yield a more reliable network, this was not the case.

Second, while the inter-arrival time is usually set by the application and is not something the user can change, it is important to know how this variable interacts with other variables. It is obvious that if the inter-arrival time is too low, meaning a large amount of packets per second are being transmitted, the network will saturate and the network will not be performing optimally and may not be able to successfully transmit or receive data at all.

Table 5 from section 4.3.1, shows the variation of the number of nodes meeting the PDR goal with varying power levels for each inter-arrival time. While with this network, as the inter-arrival time is decreased, the network performance is also generally decreased. However, if the network application requires a lower inter-arrival time, boosting the power level can help increase the number of nodes meeting the goal. Also, changing the time slot duration to a large number would also increase this number as was previously shown.

Lastly, it was shown that the timeslot duration for this type of setup can be reduced to 100ms without greatly affecting the network. If it is lower than 100ms, the particular situations need to be examined case by case to determine if the right network performance can still be achieved with the smaller timeslot duration.

For this particular setup, the network was characterized as having good performance if six or more nodes could meet the goal of 90% PDR. When examining the patterns of data for eight nodes, no patterns could be found. All of the data seemed to be shifted yet follow the same slope for the PDR. Figure 27 shows a graph attempting to analyze eight nodes. The drastic performance separation between time slot durations for a given inter-arrival time did not collate. For six nodes, a pattern of collation emerged for larger timeslot values. Figure 24, Figure 25, and Figure 26 show the relationship between timeslot duration and inter-arrival time at each power level for a six node network. For the power level of seven and an inter-arrival time of 1000ms and 500ms, the network met the goal for timeslot durations down to 125ms for the 1000ms inter-arrival time and 150ms for the 500ms inter-arrival time. These graphs show the capability limits for a six node network, and which combinations of timeslot duration and inter-arrival time can be chosen and still satisfy network performance requirements.

Overall, for the network under test, the ideal power setting was found to be at a level of 7. The ideal timeslot duration was 200ms and 150ms, with 100ms being border-line for strong network. Lastly, the ideal inter-arrival time for this type of network, if it was easily changed or set by the user would be either 500ms (two packets per second) or 1000ms (one packet per second).

5.2 Antenna Orientation in Multi-Hop Network

The network orientation was shown to have an effect on how the network creates paths from individual nodes back to the sink node. Since documentation on the antenna power pattern was not observed to be useful for analysis since it did not look repeatable, there are no strong guidelines that can be obtained from this test. Since different network topologies are found when the node is rotated in different orientations, it is obvious that the antenna direction is important. To obtain the network with the best performance it would be ideal to test the network in the specific location with different antenna orientations to determine which orientation gives the ideal network that the user desires.

For this particular setup, having the antenna turned to the right (USB pointing to the left) for each node location on the wall resulted in the optimum network with the ideal performance and reliability.

Chapter 6

Continued Research Projects in Field

Expansion of this research could be important to further characterize multi-hop networks. While most of this research was done with a single-hop network in contention, it would be important to look at the problems with multi-hop networks, and how to optimize them. Multi-hop situations will always exist concurrently with contention, so it is important to first understand contention, then how multi-hops converging in a contention situation react. All of the existing problems and obstacles with a single-hop contention are complimented with new problems from the multi-hops and would be important to learn the different problems during contention and multi-hop communications.

The following are examples or future research that could be done in both the networking and antenna areas using the Tmote Sky devices, unless otherwise noted.

(1) Repeat the experiment as outlined except for multi-hop instead of contention.

(2) Keep the single-hop structure and vary the distance for the same tests with the power level constant at a level of 11, to see if the phenomena of a smaller packet delivery ratio for higher power level can be explained, or further validated.

(3) Keep the single-hop structure and vary the distance between the children nodes and the parent/sink node, and see if similar patterns emerge at different distances, or if each setup has unique performance.

(4) Keep both the single-hop and multi-hop structures, and vary the physical environment. Such new environments could include: a crowded hallway instead of an empty one, a wet environment (after rain, for example), or in a room crowded with objects.

(5) Decrease the back-off time in the SAMAC code which would allow for more transmission time of the actual signal. Currently the most recent code has a back-off time of 1ms, with 5ms being the largest used in the code. The back-off time of 0-15ms was a large range initially set in the code to determine its effects on network performance.

(6) Measure the power pattern of the Tmote Sky to accurately characterize its' antenna. This verification can be used for more detailed analysis of antenna position and also verify if the specifications sheet shows a proper power pattern for the antennas.

(7) Use the ETRI nodes that the PhD students in this group are using with both sectored antennas and omni-directional antennas to see if sectored antennas can be more reliable than the omni-directional antennas.

Chapter 7

Conclusion and Real World Applications

The performance of wireless sensor networks is dependent on several factors. Some of those are not controllable by the user including physical environmental effects, noise and interference. Other factors that can be controlled by the user and add to the success of a network include power level, timeslot duration, and if applicable, inter-arrival time. With combinations of the above controllable factors, parameters and guidelines can be established for specific types of network uses, enabling the network to be classified as reliable for a given packet delivery ratio at a set capability limit. Since most of this type of research is done to simulate an actual environment, with extensive testing and environmental manipulation, the network can perform up to specifications, be reliable, and work efficiently, saving both power and time.

The concepts learned by studying small wireless sensor networks can be applied to larger networks, and processes created to test small networks can be modified to test large, robust networks. It is important for the user to understand how to make a network fail and also how to prevent a network from failing. Knowing both sides to this will keep the user in charge of the system. Further research in this area can greatly benefit society.

With climates or habitats that are hard for people to constantly access and monitor, these networks can be set up and left and can transmit data over a period of days, weeks and months- depending on the application and how long the nodes were transmitting, receiving and processing data on a daily basis. Networks could be set up in buildings to monitor light use and motion and if there are not people in rooms to turn off lights or heat/air conditioning, and when a nearby sensor detects movement, a signal can be sent to neighboring nodes to turn on the lights or another device that was temporarily shut off to save power. Wireless sensor networks can also be used in combat to protect troops by detecting intruders in surrounding areas, or recording a change in surroundings which can be relayed to local troops who can act on the news. These types of networks could also be used for elderly with in-home alert systems to alert the police if a fall or accident has taken place, and the person is not near a phone. The wireless sensor network could be used to transmit data from when a potential emergency button is pressed and trigger a number to be automatically dialed by the phone. These types of systems could also be used in home intrusion prevention. As technology like this becomes more reliable, and easier to classify for specific network tasks, lives can, and will be, both changed and saved.

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APPENDIX A: PDRs for Inter-Arrival Time of 1000ms

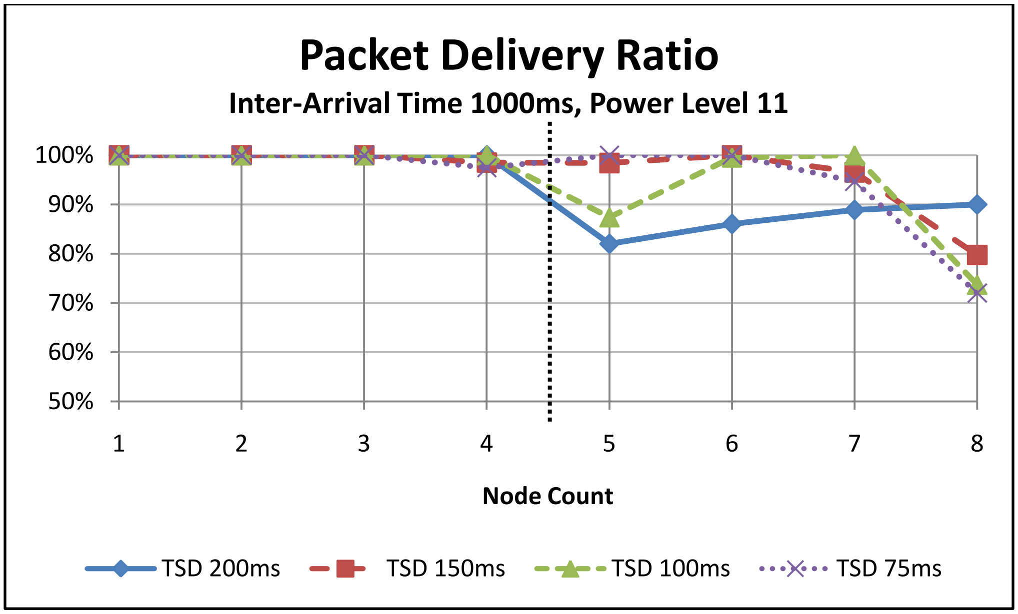

Figure 12: Packet Delivery Ratio with Constant Inter-arrival Time, Varying Power of Level 11

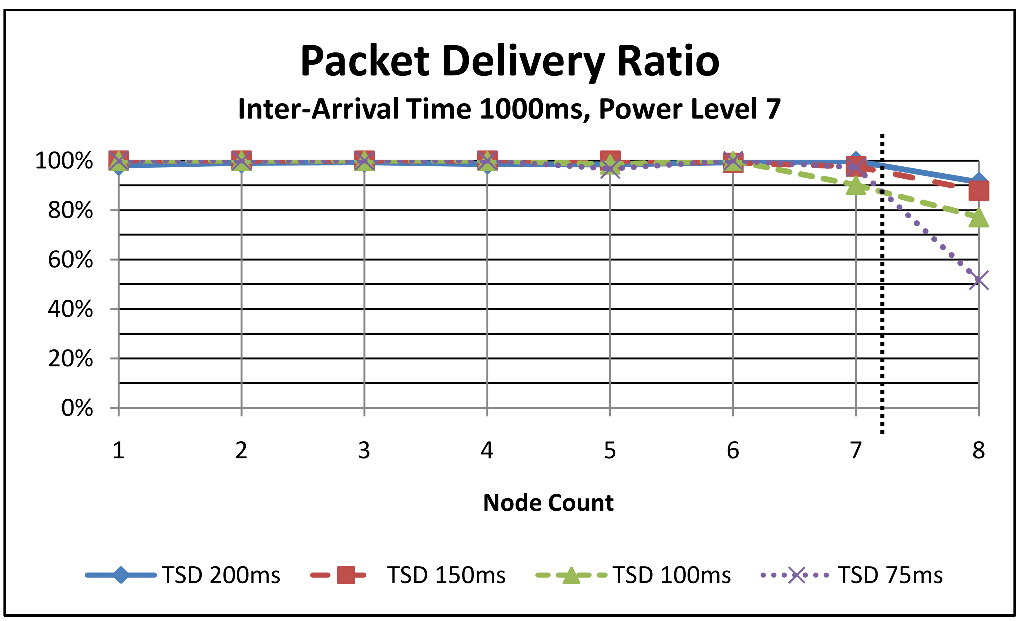

Figure 13: Packet Delivery Ratio with Constant Inter-arrival Time, Varying Power of Level 7

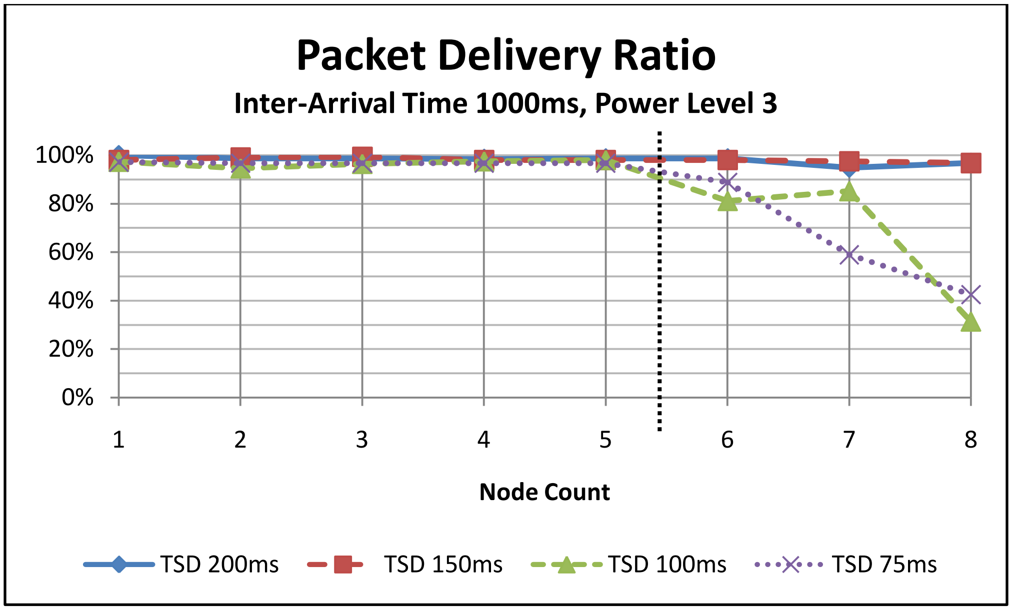

Figure 14: Packet Delivery Ratio with Constant Inter-arrival Time, Varying Power of Level 3

APPENDIX B: PDRs for Power Level of 11

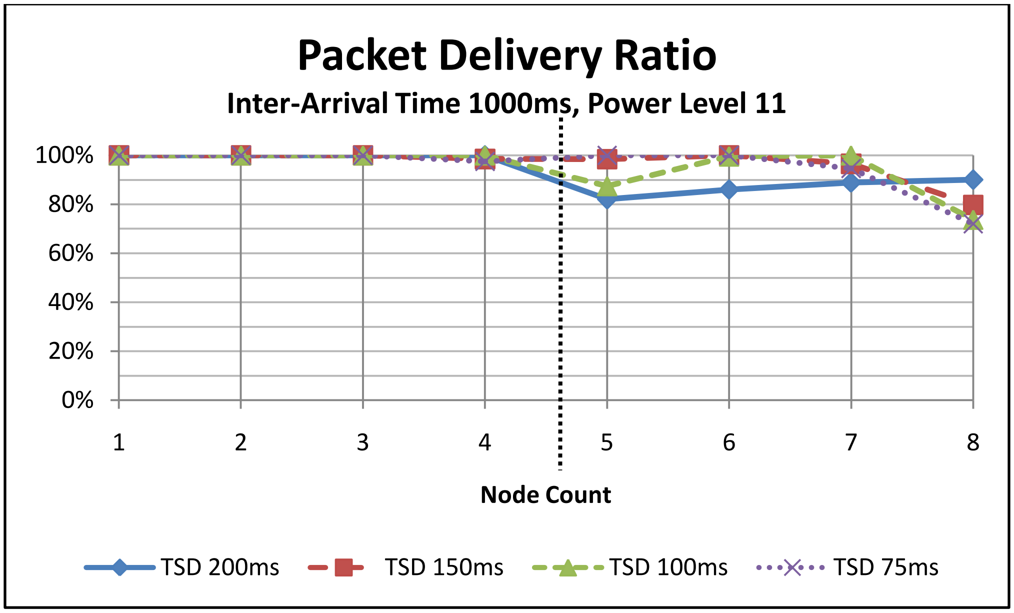

Figure 15: Packet Delivery Ratio for Varying Timeslot Durations and Node Counts (Inter-arrival Time=1000ms)

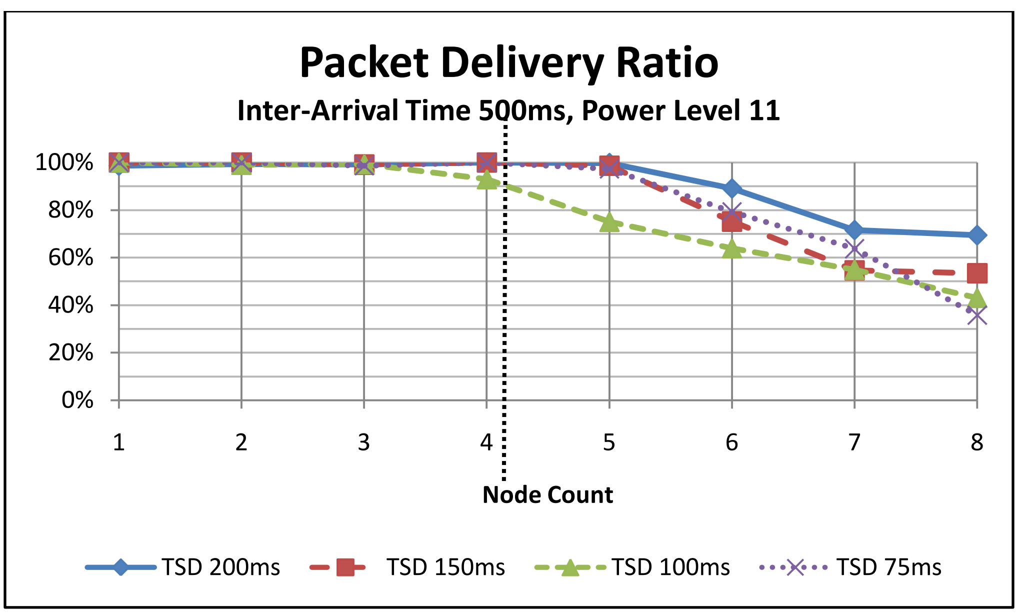

Figure 16: Packet Delivery Ratio for Varying Timeslot Durations and Node Counts (Inter-arrival Time=500ms)

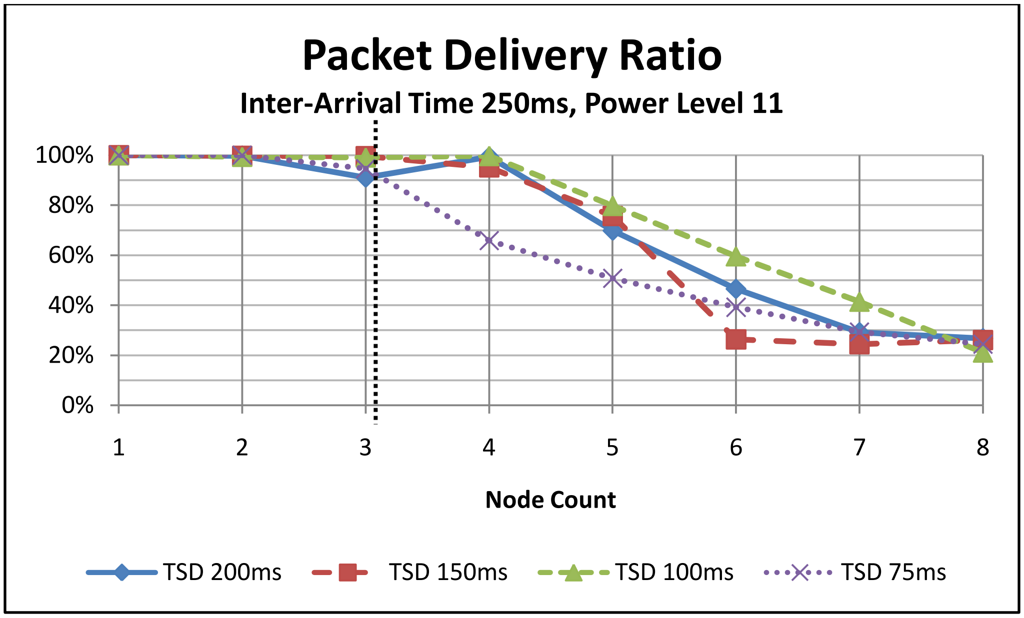

Figure 17: Packet Delivery Ratio for Varying Timeslot Durations and Node Counts (Inter-arrival Time=250ms)

APPENDIX C: PDRs for Power Level of 7

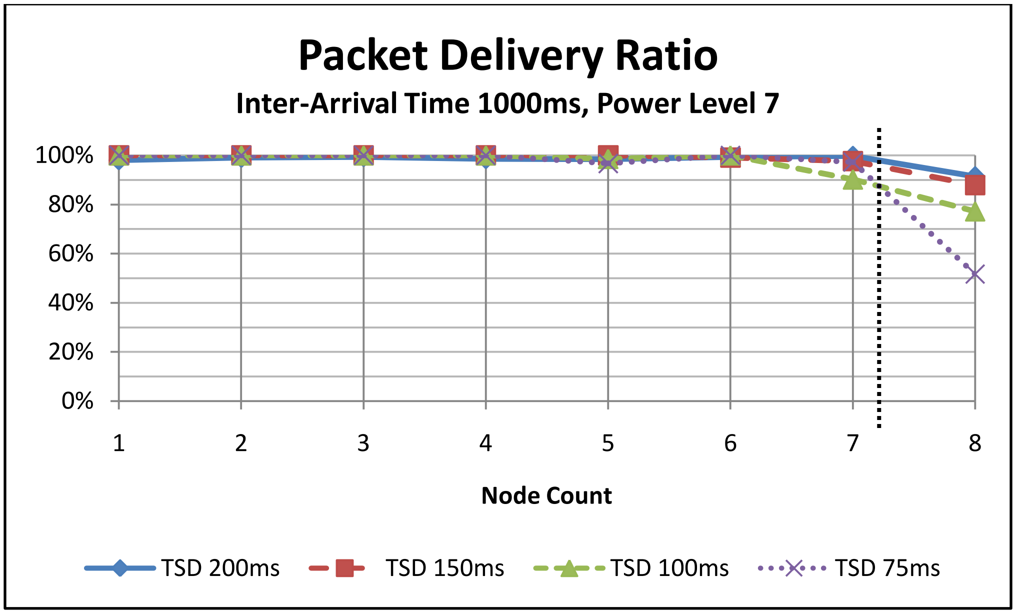

Figure 18: Packet Delivery Ratio for Varying Timeslot Durations and Node Counts (Inter-arrival Time=1000ms)

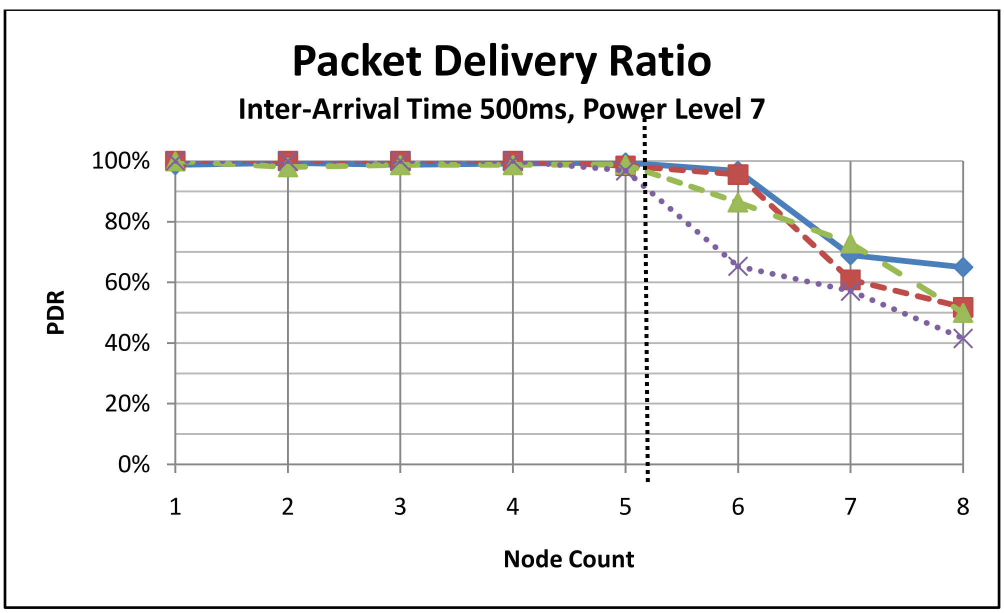

Figure 19: Packet Delivery Ratio for Varying Timeslot Durations and Node Counts (Inter-arrival Time=500ms)

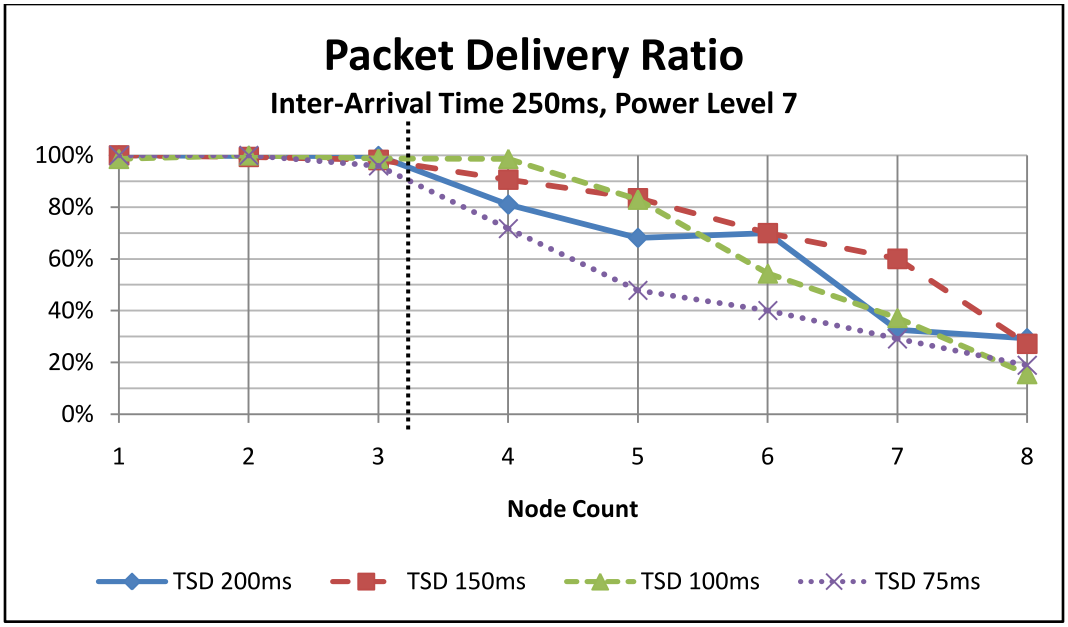

Figure 20: Packet Delivery Ratio for Varying Timeslot Durations and Node Counts (Inter-arrival Time=250ms)

APPENDIX D: PDRs for Power Level of 3

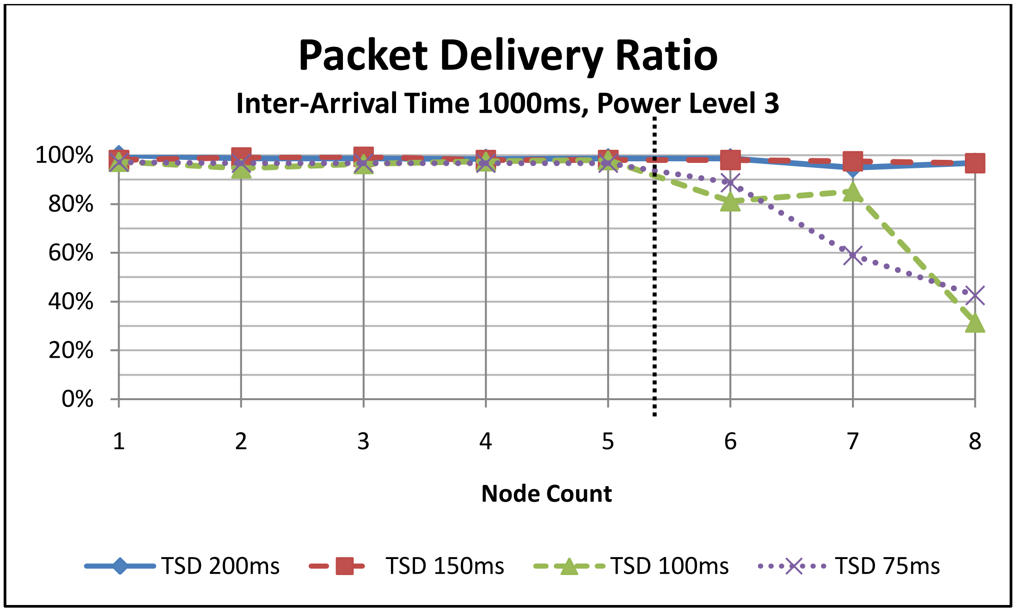

Figure 21: Packet Delivery Ratio for Varying Timeslot Durations and Node Counts (Inter-arrival Time=1000ms)

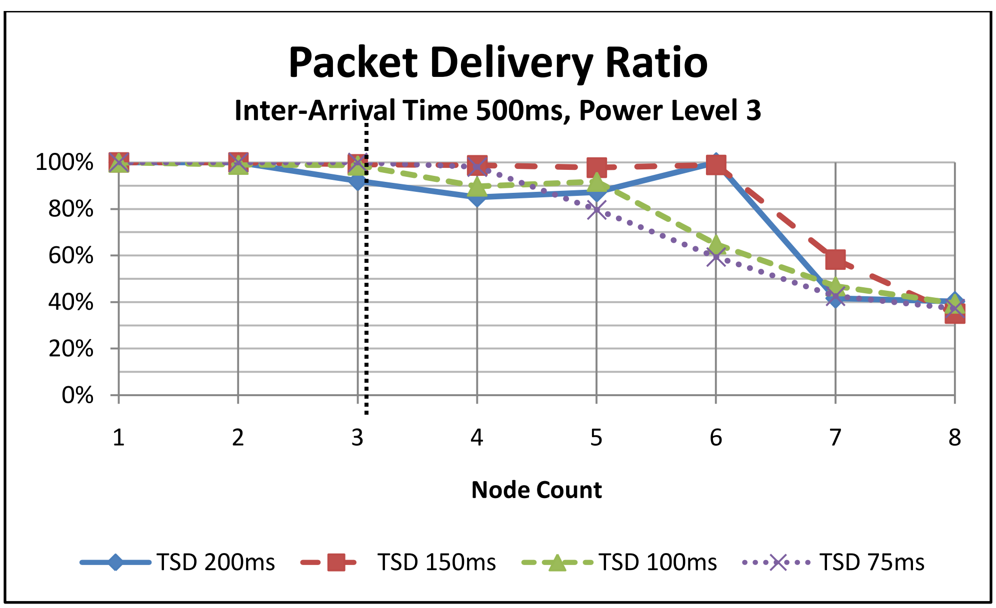

Figure 22: Packet Delivery Ratio for Varying Timeslot Durations and Node Counts (Inter-arrival Time=500ms)

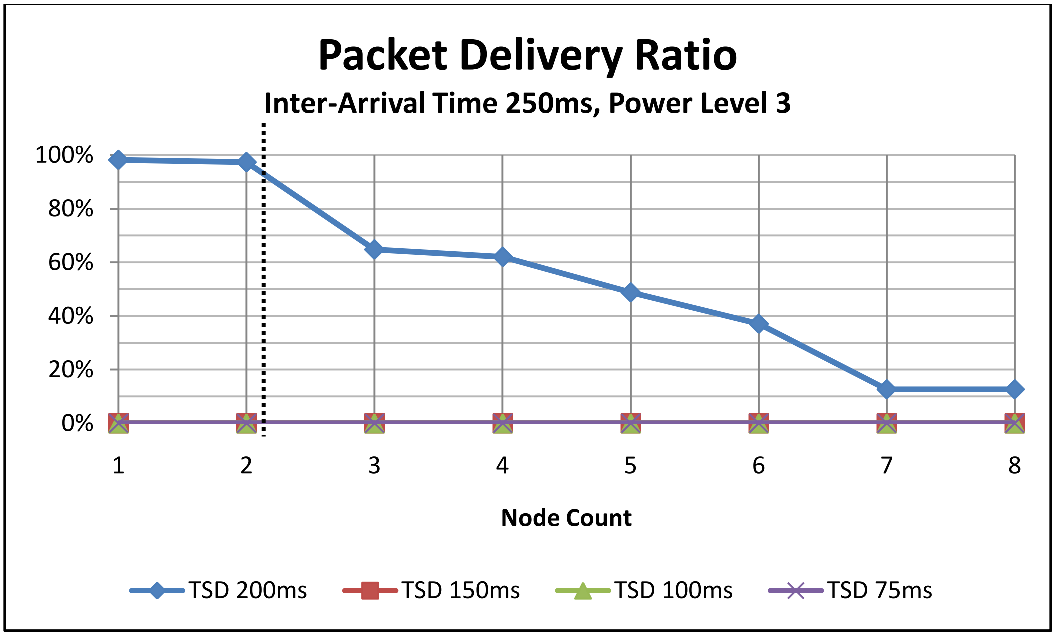

Figure 23: Packet Delivery Ratio for Varying Timeslot Durations and Node Counts (Inter-arrival Time=250ms)

APPENDIX E: Network Characterization Based on Set Node Count

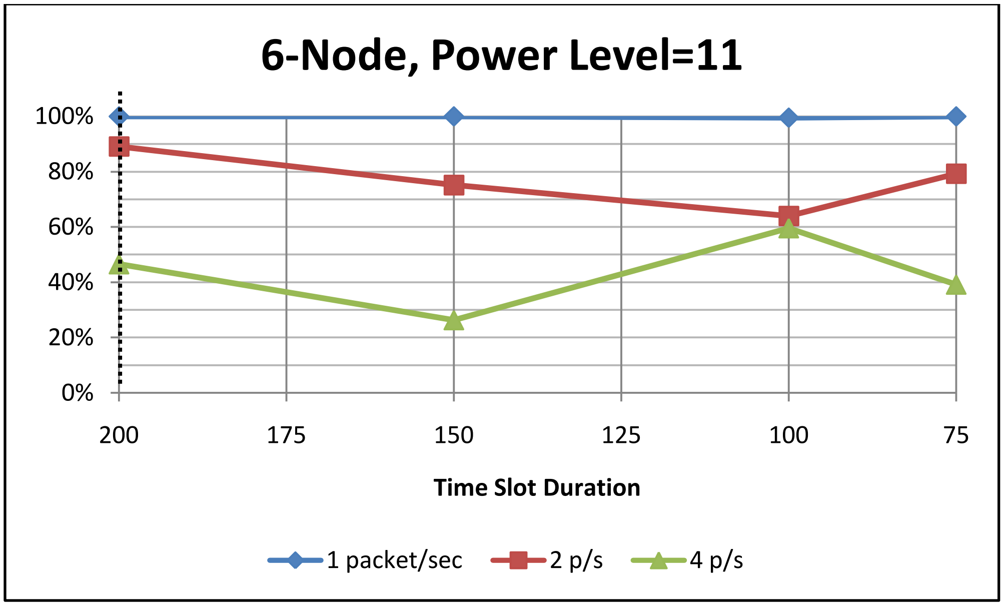

Figure 24: Network Characterization for 6 Nodes at Power Level 11

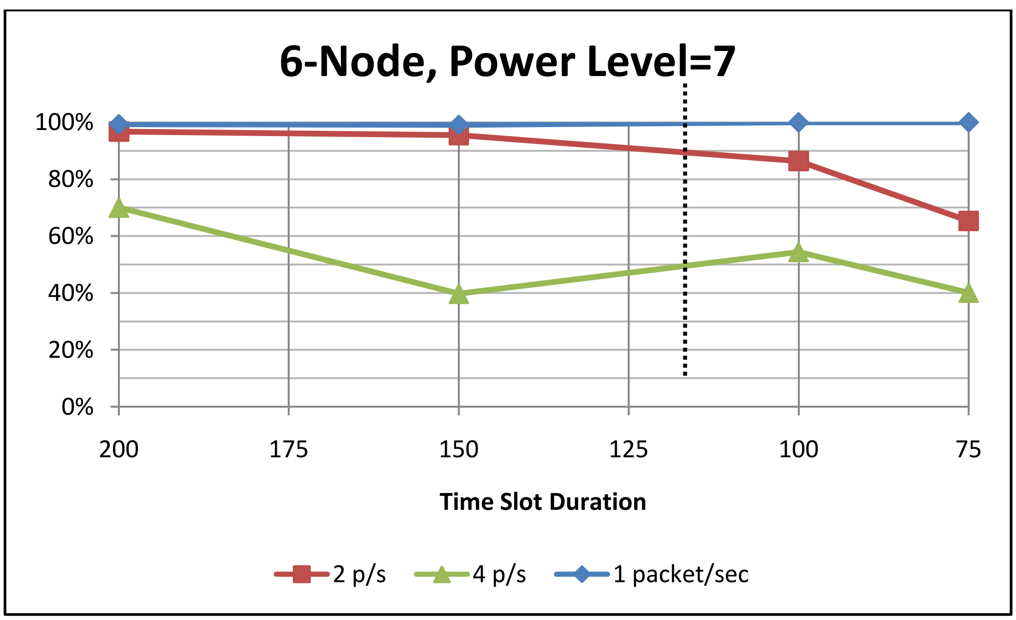

Figure 25: Network Characterization for 6 Nodes at Power Level 7

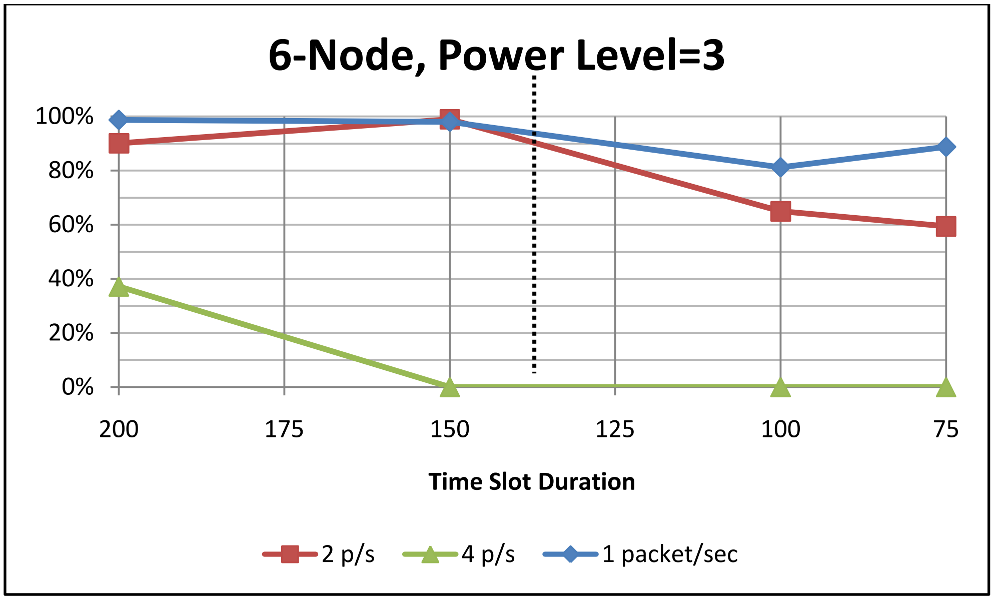

Figure 26: Network Characterization for 6 Nodes at Power Level 3

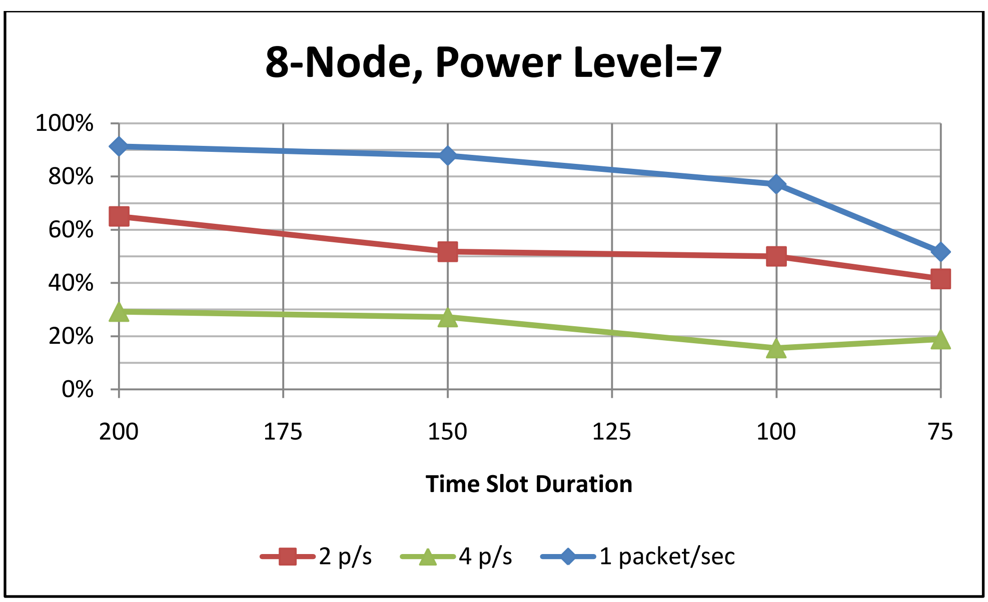

Figure 27: Inconclusive 8-Node Network Performance Characterization