COLLEGE OF ENGINEERING

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Broadband-Hamnet Microwave Communication System

Submitted to:

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Project Title	Broadband-Hamnet Microwave Communication System
Abstract	Our Broadband-Hamnet Microwave Communication System (BHMCS) is an inexpensive alternative to traditional HAM radio equipment that is still reliable to use in emergency situations. We will use readily available Linksys WRT54G routers to setup a long distance communication network that is self-configuring allowing users to easily find one another. In the process of creating a self-configuring network we create a new network protocol termed remote machine discovery protocol (RMDP). At the heart of the project is a Raspberry Pi 2 processor, which will handle all half-duplex/full duplex communications. Knowledge of data communication and transmission, statistical bit error correction, antenna design, and network programing are required to complete project. We hope our project will successfully supplement the Amateur Radio community's radio network in the Philadelphia Area.
URL	https://sites.google.com/a/temple.edu/broadband-mcomm/

EXECUTIVE SUMMARY

Broadband-Hamnet Microwave Communication System aims to provide long-distance emergency communications using low-power, portable, and inexpensive equipment. In an environment where cell reception and internet access becomes unavailable, it is important to maintain a means of communication to an area outside the area in distress. This project will also be useful in places where there is a lack of an Internet Service Provider (ISP). These countries can use this project to communicate wirelessly within their borders, as well as internationally. This project aims to be a low-cost, and reliable solution to this issue.

In order for this project to be successful, the hardware needs to be readily available and inexpensive, and the software must be user-friendly. In an environment where power may become unavailable, the equipment must consume a small amount of power, provided from an external battery or backup generator. The system must also automatically and dynamically re-configure itself due to the possibility of pre-existing nodes becoming unavailable in emergency situations and new nodes becoming available. The communication protocol implemented in the design must also have sequencing, error detection/correction, and automatic repeat request functionality.

For the reasons described above, the system will consist of a Raspberry Pi model 2, and a Linksys WRT54G wireless router. The routers will be programmed, (flashed) with a custom firmware known as Broadband Hamnet. The Broadband Hamnet firmware takes care of configuring the mesh network, which includes an optimized link state routing (OLSR) protocol, digi-peating, and discovering new nodes (new routers that come one the air). The firmware does not account for devices connected to LAN network of the nodes. Because of this, communication cannot be made between two users of the network. Therefore, it is necessary to design an application that automatically finds the IPv4 addresses of remote machines connected to the mesh network. The routers run a bare-bones Linux operating system, allowing the use of existing tools such as the address resolution protocol (ARP) and networking utility netcat as the basis for the new remote machine discovery protocol (RMDP). In order to ensure that there is not a single point-of-failure in the mesh network, each Raspberry Pi will act as a server and client. It allows every single machine on the network to know how to contact any other machine on the network. The machines will communicate using Transmission Control Protocol/Internet Protocol (TCP/IP) as the underlying protocol. It is necessary to design an application protocol so that each machine can process and reply to different types of messages. The different types of messages include new node discovery, network information requests, peer-to-peer communication requests and priority messages. The application protocol will be developed using Google's protocol buffer (Protobuf) encoder. To increase maximum distance between nodes, a Yagi antenna will be connected to the Linksys WRT54G through a coaxial cable. A Yagi antenna is a unidirectional antenna that redirects most of the signal energy in one direction. This concept increases transmission distance without any additional power requirements.

This project is very likely to be completed in its entirety within the allotted time period. The success of the Broadband Hamnet Microwave Communication System relies heavily on the community because multiple nodes are required for a successful mesh network. If successful, this project could supplement emergency communications in the Philadelphia area. Because the project is open source, only the initial investment of under $100 is required to set up a node in the mesh. In order for the mesh to be effective, the network needs to span a large area. Covering a large geographical area is possible, especially because a Raspberry Pi 2 is not needed at every mesh node. The Linksys WRT54G flashed with the Broadband Hamnet firmware can act as a repeater station, which simply forwards messages for other nodes. Because the Linksys WRT54G is only around $40, nodes can be installed to cover a large geographical area, without the help of large power amplifiers and antennas. The Broadband Hamnet Microwave Communication System also has the ability to provide underprivileged areas with an inexpensive way to communicate with family and friends because the equipment is so inexpensive and accessible.

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1. PROBLEM STATEMENT

1.1. Overall Objectives

This project aims to establish an ad-hoc mesh network over amateur radio frequencies, namely the 13 cm band. The communication link will be using a router firmware called Broadband-Hamnet, which is designed to run on the Linksys WRT54G-series routers. The firmware sets the framework of a mesh network. However, the firmware does not allow for peer-to-peer communications. Therefore, our project aims to design, on top of Broadband-Hamnet, an application that handles peer-to-peer communication, without relying on the Internet.

1.2. Historical and Economic Perspective

In the event of a disaster, conventional communication systems can be destroyed. Examples of such occurrences include but are not limited to tsunamis, hurricanes, and earthquakes. In these situations, Amateur Radio operators can provide communications to the affected areas for disaster support. Amateur Radio has been applicable and useful for emergency communications since radios were easily obtainable for the average citizen. These technologies were once limited to the 200 m band. As technology increased higher frequency operation and faster data communication became available.

For amateur radio operators to be effective in providing assistance to disaster areas, they need to be able to become mobile and travel to the disaster area. Many amateur radio operators set up mobile communication nodes in their vehicles (HRS, 2016). These vehicles can travel to the affected areas easily to provide the communications essential for successful disaster relief. However, the equipment to make said communication nodes can become expensive easily because an omnidirectional antenna is often mounted on top of the vehicle. In addition to the antenna, the operator would also need a transceiver and a microphone of some sort. The usage of the antennas also require the operator to have an appropriate license. Typically, a broadcast message is used to attempt to communicate to anyone listening.

Newer amateur radio nodes can be made with COTS (consumer off the shelf) equipment. Firmwares such as Broadband-Hamnet allow the amateur radio operator to flash a router and give the user more configuration control over a network (HRS, 2016). Broadband-Hamnet in particular sets up mesh network in which users can communicate over with the added benefit of high speeds. This allows communications to travel longer distances by travelling through several nodes. Another added benefit is the routers to flash are usually inexpensive and the firmware is open source so it is free.

1.3. Design Concept

1.3.1. Hardware

The main hardware challenge is getting the signal from the receiver located on the roof of Temple's Engineering building to a computer located on the seventh floor of the Engineering Building, which is about 200 feet away. Possible solutions include placing the Raspberry Pi right next to the antenna on the roof, and using Temple University's wireless network to "*ssh*" into the RPi from a different location. The benefit of this approach is a dramatic reduction in the amount of signal attenuation from the router to the antenna, however, the approach leaves the Raspberry Pi and router exposed to severe weather.

Another solution to this problem would be to run a coaxial cable from a router on the seventh floor straight to the antenna. This solution would require an extremely long coaxial cable, which introduces a high degree of signal attenuation, but the Raspberry Pi and router would be in a stable environment. An amplifier would be placed right before the antenna to account for the significant line loss caused by the 200 feet of coaxial cable. The coaxial cable is already installed, but another piece of hardware, the amplifier, is required for this solution to remain viable.

The final proposed solution places the Linksys WRT54G on the roof and the RPi on the seventh floor. The two machines would be connected by a 200 ft Ethernet cable. Ethernet is better than coaxial cable with respect to signal attenuation, but there is no pre-existing Ethernet cable installed in the building. This approach would remove environmental concerns for the RPi, but Linksys router is still exposed to the weather.

Table 1.3.1 Proposed Hardware Solution Comparison

	Hardware Safety	Line Loss	Reliability	Accessibility
SSH Approach	-	+	-	+
Coxial Approach	+	-	+	+
Ethernet Approach	-	+	+	-

1.3.2. Software

The software design calls for a communication protocol backbone. There are two viable transport layer protocols, namely Transmission Control Protocol (TCP), and User Datagram Protocol (UDP). The advantages of TCP include automatic packet sequencing functionality, and the transmission of the packets is guaranteed. TCP is a large protocol, however, which means increased overhead in packet size and thus reduction in transmission speeds. UDP on the other hand does not have automatic packet sequencing functionality, and does not guarantee delivery. However, sequencing packets is not difficult, and UDP is an extremely lightweight protocol, allowing for faster theoretical data rates.

Table 1.3.2 Comparison of Viable Transport Layer Communication Protocols

	Reliability	Size	Built-in-Functionality
TCP	+	-	+
UDP	-	+	-

1.4. Major Design and Implementation Challenges

1.4.1. Hardware

Setting up the hardware communication system comes with its own set of challenges. In our particular communication system, a directional antenna (Yagi) will be placed on the roof while the operator of the communication system will be on the 7th floor of the Temple Engineering building. The antenna has to be connected to a router (Linksys WRT54G) and to our machine (Raspberry Pi). One possible solution is to have the Raspberry Pi and Linksys WRT54G on the roof connected to a monitor in the radio station. This solution would require environmental protection for both the Raspberry Pi and Linksys WRT54G. A second possible solution is to have the Raspberry Pi on the 7th floor connected to the router on the roof through

Ethernet. Running Cat 5 Ethernet from the 7th floor to the roof will have a high degree of attenuation. The router will also have to be protected from harsh environmental conditions. The final solution is to keep the Raspberry Pi and Linksys WRT54G in the 7th floor station and connect the Linksys WRT54G to the Yagi antenna through a coaxial cable. Coaxial cables also introduce a high degree of signal attenuation, especially at higher frequencies. There is no environmental protection needed in this setup. To counteract the signal attenuation, an amplifier could be used. The amplifier will also help give the transmitted signal enough power to overcome the path loss, or free space attenuation that occurs. The amplifier will have to be placed as close to the antenna as possible to give the received signal power to travel through the coaxial cable. The amplifier will need to be powered on the roof. This can potentially be achieved by running DC power and RF along the coaxial cable.

1.4.2. Software

Connecting two networked machines is simple if the destination IPv4 address is known by the sender beforehand. In a mesh network, IP addresses may be forever changing making it difficult for clients to confidently determine how to locate a server to communicate with. We propose a new network protocol at the application layer termed "remote machine discovery protocol" (RMDP) that runs on a Raspberry Pi or other capable Linux machine. The new protocol handles finding server IP addresses for you upon connection to the mesh network. To accomplish an automatic remote machine resolution protocol we utilize the advantage of being directly connected to a Broadband-Hamnet mesh node to find other connected devices in the network. Each device on the network will run a local name-server that stores in a database other peer clients in the network. Each device would then be able to perform peer to peer communication directly without a need for a centralized name-server.

1.5. Implications of Project Success

The success of this project heavily relies on the community. If the amateur radio community gets behind this project, it could benefit many different groups of people. The technology can be implemented in disaster-prone areas, which would result in more reliable communication during emergencies.

The Broadband Hamnet Microwave Communication System, if successful, can also be used to provide under-privileged areas of the world inexpensive, reliable, long-distance communication.

2. DESIGN REQUIREMENTS

2.1 Target Specifications

2.1.1. Hardware

The hardware must be able to support a mesh network topology and full duplex communication. It will also give appropriate gain to transmit messages at long distances to overcome attenuation in free space (path loss) and over a potential long coaxial cable run without violating FCC transmission rules. Impedance matching between the Linksys WRT54G and the amplifier is required to maximize power transmission. The amplifier will also need to be matched to its load (Yagi antenna).

Some hardware will be exposed to extreme conditions and must be able to operate as intended. This will potentially include the Yagi antenna, an amplifier, a Raspberry Pi model 2, and a Linksys WRT54G.

2.1.2. Software

The software must be able to run on at least a Raspberry Pi model 2. This requirement implies that the software be geared toward a Linux-based operating system.

The software must be able to automatically discover devices on the Local Area Network (LAN) of each node. The LAN information of each node has to be shared with every other machine in the network.

Every machine in the mesh network must keep an up to date database of machine names paired with IPv4 addresses.

Every machine running this software must be able to handle multiple types of requests from any other machine in the mesh network. These requests include adding new machines, information requests, and chat services.

All machines must be able to communicate full duplex with any machine in the network.

3. APPROACH

3.1. Hardware Design

For creating a link between the roof of the Temple University's engineering building and the Amateur Radio Station located on the 7th floor, we propose three solutions. Solution 1 is to have the Raspberry Pi and WRT54G router situated in the radio station with a coaxial connection to the Yagi antenna on the roof. The coaxial run would be over 200ft in length with the transmission being analog at a frequency of 2.4 GHz. A second proposed solution is to have two machines. A Raspberry Pi and router situated on the roof of the building with a wireless connection to a separate desktop. The Raspberry Pi would communicate over the Wi-Fi connection and translate the information to the router to repeat into the mesh network. The last proposed solution is to have the Raspberry Pi in the radio station with an Ethernet connection to the router. The Ethernet like the coaxial would be over 200ft in length however it would be a digital signal. A digital signal would have less attenuation over such a long length of cable.

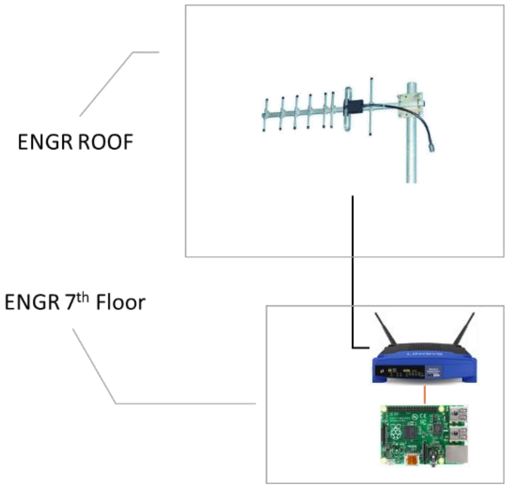


Figure 3.1.1: Solution 1 -- Router and Raspberry Pi on 7th Floor

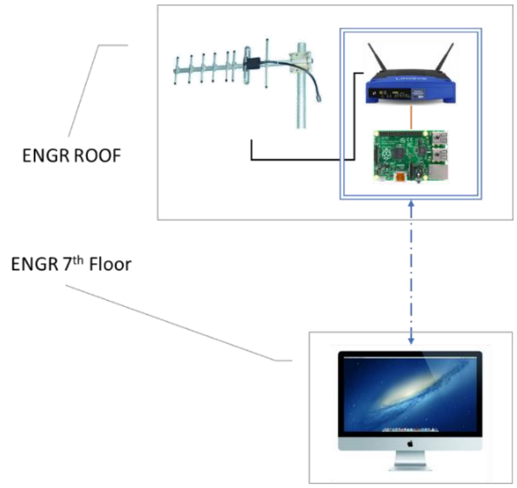
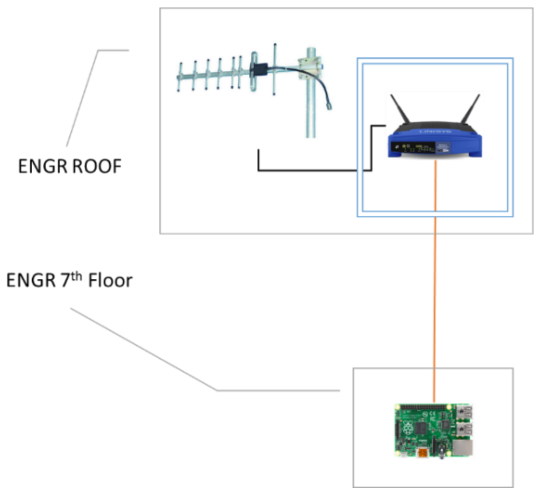


Figure 3.1.2: Solution 2 -- Router and Raspberry Pi on Roof



Key:	
Ethernet	(orange line)
Coaxial Cable	(black line)
Wifi	(blue dashed arrow)

Figure 3.1.3: Solution 3 -- Router on Roof and Pi on 7th Floor

Our team chose solution 1 seen in Figure 3.1.1 for the hardware design of the communication system. It was chosen because it eliminates the need to protect both the Raspberry Pi and Linksys WRT54G from harsh environmental conditions. The Yagi antenna and amplifier can withstand these conditions without modification. A small box may be constructed to surround the amplifier to protect it from water if needed. This setup also comes with its own set of problems. A long coaxial run is needed to connect the Linksys WRT54G to the amplifier, which introduces transmit and receive attenuation problems. The amplifier is going to be attached to the antenna on the roof to give small received signals sufficient power for the Linksys WRT54G to receive.

There are two cables available to transmit a 2.4 GHz signal at a distance of 60 m which would connect the Linksys WRT54G to the amplifier. These cables are the LMR-600 and RG213. Both the LMR-600 and RG213 are coaxial cables. The cable attenuation is found in dB/100m and is taken from standard manufacturing standards set for coaxial cables. It is also important to note the Linksys WRT54G can output power at 19 dBm (0.079 W) seen from the router firmware page.

3.1.1. Long Length Coaxial Cable Performance

Test with LMR-600

The attenuation of the LMR-600 coaxial cable at 2.4GHz will be explored. Calculating the attenuation will show how much power can be delivered to a load, in this case an amplifier. The LMR-600 has an attenuation of 14.2 dB/100 m. For 60 m, the attenuation will be 8.52 db (Coaxial Cable Attenuation Charts , n.d.). Therefore, power delivered to the amplifier is 10.4 mW which is equivalent to 10 dBm.

$$\left(\frac{P_o}{P_i}\right) dB = 10\log_{10}\left(\frac{P_o}{P_1}\right)$$ *Equation 3.1*

$$-8.52dB = 10\log_{10}\frac{P_o}{0.079W}$$

$$10^{-\frac{8.52}{10}} = \frac{P_o}{0.079W}$$

$$0.1318 = \frac{P_o}{0.079W}$$

$$P_o = 0.0104W$$

Test with RG213 Coax

Now, the attenuation of the RG213 coaxial cable at 2.4 GHz will be explored. The RG213 has an attenuation of 39.4 dB/100 m. For 60 m, the attenuation will be 23.64 db (Coaxial Cable Attenuation Charts , n.d.). Therefore, power delivered is 75 pW or << 0 dBm. This is the max power to be delivered to the output which in this case will be an amplifier.

$$-30.2dB = 10\log_{10}\left(\frac{P_o}{.079W}\right)$$

$$10^{-3.02} = \left(\frac{P_o}{0.079W}\right)$$

$$P_o = 7.5E - 5\ W$$

Both attenuation calculations assume ideal impedance matching between the Linksys WRT54G and the amplifier. The figure below compares the coaxial cable attenuation at varying distances at 2.4 GHz. As mentioned before, the LMR-600 performs better at longer distances.

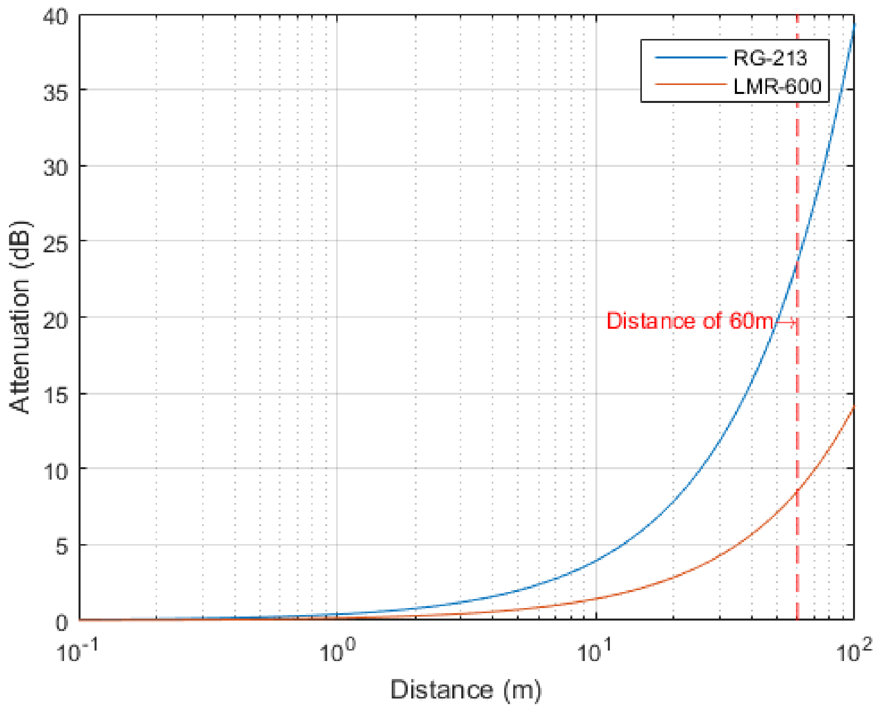


Figure 3.1.4: Attenuation of 2.4 GHz signal of Coaxial Cable

3.1.2. Power Amplification

An amplifier can be used to give the signal extra power for transmission. The specs for an inexpensive amplifier listed below.

- Operation Range: 2400-2500 MHz.
- Operation Mode: Bi-directional, half-duplex, Auto-Switching via carrier sensing.
- Frequency Response: ± 1 dB over operation range.
- Input Power: 3 dBm (Min.)-20 dBm (Max.).
- Input Power 5 ~ 20 dBm.
- Optimal Input Power 9 ~ 13 dBm.
- Output Power: 8000 mW/39 dBm nominal for 802.11 b/11 Mbps.
- Connector: SMA Receptacle, 50 ohm.
- Transmit Gain: 17dBm nominal.
- Receiver Gain: 11dBm.
- Receive Noise Figure: 3.0 dBm nominal.
- Operating Temperature: -40 to 70 degree.
- Operating Humidity: Up to 95% relative humidity.
- Material: Cast Aluminum.
- Size:10.3 cm x 7.7 cm x 2.1 cm
- Weight: 785 g

Figure 3.1.5: 2.4 GHz Power Amplifier A

Our router is operating within the 2400 MHz range, proved with the faraday cage and spectrum analyzer (see Section 4.1.2). If the LMR-600 cable is used, the optimal input power will be achieved with the power amplifier being 60 m away from the Linksys WRT54G router and right next to the Yagi antenna. The optimal input power from Figure 3.1.5 is 9-13 dBm, where the LMR-600 will supply 10 dBm as seen in Section 3.1.1.

It is also possible that the amplifier can be placed right next to the router. The router specifications state it supplies power of 79 mW (19 dBm). This power is too high for the optimal power but should still work as it is in the input power range. A pad could potentially be used here to attenuate the signal into the optimal input range, but that will also attenuate the signal being received, which is undesirable.

The next amplifier in consideration is the Wii-link Wi-Fi Amplifier. In 3.1.1 the transmissions power of the amplifier can be seen to be 36 dBm with as little as 19 dBm (the maximum output power of our router).

Operating frequency	2400-2483.5MHz
Operating mode	TDD (Time-division duplex)
Signal standard	IEEE 802.11b/g/n
Minimum input power	3dBm
Maximum output power	36 dBm(4w)
Uplink gain	15±1dB
Downlink gain	10dB - 17dB adjustable (8dB attenuation range in 1dB steps)
Noise figure	≦2.5dB
Delay	<1uS
Operating temperature	-10° C to + 60° C
Weight	0.6kg
AP/Router Interface	SMA Female
Antenna Interface	RP-SMA Male

Figure 3.1.6: Power Amplifier 2 Specs

Figure 3.1.7: 2.4 GHz Power Amplifier B

The transmitting power of the AP/Router	The reference Downlink gain	The final transmission power of the booster
>26dBm (Dangerous)	10dB(Dangerous)	>36dBm (Dangerous)
26dBm	10dB	36dBm
25dBm	10dB - 11dB	≤25+11=36dBm
24dBm	10dB - 12dB	≤24+12=36dBm
23dBm	10dB - 13dB	≤23+13=36dBm
22dBm	10dB - 14dB	≤22+14=36dBm
21dBm	10dB - 15dB	≤21+15=36dBm
20dBm	10dB - 16dB	≤20+16=36dBm
19dBm	10dB - 17dB	≤19+17=36dBm
≤18dBm	10dB - 17dB	≤18+17=35dBm

Figure 3.1.8: Power Amplifier 2 Transmission Power

Overall, Amplifier B is the better choice for the communication system. It can accept a higher input level than Amplifier A. Both amplifiers have the same gain, but with a higher input, more output can be achieved which is desired. Therefore, any Amplifier B will be the amplifier referenced throughout the project.

The amplifier will supply a gain of 17 dBm, with the input to the amplifier being 10 dBm after 60 m of LMR-600 coaxial cable, the output to the antenna will be 27 dBm (500 mW). The maximum input to this amplifier is 26 dBm.

3.1.3. Path loss

The next item of concern is the loss in free air the signal will have; commonly referred to as the path loss or path attenuation. Path loss can be defined as:

$$Path\ loss(dB) = K_u + 20\log(fR) - G_1(dB) - G_2(dB)^1 \qquad \textit{Equation 3.2}$$

K_U is a constant depending on what units the distance R is, f is the frequency in MHz, and G_1, G_2 is the gain of the receiving and transmitting antenna. The gain of the Yagi antenna in our communication system is 13 dBi. The distance was calculated as a straight line distance measurement using GPS coordinates and Google maps.

Figure 3.1.9: GPS coordinates of sending point

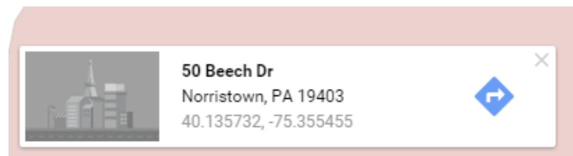


Figure 3.1.10: GPS coordinates of receiving point

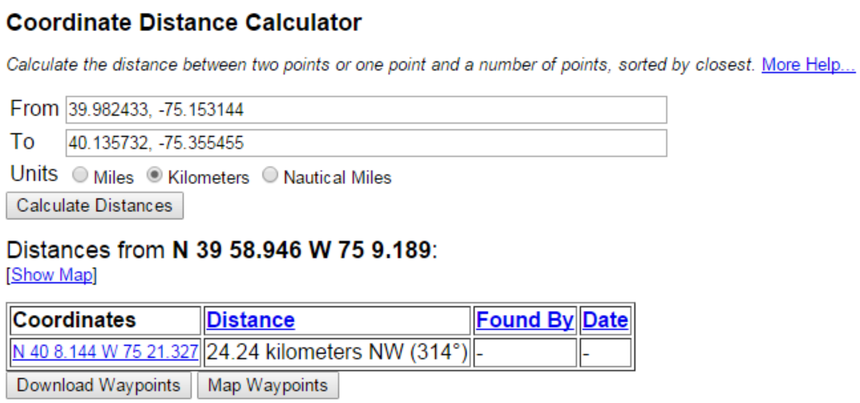


Figure 3.1.11: Distance between two GPS coordinates

Using the straight line distance, we find the loss in free space from the output of our amplifier to the output of the receiving antenna.

$$K_u = 32.45\ for\ km\ , G_1 = G_2 = 13dBi, f = 2400MHz, R \cong 25km$$

$$Path\ loss\ (dB) = 32.45 + 20\log(2400MHz * 25km) - 13 - 13 = 102.01dB$$

3.1.4. Link Budget

The link budget of a system is the total attenuation or gain of a communication system. Link budget accounts for the gain or attenuation of the transmitter, through the medium, line loss, antenna gain, receiver gain, etc.

In our communication link, the amplifier will supply a gain of 17 dBm, with the input of the amplifier being 10 dBm after 60 m of LMR-600 coax, the output to the antenna will be 27 dBm. The maximum input to

[1] (MILLIGAN, 2005)

for our amplifier is 26 dBm.

The power seen by the receiver after experiencing the path loss of 102.01 dB, assuming it is directly connected to the output antenna can be seen as follows.

$$Rx_{Power} = Tx_{Power} - PathLoss \qquad \textit{Equation 3.3}$$

$$Rx_{Power} = 27dBm - 102.01dB = -75.01dBm$$

This output assumes ideal, matching impedance connections, so no signal power is reflected back onto the transmission line.

The receive sensitivity of the Linksys WRT54G is around -80 dBm, so the received power of -75.01 dBm is within the demodulating capabilities of the router.

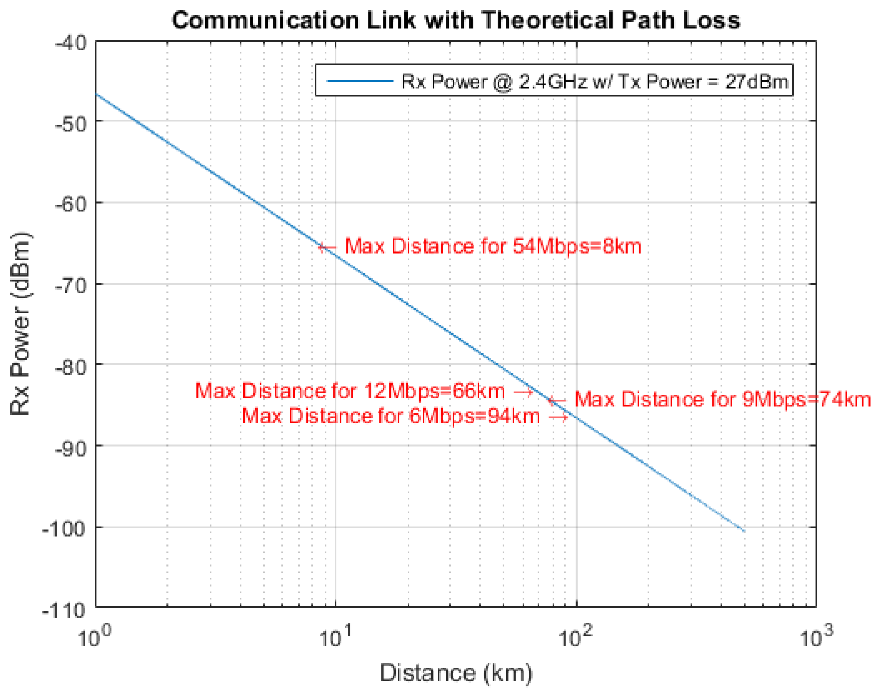


Figure 3.1.12: Communication Performance with Proposed Broadband Hamnet Equipment

3.1.5. Powering the Amplifier

The amplifier will need sufficient power to be able to give transmitting and receiving gain. The amplifier comes with a standard DC power cord however there is no AC mains outlet on the roof. Therefore, a method has to be devised to power the amplifier from elsewhere. Since the coaxial cable is connecting the roof and the 7th floor, power will be delivered across the coaxial cable along with the RF signal. First, the DC resistance of the coaxial cable (LMR-600) is 1.73 Ω/1000 ft (Systems). The DC will travel along 200 ft over the LMR-600. Therefore, there is a total DC resistance of 0.346 Ω. Using the reactance of both the inductor and capacitor, the DC and RF frequencies can get blocked from the amplifier input and amplifier power respectfully. The reactance can be thought as the frequency dependent resistance of a component.

$$X_C = \frac{1}{2\pi f C} \qquad \text{Equation 3.4}$$

$$X_L = 2\pi f L \qquad \text{Equation 3.5}$$

The capacitor is used to block the DC from entering the RF source and the RF input of the amplifier. The reactance becomes much larger at smaller frequencies. The inductor (or choke) is used to block the RF from the power supply source and power supply input to the amplifier. The reactance of the inductor will grow as the frequency increases. Additional filter capacitors are used to keep the RF out of the power supply input to the amplifier. The general schematic can be seen in Figure 3.1.13 and the verification of the design can be seen in Figure 3.1.14.

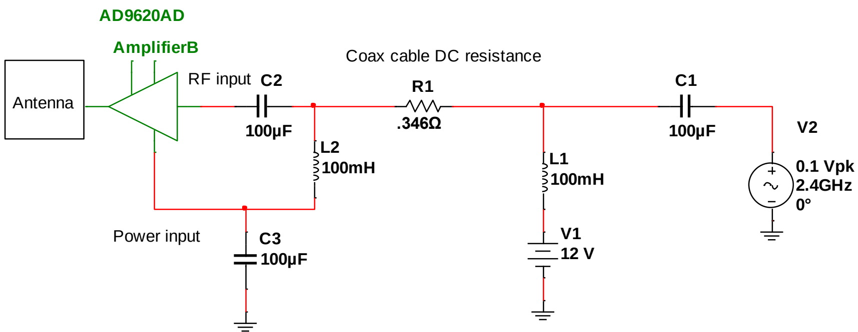


Figure 3.1.13: Schematic to power the amplifier from the 7th floor

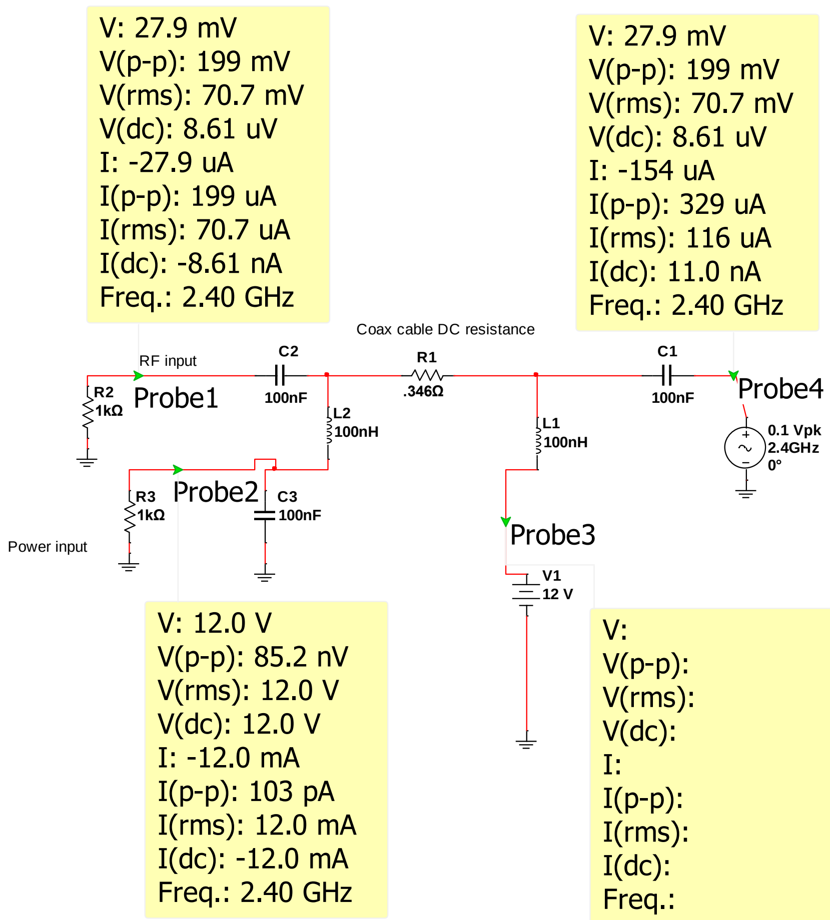


Figure 3.1.14: Simulating Power and RF down coaxial cable

3.1.6. Theory of Yagi-Uda Antenna Design

A Yagi-Uda antenna uses mutual coupling between standing-wave current elements to produce a unidirectional radiation pattern. The Yagi antenna consists of *n* elements, one of which is driven, while the other *n*-1 are parasitic elements. The driven element is the element that is fed with the signal to be transmitted, while the parasitic elements act as either reflectors or directors. Whether a parasitic element acts as a reflector or a director depends on the spacing of the individual elements from the driven element, and is determined by *Equation 3.6*. The equation describes the power pattern difference between the radiation pattern at θ=0 and θ=180˚ with respect to the driven element. Whether a parasitic element acts as a reflector or director also depends on the length of the element. In general, a reflector is shorter than both the director and driven element.

$$|\Delta E|^2 = -2I_r \sin(\partial)\sin(kd) \qquad \textit{Equation 3.6}$$

In *Equation 3.6* ΔE is the normalized pattern response, and $I_r e^{j(kd\cos(\theta)+\partial)}$ is the current of the parasitic element relative to the driven element. This means that $I_r e^{j(kd\cos(\theta)+\partial)} = \frac{I_2}{I_1}$, and I_2 and I_1 can be found from the matrix equation show in *Equation 3.7*.

$$[V] = [I][Z] \quad \textit{Equation 3.7}$$

Z is the matrix describing the mutual impedance between each of the elements on the antenna. In *Equation 3.7*, there is only one nonzero element in $[V]$, and it is the voltage applied to the driven element. It is important to note that the current in each element is assumed to be sinusoidal (Milligan, 2005).

With a known element spacing d, and after solving *Equation 3.7* for $[I]$, we can determine whether the element is a reflector or a director by solving *Equation 3.6* for ΔE. There are three possible outcomes and they are described below.

- *Case 1.* $\partial = 180^\circ$ and $\Delta E = 0$. Equal pattern levels in both directions.
- *Case 2.* $180^\circ < \partial < 360^\circ$ and $\Delta E > 0$. The parasitic element is a director because the radiation pattern is greater in its direction with respect to the driven element.
- *Case 3.* $0^\circ < \partial < 180^\circ$ and $\Delta E < 0$. The parasitic element is a reflector because the pattern in the direction of the driven element is greater than the pattern in the direction away from the driven element. (Milligan, 2005)

It has been proven that an element spacing of about 20λ, where λ is the wavelength of the driving signal, is one of the criteria describing Yagi design that yields the maximum directional gain.

3.2. Software Design

The software design begins with the version of the Broadband-Hamnet firmware that is flashed on the router. The firmware used during our time with this project is Broadband-Hamnet_v03.1. This firmware is chosen because it is the latest stable release of the firmware.

The software developed in this project is an application that provides peer-to-peer communication for users by utilizing the ad-hoc mesh framework provided by Broadband-Hamnet. When multiple machines begin to share data with one another, a protocol becomes essential. The communication protocol ensures that each side of the communication link understands what is being sent and how to respond accordingly.

There are multiple protocols implemented and developed in this project. We design a protocol that our application must adhere to and a protocol that the Linksys WRT54G routers utilize to register remote machines to the network. We also take advantage of the TCP/IP infrastructure, commonly referred to as the TCP/IP stack, which is standard on all computers.

3.2.1. Theory of TCP/IP Networking Stack

A typical protocol architecture consists of multiple layers, with each layer performing different functions. The standard architecture contains the following layers; Physical, Network Access/Data Link, Internet, Transport, Application. The Physical layer takes care of the interactions between the computer's hardware and the transmission medium. It reports data rates, signal characteristics, traffic on the medium and other related matters. The Network access/data link layer is responsible for routing functions the direct packets between two machines on the same network. The Internet layer performs similar tasks to the Network layer, however the routing functions are concerned with routing information across multiple networks. The Transport layer provides the end-to-end protocol between two computers. The application layer contains the logic that supports decoding of messages for use with a particular application **(Stallings, 2014)**.

For this application, the Transmission Control Protocol (TCP) is the best transport layer protocol. TCP guarantees message delivery and has error detection/correction and packet sequencing built in. User Datagram Protocol (UDP) was also considered, but was not chosen because UDP does not guarantee message delivery and does not have a packet sequence functionality (Stallings, 2014) (Touch, 2016). The TCP header as well as the IPv4, which is the Internet layer protocol commonly used with TCP is shown and explained below.

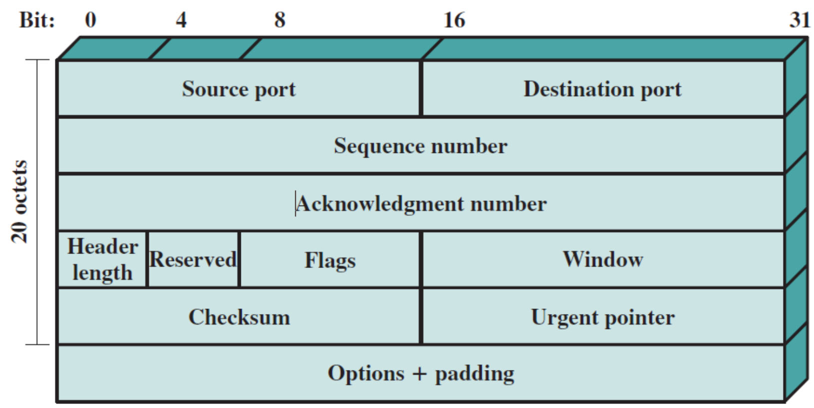


Figure 3.2.1: TCP Header **(Stallings, 2014, p. 42)**

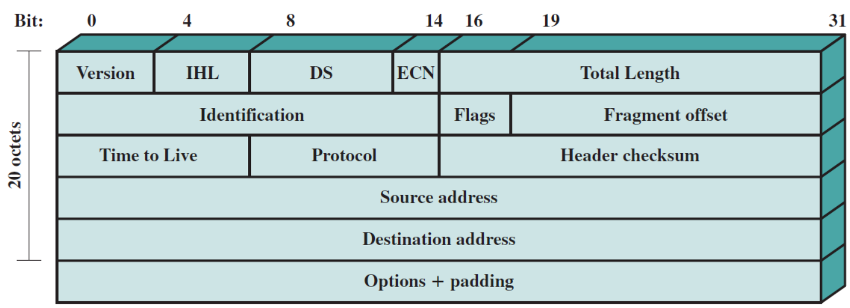


Figure 3.2.2: IPv4 Header **(Stallings, 2014, p. 43)**

In order to understand how the TCP header is used in an actual data transfer, an actual data packet intercepted by the packet sniffing program, Wireshark, will now be analyzed.

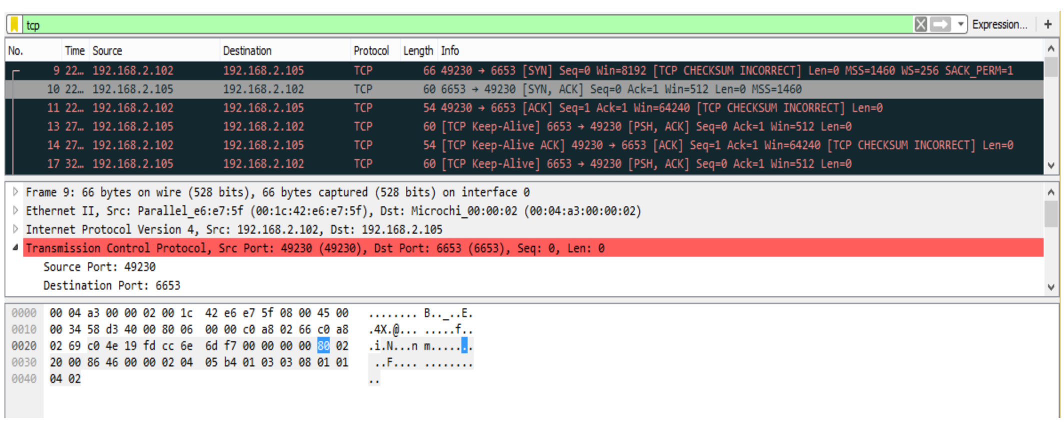


Figure 3.2.3: Data Packet from Wireshark

The 34th byte in the packet seen above marks the beginning of the TCP packet. Everything preceding the 34th byte is the IP protocol header and physical layer protocol. Those headers are out of the scope of this analysis and are ignored. The TCP packet displayed in Figure 3.2.3 is decoded in Table 3.2.1.

Table 3.2.1: TCP Header

BYTE #	Meaning	HEX Rep.	Dec. Rep.
34-35 (1-2)	Source Port	c0 4e	49230
36-37 (3-4)	Destination Port	19 fd	6653
38-41 (5-8)	Sequence Number	cc 6e 6d f7	3429789175
42-45 (9-12)	Acknowledgment Number	00 00 00 00	0
46 (13)	Header Length	8	8
47 (14)	Flags	0000 0010 (binary)	02 (hex)
48-49 (15-16)	Window	2000	8192
50-51 (17-18)	Checksum	86 46	34374
52-53 (19-20)	Urgent Pointer	00 00	0
54-57 (21-24)	Max Segment Length	02 04 05 b4	33818036
58 (25)	No-Op	01	1
59-61 (26-28)	Window Scale	03 03 08	197384
62 (29)	No-Op	01	1
63 (30)	No-Op	01	1
64-65 (31-32)	TCP SACK Permitted	04 02	1026

In Table 3.2.1, the TCP packet is broken down byte-by-byte. The first two bytes indicate the source port. All ports ranging from 49152–65535 are used for private or temporary services, as well as automatic allocation of ephemeral ports (Touch, 2016). An ephemeral port is a short-lived transport protocol port allocated automatically by the Internet protocol software. It is used by various transport protocols, including TCP as the client-side port of client-server applications.

The next two bytes indicate the port the receiving machine is listening on. The port 6653 is the port bound to the socket. Ports and sockets will be discussed in more detail later in this section.

The next four bytes indicate the sequence number. It is important to note that the sequence number does not start at 0. This is a relative sequence number, which is initially assigned randomly, but incremented after the initialization of the communication link between the client and server.

The next four bytes indicate the acknowledgement number. The acknowledgement number contains the sequence number of the next data octet that the TCP entity expects to receive.

The 13th byte serves two purposes. The 4 most significant bits represent the header length. It is important to note that the header length actually represents the number of 32-bit words in the header. Therefore, in order to calculate the number of the bytes in the header, multiply the decimal representation of these 4 bits by 4. The packet shown in Figure 3.2.4 shows an 8 in its header length. 8*4=32, which is the correct number of bytes in the header. The 4 least significant bits of the 13th byte are reserved.

The reserved bits from the 13th byte and the 14th byte are set aside for flags. Each of these twelve bits represent a different flag. The flags are shown in Figure 3.2.4.

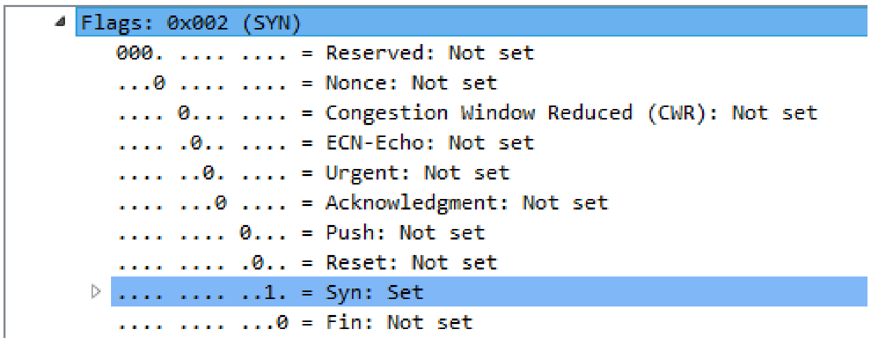


Figure 3.2.4: TCP Protocol Flags

Figure 3.2.4 requires further explanation. The Nonce flag is for ECN concealment protection. The congestion window reduced flag is set when it receives a packet with the ECN-Echo flag set. It also indicates that it responded in congestion control mechanism (Cerf & Khan, 1974). The ECN-ECHO flag is used for explicit network congestion notification. The urgent flag is for quality of service (QOS) or priority packets. The acknowledgement flag indicates that the acknowledgement flag is significant. All flags after the initial SYN packet should have this flag set. The PUSH flag, when set, asks to push the data to the receiving application. The Reset flag resets the connections. This flag is often set when a receiver blocks an incoming connection. Hackers often use this flag to search for open ports. The SYN flag is used to synchronize sequence numbers. Only the first packet sent from each end should have this flag set. The FIN flag indicates that there is no more data from the sender (Stallings, 2014) .

The 15th and 16th byte indicate the window length. The window length is for flow control credit allocations. It contains the number of octets, starting with the sequence number indicated in the acknowledgement field that the sender is willing to accept (Stallings, 2014).

The 17th and 18th bytes indicate the checksum, which is used for error checking.

The 19th and 20th bytes contain the urgent pointer. This value, when added to the segment sequence number, contains the sequence number of the last octet in a sequence of urgent data. This allows the receiver to know how much urgent data to expect (Stallings, 2014).

The 21st-32nd bytes of the packet are options and padding and the number of bytes included in this section is variable. Bytes 21-24 represent the maximum segment length able to be received. The most significant byte indicates that it is a maximum segment length option. The next byte indicates how many bytes the option takes up, and the final two bytes indicate the MSS, which in this case is 1460.

The 25th, 29th, and 30th bytes are No-Op bytes.

Bytes 26-28 indicate a window scaling option. This option is used to increase TCP's maximum receive window size of 65,535 bytes.

The 31st and 32nd bytes are the TCP SACK option. It stands for TCP Selective Acknowledgement. This flag allows receivers to tell the sender what packet it received, so the sender can retransmit the missing packets (Mathis, 1996).

3.2.2. Theory of Socket Programming

The start of the application design consists of two programs. One program sends a message termed a client and the other program receives the message termed a server. These programs each run on a Raspberry Pi.

Half Duplex Socket Programing – One Message Limit

We introduce socket programing with a simple send and receive (half duplex) example. Half duplex means that each machine can only send or receive at any given time. The example receiving program can be seen in Figure 3.2.5, while a compatible sending program can be seen in Figure 3.2.6. The receiving code must be run first to create a socket. Sockets are a high level networking programing interface that allows a programmer to send and receive data at the transport level layer of the TCP/IP stack. To create a TCP datagram we first create a socket with the predefined 'socket.AF_INET' and 'socket.AF.SOCK_STREAM' data types (Socket - Linux socket interface, 2015). 'AF_INET' tells the socket we are using the IPv4 addressing protocol. 'AF.SOCK_STREAM' is the predefined name instructing the socket to use the TCP communication protocol. The Raspberry Pi acting as the server is bound to a port and IP address creating a listening socket. The port and IP address are declared in the beginning of the PI's program. The receiving code listens for up to one client trying to connect to it that will ultimately establish the communication link. Now, the client sending information is free to a message to the server. In the example, shown below our server will simply echo the message sent by the client to stdout.

```
#!/usr/bin/env python

import socket

#TCP_IP = raw_input('Enter IP of this Machine: ')
TCP_IP = "10.119.197.29"
TCP_PORT = 5005
BUFFER_SIZE = 1024


s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
s.bind((TCP_IP,TCP_PORT))
s.listen(1)

conn, addr = s.accept()

#print 'Connection address:', addr

while True:

    data = conn.recv(BUFFER_SIZE)
    if not data: break
    print "recieved data:", data
    #conn.send(data)
conn.close()
```

Figure 3.2.5: rec_TCP.py (v00)

```
#!/usr/bin/env python

import socket

#Function send_TCP.py
#client or send
#
#declare IP of server machine(recive)
#
#TCP_IP = raw_input('Enter IPv4 address of Recipient: ')
TCP_IP = "10.119.197.29"

#Delcare port
#
TCP_PORT =  5005

#Buffer size to recieve
#
BUFFER_SIZE = 1024

#create instance of socket class (object?)
#
s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)

#create a tcp connection
#connects to TCP_IP through TCP_PORT
#
s.connect((TCP_IP, TCP_PORT))

#Use a while loop so multiple messages can be sent on the same connection
#
#while 1:

MESSAGE = raw_input("Enter Message: ")

s.send(MESSAGE)

    #if MESSAGE == 'EXIT': break

    #data = s.recv(BUFFER_SIZE)

    #print "recieved data:", data

    #print "Type 'EXIT' to close socket"

s.close()
```

Figure 3.2.6: send_TCP.py (v00)

After we have bounded the connection you will see the 'listen' instruction on the sever side. The listen command limits the number of concurrent connections the server will maintain (Python, 2016). In the simple test provided we will only allow one client to connect to the server causing all other incoming connections to be refused. Lastly, the 'socket' instruction is where our server waits for clients to connect to it. When a new client connects the server the listen function will create a new socket referenced by the 'conn' variable from the IPv4 address referenced by the 'addr' variable. We can now use this new socket to the client to 'recv' or receive the message being sent by the client.

On the client side we ignore the 'listen' and 'accept' instructions and instead jump straight to the 'connect' instruction. 'connect' is a built in function in the socket class that establishes a link to the tuple object containing the server IPv4 address and port you wish to connect to (Python, 2016). Any failure to successfully connect to a server will throw an exception such as "connection refused". A "connection refused" exception is commonly seen when the server object is not initiated to accept connections or has reached its upper limit of number of connected clients defined in the 'listen' instruction.

Running the above code demonstrates the user interaction. We are prompted with an "Enter Message:" prompt on the client side. The sever side sits idle waiting for the client to create and send a message to it.

```
pi@raspberrypi ~/senior_design/Broadband-Hamnet/src/python/TCPIP $ python send_TCP.py
Enter Message:
```

```
pi@bobs-pi ~/senior_design/Broadband-Hamnet/src/python/TCPIP $ python rec_TCP.py
```

Figure 3.2.7: Half Duplex One Message Send -- Waiting

Upon entering the message our client then proceeds to send the message over the socket. A successful completion of the program can be seen in Figure 3.2.8. The program received the message, and closed the socket, terminating any further communication between server and client.

```
pi@raspberrypi ~/senior_design/Broadband-Hamnet/src/python/TCPIP $ python send_TCP.py
Enter Message: Hello World
pi@raspberrypi ~/senior_design/Broadband-Hamnet/src/python/TCPIP $
```

```
pi@bobs-pi ~/senior_design/Broadband-Hamnet/src/python/TCPIP $ python rec_TCP.py
recieved data: Hello World
pi@bobs-pi ~/senior_design/Broadband-Hamnet/src/python/TCPIP $
```

Figure 3.2.8: Half Duplex One Message Send – Terminated

Half Duplex Socket Programing – Multiple Messages

In the previous example our socket program can send and receive one message. The next step is to send and receive multiple messages on the same connection. The receiving program did not change for this step as the 'recv' instruction is already nested inside a never ending while loop. The new sending program can be seen in Figure 3.2.9. A while loop was used around the 'send' instruction so that multiple messages can be sent to a server. Since the send program is also nested inside a never ending while loop, we program in a key phrase that when detected will cause the program to break out of the loop. In the example below any message entered 'EXIT' will cause the socket to close on the client side. Subsequently when the server knows the client socket ('conn') is closed when when it runs its 'recv' function and the received message length is less than zero. After the client socket is closed the server will know no further messages will be sent over the socket by the client so it will exit.

```
#!/usr/bin/env python

import socket

#Function send_TCP.py
#client or send
#
#declare IP of server machine(recive)
#
#TCP_IP = raw_input('Enter IPv4 address of Recipient: ')
TCP_IP = "10.119.197.29"

#Delcare port
#
TCP_PORT =  5005

#Buffer size to recieve
#
BUFFER_SIZE = 1024

#create instance of socket class (object?)
#
s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)

#create a tcp connection
#connects to TCP_IP through TCP_PORT
#
s.connect((TCP_IP, TCP_PORT))

#Use a while loop so multiple messages can be sent on the same connection
#
while 1:

    MESSAGE = raw_input("Enter Message: ")

    s.send(MESSAGE)

    if MESSAGE == 'EXIT': break

    #data = s.recv(BUFFER_SIZE)

    #print "recieved data:", data

    print "Type 'EXIT' to close socket"

s.close()
```

Figure 3.2.9: send_TCP.py (v01)

A verification of the program output can be seen in Figure 3.2.10. Notice that multiple messages are sent and received and when the 'EXIT' message is sent the program ends.

```
pi@raspberrypi ~/senior_design/Broadband-Hamnet/src/python/TCPIP $ python send_TCP.py
Enter Message: HELLO WORLD
Type 'EXIT' to close socket
Enter Message: hello world
Type 'EXIT' to close socket
Enter Message: EXIT
pi@raspberrypi ~/senior_design/Broadband-Hamnet/src/python/TCPIP $

pi@bobs-pi ~/senior_design/Broadband-Hamnet/src/python/TCPIP $ python rec_TCP.py
recieved data: HELLO WORLD
recieved data: hello world
recieved data: EXIT
pi@bobs-pi ~/senior_design/Broadband-Hamnet/src/python/TCPIP $
```

Figure 3.2.10: Full Duplex One Message Send – Terminated

Full Duplex Socket Programing – Multiple Messages

Now, the program should be able to send and receive messages from either machine once a connection is established. The connection should break when one machine types "EXIT". To create such a program requires that both sides of the communication channel run both a server and client application simultaneously. Running both will require the use of threading.

A threaded application allows for a complier to run two instructions or in our Python code two functions in parallel (Zograf, n.d.). Python gives programmers a threading class to help aid in creating thread safe code. Thread safe code ensures that one thread does not modify the memory blocks being actively worked upon by another thread. The end goal is to have one thread run the server code in the background while our main program thread runs our client-send program we created before. To create the threads, we create a thread object with a parameter of what function the thread is to run (Python, 2016). We can set the thread to be a daemon thread which informs the complier to exit the thread if all other non-daemon threads have closed. Lastly we start a thread by referencing the threading object by name and running the 'start()' instruction (Python, 2016). An example of threaded socket programming can be seen in the final project example code (see APPENDIX).

Now we need to be able to communicate between threads within the running application so that the client and know when the other each is sending or receiving a message. To communicate between threads we introduce a Python data structure called a 'queue'. A 'queue' object allows for one thread to put information into a buffer that can be retrieved by a separate thread when it is ready. Queues are a unique data structure in that follows the standard of first in first out (FIFO). Items put into the queue will be processed in the order in which they were place into the queue. When a thread needs to send data to another thread it queues the information and the second thread can then pull items from the front of the queue. 'queue' objects are a standard thread safe communication medium.

Going into detail about queues and threads is beyond the scope of this paper so we omit the source code for this portion of the application example. Instead we provided the desired output of a correctly programed threaded send and receiving application.

```
pi@bobs-pi ~/Broadband-Hamnet/src/python/TCPIP $ python trans.py
Enter IPv4 address of Recipient: 10.247.16.44
Enter Message: received data: hello
hi
Enter Message: EXIT
received data:
closing send thread
pi@bobs-pi ~/Broadband-Hamnet/src/python/TCPIP $
```

```
pi@raspberrypi ~/Broadband-Hamnet/src/python/TCPIP $ python trans.py
Enter IPv4 address of Recipient: 10.93.121.53
Enter Message: hello
Enter Message: received data: hi
received data: EXIT
closing send thread
pi@raspberrypi ~/Broadband-Hamnet/src/python/TCPIP $
```

Figure 3.2.11: Full Duplex Communication

3.2.3. Creating the Remote Machine Discovery Protocol (RMDP)

We will now use the basis of socket server/client side programing to create our new network protocol termed Remote Machine Discovery Protocol (RMDP). In section 3.2.1 Theory of TCP/IP Networking Stack, we had hardcoded the destination IPv4 address into our script. The RMDP will replaces the hardcode value and instead resolve addresses for you by attempting to connect to nearby clients.

RMDP Overview

To begin, we define our application protocol so that upon start of the application the local device will open a server socket to listen for incoming client connections. The second step is for our device to contact the local Broadband Hamnet router to begin finding other possible servers running our application. The application sends a command to the local router that informs it to contact all other routers within its vicinity, and requests the ARP table from the nearby routers. The ARP table provides a listing of all attached LAN devices attached the respective node. Compiling a listing of all ARP tables provides a status of the all connected devices in the mesh network. The local router gathers this list of potential devices which it then sends back down to our local device. After the RPi receives this listing of potential existing servers within the mesh network, it proceeds to contact each device to try and gather the most up to date information about the TOIChat network. It is important to note the distinction between the overlaying Ad-Hoc mesh network and the TOIChat network. The Ad-Hoc mesh network is the framework provided after installing Broadband-Hamnet. The TOIChat network is our project specific network or application that allows for direct autonomous peer-to-peer communications.

Once our local device has found another device running an instance of the TOIChat application, we will send a message asking for the database of other client/servers in the network. We will then use that information to setup and or update newly connected local application's NameServer database.

RMDP Implementation

To begin our discussion on RMDP implementation, an understanding of Broadband-Hamnet is required. The Broadband-Hamnet firmware looks for another mesh nodes by scanning the surrounding wireless network for a common Service Set Identifier (SSID). The SSID is the name of the wireless network broadcasted by a router, which Broadband-Hamnet setups up to uniquely define the mesh network. An example of a Broadband-Hamnet SSID is BroadbandHamnet-20-v3. Once two routers with the preset Broadband-Hamnet SSID come in each other, the mesh network is established. IPv4 addresses across both nodes can now be connected to each other as the routing tables are updated to contain the domain present at each node. This process of updating, adding, and removing nodes from the mesh-network is done automatically in the Broadband-Hamnet firmware.

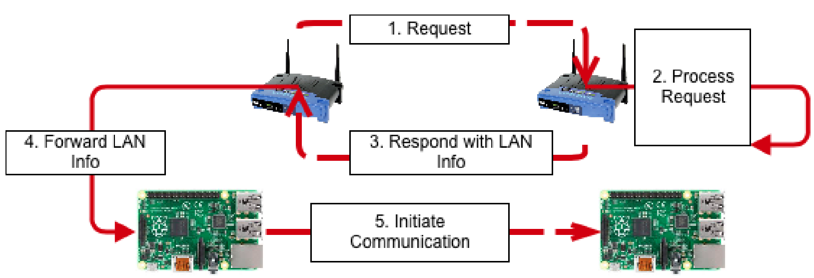


Figure 3.2.12 Remote Machine Discovery Protocol (RMDP)

The RMDP operates on the assumption that at least two routers are in contact with each other. The first step of the protocol involves one router sending a request to the other router asking for the IPv4 addresses of the machines connected to the router's LAN. The router responds to the other router's request appropriately, and sends back its LAN information. Once the router gets a response, the information is forwarded to the machine connected to the LAN, which in the scope of this project, is a Raspberry Pi. Finally, once the Raspberry Pi has the IPv4 addresses of the all remote LAN devices, it sorts the list by shortest Internet Control Message Protocol (ICMP) travel time, and proceeds to try and establish a socket connection over the TOIChat specified port 5005.

The RDMP protocol is run on the router which send requests and responses using the Linux utility netcat *("nc")*. The netcat utility allows communications between machines utilizing a TCP or UDP protocol running the Unix environment. Netcat is used in this case as opposed to the Berkeley Socket API used in the rest of the project because of the limited memory available on the Linksys WRT54G. Since netcat is a standard utility found on Unix environments over the past few decades, it is already pre-installed on the WRT54G, so there is no need to install a C complier or an interpretive programming language such as Python.

The implementation of the RMDP can be found at our GitHub page referenced in the APPENDIX.

3.2.4. TOIChat – Backend Development

Layout of the project starts by listing the desirable features for the application. First and foremost we require an internal database to store the clients and overall state of the TOIChat network. Secondly we need a server application that is continuously running in the background listening for new client connections. We need code that interacts with the Remote Machine Discovery Protocol (RMDP). We want functionality that allows users to interact with each other using text messaging similar to what you would find when using Skype or WhatsApp. A client side application is required that will send messages out onto the network to listening server objects. Finally the end user needs some user interface to interact with all the previously mentioned functionality.

toiChatNameServer

The final class design is broken up into multiple parts. The toiChatNameServer is at the heart of the application, in that it stores the state of network. In the traditional sense, Nameservers are centralized servers running on the internet that translate domain names such as http://www.google.com to IP addresses. A string such as google.com is easier to remember than an IPv4 address. For example google.com resolves to an IPv4 address of 172.217.4.78. Our Nameserver object will contain a lookup table for resolving call-signs to IPv4 address. The table is constructed using the Python dictionary data structure that allows for fast entry lookups (O(1)) since it is implemented as a hash table (Python, 2016). Functionality for this object also include the need to be able to add and remove entries from the dictionary in a thread safe manner. We use the lock object from the Python Threading library to lock that internal Python dictionary for when it is being used by various threads inside the class. The lock object provides for a thread safe environment.

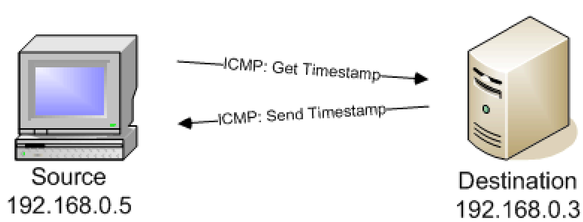


Figure 3.2.13: Internet Control Message Protocol (ICMP) Ping Packets

Since the toiChatNameServer will interact with other clients in the TOIChat network, we need to provide functionality to handle received messages. Simple packets such as the ICMP are standards that are already programmed inside the TCP/IP stack. Our applications need for more complex message types establishes the need for a more multifaceted message protocol that leads us to investigating Google Protobuf.

```
toiChatNameServer
- DNS_PING_INTERVAL: int = 20
- toiChatClient: toiChatClient
-----------------------------------------
+ printDNSTable()
+ printClients()
+ getMyIP(String iface): String myIPv4
+ addToDNS(String clientName, String clientIPv4, String dateAdded, String description)
+ removeDNSByHostname(String clientName)
+ updateMyName(String oldName, String newName)
+ lookupIPByHostname(String hostname): String clientIPv4
+ lookupHostnameByIP(String clientIPv4): String hostname
+ lookupAddedByHostname(String hostname): String dateAdded
+ lookupUpdateByIP(String clientIPv4): String hostname
+ lookupDNSLegnth(): int
+ lookupDescByHostname(String hostname): String description
+ syncDNS(String clientIPv4): Boolean
+ attemptFindServer(String toiServerPort): Boolean
+ handleDnsMessage(DnsMessage): Boolean
+ handleRegisterDNS(DnsMessage)
- handleRequestDNS(DnsMessage)
- createRegisterDnsMessage(): DnsMessage
- createRequestDnsMessage(): DnsMessage
- __loopPingDNS__()
- __pingDNSAvaliable__()
```

Figure 3.2.14: toiChatNameServer - UML Sketch

Google Protobuf

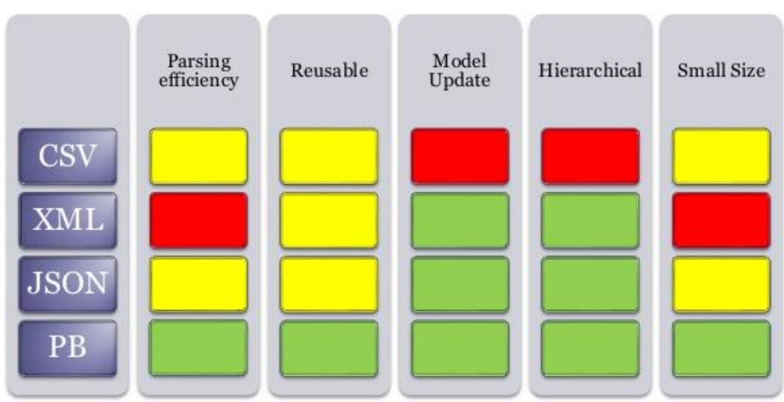


Figure 3.2.15: Google Protobuf Compared against other Popular Encoders **(Epaminondas, 2016)**

For this project we looked into various data formats that allow for serialization of data consisting of attribute-value pairs. Popular today is the JSON data format which comes from the JavaScript world. When investigating the performance of JSON for our specific needs, we found that it was outperformed by Google's Protobuf standard. The Google Protobuf standard is relatively new, and is capable of compressing data better than JSON (Epaminondas, 2016). Having a smaller message footprint ensures that the limited bandwidth available to us while using the Broadband-Hamnet mesh network is best utilized. The new

Protobuf standard also allows for upgrading of the message protocol in the future if needed. Since the software we are developing may have many unforeseen applications, having the flexibility of updating the protocol is vital for its success. A summary of the Protobuf versus other popular tools is provided via Figure 3.2.15.

The Protobuf encoder is used as the basis for all message delivered via back-end TOIChat operations. Each individual class object will have an associated Protobuf message type that it will be able to detect and handle appropriately.

toiChatServer

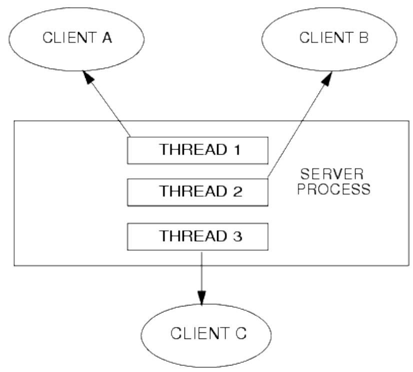


Figure 3.2.16: Server Multithreaded Client Handling

Next we define the toiChatServer, which processes any listens and process any incoming connections to the local node. The toiChatServer contains two threads: a ServerListener and a MessageProcessor. The SeverListener is a thread running solely to listen for new client connections from the overlaying BroadBand-Hamnet network. After a client has connected to the server, the server hands off message processing to the MessageProcessor thread. The MessageProcessor thread takes in a socket, receives the full message from the connected client, and outputs the message (constructed using Protobuf) to the appropriate class for message decoding and handling.

The toiChatSever has an aggregation relationship with every toiChat object referenced in this paper expect for the toiChatter object. The toiChatter object has a composition relationship (is owned) with the toiChatServer object. For every received message seen across the server socket, the toiChatServer uses a toiChatter object to handle the message for that specific client. If no toiChatter object is found, the toiChatServer creates a new toiChatter object to handle the message.

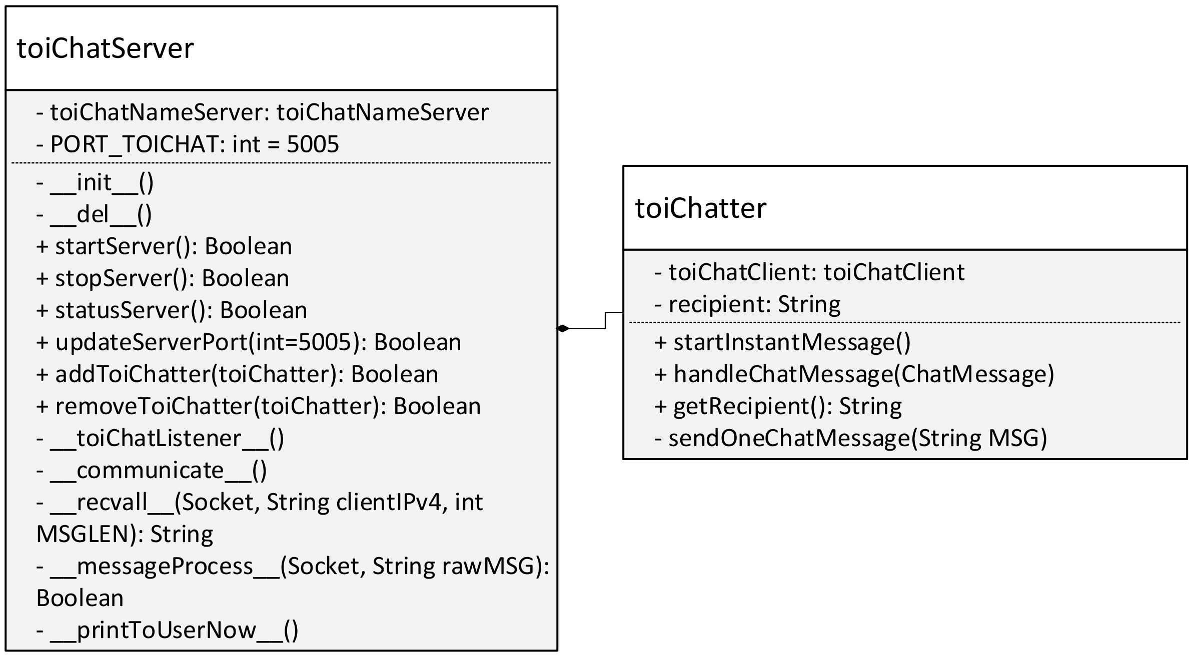


Figure 3.2.17: toiChatServer and toiChatter - UML Sketch

toiChatter

The toiChatter object implements a specific Protobuf message type containing text a client has sent and a field defining who the message is for. The toiChatter object is capable of detecting who a message is from displays it tagged with the text message.

toiChatClient

The final core object in the TOIChat application is the toiChatClient. The toiChatClient is a simple class object that interacts with any application object that desires to send a message. We force the use of sending messages with the toiChatClient as it appends a header to each message it pushes out. The header contains vital information of who originally sent the message and stamps the message as a TOIChat specific message. The stamping of the sent message is parsed by the toiChatServer object and allows for it to appropriately send the message to the correct message handler.

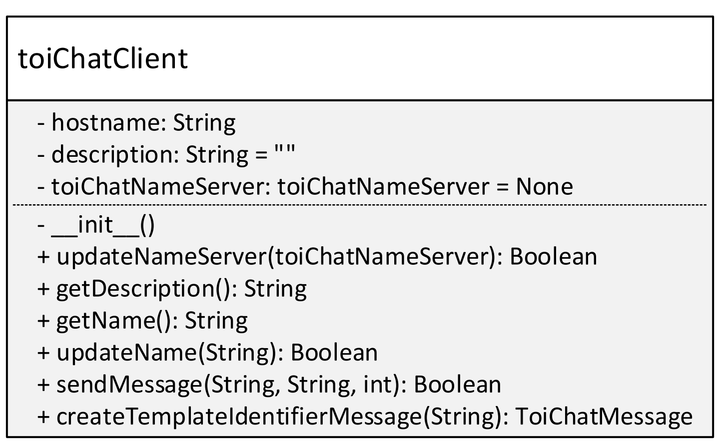


Figure 3.2.18: toiChatClient - UML Sketch

3.2.5. TOIChat - Front-End Development

Creating a Command Line Interface - toiChatShell

Once the back end of the chat software is complete, a supporting front-end is needed for user interaction. Development started with a command line interface (CLI) that brings together all back-end components.

Our CLI starts by prompting the user for call-sign they wish to use when registering themselves onto the TOIChat network. We also allow for an alternative miscellaneous field that can be used by users to provide supplemental information such as their GPS location. A prompt for your Broadband-Hamnet's router password is necessary to start the RMDP scripts.

A built-in help menu is provided for users new to the program. All expected command line features are included such as tab auto-complete, proper keyboard interrupt handling, command syntax error handling, and command history. The toiChatShell extends the standard Python cmd module (Python, 2016).

```
pi@raspberrypi: ~/projects/github/Broadband-Hamnet-devin/src/pi_scripts
pi@raspberrypi ~/projects/github/Broadband-Hamnet-devin/src/pi_scripts $ sudo python3 toiChatShell.py

What is your host-name (call sign)?:
 >>  KC3GIF
Do you want to register any misc information? (optional) (yes|no):
 >>  no

Router Password >>
ToiChatShell - A Mesh Network optimized communication application.

toiChatShell >> help statusserver
Returns status of the ToiChatServer instance.

toiChatShell >> statusserver
Server is not running.

toiChatShell >> help

Documented commands (type help <topic>):
========================================
bye             help      startchat    statusserver
forceupdatedns  printdns  startserver  stopserver


toiChatShell >>
```

Figure 3.2.19: toiChatShell - Startup

At this point in the shell startup we still have not started up the TOIChat network interface. To begin the connection to the TOIChat network we need to start the local toiChatServer instance. Trying to start a chat before starting your toiChatServer will produce error messages. By default the toiChatServer uses port 5005 to communicate with the TOIChat network. If desired, users can specify the specific port they wish to use allowing for creating two entirely separate TOIChat network running off different ports all on one Broadband-Hamnet network.

```
pi@raspberrypi: ~/projects/github/Broadband-Hamnet-devin/src/pi_scripts

toiChatShell >> startserver
Do you want start your server on a non-standard port? (yes|no):
 >>  no

toiChatShell >> forceupdatedns
Do you want to search for server on a non-standard port? (yes|no):
 >>  no
Connection to a toiChatNetwork successful.

toiChatShell >> printdns
{'KC3GIG': {'clientId': '10.119.197.28',
            'dateAdded': '20160415 - 22:32:47',
            'description': '',
            'lastPingVal': 4.527886708577474},
 'kc3gif': {'clientId': '10.247.16.45',
            'dateAdded': '20160415 - 20:28:21',
            'description': '',
            'lastPingVal': 0.5609989166259766}}

You have a new message from : KC3GIG. Open a chat window to talk back.
 >> startchat
Available users to Chat:
['KC3GIG']
Who do you want to talk to?
 >> KC3GIG
```

Figure 3.2.20: toiChatShell – Connection to TOIChat Network and Chat Messaging

Running the *forceupdatedns* function will force a toiChatNameServer sync with the closest client in the TOIChat network. After which, a user can run the *printdns* function to print the console the current state of the TOIChat network.

Now if a user is running the toiChatShell, and a message comes in from a client they will be prompted in real-time that they have a message from a TOIChat user. It displays the call-sign of the user that attempt to contact them and a recommendation to start a toiChatter instance for that user. As seen in Figure 3.2.10 KC3GIG attempt to contact us before we started a chat with the user.

```
pi@raspberrypi: ~/projects/github/Broadband-Hamnet-devin/src/pi_scripts

Start Chatting with : 'KC3GIG'.
(Escape Sequence: Ctrl+c)
------------------------------------------------------------------------------

kc3gif: KC3GIG. Its been a while! What's up buddy?
KC3GIG: no it hasn't
 >>
```

Figure 3.2.21: toiChatShell – Chat Environment

We can start a chat instance with KC3GIG by issuing the CLI *startchat* command. The application will prompt you with available TOIChat users in the active network, which you will be able to communicate with. Upon opening a chat instance with a user, a special environment opens up that allows you to have peer-to-peer communications with the selected user. After communication has ended with the user, the keyboard control sequence CTRL+C will exit you out of the chat environment. A second CTRL+C interrupt will close the toiChatShell application.

The implementation of TOIChat can be found at our GitHub page referenced in the APPENDIX.

Creating a Graphical User Interface (GUI) - ToiChatGui

An alternative environment is provided for users who prefer a simpler graphical user interface (GUI). Note the GUI implementation of TOIChat is fully compatible with the toiChatShell as they use the same back-end resources.

The GUI is created in Python using a third-party module named Gtk. To aid in rapid GUI development, a program Glade aids in the construction and layout of the application. With Glade, a GUI can be created graphically with some handy features so that it does not have to be explicitly programmed. Glade generates an XML file that can be parsed and used with Gtk. With glade and Gtk, buttons and textboxes are referenced as objects. Gtk has an Application Program Interface (API) that allows the programmer to easily interact with built in functions. Examples include getting text from an entry box, writing text to a textbox, or connecting a button click to an event handler.

The GUI was split into several sections: a login screen, a display of available chatters, and a chat window for every chatter. The login page consists of several text boxes that prompt the user to enter their username, router's password, and optional miscellaneous information. A quaternary text box also exists to display error messages to the user. The user has the option to Quit the program if it was opened by mistake.

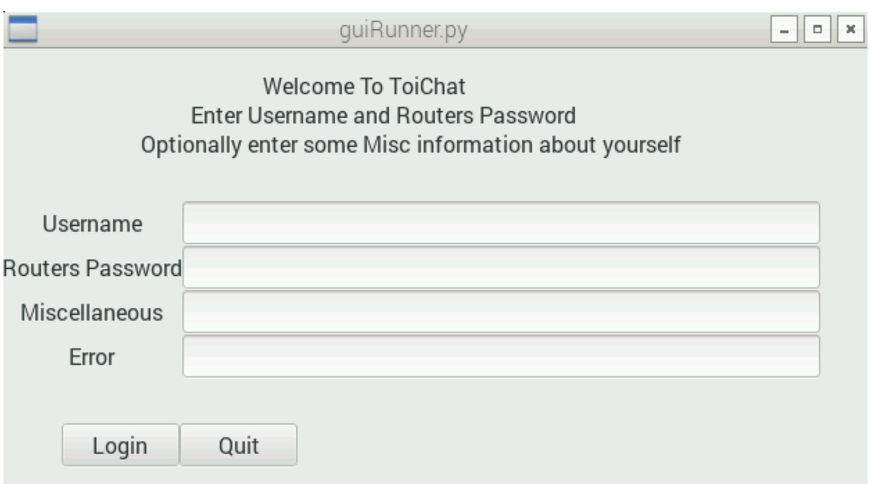


Figure 3.2.22. GUI login screen

Once the login button is clicked, the backend of TOIChat operations start. This process can take a few seconds to complete as the application is actively scanning the network for available TOIChat clients. The user can visually see the program working with a spinner.

The GUI and backend software must be in separate threads. If it is not run in threads, the GUI will freeze and not update when the backend software is running. The program will also check if the user did not enter a Username or Password. Informative status messages are written to the error display box. Messages that could appear here include errors informing the user of the program state. Such errors could be 'No Username Entered', 'No Password Entered', or 'Router's Password is incorrect'. Informative error messages are critical for any satisfying user experience.

Figure 3.2.23: Login screen error message

After a successful login, the user is registered with TOIChat network and the login window is closed and a new window opens displaying a pull down box. The new window can be seen in Figure 3.2.24. Elements in the window include a dropdown combo-box containing available active clients, a button to start a chat instance, a button to update the available client listing, and a status display textbox. The initially empty status textbox will display error messages upon occurrence to the user. Example error messages for this window include 'Connection to TOIChat Network Failed. Please try again in a few minutes' or 'Nothing Selected. Select a name to continue'. If the user clicks the update chat list button, the spinner will start and a new list of names will appear in the drop down box.

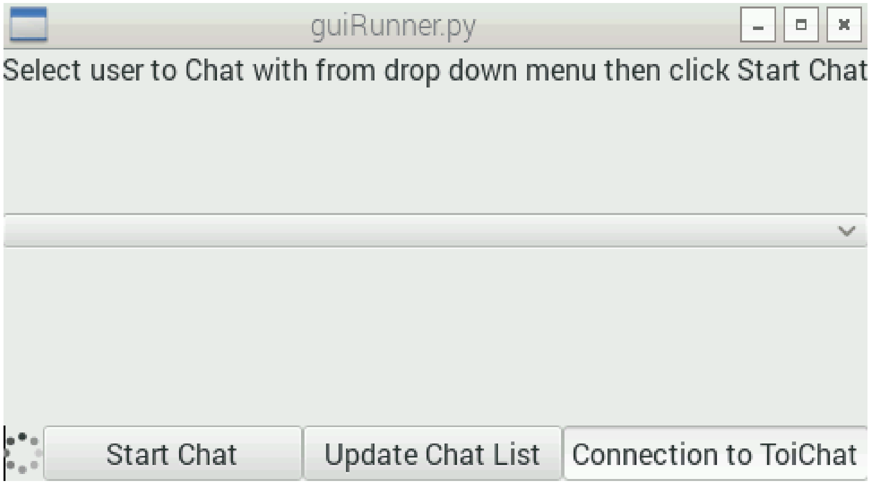


Figure 3.2.24: Choose chatter screen

To start a chat with an active client, the user must select a name from the combo-box and click the Start Chat button. A separate window will appear displaying a large space where the chat is displayed, a textbox where the user can enter their message, and a button to send a message.

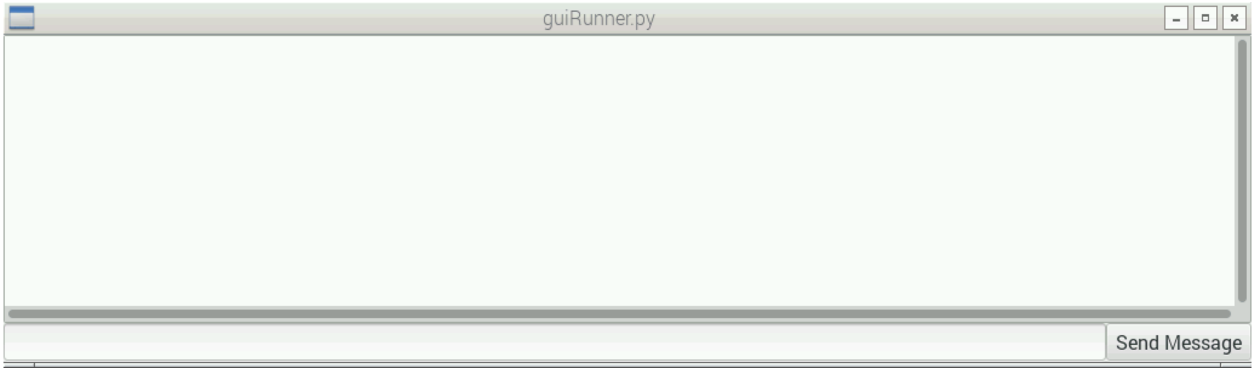


Figure 3.2.25: Gui chat window

The user can send a message by entering a string into the textbox and clicking the send message button. The message the user sent will appear in the display window tagged with the corresponding username (‘Username : message’). Any received messages will also be displayed inside the window.

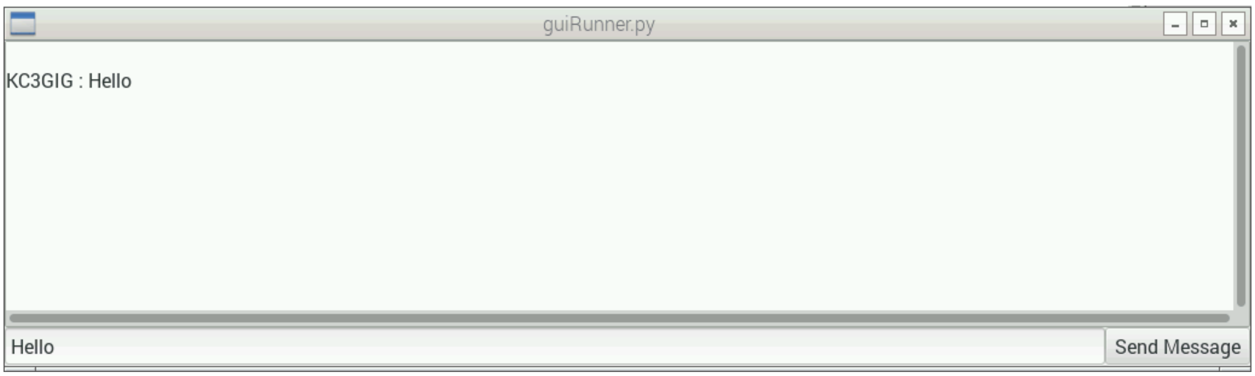


Figure 3.2.26: Sending message

The TOIChat software support communication to multiple users at once. The TOIChat GUI’s display window is capable of scrolling allowing the users to enjoy longer chat sessions. As expected, closing the chat window will not close the program. However, closing the login window or the choose chatter window will exit the program.

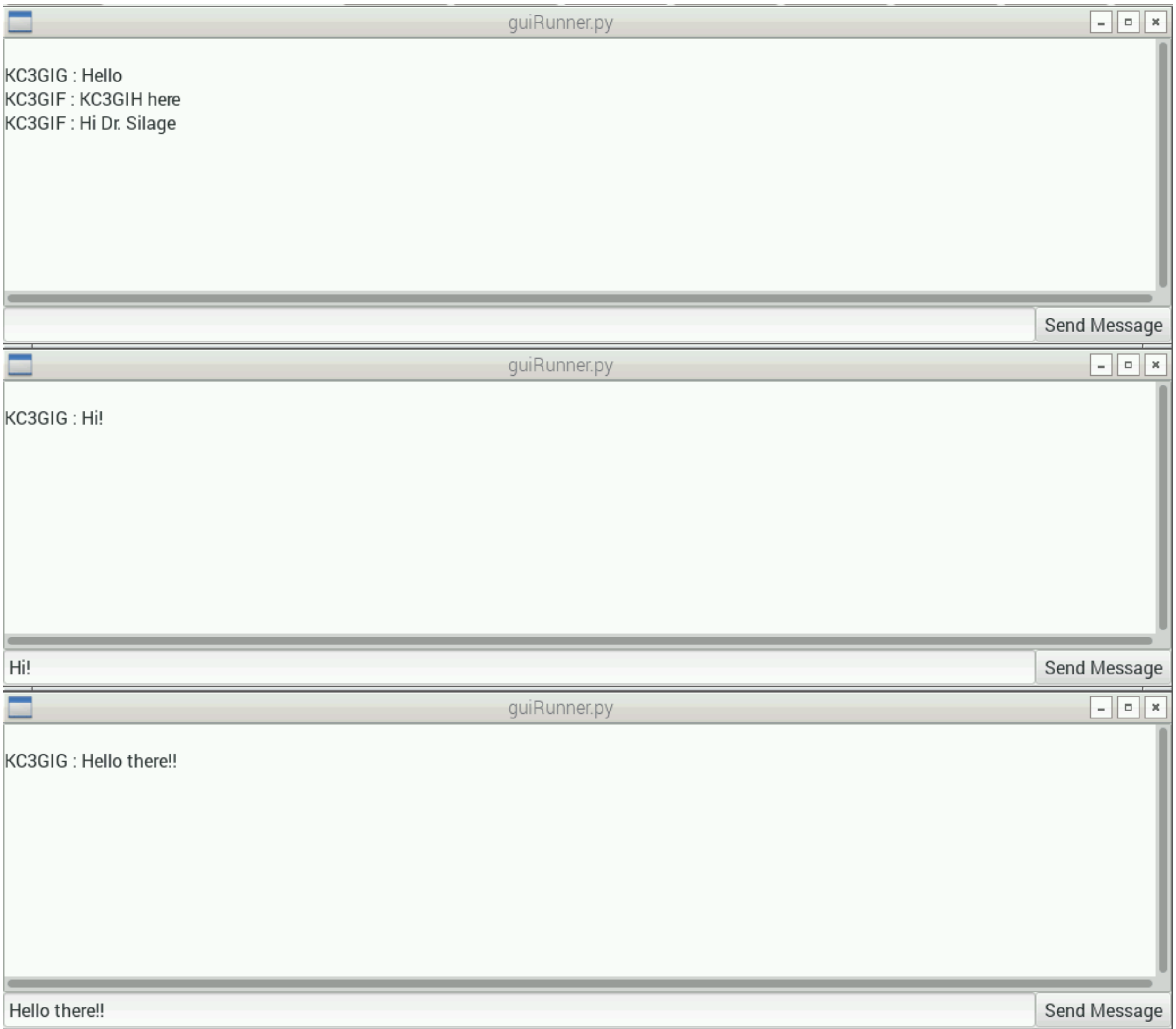


Figure 3.2.27: Multiple chat windows open simultaneously

The GUI was structured as a class called ToiChatGui. This class is instantiated once in the main program and run in a loop expecting interrupts from the user which can be serviced appropriately. The class has specifications for chat window structure. This allows for multiple windows to be instantiated and organized properly in the code. This was implemented with a list of chat window objects.

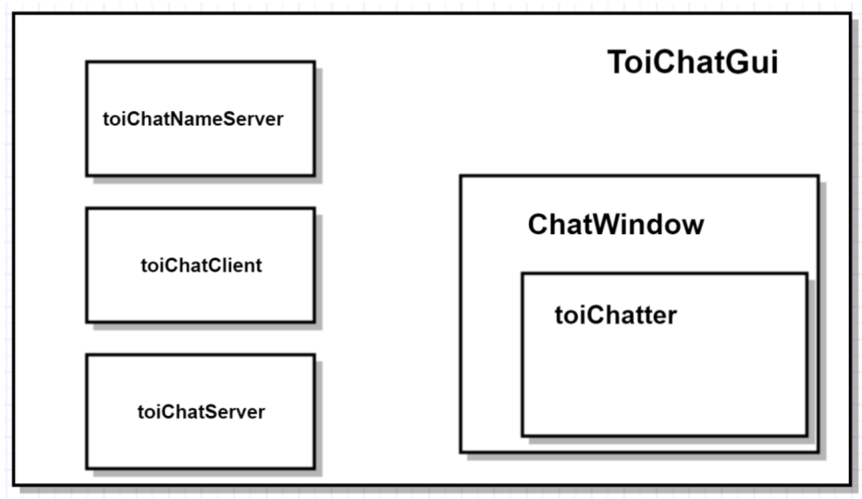


Figure 3.2.28: ToiChat high level software arc0hetecture

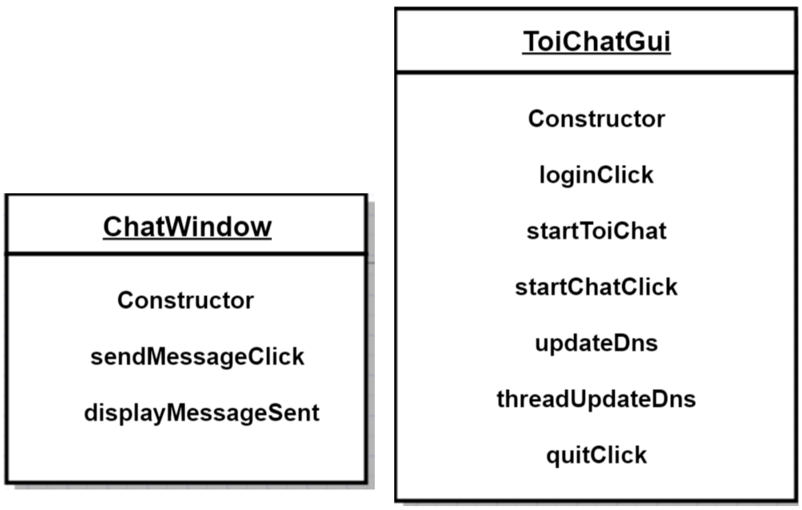


Figure 3.2.29: Methods in ToiChatGui and ChatWindow Class

ToiChatGui was also designed using standard UML diagrams. As is seen in the figures above each class contains class constructors which initializes both the login and select chatters windows. Each class had corresponding event handlers such as the *loginClick* function inside ToiChatGui which handles the user clicking the login button. More specifically, it checks the users' inputs and calls the *startToiChat* function, after which a ChatWindow for the desired client is opened. The *startChatClick* handles the start chat button and instantiates a ChatWindow class in a list. The *sendMessageClick* handles the send message button which sends a message to other chatter. The *sendMessageClick* function displays its message on the screen by calling the *displayMessageSent* function. The *updateDns* updates the chat list and the *quitClick* calls the destructor cleaning up the program properly.

4. EVALUATION

4.1. Test Methods

4.1.1. Simulation

Network Stability and Performance Testing at Various Ranges

The entire setup would be placed on the roof of the engineering building, and the system would be tested by transmitting to Montgomery County Emergency Center, which is about 25 km from the College of Engineering at Temple University. Due to administrative constraints, it is impossible to install the system on the roof. Therefore, we will have to simulate the 25 km path.

It is possible to simulate the 25 km path by dropping the output power of the router, and removing the amplifier and Yagi antenna from the system. By making use of the path loss and link budget equations in section 3.1 Hardware Design, it is possible to calculate a distance the transmitter and receiver need to be separated by to obtained the received power calculated in section 3.1.4 Link Budget. Recall our calculated received power is:

$$R_{x_{power}} = -75.01\ dBm$$

Referencing *Equation 3.3* we can find the a simulation distance (R) required that mimics a longer distance with the desired $R_{x_{power}}$.

$$R_{x_{power}} = T_{x_{power}} - Path\ Loss(dB),$$

Recall from *Equation 3.2* Path Loss is:

$$Path\ Loss(dB) = K_u + 20\log(fR) - G_1(dB) - G_2(dB)$$

The $T_{x_{power}}$ will be set to the minimum possible WRT54G power output, which is 1dBm. To solve for the distance that will effectively simulate the 25km link, the above equations are rearranged as follows,

$$T_{x_{power}} - R_{x_{power}} = Path\ Loss\ (dB),$$

Substituting appropriate values and solving for simulated distance (R) reveals that separating the routers by a distance of 62.8 m will simulate a larger distance of 25 km. Again this simulated distance is with power output of the Linksys WRT54G set to 1dBm, and removing the 2.4GHz amplifier and Yagi-Uda antennas.

$$1 + 75.01 = 32.45 + 20\log(2400 * R) - 0 - 0$$

$$R = \frac{10^{2.178}}{2400} = .0628km = 62.8m$$

We are not limited to testing only the 25 km range. There is interest in obtaining the performance metrics as a function of distance. We can simulate different distances by keeping the routers 62.8m apart, and increasing the power output on the routers. Utilizing the same equations above, we test performance at the simulated distances of 20km, 16km, 10km, and 3.1km with the results tabulated in Table 4.1.1.

Table 4.1.1: Required Power to Simulate Long Distance Communication

Distance (km)	Tx Power (dBm)
25	1
20	3
16	5
10	9
3.1	19

We will use the Linux utility Data Description (*"dd"*) along with netcat (*"nc"*) to test the effective data rates at each of the aforementioned distances as well as connectivity stability (Linux/Unix, n.d.). The actual data speed transmission script will be provided in the example directory section referenced by the project GitHub page seen in the APPENDIX. For quick reference, the Unix command seen below sends 100 packets, each containing 1000 zeros, which is a total of 100kB of data.

```
$ dd if=/dev/zero b=1k count=100 | nc –vvn $RECEIVEIP $RECIEVEPORT
```

4.1.2. Hardware

WRT54G Spectrum Test

As the amateur radio band is 2.4 GHz, it is imperative the WRTG54G is transmitting at 2.4 GHz. Testing the transmission frequency is often done inside a Faraday cage, which keeps the WRTG54's signal in, and noise signals, such as Wi-Fi, out. A Faraday cage is an enclosure surrounded by an electrical conductor. The theory behind the Faraday cage states that an externally applied electric field causes a current on the conductor of the cage that rearranges the charge carriers in a way that cancels the applied field inside the cage. Once the field inside the cage is cancelled, the current stops which reduces noise signals inside the cage (Zakaria, Sudirman, & Jamaluddin, 2008).

For this test, the WRT54G router was flashed with the custom firmware Broadband-Hamnet_v1.0.0. To test the transmission frequency, the communication system was set up in a Faraday cage with the probes of a spectrum analyzer inside the cage. The Faraday cage is necessary for this test to ensure that the spectrum analyzer is picking up our signal, as opposed to a stray Wi-Fi signal. The cage is shown here in Figure 4.1.1. The communication protocol was executed and the results were recorded. To test the effectiveness of the Faraday cage, a speed test was run from an Android device with the spectrum analyzer's probes outside the cage, followed by the same test with the probes inside the cage.

Figure 4.1.1: Com Setup inside Faraday Cage

WRT54G Output Power Test

To ensure we will we are actually seeing 19dBm outputting from the router, we hook up the output terminal of the router to the spectrum analyzer. The spectrum analyzer power measurement tool will allow us to set a frequency range and reports the power output in dBm. Before performing the test we ensure we have the router set to output the maximum possible output via the Broadband-Hamnet web portal interface.

Figure 4.1.2: Broadband-Hamnet Web Portal

4.1.3. Software

Software testing is accomplished by ensuring the application is setup to be easily installed on any RPI2. Installation instructions are provided on the GitHub homepage. Project dependencies to install the project are mostly handled by the Python module "*SetupTools*", but includes:

- Root privileges on your PI for utilizing raw sockets. ICMP messages are implemented directly in Python.
- Router scripts router_request_arpinfo.sh, and router_tx_arpinfo.sh need to be preloaded onto your router.
- Python 3.2 or Greater.
- Google Protocol Buffers 3
- Requires 'sshpass' for recurring ssh communications with Broadband-Hamnet router.
- python3-gi installed via the Raspbian Package Manager

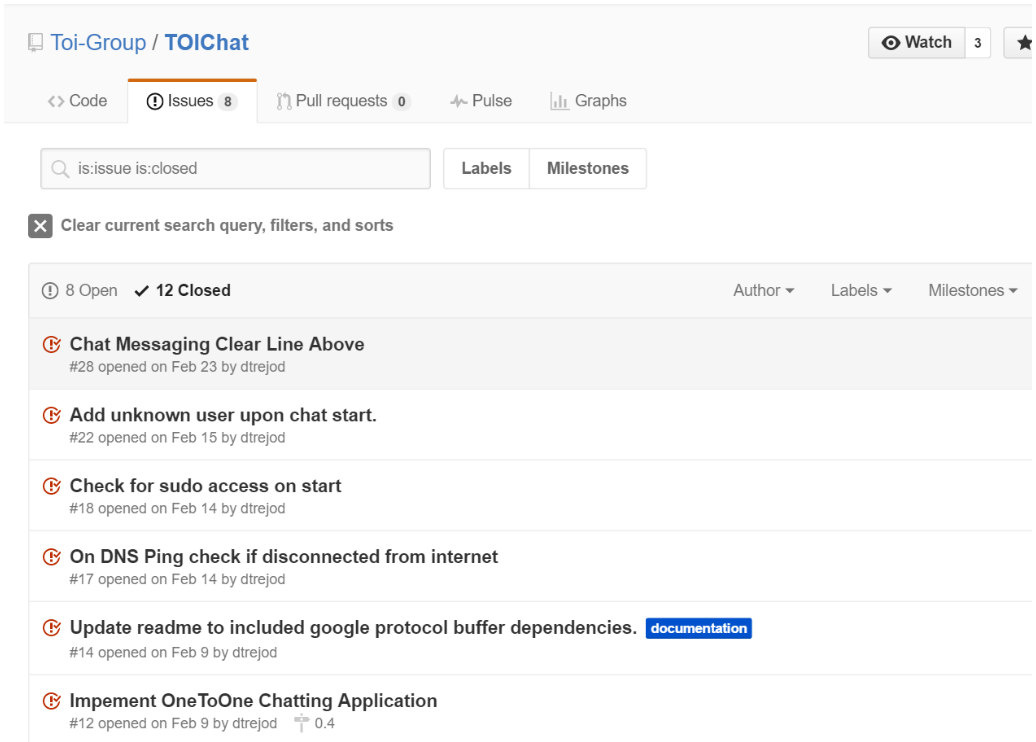


Figure 4.1.3: GitHub Issue Tracker

Extensive unit testing and bug squashing was done beforehand to ensure program stability. Bugs were tracked using the GitHub issues tracker seen in Figure 4.1.3. The inclusion of a several verbose output modes available only when running inside the command line interface (CLI) will save any information, warning, and error messages to a ToiChat.log file store in the root directory of the application.

4.2. Results

4.2.1. Simulation

Network Stability and Performance Testing at Various Ranges

The range test was performed in the hallway connecting the Science Education and Research Center (SERC) to the College of Engineering. Figure 4.2.1 and Figure 4.2.2 show the two systems set up with line of sight.

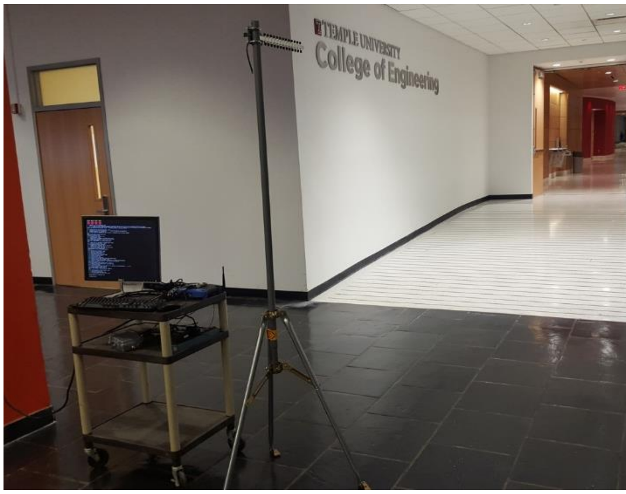


Figure 4.2.1: Performance Test Station 1

Figure 4.2.2: Performance Test Station 2

As predicted in Section 4.1.1, by dropping the power output of the routers to 1dBm, we were able to simulate a communication link of 25 km, 20 km, 16 km, 10 km, and 3.1 km by separating the routers by an actual distance of 62.8 m and adjusting the power output on the routers accordingly.

The results in Figure 4.2.3 and Figure 4.2.4 are expected for this experiment. The signal to noise ratio decreases as a function of distance, which in the case of this experiment directly relates to the output power of the Linksys WRT54G. The same is true for the effective data rate, which ranges from about 21 Mbps to 6 Mbps. The decrease in data rate directly relates to the signal to noise ratio because the probability of bit error increases as the signal to noise ratio decreases (Nguyen & Shwedyk, 2009). Therefore, due to the functionality of TCP, the data rate is reduced due to more frequent retransmissions caused by erroneous packets.

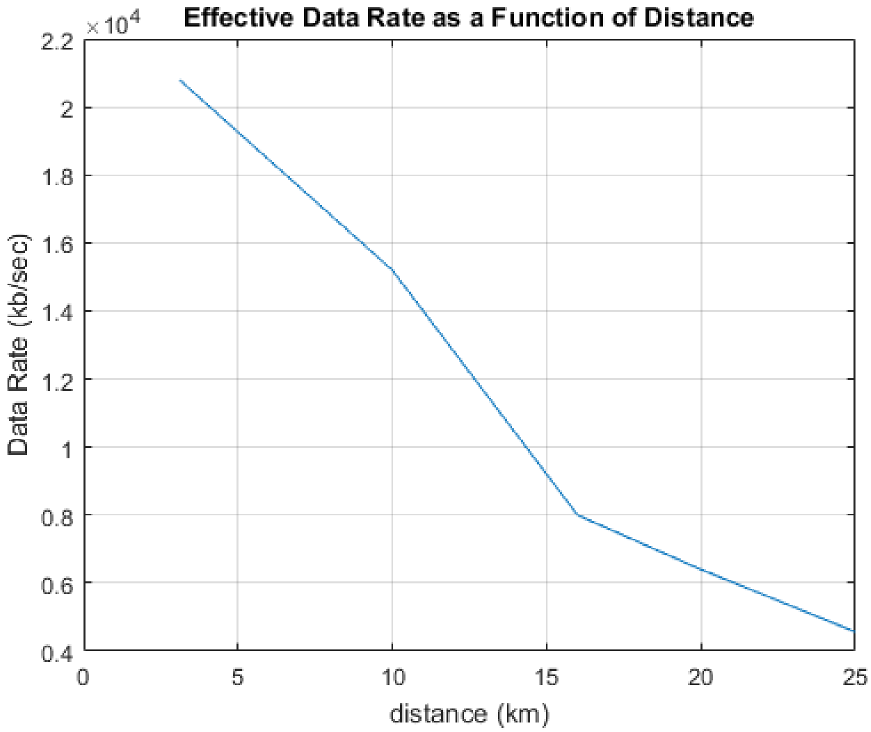


Figure 4.2.3: Effective Data Rate vs Simulated Distance

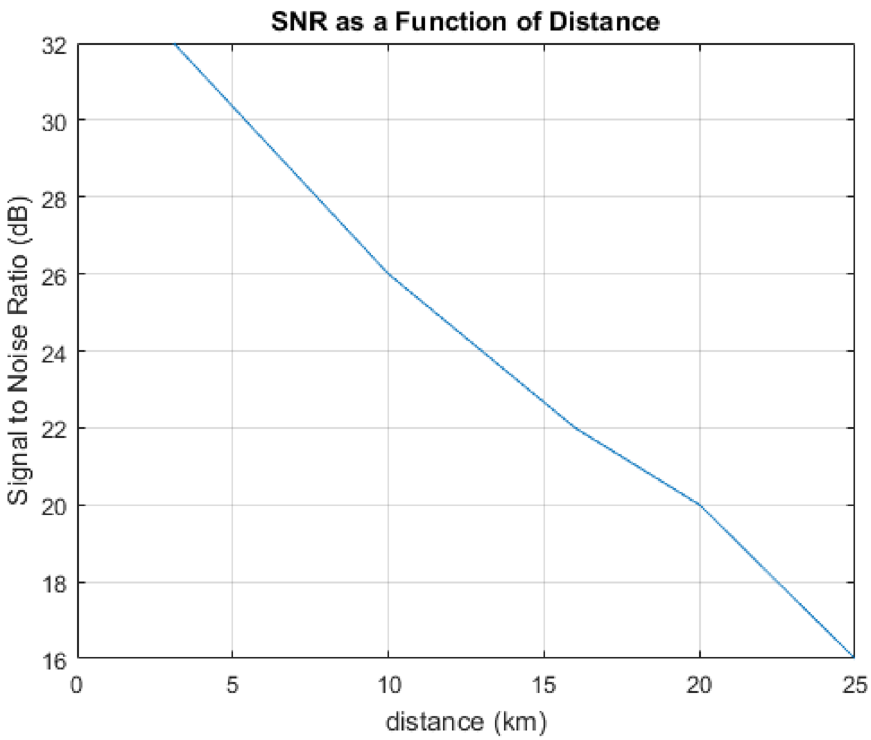


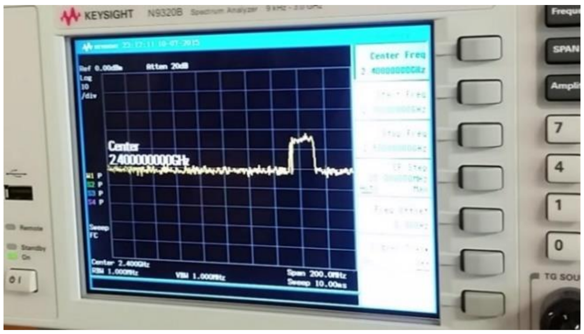
Figure 4.2.4: SNR vs Simulated Distance

Figure 4.2.3 shows lower data rates than those predicted in Figure 3.1.12. The data rates predicted in Figure 3.1.12 assume error free transmissions, or an infinite signal to noise ratio. In the experiment proposed to test the data rates in Section 4.1.1, there is not an infinite signal to noise ratio which means errors will occur, and retransmissions cause the data rates to drop. Another reason the actual data rates are lower than the projected data rates is a technology implemented by the Broadband-Hamnet firmware called carrier sense multiple access (CSMA). A communication system utilizing CSMA must wait for the channel to be clear before transmitting data (Popiel). Because the amateur bands that Broadband-Hamnet utilizes for transmission are the same bands as standard Part 15 wireless devices, the Linksys WRT54G sense WiFi signals on the channel, making them wait to transmit. This is especially likely because we tested the system inside the College of Engineering, a place where there a multiple access points throughout the building.

4.2.2. Hardware

WRT54G Spectrum Test

For our spectrum test we found that indeed our router was operating in the expected 2.4 GHz range. The spectrum analyzer picked up a lot of activity when the Faraday cage was open, and picked up a mere fraction of that signal with the cage closed. These results are shown in Figure 4.2.5 and Figure 4.2.6.



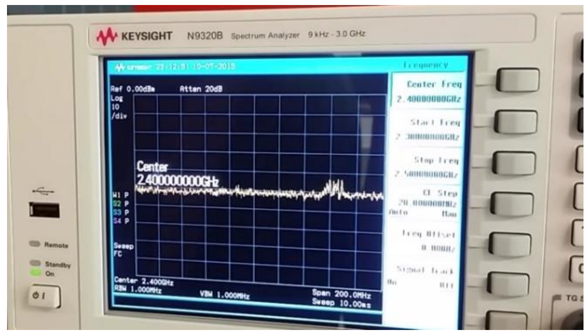


Figure 4.2.5: Speed Test, Cage Open

Figure 4.2.6: Speed Test, Cage Closed

Because it is evident that the Faraday cage would block stray signals, the transmission frequency of the router could be properly tested. The transmission frequency was in the 2.4 GHz band and the spectrum analyzer seen in Figure 4.2.7 depicts this.

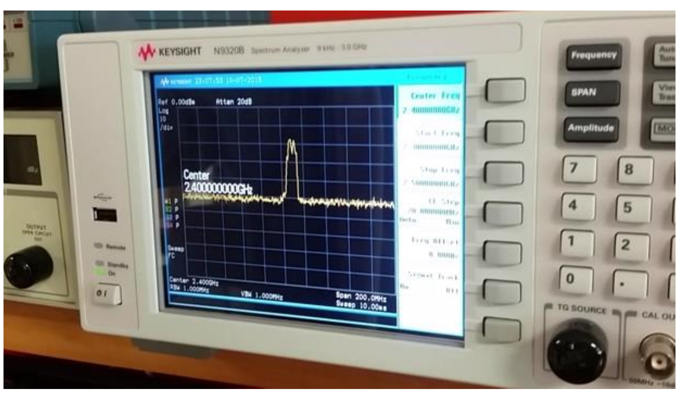


Figure 4.2.7: Transmission Frequency

WRT54G Output Power Test

For the spectrum test we used an antenna to pick up the 2.4 GHz signal put out by our router. For the power test we needed a direction connection to our router so we picked up an adapter cable to take power straight from the RF terminal of the router to the spectrum analyzer. Thus, what we are measuring is the full output power of the router.

According to the IEEE 802.11g standard we know the bandwidth of our signal to be ~20MHz (or exactly 22MHz). Also the standard for IEEE 802.11 states that on the 2.4GHz spectrum a channel setting of one within the router firmware is equal to an actual transmission frequency of 2.412GHz (see Figure 4.2.8). The Broadband-Hamnet web console allows us to set these settings. We set our router output channel one with max power (19dBm) with both Tx/Rx (transmit and receive) on the left output terminal (see Figure 4.2.9). The Tx/Rx on one terminal setting is explained since our YAGI antenna will interface with the router via a signal RF interconnect.

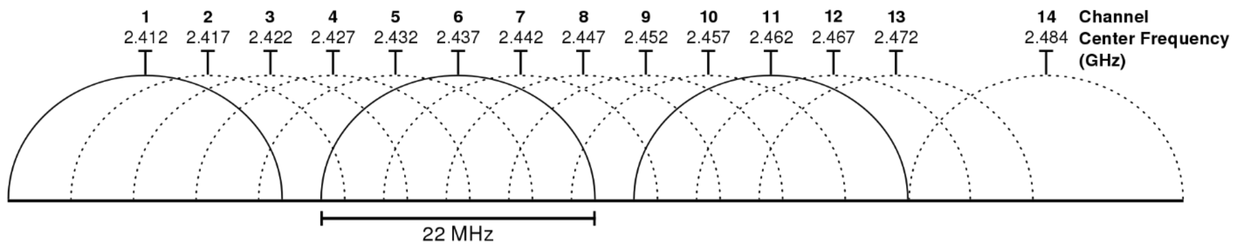


Figure 4.2.8: IEEE 802.11 2.4GHz channel spacing

Figure 4.2.9: Broadband-Hamnet Web Portal – Configuration Settings

We found the max output power of the router over a 30 second observation time to be equal to ~15dBm.

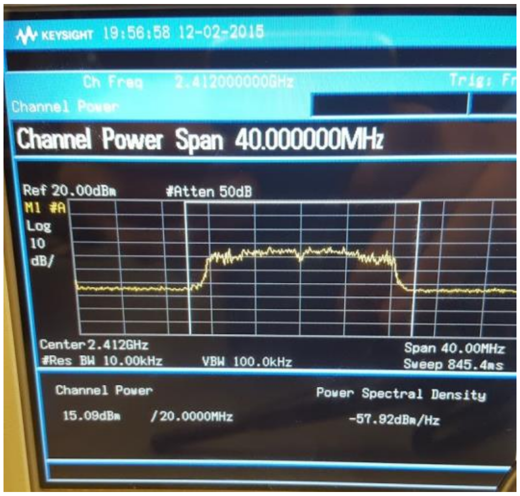


Figure 4.2.10: Power of WRT54G (Frequency Range: 2.22GHz→2.62Ghz)

4.2.3. Software

TOIChat Application Debugging

To analyze the performance of the actual TOIChat application we put the program in verbose mode. Verbose mode at this time is only available via the command line interface (CLI) and is set by passing a number of "-vv" flags when starting the application. The more v's provide the more verbosity output by the application. By default, a log file is maintained that only stores error message produced by the application. Providing one (*"–v"*) flag will display information messages such as "Server start was successful" and "Adding <callsign> to DNS table". Providing two (*"–vv"*) flags will put the program in full debug mode, allowing for monitoring of background threaded processes such as continuous pinging, and monitoring of all received serialized and decoded messages.

```
pi@raspberrypi: ~/projects/github/Broadband-Hamnet-devin/src/pi_scripts
20160413_19:57:20:236-modules.toiChatNameServer-INFO: Starting new toiChatNameServer insta
nce.
20160413_19:57:20:243-modules.toiChatNameServer-INFO: Adding - 'kc3gif' to DNS table.
20160413_19:57:24:664-modules.toiChatServer-DEBUG: Server Listener thread started.
20160413_19:57:24:665-modules.toiChatServer-DEBUG: Message Processor thread started.
20160413_19:57:24:666-modules.toiChatServer-INFO: Server start was successful!
20160413_19:57:26:306-modules.toiChatNameServer-DEBUG: 'kc3gif' responded. Average ping ti
me = 0.713189442952474 ms.
20160413_19:57:46:285-modules.toiChatNameServer-DEBUG: 'kc3gif' responded. Average ping ti
me = 0.5824565887451172 ms.
20160413_19:58:06:289-modules.toiChatNameServer-DEBUG: 'kc3gif' responded. Average ping ti
me = 0.626524289449056 ms.
20160413_19:58:26:291-modules.toiChatNameServer-DEBUG: 'kc3gif' responded. Average ping ti
me = 0.6117026011149088 ms.
20160413_19:58:46:292-modules.toiChatNameServer-DEBUG: 'kc3gif' responded. Average ping ti
me = 0.6146430969238281 ms.
20160413_19:59:06:297-modules.toiChatNameServer-DEBUG: 'kc3gif' responded. Average ping ti
me = 0.7163286209106445 ms.
20160413_19:59:26:298-modules.toiChatNameServer-DEBUG: 'kc3gif' responded. Average ping ti
me = 0.6566047668457031 ms.
20160413_19:59:46:300-modules.toiChatNameServer-DEBUG: 'kc3gif' responded. Average ping ti
me = 0.5772113800048828 ms.
20160413_20:00:06:303-modules.toiChatNameServer-DEBUG: 'kc3gif' responded. Average ping ti
me = 0.5766550699869791 ms.
:
```

Figure 4.2.11: TOIChat.log - TOIChatShell.py Startup

An example of the debug functionality upon program start of TOIChatShell.py can be seen in Figure 4.2.11. As is demonstrated by the log, we can see the class object instantiation is for the toiChatNameServer class. Once the class object is created the program adds the local user to the internal NameServer or IPv4 client database.

An example of the debug functionality upon program start of TOIChatShell can be seen in Figure 4.2.11. As is demonstrated by the log, we can see the class object instantiation is for the toiChatNameServer class. Once the class object is created the program adds the local user to the internal NameServer or IPv4 client database.

After creating the name server object, a user will most likely start the server listener. Doing so spawns two server threads: a ServerListener and a MessageProcessor. If both threads spawn successfully no error is thrown and the program continues to run. If another instance of the toiChatShell or ToiChatGUI is already running, an error may occur. If this error occurs, then the server listener thread will raise a socket exception. The error indicates to the user that the program can not bind to the default server port of 5005 because the port is being used by another application.

At this point the application and background processes are running, namely, the background pinging service found inside the toiChatNameServer. The toiChatNameServer keeps track of the average ping time to each client registered in the Nameserver. It even pings the local host to ensure network connectivity is maintained. If for some reason the ping to the local host fails, the application detects the error and prompts the user that their network connectivity is unstable or disconnected. If there is network loss, the toiChatNameServer is smart enough to not delete any non-responsive clients in the network. In doing so, it maintains an up to date database of clients in the network once network connectivity is re-established.

```
pi@raspberrypi: ~/projects/github/Broadband-Hamnet-devin/src/pi_scripts
20160413_20:01:36:924-modules.toiChatServer-INFO: ('10.119.197.28', 51775) - connected
20160413_20:01:36:925-modules.toiChatServer-DEBUG: expected len message = 59
20160413_20:01:36:926-modules.toiChatServer-DEBUG: actual len message = 59
20160413_20:01:36:927-modules.toiChatServer-DEBUG: RAW Received MSG = b'\n9\n.\n\x06KC3GIH
\x12\r10.119.197.28\x1a\x1320160413 - 23:48:23"\x00\x12\x07request'
20160413_20:01:36:930-modules.toiChatServer-DEBUG: Decoded Received MSG = id {
  clientName: "KC3GIH"
  clientId: "10.119.197.28"
  dateAdded: "20160413 - 23:48:23"
  description: ""
}
command: "request"

20160413_20:01:36:931-modules.toiChatNameServer-INFO: Received a 'request' DNS message fro
m '10.119.197.28'.
20160413_20:01:36:932-modules.toiChatNameServer-INFO: Sending a 'request' message to '10.1
19.197.28'.
20160413_20:01:36:952-modules.toiChatClient-INFO: Message sent to ('10.119.197.28', 5005).
20160413_20:01:36:953-modules.toiChatServer-INFO: ('10.119.197.28', 51775) - disconnected.
20160413_20:01:38:926-modules.toiChatServer-INFO: ('10.119.197.28', 51776) - connected
20160413_20:01:38:930-modules.toiChatServer-DEBUG: expected len message = 156
20160413_20:01:38:930-modules.toiChatServer-DEBUG: actual len message = 156
20160413_20:01:38:931-modules.toiChatServer-DEBUG: RAW Received MSG = b'\n\x99\x01\n.\n\x0
6KC3GIH\x12\r10.119.197.28\x1a\x1320160413 - 23:48:23"\x00\x12\x08register\x1a-\n\x06kc3gi
:
```

Figure 4.2.12: TOIChat.log – New Client Connect

When a new client connects (KC3GIH) to the TOIChat network, we can see the exact process taken by the application. First, we see a new client connecting from the toiChatServer ServerListener thread. The server hands the connection to the new client referenced by an open socket to the MessageProcessor thread. Recall from 3.2.2 Theory of Socket Programming section that communication between threads is handled by putting the item into a queue data structure. A perfect demonstration of this functionality is seen here when our ServerListener thread puts the socket connected to the new client on an internal class queue which is monitored by the MessageProcessor thread. It allows for the ServerListener thread to continue listening for new client connections while messages are being decoded, and processed in a separate thread.

The MessageProcessor takes the new client socket and begins receiving data from the client. We can see from Figure 4.2.11 both the RAW Google Protobuf encoded serialized version of the message and the decoded version of the message. When a new client connects to the network it pushes a toiChatNameServer bound “request” message. A “request” message is the new client telling the existing client that it is just connecting to the network and needs to pull a database of known devices from this pre-existing client. The local client detects the message successfully and passes the message to the toiChatNameServer class for handling. The toiChatNameServer message handler is capable of detecting the message type and responding with the appropriate requested information. It uses the toiChatClient to open a new socket to the connected client’s toiChatServer class for responding to the message it sent before.

```
pi@raspberrypi: ~/projects/github/Broadband-Hamnet-devin/src/pi_scripts
20160413_20:01:38:931-modules.toiChatServer-DEBUG: RAW Received MSG = b'\n\x99\x01\n.\n\x0
6KC3GIH\x12\r10.119.197.28\x1a\x1320160413 - 23:48:23"\x00\x12\x08register\x1a-\n\x06kc3gi
f\x12\x0c10.247.16.45\x1a\x1320160413 - 19:57:20"\x00\x1a.\n\x06KC3GIH\x12\r10.119.197.28\
x1a\x1320160413 - 23:48:23"\x00'
20160413_20:01:38:935-modules.toiChatServer-DEBUG: Decoded Received MSG = id {
  clientName: "KC3GIH"
  clientId: "10.119.197.28"
  dateAdded: "20160413 - 23:48:23"
  description: ""
}
command: "register"
clients {
  clientName: "kc3gif"
  clientId: "10.247.16.45"
  dateAdded: "20160413 - 19:57:20"
  description: ""
}
clients {
  clientName: "KC3GIH"
  clientId: "10.119.197.28"
  dateAdded: "20160413 - 23:48:23"
  description: ""
}

:
```

Figure 4.2.13: TOIChat.log – Database Synchronization

The next sequence of communication links between the local client and the newly connected client show how the database is synced between the two toiChatNameServer objects. From the previous "request" message received, our local client responds with a "register" message containing a listing of all known clients in the network. The "register" message contains the entire database of known clients and status of TOIChat network. The new client responds with its own "register" message shown in Figure 4.2.13. The process is ever-looping until both sides have agreed that the two databases are identical. Any conflicting discrepancies are handled by the toiChatNameServer which uses the information from the client to determine which side has the most up to date version of the database by checking the "dateAdded" field.

```
pi@raspberrypi: ~/projects/github/Broadband-Hamnet-devin/src/pi_scripts
20160413_20:05:56:524-modules.toiChatServer-INFO: ('10.119.197.28', 51791) - connected
20160413_20:05:56:525-modules.toiChatServer-DEBUG: expected len message = 64
20160413_20:05:56:526-modules.toiChatServer-DEBUG: actual len message = 64
20160413_20:05:56:527-modules.toiChatServer-DEBUG: RAW Received MSG = b'\x12>\n.\n\x06KC3G
IH\x12\r10.119.197.28\x1a\x1320160413 - 23:51:45"\x00\x12\x06kc3gif\x1a\x04cool'
20160413_20:05:56:530-modules.toiChatServer-DEBUG: Decoded Received MSG = id {
  clientName: "KC3GIH"
  clientId: "10.119.197.28"
  dateAdded: "20160413 - 23:51:45"
  description: ""
}
recipients: "kc3gif"
textMessage: "cool"

20160413_20:05:56:532-modules.toiChatServer-INFO: ('10.119.197.28', 51791) - disconnected.
20160413_20:06:00:275-modules.toiChatClient-INFO: Message sent to ('10.119.197.28', 5005).
20160413_20:06:06:359-modules.toiChatNameServer-DEBUG: 'kc3gif' responded. Average ping ti
me = 0.6734132766723633 ms.
20160413_20:06:12:375-modules.toiChatNameServer-DEBUG: 'KC3GIH' responded. Average ping ti
me = 11.780460675557455 ms.
20160413_20:06:12:690-modules.toiChatClient-INFO: Message sent to ('10.119.197.28', 5005).
20160413_20:06:14:945-modules.toiChatServer-INFO: ('10.119.197.28', 51792) - connected
20160413_20:06:14:947-modules.toiChatServer-DEBUG: expected len message = 120
20160413_20:06:14:947-modules.toiChatServer-DEBUG: actual len message = 120
:
```

Figure 4.2.14: TOIChat.log – Chat Messages

Inspection of the application while chat messaging is occurring is seen in Figure 4.2.12. Chat messaging is handled by the toiChatter object and accepts messages ProtoBuf ChatMesage type. In Figure 4.2.12, we see KC3GIH sending recipient KC3GIF (the local client) a message containing the string “cool”.

Another interesting aspect to note in Figure 4.2.12 is while chat messages are exchanged between clients, concurrently running inside the toiChatNameServer pinging thread in monitoring the state of the TOIChat network. Finally a failed ping and removing of lost node shown in Figure 4.2.15. At this point any future references in the TOIChat network to the disconnected KC3GIH client are removed.

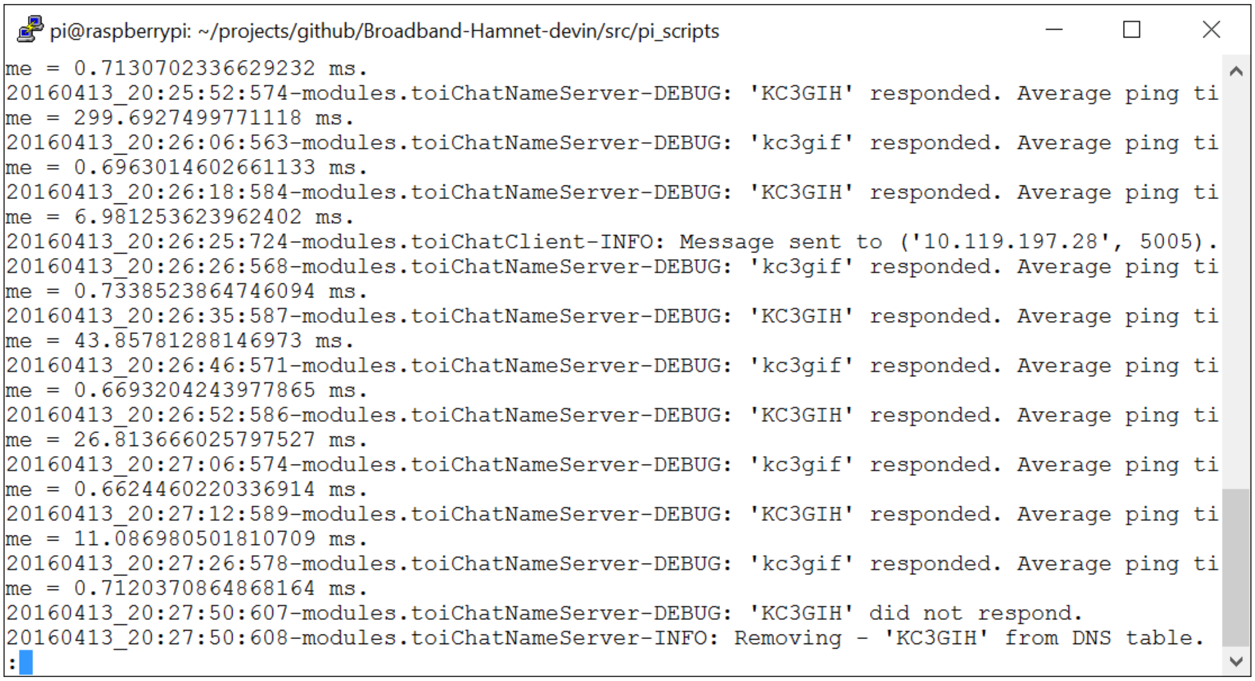


Figure 4.2.15: TOIChat.log – Failed Ping and Node Removal

5. SUMMARY AND FUTURE WORK

The Broadband-Hamnet Microwave Communication System met the design requirements for both hardware and software. This project was successful in utilizing inexpensive, COTS hardware such as the Raspberry pi and the Linksys WRT54G. The long distance communications were never set up due to not being able to not find an appropriate suitor to maintain the receiving end. This project therefore sets up the basis and shows the capabilities of a theoretical communication apparatus. We showed comparable communication distances and their speeds which classifies as a high-speed network. These calculations could not be fully tested but instead were simulated successfully. The hardware successfully supported a mesh network topology and full duplex communication. For software, achieving project success entailed developing an application that provides peer-to-peer communications for users utilizing a mesh network topology for a reliable Amateur Radio Network. A protocol, RMDP, was developed to facilitate the initial peer-to-peer communication setup and a new communication protocol ensures that each node of the TOIChat network is capable receiving multiple unique messages. Further, the software is designed to handle multiple types of requests from any other machine in the mesh network. These requests include adding/removing new TOIChat nodes, syncing of a large amounts of data across the mesh network, and initiating chat services. Furthermore, TOIChat's unique feature is able to automatically discover devices on the LAN of each node. Each machine successfully keeps a self-updating database of active machines and their associated IPv4 addresses.

Any team that decides to continue this project may should consider as possible contributions to the work already done. The current TOIChat software is limited to peer-to-peer communications. An improvement would be to broaden the functionality to support one-to-many or group chat rooms. The addition of one-to-many communication is feasible based on the software already in place; one would have to either implement a connection-less protocol and dedicate a range of ports to group chatting, or keep track of a list of socket objects that are involved in the group chat.

Future development could also implement a live streaming service for users on the network using a

PiCamera or some attached USB camera. Video streaming is a feasible task based off of the infrastructure already in place. The streaming service could effortlessly support high-definition video, as the data rate of 1080p video is 8Mbps, and we have reported data rates well above this standard (YouTube, n.d.).

The third area for improvement is improving the data rate of the system. It is possible to accomplish faster data rates by fully converting to a connection-less based protocol such as UDP. Implementing UDP would increase the data rate because of less overhead in the transport protocol header. A team pursuing this direction would then have to incorporate acknowledgement functionality and error detection/correction coding themselves. We would encourage anyone pursuing this direction to consult Stallings's *Data and Computer Communications* textbook which contains in depth analysis on cyclic codes, linear block codes (LBCs) and various other implementations of error detection and correction.

The final area for improvement would be to improve the hardware used in this project. While the Linksys WRT54Gs are good routers, there are currently more powerful routers on the market capable of running similar firmware to Broadband-Hamnet. The AREDN firmware is a continuation of Broadband-Hamnet and is compatible with Ubiquiti wireless routers (Popiel). The Ubiquiti routers have more flash memory, higher output power ratings, and are weather resistant. The weather resistance is a major improvement over the Linksys WRT54G due to the fact that it simplifies the overall design of the system by eliminating long coaxial runs from the router to amplifiers and antennas. In a future release, AREDN also plans to support communication in the 0,-1, and -2 channels in the 2.4GHz band (Popiel). Support on these channels would inherently increase data rates because the operation of the mesh network would be separate from standard WiFi signals.

6. ACKNOWLEDGEMENTS

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Special appreciation is in order for Dr. Biswas who gave our team a place to work after unforeseen circumstances removed us from the SCDL.

Note the TOIChat project contains a reference to GitHub Project: "python-ping" which is distributed under the GNU General Public License (GPL) License.

7. REFERENCES

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APPENDIX A – Project Site and GitHub Source Code

For further project information we encourage you to check out our project and GitHub site:

- Official Project Site -- https://sites.google.com/a/temple.edu/broadband-mcomm/
- Official Project GitHub -- https://github.com/TOI-Group

Our GitHub contains example code for getting started with half-duplex, and full-duplex socket programming. It also contains our most recent release of the TOIChat application. Instructions for setting up and installing the software yourself are provided via the GitHub README. Lastly, the GitHub contains MATLAB code that uses the equations throughout this paper to simulate and produce the theoretical results proposed by this paper.

APPENDIX B – Project Contact

Any further questions or concerns should be directed towards team lead Devin Trejo (email: devin.trejo@temple.edu).