Journal of Mobile Multimedia, Vol. 10, No.1&2 (2014) 141-159

FIELD MEASUREMENTS OF AN URBAN TWO-TIER WIRELESS MESH ACCESS NETWORK: END-USER PERSPECTIVE

DRISS BENHADDOU and JULIAN NARANJO

University of Houston, TX, USA

dbenhaddou@uh.edu, julionaran@yahoo.com.ar

Multi-tier wireless mesh networks are promising technologies that are deployed to provide economic high speed Internet access. In an effort to provide low-cost broadband Internet access to a low income neighborhood in Southeast Houston, Rice University and Technology for All (TFA) organization deployed a multi-tier mesh Wi-Fi Network that extends a single fiber-optic channel to serve a large coverage area. The access tier connects homes to the nearest Wi-Fi Mesh Access Point (MAP); several MAPs are installed in specific locations for complete coverage of the neighborhood. The MAPs form a multi-hop wireless network to the fiber back-haul. This paper presents an extensive in-home performance measurement of the TFA network to characterize the network performance from user perspective. The results show that the current design need improvement to fulfill user expectation and implementation of wireless mesh network as an access technology for end-users' broadband access. In addition the paper simulates the effect of directional antenna on the design of such network.

Key words: Wireless Mesh Network, Field measurements, Received Signal Strength Indicator

1 Introduction

Wireless technologies are developing in very high pace and are enabling numerous applications impacting all aspect of our lives. They played a key role in reducing the digital divide of underserved population in developed countries as well as developing countries and enabled fast extension of the Internet connectivity in cost effective manner. In particular, the cost effectiveness of WiFi technology, and the flexibility and scalability of 802.11 protocols allowed the implementation of Internet access hot spots using one hop access points architecture as well as wireless mesh network (WMN) architecture. In WMNs, data from end-user is routed through the multi-hop wireless network toward the wired gateway (see Fig. 1). These kinds of networks are deployed to extend Broadband Internet access to users in underserved, suburban or rural areas without a heavy investment on infrastructure where the return on investment (ROI) is low.

WMN is a flexible architecture that can be deployed as multi-tier wireless mesh network to provide access to Internet services [1]. A two-tier mesh configuration is composed of two components; access tier that provides wireless connectivity to clients and a backhaul tier that forms a mesh topology and forwards traffic to the nearest wired Internet entry point [2]. This configuration has been deployed as a cost effective alternative to provide high-speed Internet access to neighborhoods.

In the city of Houston, Rice University and Technology For All (TFA) organization deployed a multi-hop two-tier Wireless mesh network, called TFA-Rice network, that provides Internet access through a single fiber optic channel to a large coverage area [2]. The TFA-Rice Wireless Mesh Network provides services to clients inside homes who connect through the closest Wi-Fi Mesh Access Point (MAP), as depicted in Fig 2. MAPs are deployed in strategic locations for complete coverage of the neighborhood. The back-haul link interconnects several MAPs and forwards the traffic to the wired gateway (through a fiber optic link). To inject bandwidth in different locations throughout the network, point to point links, were established between the Gateway and selected MAPs. The network operates in the 2.4 GHz ISM Frequency band.

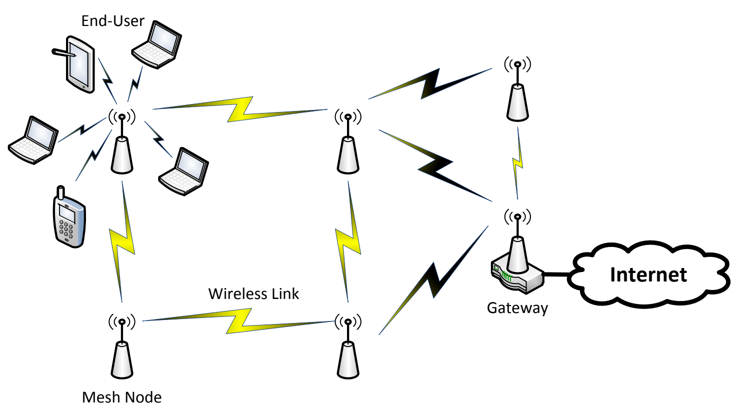

Figure 1: A two-tier WMN where mesh nodes take traffic from end-user and forward it to the gateway through backhaul (mesh node to mesh node).

The TFA network went through an extensive measurement of physical and application layers parameters to characterize access and backhaul links performance [1]–[4]. The previous work measured the performance of links in different locations and distances and used linear regression to determine the throughput on overall network coverage, especially in locations where measurements were difficult to conduct (e.g. inside homes). Based on the measurements, the network was expected to provide good Internet access to users inside homes. However, the survey conducted in [5] within the scope of an anthropology study to understand the impact of technology on under-served population culture showed that users were not using TFA-Rice network for Internet access as expected. One of the reasons was the weakness and the intermittent availability of the wireless signal. Based on those observations, we conducted other measurements inside homes to catheterize the performance of the network from user environment perspective. In our measurement instrument, we used equipment typical to that used by end user to mimic as close as possible to user environment.

This paper extends the work done in [2] and characterizes the TFA-Rice network connectivity through extensive field measurements of Received Signal Strength Indicator (RSSI) and interference level inside homes (from end-users perspective). Note that these homes do not have access points and rely on the TFA-Rice network to access the Internet. The previous work on the same network did measurements on streets and nearby homes assuming that the extrapolations from those measurements will predict what the user will experience inside home. Our study shows that extrapolations are not enough and real measurement need to be done to confirm the design. We don't attempt to develop a mathematical model but we use the same model used in the previous work in this network to show that even though prediction were accurate, those predictions did not convey the real status of the network. Further extensive work need to be done in the area of RF modeling, which is not within the scope of this paper. The research question this paper address is what is the measurement methodology that engineers should do in order to fully characterize the end-user experience. What impact signals inside home and how WMN should be designed to provide the proper signal to users in home or vehicles?

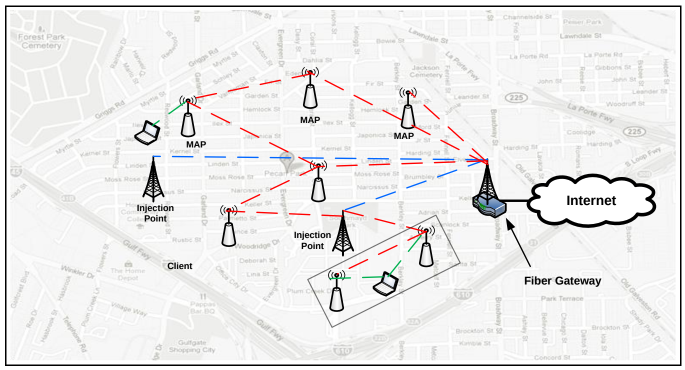

Figure 2: TFA-Rice Wi-Fi Mesh Network in Pecan Park in SE Houston

Our work uses application layer measurements and end-user performance measurement and focused on physical layer performance to understand the quality of the physical signal inside home in terms of power distribution and signal to noise ratio (S/N). The physical measurement gives information about RF engineering design while application measurement gives an indication of end user perspective and perception. As an outcome, this work identifies crucial parameters related with the signal propagation; path loss exponent, signal strength variations, interference power and noise that have an effect on the signal inside homes. The collected data is analyzed and used as input for a simulation tool to determine a feasible solution to provide recommendations on the SNR level required at homes for consistent Mesh Access Point (MAP) connectivity (a first step towards a good internet access), which will improve the service to the users in the neighborhood and can be used as an input in the design process of broadband wireless mesh networks.

The paper is organized as follows. Literature review is presented in section 2. Section 3 presents the methodology, experimental data collected and its analysis while Section 4 describes the simulation developed and its results. Finally, general conclusions are summarized in Section 5.

2 Background

A typical two-tier wireless mesh network is shown in Fig. 1. The backbone of the network is established through the backhaul tier that interconnects the mesh nodes and forwards the traffic to the gateway, which connects to the Internet through a fiber optic line. The same mesh nodes connect end-user devices through the access links. Both access links and backhaul links use the same radio frequency channel and traffic management is used to distribute resources fairly among the access and the backhaul links [2]. TFA-Rice network implements this architecture in South East Houston urban area, called Pecan Park, spanning 4.2 square kilometers [2, 3]. The area is heavily covered with trees, with height up to 20 meters, and is populated with about 20,000 resident living in single family homes with one or two stories.

In this project we use the specifications deployed by Rice-TFA project. The measurement is focused on the MAP wireless access card SMC 2532-B 802.11b which is the interface connecting user. It has a 200mW (23dBm) of transmission power and a receiver sensitivity going from -89 dBm for 11 Mbps up to -94 dBm for 1Mbps transfer rate. Each MAP is equipped with an external omnidirectional antenna with a nominal gain equal to 15 dBi. The electrical specifications of the antenna indicates the Vertical Beam Width equal to 8^o and the Horizontal Beam Width equal to 360^o (Omnidirectional). This antenna has a radio signal range of 225 to 275 meters depending on the obstructions and attenuations in every direction [2].

The field experiments consisted of a systematic data collection using the Cisco® Spectrum Expert Analyzer. The analyzer consists of a hardware-based Cisco Spectrum Expert Sensor Wi-Fi and software that records all signal and noise power levels with respect to specific frequency channels. To perform the measurements one laptop (Using an Intel Pro/Wireless 2915ABG card with 40mW (16dBm), 0dB antenna gain and a receiver sensitivity of -89dBm for 11 Mbps and -97dBm) was equipped with the Cisco Spectrum Expert PCMCIA card, the Spectrum Analyzer software and WireShark, which measures the activity of a second laptop (accessing the TFA network as the user) during the test.

Several studies have been performed on the TFA network [1], [3], [4], [6] that correlate signal propagation, and network coverage with application throughput. Related with the propagation model, the environment path loss exponent and the shadowing standard deviation were determined [2]. These parameters are considered for the design and deployment of wireless network to establish maximum allowable distances between nodes. The information collected provides significant information about critical considerations for an efficient design. A consideration of the factors for deployment in Wireless Mesh Networks [4] defines the coverage area of a MAP as the area where a client connects to the MAP if the RSSI captured at the client is above a defined threshold, considering the propagation metrics for the scenario. In a related paper, a framework to predict the coverage area of an Access Point [7], in order to expand, improve the performance, or deploy a wireless mesh network was proposed. However, all these studies used signal measurements in the streets but not inside homes while using measurement equipment with high sensitivity. Our work in this paper completes these works by performing measurement inside homes and using equipment with sensitivity similar to users' computers which will provide a more realistic insight about signal distribution in the network (including homes).

Other studies developed in different environments [8]–[11] provide characterization of the propagation model considering to specific parameters for the evaluated area. The work published in [7-10] focus on developing the propagation model of RF signals based on outdoor measurements of different configurations. While work published by Yu [17] is experimental and measurement-based, the focus is mostly on using the resultcfor performance Prediction. Wollenberg [18] work is experimental but focuses mostly on routing issues in MANET. work Experimental work by Kawade

[12] analyzed the impact of interference on the in-home Internet access by external users who connect to the same Access Point through one-hop Urban Wi-Fi sharing. While this study explains several parameters related to the degradation of the signal due to external interference, mainly due to Adjacent Channel Interference and Co-Channel Interference, Access Points are directly connected to a wired DSL line. This measurement is done in a one hop network, which does not take in consideration multihop scenario that introduces starvation problem where access point and long-haul communication compete for bandwidth. Our work is done in multi-hop two-tier network where client traffic as well as traffic from other MAPs compete for the wireless channels. This is important aspect related to physical layer that has not been considered which will help establish the cause of the low performance observed inside homes. Other work on home measurement [13]–[15] published focusses on network measurements for access points set up inside homes. GENI [16], a big project funded by the National Science Foundation in the USA, is established to develop testbed to implement innovative ideas in a real world testbed. Measurements within the scope of GENI project remain in a controlled environment for a general purpose networking solution including wireline and wireless technologies.

3 Access-link Field Measurement

3.1 Methodology

First the user identifies the SSID corresponding to the TFA Network. Second, the association is initiated by the client to gain access to the network. Third, an IP address request is initiated by the client through a DHCP server running on the MAP. Once the user receives an IP address from the DHCP server embedded on the MAP, a continuous ICMP (Ping) test between the client and the MAP was performed. The basic connectivity test evaluates the consistency and availability of the link between the user and the MAP in the access link. Fourth, an Internet browser was used to access the Internet. Internet connectivity was measured through the ability to access HTTP services. Next, reliability and consistency of the Access-Link was measured by collecting the Received Signal Strength Indicator (RSSI) and the Signal-to-Noise Ratio (SNR).

User connectivity in wireless networks is highly dependent on the signal propagation, the noise and interference power received on the user device. Wireless cards used by clients and Access Points requires a minimum threshold in the RSSI to define the data rate, a minimum in the SNR to be able to lock the signal in physical layer and transfer the data to the MAC layer.

Our methodology uses a systematic field measurement approach to evaluate the Access-Link performance. The field measurement data was represented and matched to the mathematical model to determine the characteristics of the signal distribution in this particular neighborhood. The mathematical model was then used to develop a simulation to predict the system behavior given certain improvements. The following are the expected outcome and the parameters and metrics used to evaluate the system:

- Services and Outcomes: Reliable and consistent connectivity for the users in the covered area with Internet Access up to 1Mbps.
- Metrics used are the Signal to Noise Ratio (SNR), Received Signal Strength Indicator (RSSI), and Link Availability for end user (ICMP test).

- Parameters used are, distance, propagation model, interference power, client wireless card characteristics, MAPs characteristics.
- Experiments design: A set of 60 measurements were collected inside homes and the work procedure was performed as follows:
  - Perform 10 minutes measurements per location
  - Identify the closest MAP (Stronger RSSI)
  - Do spectrum Analysis
  - Determine the distance to the MAP
  - Association and connection (DHCP request) with the MAP
  - Test connectivity to MAP using ICMP test (400 packets, 32 bytes per packet)
  - If the connection to MAP is successful, access the Internet
  - If there is no connection, disconnect and start the process again
  - Save results from spectrum sensing and the ICMP test

Based on the collected data, the propagation model, Interference power and sources, Access-Link reliability and other parameters with an incidence on the Access-Link performance have are to be identified. The outcome of this study can be used as reference for design and troubleshooting purposes in Wireless Mesh Networks for similar environments.

A simulation was developed taking in consideration the collected data on the field measurements. In this phase of the project, the first step was to simulate the Access-Link environment to compare with the field measurements.

3.2 Connectivity characterization

A total of 60 Homes were visited for measurements collection. At each location, a minimum of 10 minutes of data was captured using the spectrum analyzer attached to a laptop, providing 20 signal strength samples per home. From the total set of measurements, 60% of the data provided information about the network signal inside the Home. From that percentage just 23.33% have a SNR value above 15 dB. Consistent bi-directional connectivity between client node and MAP was observed in only 15% of the visited homes. In this case, connectivity is referred to as a consistent bi-directional link between MAP and client node in which a client node is able to identify, associate and successfully complete a DHCP request with the MAP and then, at least 95% of the ICMP requests by the client node are positively replied by the MAP. Fig. 3 shows the results for the connectivity test experienced during the measurements.

Finally, Internet access was successfully achieved in only 8.3 % of the locations measured. To validate this connectivity test, WireShark was used in order to count and analyze the packets exchanged between client node and MAP. This simple procedure allowed testing and verification of the first three layers of the OSI model.

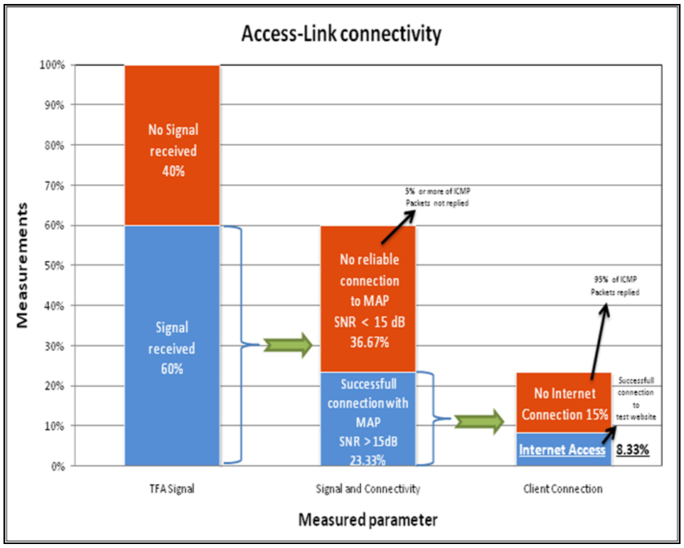

Figure 3: User connectivity measurements.

3.3 Received Signal Strength Indicator

Given that the in-home connectivity was low, the next step in the characterization was to measure the physical signal characteristics inside homes. To represent the signal propagation and characterize the Access-Link, several in-home measurements were performed at different distances from the MAPs, starting at homes located around 10 meters and moving up to 150 meters.

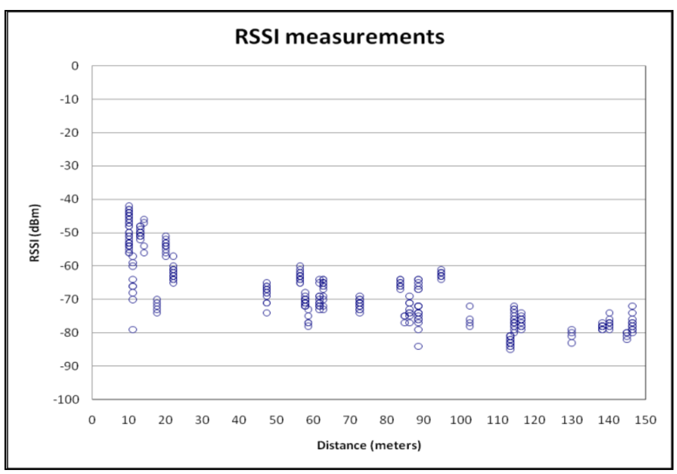

Figure 4: Received signal strength indicator measurements.

Fig. 4 represents the signal strength as a function of distance. A total of 670 measurements were collected from all the places that were visited. (The signal was not detected at every home that was visited). As expected, the signal attenuates as a function of the distance, but at similar distances, the signal can differ due to obstructions and building materials.

3.4 Signal-to-Noise Ratio

After collecting RSSI, the spectrum analyzer provided information about the SNR, a key element to define the connectivity in the Access-Link. The following figure represents the SNR as a function of the distance.

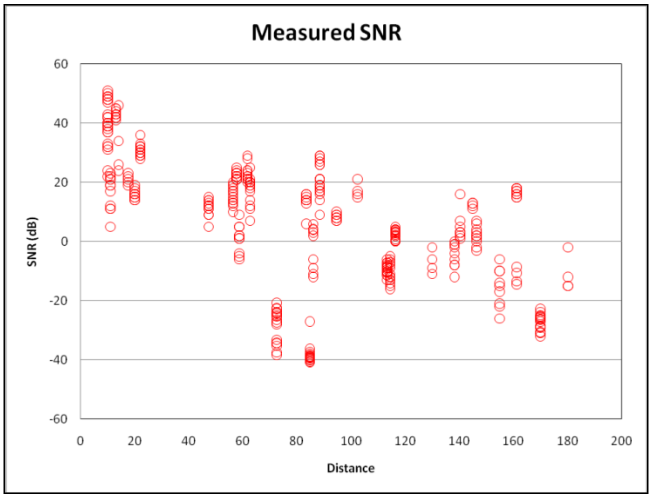

Figure 5: Signal-to-Noise measurements.

The results in Fig. 5 shows that a lot of houses exibit a SNR bellow a threshold for connectivity to be established (10 to 15 dB) with a relaible Access-Link. In some cases SNR is negative, mainly due to interferences, noise and low RSSI.

3.5 Theoretical Analysis of Measurements

Wireless channel models are used to predict the behavior of the signal under deployment conditions so that the network is designed properly to provide a predictable signal distribution and signal to noise ratio levels (see Fig. 6). Wireless propagation can be degraded by path loss, shadowing and multipath fading. Predicting multipath fading is complex and therefore the theoretical analysis will focus mainly on path loss and shadowing effects. Path loss is the attenuation of the signal as a function of the distance and is described by a pathloss exponent describing a certain propagation medium. This exponent will vary depending on the objects types and their position in the environment [4]. Measurements will be used to characterize the path loss of the neighborhood where the network is deployed. The variation of the pathloss between similar propagation scenarios is described by shadowing factor. For example, given a certain distance from the access point, multiple locations around the access point at the same distance will have different path loss values. These variations of the path loss represent the shadowing. This makes the signal prediction probabilistic within certain Gaussian distribution of shadowing. Therefore many measurements should be conducted to full characterize the signal in the network. Radio Frequency (RF) signals within 2.4 GHz band are modeled by the following path-loss exponent and shadowing standard deviation equation [2]:

$$P_{dB}(d) = P_{dB}(d_0) + 10.n.\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \quad (1)$$

In the equation, X_σ represents the shadowing effect, n is the path-loss exponent, and d_0 is a reference distance for which a measurement has been performed. The path loss component of the equation is describe by the Friis Formula. It is dependent on transmission power (P_{Tx}), transmission antenna gain (G_{Tx}), reception antenna gain (G_{Rx}), frequency (or wavelength λ) and the reference distance d_0. For picocell systems such as 802.11, this value is 1 meter. Consequently, the Friis Equation is defined as follows:

$$P_{Rx} = P_{Tx} G_{Tx} G_{Rx} \left(\frac{\lambda}{4\pi d}\right)^2 \quad (2)$$

This propagation model is called *Log-normal Shadowing*. It is based on combining analytical data and empirical methods. The model is very useful because it considers all known and unknown factors through measured data. By calculating the path loss exponent n and the X_σ, a prediction of the signal propagation for a specific system can be estimated.

There are several other parameters that have an effect the signal propagation, starting with multipath fading, in which the superposition of waves creates a sum or subtraction of waves. Inter-Symbol Interference and Delay Spread such as the multipath fading, a distorted waveform is generated. Those conditions affect the performance of 802.11 networks, but are not considered for the scope of this work.

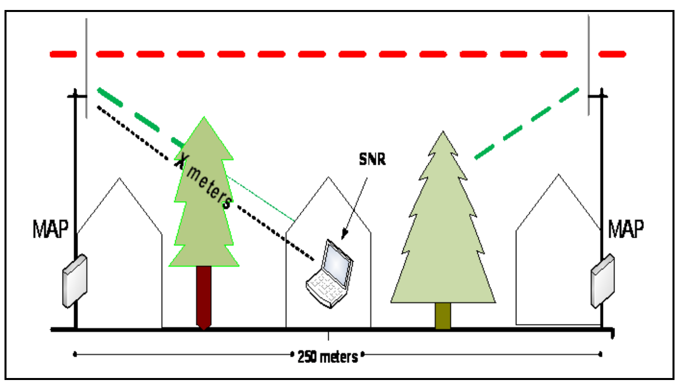

Figure 6: MAP to client node communication link showing tree objects obstructing the signal.

1) *Receiver sensitivity*

Another parameter that should be taken in consideration in designing wireless networks is receiver sensitivity. The receiver sensitivity is the indication of the power in which a device can successfully receive an incoming signal. If a device is able to understand and successfully complete the reception process of a signal in a lower power, it means the device has better receiver sensitivity. For 802.11 equipment, the receiver sensitivity is associated with a specific data rate. This is because more signal power at the receiver is required to support higher data rates. The importance of the receiver sensitivity is related with the transmission between Access-Points to clients and vice versa, given the difference in transmission power used by both entities. In taking measurement the receiver used should have the typical sensitivity used by end-user who will eventually use the network. If the equipment used has sensitivity higher than what a regular user will have, a signal characterization will not give a realistic values that will mimic the end user case.

2) Antennas for 802.11

Antennas are the most critical component of a Radio frequency system such as 802.11; its main function is to convert the electrical signals from the transmitter to radio waves and vice versa. The antennas for Wi-Fi systems are classified mainly by their pattern characteristics; Omnidirectional and directional antennas. The main difference between these two is the way the antenna receives and radiates signals. The Omnidirectional antennas can send and receive signals from every direction, 360^0 for the Horizontal Beam Width, and a defined Vertical Beam Width. In the case of the directional antennas, the reception and transmission of signals is narrowed in a specific direction in the vertical and horizontal, providing higher radiated power (Gain) at larger distances compared with the omnidirectional antennas. For both kinds of antennas, the propagation pattern plot represents the signal radiation related with the direction for the horizontal and vertical plane. The gain is represented in dBi, with is related with the forward gain of an antenna compared with an ideal isotropic radiator distributing energy uniformly in all directions. In general antenna in WiFi networks are omnidirectional to cover as much space around the network as possible. This paper studies the impact of directional antenna on WiFi network and how it can be used to accommodate users with weak receiver sensitivity.

The measured RSSI in different location was used to calculate the theoretical Path-Loss exponent and the shadowing standard deviation to determine how the signal attenuates as a function of the distance, including obstacles, building materials and other factors (multipath fading - delay spread). With the set of measurements, a regression model was used, based on the Path-Loss model, to calculate an empirical path-loss exponent and shadowing standard deviation was done using equation 1.

Fig. 7 depicts the measurement results (round circles) and their calculated regression curves. For a distances above 40 meters, the measurements are around the red curve representing a Path-loss exponent of $n = 3.7$, which concur with path-loss found by Camp [2]. Curves were plotted with shadowing standard deviation $X_{\sigma 1} = 2.39$, to represent the signal variations due to shadowing.

An interesting observation is noted in Fig. 7 for signal measured at distances below 40 meters, Which are homes close to the antenna including those where antenna is attached. For this distance range, Path-loss (represented by brown curve) is $n = 4.5$ with a shadowing $X_{\sigma 2} = 2.70$. This path-loss exponent represents higher signal attenuation which resulted in lower RSSI received at those locations. This is probably due to the antenna that was not properly designed for homes close to it.

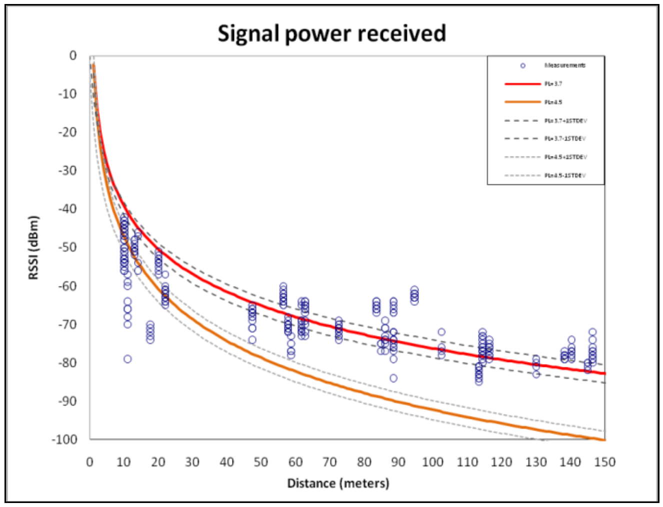

Figure 7: Signal received at the client node inside the home from 10 meters to 150 meters to the MAP.

Fig. 8 and 9 depict the probability distribution of the deviation of measured signals from the mean RSSI value. Using these figures, it is possible to determine the variations of RSSI, based on the shadowing standard deviation. For a specific location, the RSSI can be predicted as the value based on the curve with an approximated standard deviation of $X_{\sigma 1}$ or $X_{\sigma 2}$.

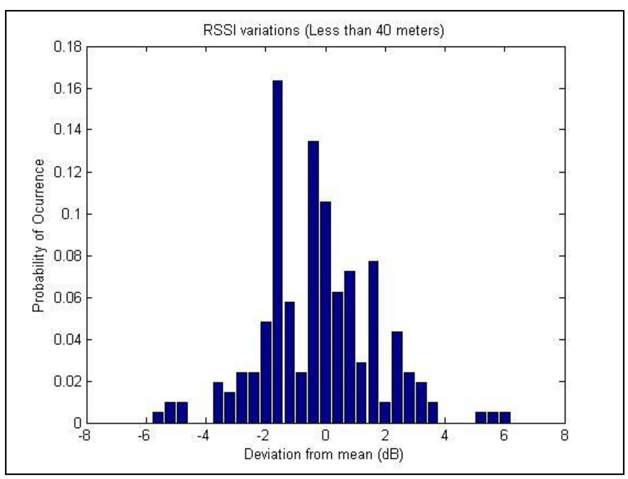

Figure 8: Variations on RSSI observed at the client node (less than 40 meters).

The spectrum analyzer detected several other devices using the ISM band during the measurements; cordless phones, cellular phones, microwaves, console games, blue-tooth devices, in-home access points and several un-identified devices. The analyzer provides information about the noise level and interference power detected in each channel and affecting the Access-Link. Each location has a different noise value and a significant amount of interference. Both co-channel and adjacent channel interference were identified which degrades the signal of interest.

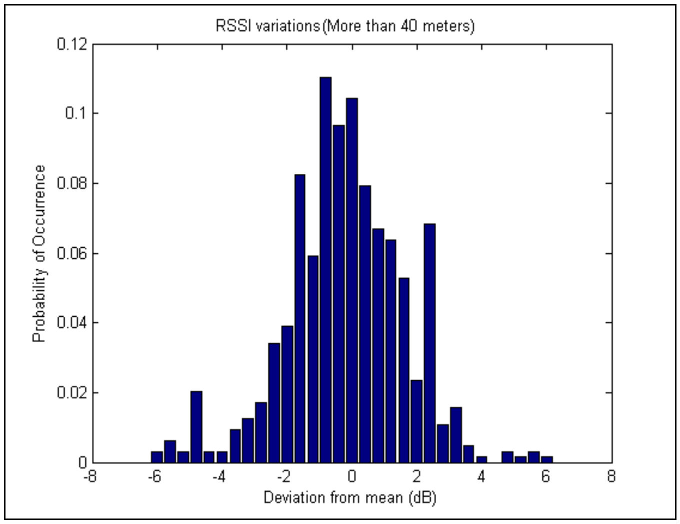

Figure 9: Variations on RSSI observed at the client node (more than 40 meters).

Fig. 10 shows the cumulative distribution function of the noise for the set of measurements. From this graph we can conclude that 50% of the measured locations exhibit a noise of -80 dBm or more. With this consideration the SNR is degraded by the interference power and the reliability of the Access-Link is affected with a high amount of packets dropped, disconnection from the network and several unsuccessful attempts to reconnect to the network. This resulted in users' frustration and disappointment of the service, as expressed to us in several opportunities by end users where we conducted the measurements.

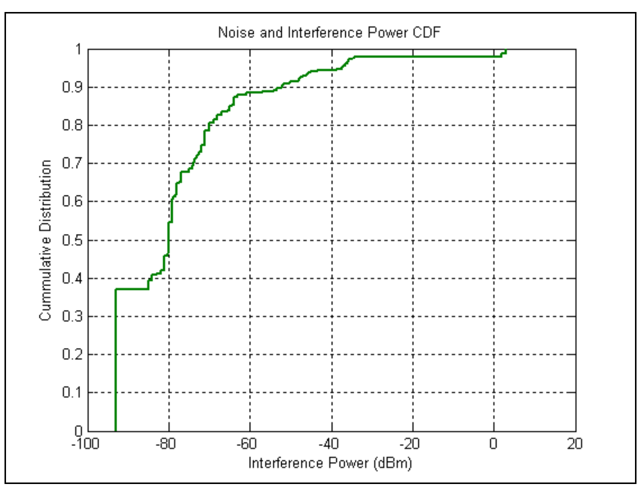

Figure 10: Cumulative distribution of Interference power observed during the measurements.

3) Signal-to-Noise ratio distribution

To achieve a reliable connection in areas covered by the TFA network, the SNR threshold has to be at least 25 dB [7]. Fig. 11 depicts the cumulative distribution of the SNR of the entire set of collected measurements.

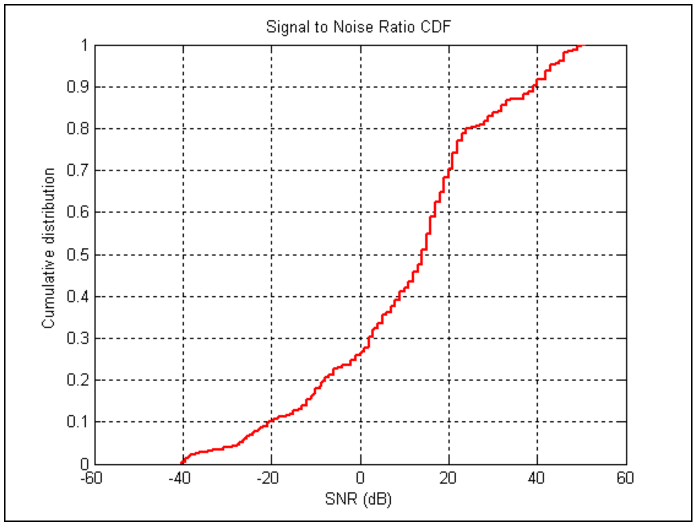

Figure 11: Cumulative distribution of SNR.

The figure shows that close to 80% of the measurements are below 25 dB threshold, confirming the observation in the poor connectivity experienced during the tests.

4 Proposed Access Link Improvement

One of the solutions to improve poor user connectivity is to deploy a different antenna design in the TFA network. This section studies, through simulation, the improvements that directional antenna can bring to the network. The use of directional antennas is common in many applications because the signal quality in the desired direction is strengthened. It also provides an extended sensing range, making the access point sensible to weaker signals transmitted by the wireless clients. Another parameter to be considered for the deployment of directional antennas is the orientation.

The use of directional antennas is common in many applications because the signal quality in the desired direction is increased. This take place because the amount of energy transferred to the antenna remains the same, but the energy is radiated over less area, resulting in a higher signal strength providing an extended transmission range. It also provides an extended sensing range, making the Access Point sensible to weaker signals transmitted by the wireless clients. Another parameter to be considered for the deployment of directional antennas is the orientation. With an adequate tilt, the antenna can enhance the system performance or in the opposite side degrade it due to interference. Currently, the TFA WMN uses omnidirectional antennas as described before with the radiation pattern of the antenna it is shown on Fig. 12.

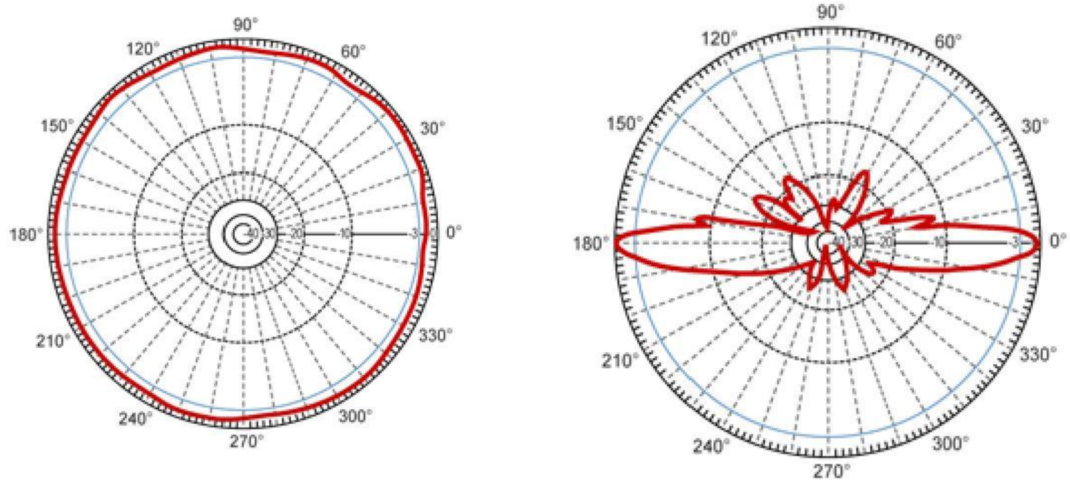

Figure 12: Omnidirectional Antenna Patterns. Top figure represents horizontal beam width while bottom figure represents vertical beam width.

The horizontal beam width provides a complete coverage in the horizontal plane around the MAP. In the case of the vertical plane, the propagation of the signal is defined by the beam width of 8^0 represented on the graph. The useful beam width in any plane is the angular separation between the half power points (3dB) in the radiation pattern, as shown in figure 13.

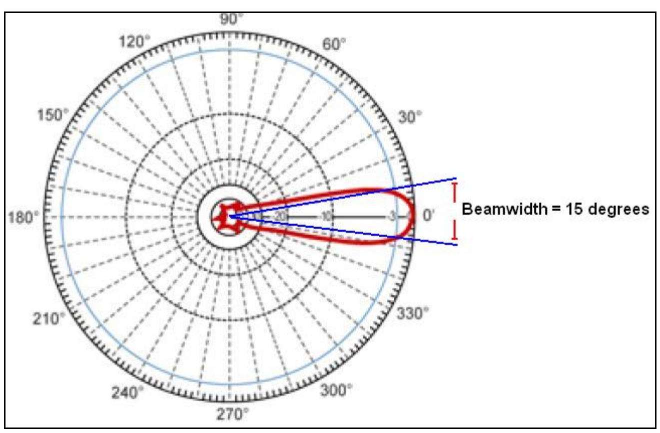

Figure 13: Effective vertical beam width of 15 degrees.

The deployment of directional antennas rather than omnidirectional antennas at the TFA MAPs offers an increased RSS at the users' locations. The use of a set of three directional antennas in an array with a total horizontal beamwidth of 360^0 and a vertical beam width of 15^0 has a potential for performance enhancement to improve the reliability of the Access-Link. Each one of the directional antennas has 120^0 in horizontal plane and 15^0 in vertical plane. Each antenna can propagate the signal according to the radiation pattern in Fig. 13 and 14. The combination of the three antennas will have the patterns represented in Fig. 15.

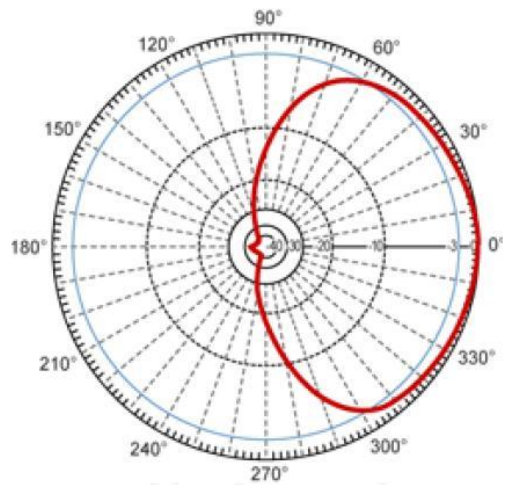

Figure 14: Horizontal beam width.

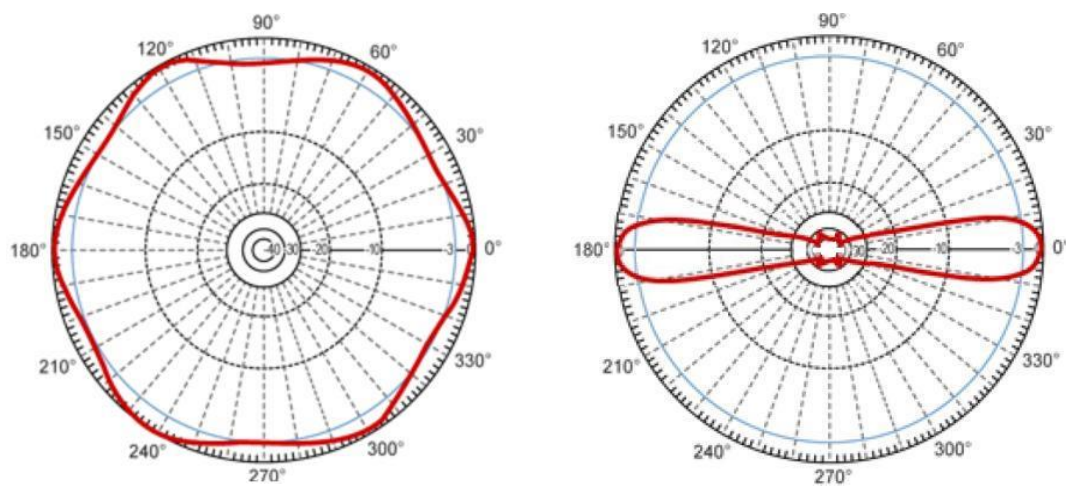

Figure 15: Array directional antenna patterns. Top figure represents the horizontal beam width while the bottom figure represents the vertical beam width.

The directional antennas provide two advantages over an omnidirectional radiation pattern. First, the vertical beam-width is almost twice as the one in the omnidirectional antenna, which means users located at closer distances are going to receive a higher RSSI signal. Second, given the fact that the omnidirectional coverage in the horizontal plane can be achieved by the use of a set of directional antennas, the orientation of each directional antenna in the vertical plane can be adjusted independently based on the coverage needed and the propagation environment in each direction, taking on consideration the links between MAPs to form the Multihop network.

The deployment of directional antennas at the TFA MAPs would offer an increased RSSI at the users' locations. The use of a set of three directional antennas in an array with a total horizontal beam width of 360^0 and a vertical beam width of 15^0 has a potential for performance enhancement to improve the reliability of the Access-Link. Each one of the directional antennas has 120^0 in horizontal plane and 15^0 in vertical plane. Consequently, users located at closer distances, that could not receive good signal in omnidirectional design case, are going to receive a stronger because they will be located within the main propagation lobe of the antenna. Second, given the fact that the omnidirectional coverage in the horizontal plane can be achieved by the use of a set of directional antennas, the orientation of each directional antenna in the vertical plane can be adjusted independently based on the coverage needed and the propagation environment in each direction, taking in consideration the links between MAPs to form the Multihop network. To show the difference between the two antennas, Fig. 16 represents the geometric ray propagation model of the vertical aperture of the omnidirectional and the directional antennas. If there are two MAPs within a 225 meters distance from each other, the client can be located in any place between them and be receiving the strongest possible signal. The main lobe signal propagation for the omnidirectional antennas is represented by the red lines, while the blue and green lines represent the main lobe signal propagation of the directional antenna, and the directional antenna with 3.50 down tilt respectively. The closer the signal propagated to the ground, the better signal the users receives. The directional antenna, with and without tilt presents better performance due to its higher vertical aperture.

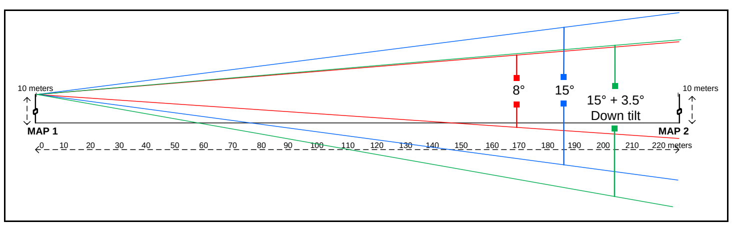

Figure 16: Antenna propagation based vertical aperture angle.

A simulation tool was developed using QualNet® taking on consideration the collected data on the field measurements. The simulation focused on measuring the physical characteristics of the signal, namely RSSI. The first simulation mimics the exact field situations with omnidirectional antenna, to make sure the simulation provides meaningful data. The second simulation uses directional antenna while keeping the same environment to gauge how directional antenna will improve the system.

To simulate the system, two main elements were considered; Path-Loss propagation model and antenna propagation pattern. Based on the measurements and the regression model, a Path-Loss matrix file was developed using the simulator to determine the actual signal attenuation between the MAP and the client node, taking into consideration the elements affecting the bi-directional communication.

In the simulator the Antenna propagation pattern file allowed us to define the specific propagation pattern of the antennas currently used in each MAP. The signal is propagated with maximum gain in the 8 degrees pattern for the vertical plane allowing a reliable communication between MAPs, but the signal is not amplified in other directions limiting the communication mainly with client nodes located in lower altitudes related to the antenna placement.

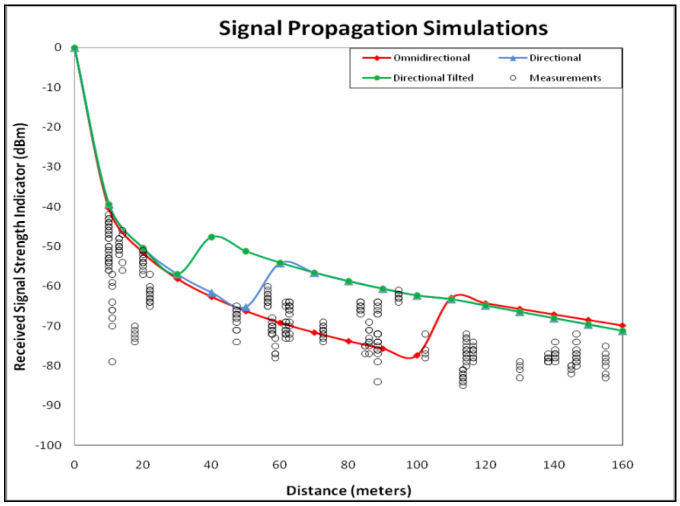

Figure 17: Signal propagation comparison using different antennas.

Fig. 17 shows the improvement of RSSI at distances below 100 meters and up to 20 meters when using the array of directional antennas (14dBi); the best performance is achieved by downtilting the directional antenna a few degrees. For really short distances, below 20 meters, there is no significant change between signal received due to the proximity to the antenna, and the height (10 meters) of the antenna location. Improving the RSSI that is perceived at the end user location, and considering the limitations imposed by the FCC, the SNR can be increased. This can mitigate to a certain degree the negative effects of the noise interference, improving the quality of the Access-Link, and finally providing a better performance for the bi-directional communication required to allow the end users effectively connect to the network. A first step to providing a reliable connection to the Internet is to make sure the lower layers can communicate effectively between end points.

5 Conclusions

Multi-tier wireless mesh network is promising architecture that will enable fast and economical deployment of high speed Internet access networks. Current experimentation of TFA network provides an excellent environment to study the limitations and promises of such technology.

This paper presents the first in-home measurement of two-tier network connectivity in TFA networks. The results underlined the importance of in home measurements as they represent value seen by end users. The data shows that TFA users suffered from the quality of the link. Several parameters affecting the wireless access-link performance have been identified. Mainly, the impact of noise on weak RF signals of IEEE 802.11b and the different path-loss exponents due to antenna propagation pattern. The SNR measurements gave a good indication of the impact of the link in the presence of the unlicensed ISM band used by other devices and produces with a negative effect on access-link connectivity. The interference power cannot be controlled but it can be mitigated if the SNR at the client location is increased using directional antenna. Evaluation of the network performance with directional antennas was performed, through simulation. The results show the directional antenna provides an improvement in the RSSI signal inside homes which will improve the SNR and provide better connectivity. One of the key important point is the use of measurement equipment that will mimic similar end-user environment. For instance the receiver sensitivity plays a big role in users' connectivity. While previous measurement [4] showed that users will be able to receive Internet connectivity inside home, our measurement shows that only 10% of users has Internet connectivity. The measurement results in [4] and this paper showed similar network characteristic but the main difference is that our work uses test equipment with sensitivity level similar to end-user equipment. Future work should take on consideration designing a network with hybrid technology such LTE or WiMax for MAP to MAP communication and WiFi for wireless access.

Acknowledgements

The authors would like to thank Dr. Jerome Crowder, and Anthropology group, for engaging Julian Naranjo with the home owners. We would like also to thank Dr. Enrique Barbieri for funding student time through EDA grant. The authors would also like to thank Jim Forrest (TFA) and Drs. Ed knightly and Joseph Camp (Rice University) for providing access to the network to take measurements.

References

[1] J. Robinson, "Deployment and Assessment of Wireless Mesh Networks," Rice, 2009.

[2] J. Camp, J. Robinson, C. Steger, and E. Knightly, "Measurement driven deployment of a two-tier urban mesh access network," in *Proceedings of the 4th international conference on Mobile systems, applications and services - MobiSys 2006*, 2006, p. 96.

[3] J. Camp and E. Al., "Developing and Deploying Multihop Wireless Networks for Low-Income Communities," *J. Urban Technol.*, vol. 13, no. 3, pp. 129–137, 2006.

[4] J. Robinson and E. Knightly, "A Performance Study of Deployment Factors in Wireless Mesh Networks," in *INFOCOM 2007. 26th IEEE International Conference on Computer Communications*, 2007, pp. 2054–2062.

[5] J. Crowder, J. Wilson, and E. Vredenburg, "Wireless Networking in an Underserved Neighborhood: Ethnographic Methods for Understanding Technology and Culture," *Soc. Appl. Anthropol.*, vol. 31, no. 1, pp. 11–15, 2009.

[6] M. Fiore, "Characterization of Coverage and Signal Propagation in the TFA Network Through Wardriving," Rice, 2007.

[7] J. Robinson and E. Al., "Assessment of urban-scale wireless networks with a small number of measurements," in *ACM, 2008, Proceedings of the 14th ACM international conference on Mobile computing and networking*, 2008, pp. 187–198.

[8] V. Dasarathan and E. al., "Outdoor Channel Measurement, Pathloss Modelling and System Simulation of 2.4 GHz WLAN IEEE 802.11g in Indian Rural Environments," in *Microwave Conference, APMC 2007, Asia-Pacific*, 2007, pp. 1–4.

[9] D. B. Green and A. S. Obaidat, “An accurate line of sight propagation performance model for ad-hoc 802.11 wireless LAN (WLAN) devices,” in *IEEE International Conference onn Communicatio*, 2002, pp. 3424–3428.

[10] L. Piazzi and H. L. Bertoni, “Achievable accuracy of site-specific path-loss predictions in residential environments,” *IEEE Trans. Veh. Technol.*, vol. 48, no. 3, pp. 922–930, 1999.

[11] S. Srinivasa and M. Haenggi, “Path loss exponent estimation in large wireless networks,” in *Information Theory and Applications Workshop*, 2009, pp. 124–129.

[12] S. Kawade and D. van Bloem, J.-W. Abhayawardhana, V.S. Wisely, “Sharing your Urban Residential WiFi (UR-WiFi),” in *63rd IEEE Vehicular Technology Conference*, 2006, pp. 162–166.

[13] A. Ritacco, C. Wills, and M. Claypool, “How’s My Network? A Java Approach to Home Network Measurement,” *2009 Proc. 18th Int. Conf. Comput. Commun. Networks*, pp. 1–7, Aug. 2009.

[14] D. Kong, E. Mellios, G. Hilton, A. Doufexi, and A. Nix, “Enhancing In-Home 802.11 Performance: Mesh or MIMO?,” in *78th IEEE Vehicular Technology Conference (VTC Fall)*, 2013, pp. 1–5.

[15] A. Reggani, F. Schneider, and R. Teixeira, “Tracking application network performance in home gateways,” *2013 9th Int. Wirel. Commun. Mob. Comput. Conf.*, pp. 1150–1155, Jul. 2013.

[16] GENI, “Exploring networks of the future.” [Online]. Available: http://www.geni.net. [Accessed: 01-Sep-2014].

[17] H. Yu, K. Zeng, P. Mohapatra, "Measurement-Based Short-Term Performance Prediction in Wireless Mesh Networks," in *Proceedings of 20th International Computer Communications and Networks (ICCCN)*, pp. 1-6, 2011.

[18] T. Wollenberg, "Performance measurement study in a wireless OLSR-ETX mesh network," in Wireless Days (WD) Conference, pp. 1-7, 2012.