Investigation of a Dual-band Dual-radio Indoor Mesh Testbed

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Abstract — **Scalability of community wireless mesh networks in terms of mesh nodes and mobile end-users along with their anticipated usage profile remains unexplored territory. However, conducting such experiments on a live community network could cause network breakdown leading to disrupted network services, and discomfort to end users. Indoor testbeds as opposed to simulations present a viable option for emulating outdoor scenarios since they use the actual devices used in the field deployments. This paper presents the preliminary results of a 6-node indoor mesh testbed inspired from an outdoor live community mesh network deployment, Zenzeleni, which uses routers with dual-band and dual radio functionalities. Using actual mesh routers and configurations used for Zenzeleni, we setup the indoor testbed to function on the 5 GHz frequency for the mesh backbone, and 2.4 GHz frequency for the access point, both using separate radios. In order to create multi-hop connections, a) the routers were shielded using self-built Faraday cages; b) transmission strength of antennae was reduced; and c) routers were kept at different angles. We set up two 3-node topologies which connected to each other through a single link. The current setup forms connections of up to 3-hops and if mobile clients are added then up to 5 hops. Experiments using D-ITG were conducted for latency, bandwidth, jitter and packet loss experiments and obtained results were evaluated to test the readiness of the testbed for scaling with further experiments involving Voice over Internet Protocol calls.**

***Keywords*— Limited range communications; ad-hoc; WiFi**

I. Introduction

Operator and government-driven top-down and centralized initiatives to roll out information communication and technology (ICT) services in the rural areas of Africa have had little success due to lack of interest from ICT providers caused by low return on investments [1]. Typical rural conditions, e.g. no electricity, harsh climate, difficult terrain, theft and vandalism, also make it hard to setup and maintain rural ICT infrastructure [2]. To fill this gap, bottom-up ICT projects such as Zenzeleni are being initiated [3]. Zenzeleni was a user-driven, self-organized, decentralized and bottom-up wireless mesh network (WMN) deployed and operational in the Mankosi community of the Eastern Cape Province, South Africa [3]. Due to absence of electricity in much of the community, much of the network is powered using solar charged batteries; and where power is available, batteries are trickled charged. A typical mesh node setup on top of a thatched roof community house is shown in Fig. 1. The Zenzeleni network currently has 7 commercial customers, 3 schools online, 4980 unique devices and 1.5 Terabytes per month usage from March-April 2018. Zenzeleni high-level management is provided by a not-for-profit company (NPC) called Zenzeleni Networks (ZN); and a community cooperative is responsible for maintaining infrastructure as well as billing, and selling of data services [4]. As far as we know, Zenzeleni is South Africa's only community owned and run ISP (Internet Service Provider).

Figure 1: Solar panel and mesh router unit

Other notable community mesh network deployments around the world include: Sarantaporo in Greece[1], Freifunk.net in Germany[2], Peebles Valley Mesh in South Africa [5], and Macha Works in Zambia [6].

As Zenzeleni began as a pure mesh network, we are interested in mesh characteristics. It is often reported that the quality of service (QoS) of a WMN is affected by addition of new nodes and new users because it changes network topology and traffic patterns. Table 1 shows a list of experiments to support this claim. WMNs exhibit drops in performance metrics, e.g. delay, packet loss, and jitter due to a) increase in number of hops thus changing the network size and topology; b) interference; c) routing protocol overhead; and d) the half-duplex nature of single radio mesh routers.

TABLE I
WORK SHOWING PERFORMANCE DEGRADATION IN WMNS WITH CHANGES IN TOPOLOGY

References	Issues	Reasons
[7]	VoIP call drops	Self-interference, multiple hops, and high protocol overhead.
[5], [8], [9]	Throughput drop	Increase in number of hops.
[10]	Rise in delay, packet loss and jitter	Increase in number of hops.

From the examples of community networks presented, it can be observed that even though scalability causes QoS issues in WMNs, there have been continuous deployment of community WMNs all over the world. This is evidence that bottom-up ICT initiatives have opened doors to cheap 'last-mile' access to network services such as Internet, social

[1] www.sarantaporo.gr
[2] www.freifunk.net

networking, and VoIP for underprivileged Africans: 63% of sub-Saharan Africa is rural [11]; 81% of 63% rural sub-Saharan African population has limited to zero access to electricity [11]; 73% sub-Saharan Africans live on less than $2 per day and 51% on $1.25 per day, due to uneven income distribution [12].

Zenzeleni's mesh origin serves as the motivation for the work presented in this paper. The mesh network utilized dual-band and dual-radio routers which separated the mesh backbone on 5GHz and access point (AP) on 2.4 GHz frequencies, each using designated radio. Investigation of scalability of the aforementioned mesh network with continuous addition of end users, while maintaining acceptable QoS, remains unexplored in a real world scenario. We are not interested in simulation, and due to the active nature of the network, along with the transition of the academic project to a community owned and run ISP business which provides daily network services to community members, local businesses and schools, carrying out scalability and QoS experiments on the actual network would interfere with the actively used ICT infrastructure. This paper therefore presents the results of ongoing investigations into an indoor mesh testbed aimed at predicting the network capacity under the assumption that experiments conducted on an indoor testbed composed of mesh routers used for Zenzeleni will yield results representative of actual outdoor performance.

The rest of the paper is organised as follows: Section 2 identifies related work; Section 3 details the testbed architecture; Section 4 presents testbed results and discussion; Section 5 outlays the conclusion and future work.

II. Related Work

The section looks at: a) QoS requirements for multimedia services; b) general requirements of a wireless testbed; and c) testbed deployments.

A. *Quality of service requirements for multimedia services*

In recommendation E.800 of International Telecommunications Union – Telecommunication Standardization Sector (ITU-T), QoS is defined as *"Totality of characteristics of a telecommunications service that bear on its ability to satisfy stated and implied needs of the user of the service"* [13]. According to Cisco, telecommunications service such as voice calls, either one-to-one or on a conference connection, require the following [14]:

- ≤ 150 ms of one-way latency from mouth to ear (per the ITU G.114 standard)
- ≤ 30 ms jitter
- ≤ 1 percent packet loss
- 17 to 106 kbps of guaranteed priority bandwidth per call (depending on the sampling rate, codec, and Layer 2 overhead)
- 150 bits per second (plus Layer 2 overhead) per phone of guaranteed bandwidth for voice control traffic

The same end-user performance expectations of network services for top-down provision also hold for users of bottom-up community networks.

B. *General requirements of a wireless testbed*

According to De et al., some general requirements for an ideal multi-hop wireless testbed include [15]:

1) Cost-effectiveness: the testbed setup should have a favourable cost and performance trade-off in terms of hardware, manpower, space, time, and maintenance.

2) Management: beginning with the initial setup including hardware/software configuration and deployment of the nodes, management, especially in terms of monitoring and maintaining, continues through the entire lifetime of the testbed.

3) Resource sharing: ability to share the testbed resources to conduct multiple experiments by multiple users. However, it must be ensured that multiple experiments conducted on a testbed are isolated in the spatial, frequency, and/or temporal domain.

4) Experimental control: defining testbed experiments to get relevant results involves several steps such as: a) topology, application, and mobility configurations; b) setting node properties; c) fine-tuning experiment execution; and c) protocol debugging.

5) Experimental analysis: providing the user with visualization and filtering tools to analyse collected data.

6) Applicability: the testbed should support testing and evaluation of diverse protocol suites, both at the application layers and PHY/MAC layers.

7) Repeatability: achieving repeatability without sacrificing realism by creating controlled environments for a testbed by placing it in anechoic chambers, introducing interference in a regulated manner, and/or using shielding to prevent external interference.

C. *Mesh testbed deployments*

This section presents some indoor and outdoor mesh deployments deemed relevant to our research.

1) Roofnet [16]: In order to facilitate large scale mesh networking research, Massachusetts Institute of Technology (MIT) built an outdoor testbed spread across students' apartment rooftops. The testbed, which started with 9 nodes, has over 54 nodes and provides access to MIT's campus net and the Internet through multi-hop routing. The hardware consists of a PC with an 802.11b WiFi card, and a roof-mounted 8 dBi omni-directional antenna. The antenna is connected to its node with coaxial cable which introduces 6 to 10 dB of attenuation. In addition, three nodes are placed on the roofs of tall buildings with 12 dBi Yagi directional antennas. Each Roofnet node runs routing software based on Click Modular Router, a DHCP server, and a web server. Roofnet uses the SRCR routing protocol, a variant of the Dynamic Source Routing (DSR) protocol. SRCR has the capabilities of addressing self-interference and forwards traffic by selecting the optimal of five routes, chosen based on observed performance rather than relying on predictions. Roofnet nodes are static, therefore, new topologies can be only be created by changing transmit power, thus breaking/introducing links.

2) Meraka mesh testbed [17]: The indoor mesh testbed consists of 49 nodes in a 7x7 grid pattern constructed inside a 6x12 meter room. Each mesh node in the testbed consists of a rectangular metallic PC case and a 5dB gain dipole antenna connected to a WiFi card with 802.11a/b/g capability. This antenna is connected to the wireless network adapter via a 30 dB attenuator, which causes a path loss of 60 dB between the sending node and the receiving node. Reducing the radio signal forces a multi-hop environment. The Meraka mesh testbed was developed to evaluate performance of Ad-hoc On-demand Distance Vector (AODV), Dynamic MANET On-demand (DYMO), and Optimal Link State Routing (OLSR) routing protocols.

3) MeshTest [18]: An indoor mesh testbed built in modular racks of 12 PCs. The PCs have two WiFi cards and are placed in RF-shielded enclosure. The enclosure provides approximately 80 dB of signal isolation and prevents inadvertent cross-talk. The RF from each PC's WiFi card is cabled through the enclosures into an RF matrix switch of programmable attenuators. The testbed uses the nodes and testbed management software used in ORBIT to control the nodes

4) ScaleMesh [19]: This indoor testbed is built in a 10x6 meter lab and comprises 20 wireless mesh nodes. Each node is PC with two 802.11 b/g wireless cards. Each wireless card is connected to a 2.1 dBi low-gain antenna and a variable signal attenuator. Using the attenuators, the signal power of the wireless cards can be lessened to limit the transmission range of each node and thus forcing a multi-hop environment. Testbed nodes run a SuSE Linux operating system and uses either static routing or the Optimized Link State Routing Protocol (OLSR) for multi-hop routing. The implementation of OLSR incorporates the Expected Transmission Count (ETX) metric for selecting routes based on the current loss probability of the links. The peculiarity of ScaleMesh is that it supports dual-radio communication by assigning different channels to each of the two wireless cards in a node. Also, different mesh topologies can be emulated using ScaleMesh by adjusting the positions of the *antenna stations* which are magnetic boards with two antennas of each mesh node attached to them.

Each of the mesh testbeds reviewed in this section play a key role in our work. We intended to build an indoor unplanned mesh testbed like the Rooftop mesh with no shielding or attenuators. However, due to closeness of the nodes in an indoor environment, this type of setup is unlikely and some type of signal attenuation or shielding will have to be introduced. The Meraka and Scale Mesh testbeds demonstrate use of attenuators to control transmission signal strength. The MeshTest shows use of RF shielding enclosures for signal isolation and eliminating cross-talk. However, acquiring attenuators and RF shielding enclosures can be a costly affair, and we want to keep the setup cost as low as possible. The Rooftop and Meraka mesh are single radio setups. MeshTest does present use of dual-radios but both radios use 2.4 GHz frequency. We were unsuccessful in finding specific related work on 2.4/5 GHz focusing specifically on indoor wireless mesh testbeds. The next section presents the testbed setup procedure.

III. Testbed Architecture

A. The Mesh Router

The initial router used by Zenzeleni was an off-the-shelf 2.4/5 GHz router called Mesh Potato - All Wheel Drive[3] (MPAWD) and thus used in the testbed. The MPAWD[4], as shown in Fig. 2, has following features:

- Atheros AR9331 system-on-chip with a 2.4GHz 802.11n 1×1 router in a single chip.
- Internal antenna for 2.4GHz operation.
- A second 5 GHz radio module based on the mediaTek/Ralink RT5572 chipset which supports IEEE 802.11b/g/n 2T2R (2×2 Multiple Input Multiple Output) operation on 2.4 and 5 GHz bands.
- Firmware based on OpenWRT Chaos Calmer version 15.05.1 called Village Telco – Small Campus Enterprise Network (VT-SECN).
- Better Approach to Mobile Adhoc Networking – advanced (BATMAN-adv) routing protocol version IV.

Figure 2: MPAWD with power and PoE/TL adapters

B. Shielding of MPAWD:

In order to isolate signal transmission, Faraday cages were built using readily available and cheap aluminium mesh wire. In order to shield high 5 GHz frequency with shorter wavelengths, mesh wire with holes less than approximately 3x3 millimeter was chosen. The hole size was calculated using (1) where: HS is holesize in meters; *C* = speed of light on meter per second; and *F* = Frequency in Hertz.

$$HS = (C/F)/20 \quad (1)$$

The computation was based on the assumption that the hole size for a mesh wire to effectively shield a given frequency should be less than the wavelength of that frequency. Fig. 3 below shows double mesh wire shielding on a 25x8x8 centimeter cardboard box housing the mesh router. The enclosure provides approximately 20 dB of isolation.

[3] https://store.villagetelco.com/mesh-potatoes/mp2-awd.html
[4] The mesh potato is no longer available. Zenzeleni is migrating old mesh potatoes to Ubiquiti equipment and had intended to migrate to the LibreRouter when it becomes available.

Figure 3: Hand built Faraday cage for shielding MPAWD

C. *Network performance monitoring tools*

The four common network performance parameters; latency, jitter, throughput, and packet loss, are monitored for experiments presented in this paper. BATMAN-adv built-in debugging tool, batctl[5] *ping*, was chosen to measure latency. We preferred using batctl because BATMAN-adv operates on Layer 2, thus, all hosts participating in the virtual switched network are transparently connected together for all protocols above Layer 2. Therefore the common diagnosis tools do not work as expected. Iperf-2.0.5 [6] was selected to measure maximum achevable link bandwidth. Distributed Internet Traffic Generator (D-ITG) version 2.8.1 was used to generate and emulate baseline VoIP traffic. D-ITG is able to replicate statistical properties of traffic of different well-known applications (e.g, Telnet, VoIP - G.711, G.723, G.729, Voice Activity Detection, and Compressed RTP - DNS)[20].

D. *Testbed setup*

A 6-MPAWD testbed was setup over an area of 9.5x4.24m. The mesh backbone utilizes 5Ghz, where as the access is on 2.4 GHz. In order to create multi-hop connections, four out of six MPAWDs are placed inside Faraday cages and 2 are kept unshielded. Two 3-node topologies were built as shown in Fig. 4 , respectively, which connected to each other over a single link. Fig. 5 shows the connectivity diagram, with red and green blocks representing caged and uncaged MPAWDs, and arrows representing connections. All the MPAWDs are mounted on top of 85 cm high tripod stands. Presence of two 14 cm thick concrete walls between the two unshielded MPAWDs further promoted the muti-hop network. Fig. 6 shows the current testbed blueprint. Further tweaks during setup of the testbed were applied to the MPAWDs such as:

- Reduced transmission strength of 5 GHz radio of caged MPAWDs to 1dBm. Default settings were 29 dBm.
- Reduced transmission strength of 5 GHz radio of uncaged MPAWDs to 3 dBm.
- High Throughput (HT) mode disabled thus disabling MIMO capabilities. Therefore mesh backbone operated in legacy 802.11a mode.
- The AP was connected to Subminiature version A (SMA) connectors present on the MPAWDs to have external antennae, out of the shielding. 2 dBi omni-directional antennae were attached to each MPAWD.

It is evident from Fig. 5 that multi-hop connections of up to 3 hops are possible with the current testbed setup, excluding clients.

Figure 4: Two 3-node topologies

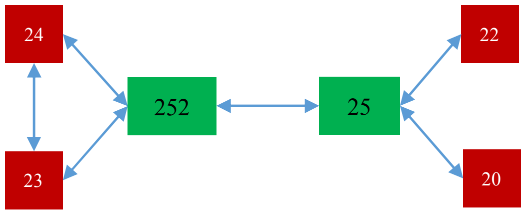

Figure 5: Block diagram of the topology connectivity map

IV. Testing and Results

A. *Latency*

Using *batctl ping* tool, ping tests to measure minimum, average and maximum round-trip-time (rtt) were conducted in succession starting with a single hop. 20 iterations of 50 pings each were sent from nodes 24 and 23 to nodes 22 and 20 and vice-versa. Table 3 shows the min, avg, and max rtt results in milliseconds (ms). An overall representation of increase in average rtt with increasing number of hops is presented using a graph in Fig. 7. Even though rtt increases with number of hops, the values are well under the limits mentioned in [14].

TABLE II
MIN, AVG, AND MAX RTT VALUES WITH INCREASING HOPS

		1-hop	**2-hops**	**3-hops**	
		252	**25**	**22**	**20**
	min	.539	1.267	2.23	2.186
24	avg	.843	1.796	2.836	2.735
	max	1.888	3.741	5.735	4.478
	min	.531	1.333	2.182	2.211
23	avg	.878	1.792	2.807	2.814
	max	2.814	3.601	5.554	5.670
[redacted]					
		25	**252**	**24**	**23**
	min	0.62	1.352	2.154	2.234
22	avg	0.904	1.736	2.672	2.846
	max	2.808	2.829	4.355	5.579
	min	0.539	1.352	2.201	2.195
20	avg	0.856	1.830	2.684	2.71
	max	2.163	3.667	4.278	4.858

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[5] https://downloads.open-mesh.org/batman/manpages/batctl.8.html.
[6] https://iperf.fr/iperf-doc.php#doc.

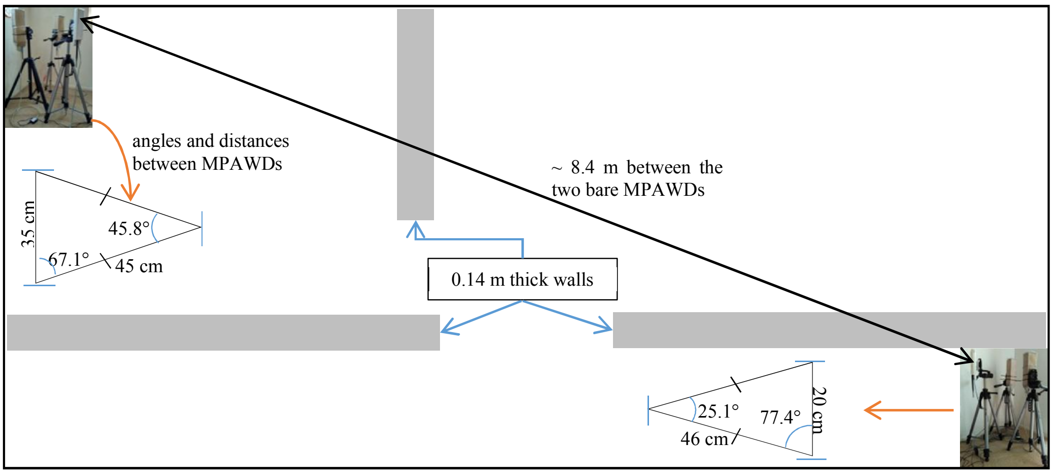

Figure 6: Testbed blueprint

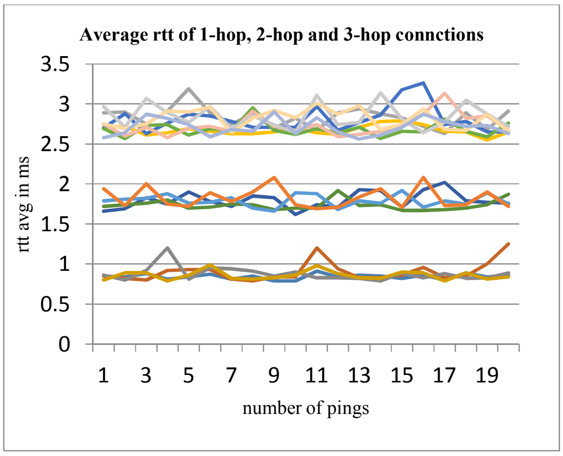

Figure 7: Average rtt with increasing hops

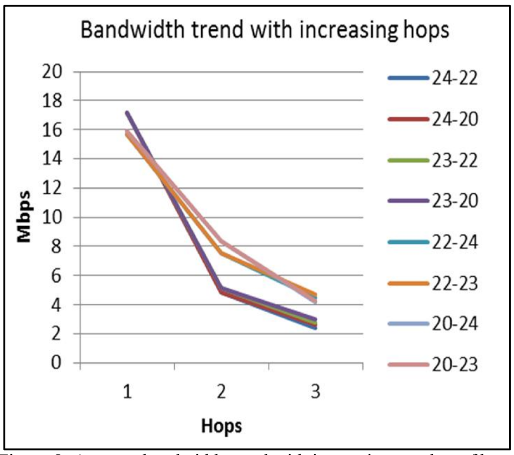

Figure 8: Average bandwidth trend with increasing number of hops

B. Bandwidth

We tested bandwidth performance with Iperf Transmission Control Protocol (TCP) tests. TCP traffic was sent from nodes 24 and 23 to nodes 22 and 20, and vice versa. The tests were conducted in succession, that is, bandwidth was tested for 1-hop, then 2-hops, and lastly to destinations which were 3-hops away. 20 iterations of 1 minute Iperf TCP tests were conducted for each connection. The TCP window size was left at default 85.3 KiloByte (KB). Table III below presents the average bandwidth values in Megabits per second (Mbps) with increasing number of hops. Fig. 8 shows the declining bandwidth trend with increasing number of hops.

TABLE III
AVERAGE BANDWIDTH VALUES IN MBPS

	1-hop	2-hops	3-hops	
	252	**25**	**22**	**20**
24	17.19	4.86	2.43	2.64
23	17.15	5.20	2.79	2.97
	25	**252**	**24**	**23**
22	15.65	7.57	4.49	4.69
20	15.88	8.36	4.18	4.30

The trend shows that when traffic is sent from nodes 24 and 23 (towards nodes 22 and 20), the drop in bandwidth at second hop is higher than when traffic is sent from nodes 22 and 20 (towards nodes 24 and 23). We performed similar Iperf tests between nodes 252 and 25. The results showed that the average bandwidth between nodes 252 and 25 is 10.7 Mbps and nodes 25 and 252 (vice-versa) is 15.2 Mbps. We expect these two values to be similar. We are investigating the issues causing this huge mismatch.

C. Jitter and Packet loss for Voice over Internet Protocol

Using D-ITG on MPAWDs, 5 minute VoIP calls utilizing the G.711.1 codec were emulated. By default, D-ITG sends 100 packets per second of frame size 80 Bytes (B) and packet size 92 B. Calls were made from nodes 24 and 23 to nodes 252, 25, 22, and 20, and vice versa. Table IV presents the average jitter (Jit), in ms, and packet loss (PL) in percentage (%) with increasing number of hops for the emulated calls. The results show that jitter values remain in between 5-6 ms irrespective of the number of hops. However, PL increased with increasing number of hops in case of calls made (emulated) from nodes 24 and 23 to other nodes. When calls were made from nodes 22 and 20 towards nodes 24 and 23, PL values did not exhibit any increase with more hops as expected. This peculiarity was further investigated by emulating 5 minute voice calls between nodes 252 and 25 and the results of average jitter and PL are presented in Table V.

TABLE IV
AVERAGE JITTER AND PACKET LOSS FROM D-ITG

	1 hop		2-hops		3-hops			
	252		**25**		**22**		**20**	
	Jit	**PL**	**Jit**	**PL**	**Jit**	**PL**	**Jit**	**PL**
24	5.70	0.10	5.66	0.62	6.06	2.46	6.0	3.22
23	5.73	0.08	6.03	1.76	6.30	3.22	5.94	2.74
[redacted]								
	25		**252**		**24**		**23**	
22	5.98	.08	4.97	0.10	6.01	0.13	5.93	0.09
20	5.29	0.1	5.45	0.08	5.87	0.13	6.07	0.10

TABLE V
AVERAGE JITTER AND PACKET LOSS BETWEEN NODES 252 AND 24

	252		
	as source	as destination	
25	5.80	5.98	Jit
	0.91	0.08	PL

The PL, as shown in Table V, is higher when call is made from node 252 to node 25 than in the opposite direction . The results can be correlated to the bandwidth results in previous section which showed higher drop in bandwidth during transmission of traffics from nodes 24 and 23 towards nodes 22 and 20 at second hop as compared to vice versa.

V. CONCLUSION AND FUTURE WORK

This paper presents preliminary results of a multi-hop dual-radio dual-band indoor WMN testbed. Through use of hand-made Faraday cages, alteration in antennae transmission strength; and different angles and positions of nodes, we were able to setup a 6-node testbed. The testbed has links of up to 3 hops, without clients. If clients are connected to nodes at maximum distance, then 5-hop connections are possible. The testbed architecture is very cost-effective as the only major expenditure was on acquisition of the mesh routers. Baseline latency tests using batctl *ping* tool showed the results to be well within acceptable limits mentioned in [14]. We experienced steep drops in bandwidth with increasing number of hops, a common scenario experienced and reported by many researchers in the field of WMN. However, these bandwidth values need to be further tested to find out how many concurrent voice calls can be conducted. The average jitter and packet loss values obtained from emulated voice calls in D-ITG does show results within the acceptable limits presented in [14]. We expect the jitter, and packet loss values obtained from D-ITG to rise with increase in traffic.

In future, we look to load up the testbed with heavier concurrent voice traffic using D-ITG and the different voice codecs. Afterwards, we intend to move to actual voice calls using mobile devices since the routers allow SIP calling functionality. We expect to scale the testbed to the maximum and use the results to make predictions on capacity for larger outdoor mesh networks such as Zenzeleni.

ACKNOWLEDGMENTS

We thank OpenServe and Aria Technologies for financial support of the project. We also thank the NRF for supplying additional financial support of the main author's PhD studies.

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Shree Om is a PhD student in Computer Science at UWC. He is interested in enabling rural community networks and has looked into evaluating battery life on mobile devices and figuring out how many can safely participate on a rural mesh.

Bill Tucker is an Associate Professor of Computer Science at UWC. He leads the academic side of the Zenzeleni project which is South Africa's only community-owned and run rural ISP. He is interested in both social and technical aspects of getting these networks to transfer from one community to another.