

# Optimisation of a Mid-Range Wireless Mesh Network for VoIP in Rural Southern Africa

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**Abstract** - This paper presents the business context and results of an optimisation exercise for a single-radio mid-range multi-hop wireless mesh network for the provision of VoIP services. This WiFi mesh network physically covers 30 square kilometres in rural South Africa with a dozen solar-powered nodes. The firmware multiplexes the single radios in adhoc and infrastructure modes, essentially providing a distributed hotspot that can be used for WiFi-based Asterisk attachment in addition to POTS handsets via an ATA adapter in a node. We argue that this architecture is comparable yet cheaper and easier to install and maintain than multi-radio systems with directive antennas. Measurement of a range of values revealed a SlotTime setting that maximises throughput by 115%. We leverage this finding to argue a business case for a ground up community-based mesh network like this one; to provide a win-win situation for local residents and operators with free internal calls backed up by revenues from low cost voice breakout, Internet services and solar-based mobile phone charging. Our novel approach offers an accessible and affordable business model based on increased traffic volume from residents in a rural area that have mobile connectivity yet cannot afford to use it. The optimised architecture described herein offers an attractive and complementary alternative.

**Index Terms** - Limited Range Communications, Ad-hoc, Wi-Fi, 802.11.

## I. INTRODUCTION

Access to information and communication technologies (ICT) in Southern Africa is quite uneven. While in cities first class services can be experienced, the reality in rural areas starkly differs. Although the situation may appear to have changed dramatically in the last few years with the increasing availability of 3G and 4G services, both Internet and voice services remain unaffordable for most people.

The literature is abundant with regards to the application using wireless mesh networks (WMN) to tackle this situation. Nowadays, WMN based on the 802.11 family of protocols can provide a mature solution with several off-the-self products, e.g. Locus, Mesh Potato, Skylink and Tropos, that offer stable solutions. However, it is difficult to compare the different real deployments reported in the literature given the various architectures available to create a mesh network.

One of the key factors to determine an architecture is the distance among the nodes forming it. There is a large body of work on long-range wireless mesh networks [1, 2, 3, 4];

long-range being understood as tens of kilometers (km). In most of those interpretations, long-range comes together with directional antennas due to the link budget and the power limitations in non-licensed bands. With directional antennas, static mesh networks are only feasible if each mesh node has several radios installed for connecting to several neighbors. A similar architecture is also used when distances are smaller [5] where limitations on available non-overlapping channels, number of radios, and power consumption strongly limit possible topologies.

Other approaches consider that a mesh node is a low-cost low-power node with only one radio [6, 7, 8]. Hence the whole mesh network operates on a single channel and performance is sacrificed because each node acts as a source/sink/router and forwarding packets over a single wireless interface halves the performance. Other effects reduce the performance even more. On the other hand, the gains include being cheaper, easier to install and maintain, and more flexible. From this second body of work, only [8] works on the range of few km (with a link up to 5km). However, in that work there is no reference to the effect that distance over the standard limits may have played upon the performance of the network under analysis.

This paper is an expansion on [9] which focused solely on the performance improvement by finding the optimal SlotTime value; and leverages the performance improvement to suggest a revised business model that commenced with [10]. In this paper, a real example for such a mid-range architecture used to provide voice over Internet Protocol (VoIP) services is described in detail, together with a preliminary optimisation of its performance. To the best of our knowledge, we are the only ones providing evidence of feasibility that a real single radio mid-range multi-hop wireless mesh network is capable, after tweaking some 802.11 parameters, of handling VoIP services. We believe that the empirical results presented in this paper contribute to increase the range of options to provide low-cost communications services to rural areas in Southern Africa, where such distances are common between homesteads.

The rest of the paper is organised as follows. Firstly, related work is introduced in Section II. Section III presents the architecture theoretically and includes a description of the network under analysis. Then a theoretical and practical background of the tools used is provided in Section IV, with the methods used to collect data described. This is followed by the results obtained which are presented and analyzed in Section V. A discussion of results and future work to further optimise mid-range mesh networks concludes the paper.

## II. RELATED WORK

Using VoIP services over single-radio WMN to provide an alternative to cellular technologies has been explored by [6]. However, their work focused on urban scenarios where the density of users and the lack of line of sight (LoS), requires a higher number of nodes, where costs surpass those of the cellular coverage. The reduced population density, and lack of buildings in rural areas could reverse these economics.

Eventually, the limitations of single-radio mesh networks also led some authors to discard this architecture as a feasible scalable solution to provide access in rural areas [4]. They acknowledge the potential benefits of combining both approaches above, using the latter for the access tier of the architecture, and the former to interconnect mesh cells, which although not explicitly stated, are considered to be made of links of tens of meters, like, for instance, in the Roofnet network [7]. We fundamentally agree with the tiered architecture, reinforced by the evidence presented by [8] that by widening the range of the mesh, with links on the range of a few km, it is possible to provide connectivity to rural villages, up to 30km<sup>2</sup> in our case, with a dispersed population using a single radio mesh network. Such a network can be linked up to the Internet by using a single long range point-to-point (PtP) WiFi link as suggested by [4], or another suitable technology, to cover the distance to the closest wireline Internet access point. Providing special attention to voice services, this is exactly the architecture that is proposed by Village Telco [11], although they have not explored the possibility of having links longer than 1km.

Little work has been done in studying the Medium Access Control Layer (MAC) of single radio mid-range WMN based on 802.11. Most of the literature around long-range mesh networks refers mainly to the multiple radio mesh architecture described above. For that architecture, several optimisation proposals have been made available. In [12] a MAC layer based on Time Division Multiple Access (TDMA) is proposed to optimise performance of PtP links. This work was further optimised by [1], and adapted to point-to-multipoint links [2]. However, this alternative MAC does not provide support for single radio mesh, e.g. multipoint-to-multipoint (MtM) and so no results are available in this regard. Other authors, e.g. [3], have provided a model to analyze the performance of standard 802.11 MAC with long distances and proposed ways to optimise the performance by tweaking the values of some MAC parameters. However, in the simulations for MtM included by such work, only single hop communications were considered.

## III. ARCHITECTURE IN THEORY AND PRACTICE

### A. Description of the architecture

The architecture presented herein aims primarily at reducing the cost of voice communication in rural areas, acknowledged as the most important service for their dwellers [13]. Mobile or cellular voice services, although available, remain unaffordable for many. Thus, the ad-hoc mesh nodes described below (see Table 1) are multiplexed as infrastructure-mode access points; have a VoIP server like Asterisk configured; and when possible have an Analogue Telephone Adapter (ATA) so an analogue phone can be directly connected to a fixed point.

The mid-range single radio mesh network described herein

is not intended to reach regional scalability, but rather to provide sufficient fixed points of access (as many as nodes form the mesh backbone) to provide blanket coverage to rural villages that will then be linked up to the Internet, with the most convenient technology available. Sharing an Internet connection is a solution that has been used successfully by community networks worldwide. These fixed points of access forming the mesh backbone additionally provide the functionality of distributed wireless access points and so allowing for Wi-Fi clients, which enjoys worldwide availability and mass production. Production of Wi-Fi chipsets outgrew that of mobile phones in 2012 and by 2017 it will nearly double it [14] and [15], and it is now present in every computer, tablet, all ranges of smart phone and in many feature phones, too. The current prediction for 2017 is that 74% of all mobile phones manufactured will be smart [14]. Considering the uptake of these devices in emerging markets, our architecture will provide the possibility of using either GSM or WiFi for voice communications on a single device.

Although it might be considered that this architecture will only benefit VoIP providers and the community members, we see other stakeholders benefiting too. Using data from a survey conducted in December 2013 in 255 households from the community in the Eastern Cape Province of South Africa where we work, following a stratified random sampling, only 26,7% of the individuals have reported making all or most of their calls to people staying in the community. This correlates well with the high emigration rates in the area, resulting in families split in urban and rural dwellings. This means that greater proportion of the calls will still terminate in the incumbents' networks, thus entitled to receive the Mobile Termination Rate (MTR). It is expected that with the cheaper rates (described in [16]) people will communicate more, and so the money received from the MTR will eventually surpass the meager profit obtained from the few calls made in the current scenario. That would be the case if all calls were made from the WMN architecture described. However, a more realistic scenario is a blend of pre-existing mobile calls and VoIP using the mesh network. We expect both to grow considerably.

The Internet requirements for VoIP provision could be covered by existing 3G, where available, as satellite technology is not well suited for simultaneous voice services. Additionally, the increased capillarity of fibre optics, especially in South Africa, opens up the possibility of providing broadband services using a similar architecture, while the increasing demand for Internet services also provides a business case for those operating the fibre. We see this as a win-win situation for all involved.

### B. Description of the real network

In the case study described below, the only service available in the network thus far is the provision of intra-community calls, i.e. calls among the analogue phones connected to the nodes creating the mesh. In the near future break out calls will be allowed; once the community has established the institutional and legal capacity to contract an Internet connection and pay for it, and the VoIP services, on a regular basis. In the meantime, while these capacities are generated, income to carry out the initial investment for these services is being generated by using the spare solar power generated in the nodes to bill community members for charging their mobile phones. After conversations with

different providers, calls from the fixed phones could be made for a price a third of the ones currently being paid by community members [16].

The minimal presence of WiFi-enabled phones or computers in the area has prevented the additional functionality of allowing these devices to make calls at the moment; something that, as argued above, will become a possibility in the long run.

The mesh network consists of 12 nodes scattered around 30km<sup>2</sup>. The connectivity graph of the network is shown in Figure 1. The colours correspond as follows: green for links with reported RSSI (received signal strength indication) using the lowest sensitivity by the driver on both sides above 12 dBm, orange for links with one or both sides with values between 9 and 12 dBm, and red where one or both are below 9 dBm. Yellow links so weak that they disappeared when setting the operating mode to 802.11g from 802.11b/g.

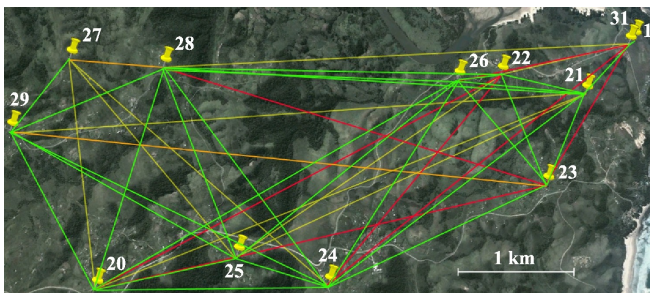


Figure 1: Network links and distances.

Ten of the 12 nodes are located in private houses chosen by the local authority. One of the other two nodes provides access to the server (.1) and the last one is a repeater connecting the latter to the rest of the network (.31). The server is located in the headquarters of a local NGO (non-governmental organisation), which has access to grid electricity and a backup battery system during power outages, but is located behind a hill so a repeater is needed. One of the design criteria to select hosting homesteads was seeing at least other three houses [17]. Thus, most of the chosen houses were those on top of hills and provide clear LoS with multiple neighbor nodes.

The 10 nodes in private houses are first generation Mesh Potato (MP01) with an external antenna attached; the repeater is an off-the-shelf Ubiquiti NanoStation (NS2), and the remaining node is an off-the-shelf MP01. Their technical specifications can be found in Table 1.

Table 1: Hardware features.

	NS2	MP01
Weight	0.4 Kg	1.1 Kg
Consumption	4W	2.5W
Chipset	Atheros AR2315	Atheros AR2317
Operation Modes	802.11b/g	802.11b/g
Max Tx Power	26	20
Antenna Gain	10dBi panel	8 dBi omni

The NS2 utilises power over Ethernet (PoE) and the MP01 runs with an innovative power over telephone line (PoTL), a la PoE, but rather connecting an analogue telephone to the router along with power, which greatly simplifies the installation. The light weight of both antenna (MP01) and router allow them to be mounted on a standard

aluminum TV pole attached to a house, thus avoiding the need for a tower and also reducing deployment costs. Low power consumption further helps to reduce the cost of operation. The MP01 also includes a Foreign eXchange Station (FXS) port that allows for direct connection of an analogue two-wire telephone.

All nodes have been flashed with version 1.1 of the Village Telco Small Enterprise and Campus Network (VT-SECN) firmware which is a customised version of OpenWRT Kamikaze. SECN includes madwifi-trunk-r3314 and batman-adv version 2011.2.0 and configures the wireless card to operate in ahdemo and ap modes simultaneously, utilising madwifi virtual interface functionality. The firmware for the MP01 also runs an Asterisk server that allows direct voice communication with any other MP01 flashed with VT-SECN as long as they have different IP addresses. A call can be setup by dialing the last octet of the IP address on an analogue phone, and the device itself can be configured following voice prompts, so avoiding the intervention of an expert. The firmware also automatically configures batman-adv over the interface operating in ahdemo mode, and the resulting bat0 interface created to run the protocol is bridged to the Ethernet and the Access Point interfaces. This allows end-devices to communicate transparently through the nodes without any additional configuration other than setting up an IP address within the range of the network (and selecting its SSID).

## IV. MATERIAL AND METHODS

### A. Theoretical and practical background

In 802.11, access to the wireless channel is based on Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA). [3] provides a very in-depth explanation of the parameters that influence the behaviour of CSMA/CA when long distances are considered. These parameters are different for each of the 802.11 PHY layers, and the standards values for those PHY layers available in the devices used are shown in Table 2.

The presence of two alternate values for several parameters in HR-DSSS (High Rate / Direct Sequence Spread Spectrum) is due to the compatibility mode of 802.11g: the second values are selected only if there is not an 802.11b-only station in the network.

Table 2: CSMA/CA parameters per PHY.

PHY layers in 802.11b/g	DSSS	HR/DSSS	OFDM
SIFS	10 $\mu$ s	10 $\mu$ s	16 $\mu$ s
SlotTime	20 $\mu$ s	20/9 $\mu$ s	9 $\mu$ s
DIFS (= SIFS+2*SlotTime)	50 $\mu$ s	50/28 $\mu$ s	34 $\mu$ s
CWmin	31	31/15	15
CWmax	1023	1023	1023

The ACKTimeout is not given a closed value in the standard, but it is defined as  $ACKTimeout = aSIFSTime + aSlotTime + aPHY-RX-START-Delay$ ; with aSIFSTime and aSlotTime, the SIFS and SlotTime included in Table 2. The third value is the time required for the PHY layer to realise it is receiving a frame and generates the alarm that a frame is being received. Its value is PHY-dependent, and practical implementations, like the one made for madwifi, account for this parameter internally. Tests done using athctrl for different PHYs set the same value for ACKTimeout. Then

when madwifi refers to ACKTimeout, it does not refer to its complete definition in the standard, but only to the sum of the first two parameters shown above, plus some extra calculations to take into account the distance. In this paper, we will refer to the ACKTimeout similarly.

The timing structure in the standard is built considering that the propagation delay is always shorter than 1  $\mu$ s. For distances longer than 300m this is no longer true<sup>1</sup>, and then the standard CSMA/CA mechanism does not operate as expected and collisions may appear with higher probability. Furthermore, if the ACKTimeout is not adjusted accordingly, the available throughput gets severely reduced since the ACK may arrive but get discarded since it does so late. Then the same packet is transmitted until the maximum number of retransmissions is reached. The madwifi driver allows the modification of the ACKTimeout and the SlotTime either individually or using the `athctrl` tool that sets them automatically when a given distance (in meters) is provided as an argument. When the second option is used, the SlotTime value is fixed to 9 plus the propagation delay for that distance, and ACKTimeout to SlotTime \* 2 + 3.

Detailed descriptions of other standard mechanisms in the operation of mesh networks, like determining IBSS and time synchronisation, are skipped for simplicity since the use of *ahdemo* bypasses these mechanisms. *ahdemo* is a non-standard implementation that does not transmit beacons to form the mesh network. While this solves the Cell-Split and ‘stuck beacon’ problems, it requires the routers to individually configure the shared cell identification and to use internal timers instead of one provided by the network.

The driver allows using different transmission rates with each neighbor (unicast rate) when configuring the transmission rate to auto. Several algorithms are allowed, but, again, one is considered to be standard: Minstrel. It records statistics of all packets transmitted (successfully or not) towards each neighbor and the rate used for each one. This should be enough for selecting the optimum for static channels. However, the wireless channel changes; so it is required to try other rates. Minstrel uses a percentage (10% by default) of the unicast packets that are sent at a rate other than optimal to adapt to the channel changes.

The broadcast rate is fixed using the parameter `mcast_rate`, which by default is 1 Mbps. The standard suggests that this rate should be the minimum rate supported for all neighbors, but tests have shown that configuring all nodes to 802.11g with a minimum operating rate of 6 Mbps, sets `mcast_rate` to 1 Mbps and so requires manual setting.

### B. Optimisation methodology

Drawing on the background provided above, when possible, a fixed value will be provided for the parameters described. For the SlotTime, where no previous work exists on how it affects the performance in a mid-range mesh network, traffic will be generated on the network to assess the effect of varying its value. The relevant parameters were configured as follows:

- Radios used 802.11g PHY.
- Broadcast messages sent at 6 Mbps. This value was used only for the last set, as explained below; in the two

<sup>1</sup>The `AirPropagationDelay` parameter in the standard is said to be  $\ll 1 \mu$ s but, in fact, in most 802.11 hardware implementations, the electronics are faster than required by the standard and it works properly for longer distances; up to almost 1.4 km in 802.11a/g and up to almost 3 km in 802.11b.

other ones broadcast messages were sent at 1 Mbps.

- Unicast messages sent at rate chosen by Minstrel.
- Radios operated in basic mode, not using RTS/CTS.
- ACKTimeout fixed to 57  $\mu$ s.

In [3] it is recommended to set the value of ACKTimeout to the default used on the chipset plus round trip propagation delay for the longest link in the network, for all nodes. Thus, considering a link in which two nodes receive signal from each other, the longest link that is present in our mesh network is 5.05km (in between nodes 21 and 29). Further analysis of the network has shown that this link is not an active one, i.e. it is never used by `batman-adv` for unicast traffic due to its weakness, preferring several hops instead. The longest active link in the network is 4.65km (in between the nodes 23 and 29). For madwifi the default value for the ACKTimeout is 23  $\mu$ s, to which we have added 34  $\mu$ s of the round trip delay on the 5.05km link, for a final value of 57  $\mu$ s. Trying to optimise further, we could have used 54  $\mu$ s if the longest active link would have been considered instead, but the difference would have been negligible (3  $\mu$ s less waiting for the ACK when collision occurs), and we preferred to cover all potential single-hops in the network.

For SlotTime, we tested different values from 9  $\mu$ s (the standard value for 802.11g) to 999  $\mu$ s, as will be explained below. The SlotTime value used in each test was configured on all nodes before generating traffic using `iperf`.

To find the optimum SlotTime, we saturated the links to get the maximum throughput achievable in between every pair of nodes. To do so, we generated UDP traffic for 20 seconds in between two pairs of nodes consecutively. UDP traffic was chosen since the network is intended to be used mainly for VoIP traffic. The amount of traffic that saturated every pair of nodes was not straightforward. Initially 20 Mbps were generated in each direction, but `iperf` failed to handle such an amount of traffic and some links that allowed real calls presented 0 bps throughput. The maximum value of total throughput (sum of both directions) obtained in each per link, after having tested all the SlotTimes in the first set (from 9  $\mu$ s to 54  $\mu$ s), was multiplied by 0.75 and injected in each direction instead of 20 Mbps.

The results were far more ‘real’ with this setup, with almost all links providing some bps for all the SlotTime values tested (second set, from 24  $\mu$ s to 119  $\mu$ s). In this set, which was carried out at night, values of SlotTime from 39  $\mu$ s to 84  $\mu$ s were not valid since one node shut down during the night thus changing the topology of the network. Again, some of the links were able to handle all the traffic injected for some of the SlotTime values tested. So for those links a similar procedure like the one described above was repeated. In addition, during this second set, we realised the broadcast rate was not being updated as mandated in the standard. So for the next set it was manually configured to 6 Mbps. With these two changes, a third set of results was produced with different SlotTime values ranging from 9  $\mu$ s to 999  $\mu$ s. In this third set, a total 49 values were tested, and it is for this set that results values are discussed below.

## V. RESULTS FROM TRAFFIC GENERATION

### A. Modifying SlotTime

In this section we show the results obtained from the third set of traffic generation as described in the methodology above. Figure 2 shows the aggregated end-to-end traffic

between each pair of nodes in the network per value of SlotTime. We acknowledge that this indicator does not show the maximum traffic the network can handle simultaneously, since several internal links are counted more than once as they are part of longer routes and the effect of the exposed node is neglected. However, it does offer a single value that can be compared among different SlotTime values.

As Figure 2 shows, aggregated traffic peaks for SlotTime at 199  $\mu$ s, for which 92.75 Mbps are obtained. Although a single repetition was carried out for every SlotTime value, a similar trend is confirmed by the curve shown, and other values around the peak exhibit similar performance.

These values contrast heavily with the value for SlotTime of 9  $\mu$ s (standard for 802.11g), for which 43.11 Mbps are obtained, i.e. for the optimum value found, an increase of 115% is obtained over the standard value. Madwifi's *athctrl* sets the SlotTime value to that of the standard plus the propagation delay of the longest active link for PtP links. For that value of the SlotTime, 24  $\mu$ s, 74.87 Mbps are obtained, showing a considerable improvement (57%) over the standard value. However, the maximum obtained for SlotTime 199  $\mu$ s is still 23.9% higher.

For this value, end-to-end traffic has on average 1.40 Mbps, with the route between 22 and 26 being the one handling the most traffic, 4.49 Mbps, and the route between 1 and 27 being the one carrying the least, 0.142 Mbps.

### B. Considering the number of hops

Due to using batman-adv, routes are likely to have changed from test to test, and even within tests. However, by looking at the next best hop to reach the other nodes in the network at the end of every test, Table 3 shows the most probable number of hops between every pair of nodes.

Using this table, the total throughput per number of hops was obtained for each of the values of SlotTime tested. Results were normalised in order to compare the result for each number of hops, and these are shown in Figure 3.

It can be seen how the total throughput increases with the SlotTime value in two phases. First, it gets a local maximum for all cases in 24  $\mu$ s, a value that considers the one-way

propagation delay in the network. Secondly, the total throughput for each case continues to increase up to a global maximum that happens in a strict order of number of hops. Then, oscillations occur around the maximum value, which peaks at different individual experiments. This shows that the optimal SlotTime value must be chosen according to the entire network topology and not only based on the one-hop propagation delays.

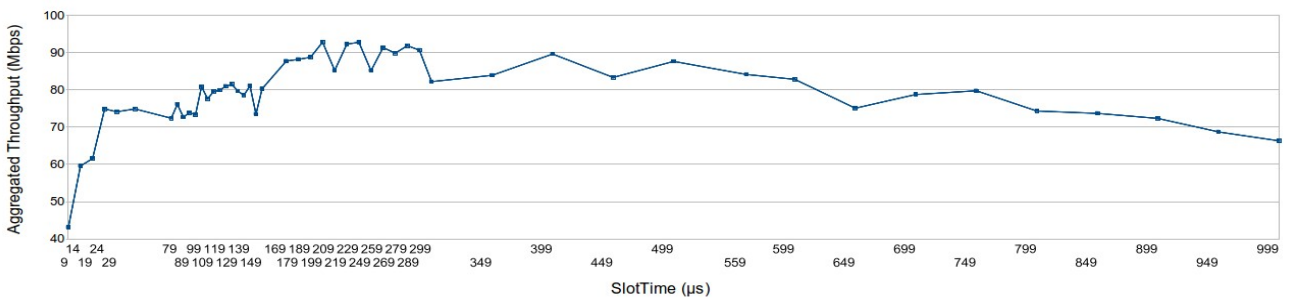
**Table 3: Number of hops for potential routes among the 12 nodes in the network.**

	1	20	21	22	23	24	25	26	27	28	29	31
1		4	2	3	3	3	4	3	5	3	4	1
20			3	4	2	2	2	3	2	2	1	4
21				1	1	1	2	1	3	1	2	1
22					1	3	2	1	4	2	3	3
23						1	2	1	2	2	1	2
24							2	1	2	1	1	3
25								1	2	1	1	3
26									3	1	2	2
27										2	1	4
28											1	2
29												3
31												

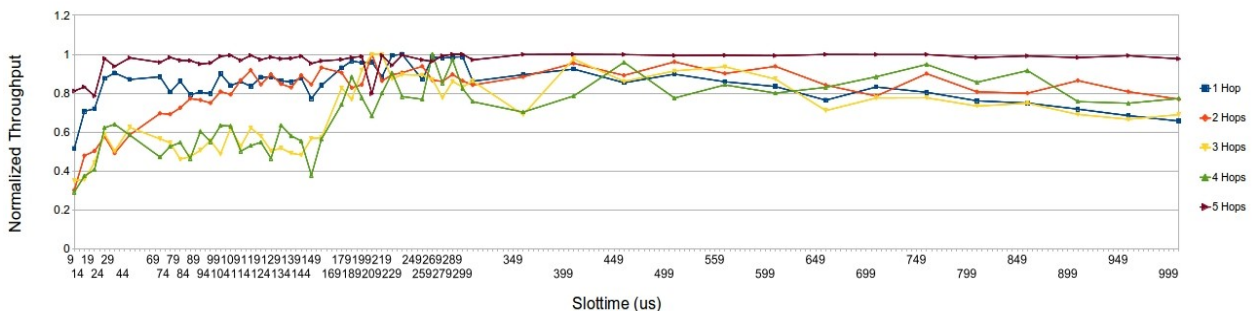
In the values obtained per number of hops, there seems to be a very strong correlation between the final throughput obtained in each route and the throughput of the slowest hop in the route divided by the number of hops.

## VI. DISCUSSION

There are two factors that appear to have an influence on increasing the throughput. Firstly, increasing the SlotTime taking into account the propagation delay of the longest active link in the network, 24  $\mu$ s for 4.65km, when we pass from 9  $\mu$ s to 24  $\mu$ s, a noticeable increase can be seen. Secondly, for values much higher than 24  $\mu$ s, one can get a sense of how the throughput for routes longer than one hop also experience a noticeable increase; the longer the route, the bigger the SlotTime value that produces such an increase. A tentative explanation for this may arise from the exposed node problem provided that the interference range for a node is much larger than its transmission/reception



**Figure 2: Variation of the aggregated throughput with SlotTime.**



**Figure 3: Variation of the normalised aggregated throughput with the SlotTime per number of hops.**



range. Possibly, the longer the SlotTime is, the smaller the impact of the exposed-node problem results. However, the distance between the furthest nodes in the network able to cause this problem is not enough to justify the SlotTime values that maximises traffic. Cross-interference between non-contiguous links could also play a role when the number of hops is bigger than two, but would not explain the steady increase in available throughput for two-hop routes up to SlotTime 114  $\mu$ s. Thus, more research is needed to justify these positive empirical results.

## VII. CONCLUSION

In this paper, an architecture for a single-radio mid-range multi-hop wireless mesh network for the provision of VoIP services in rural areas of Southern Africa has been introduced and a case study of its optimisation described. Optimisation of the aggregated throughput in the network has been carried out to find the value of SlotTime that maximises throughput. This optimisation allows improving the aggregated throughput in the network by 115%. Further improvements can be obtained by optimizing the CSMA/CA parameters as well as by using other techniques available and can be studied as future work. Still without them, the throughput measurements obtained for our multi-hop network show values clearly sufficient for carrying out VoIP traffic. Our network is cheaper, and easier to install and maintain, than multi-radio systems with directive antennas that are considerably more expensive and complex. However, they may be somewhat restrictive for sharing access to an Internet connection that the multi-radio mesh architecture allows. If further optimisation do not improve sufficiently the performance, a combination of both single and multiple radio nodes could provide a feasible and cost-effective solution.

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