Performance Evaluation of WiMAX for Rural Backhaul

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Abstract—Technologies such as WiFi and WiMAX, can be powerful driving forces for increasing rural connectivity. This paper proposes the use of WiMAX as backhaul to WiFi hotspots in order to provide sustainable and easy to deploy rural telecommunication services. The hotspots will take the form of telecentres. The IP-based network will provide voice, data and Internet services. This work evaluates the performance of WiMAX as a backhaul technology based on a typical South African rural region as a case study. Telecommunication traffic estimates for the region are determined. The future demands on the proposed network are also considered. Quality of service measurements based on these user requirements include IP packet loss and delay, as well as perceived voice quality during peak traffic periods.

Keywords— backhaul, VoIP, WiFi, WLAN, WiMAX

I. INTRODUCTION

The Integrated Sustainable Rural Development Programme (ISRDP) is a government poverty relief program that has identified thirteen District Municipalities around South Africa that are under-developed in terms of basic service, telecommunication infrastructure and economic activities. This research investigates the use of wireless technology integrated with telecentres as a solution for one of these nodes, the Zululand District municipality, and in particular the Nongoma locality.

Nongoma is situated in the western region of Zululand in the KwaZulu-Natal Province. It extends over an area of 2184 km^2 and has a population in excess of 237 362. It comprises 19 wards, and is Zululand's second largest municipality in terms of population and area. Rural communities are located around Ward 19 in Nongoma which is regarded as their primary service centre. Ward 19 and its immediate vicinity are looked at as the coverage area for the proposed wireless network. The region is endowed with an unsurpassed mix of eco-attractions and is a potential tourist destination. The prospective economic and social growth for the area is immense.

Approximately 98% of Nongoma's residents live in rural areas which have an underdeveloped telecommunication infrastructure, consequently, majority of households have no access. Less than a tenth of the population is economically active [1], thus the creation of employment opportunities for recently matriculated people in Nongoma is a high priority for the development of the local district.

The use of wireless technology (WiMAX and WiFi) to provide Internet access will alleviate the endemic poverty and strengthen the local institution. Telecentres are envisaged as the medium for expanding the reach of these rural communities to online services. Thus, the proposed telecentre solution holds the promise of providing a means for these communities to be able to participate in the global economy.

Although there are many complexities or risks involved in provisioning telecentres in rural disadvantaged areas, it has been found that with committed management that involves people from the local community, and with focus on the benefits of ICT with respect to local needs, these barriers can be overcome. More information on telecentre deployment in marginalized communities can be found in [4], [13] and [14].

II. TELECENTRE PROFILING

The network will comprise of four telecentres, a simple telecentre, a hospital telecentre and two clinic telecentres. Fig. 1 below show the placement of these telecentres on the topographical map of the region.

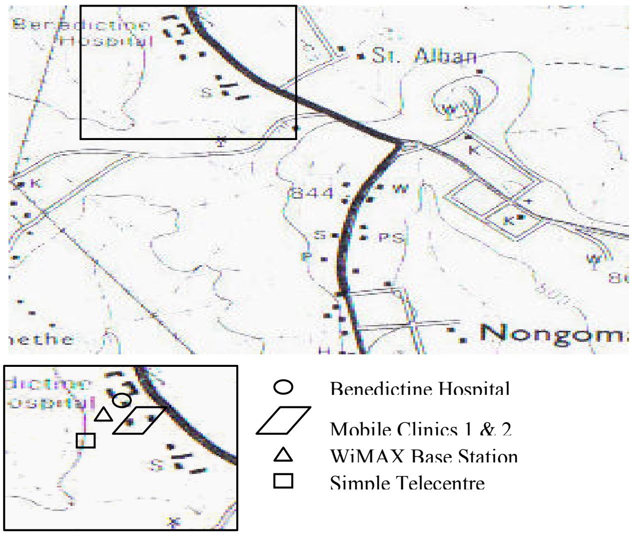

Fig. 1 - Topographical map of Nongoma

The hospital telecentre and clinic 1 are situated approximately 5 km from the base station. Clinic 2 is 10 km away from the BS, and 5km away from the hospital and clinic 1. The simple telecentre is approximately 15 km away.

All of the telecentres include Internet, VoIP and data applications. These applications act as tools for accelerating development and improving rural welfare.

The initial deployment for infrastructure at the telecentres is illustrated in the Table I below. The proposed numbers for the infrastructure at the telecentres were chosen based on a survey of telecentres around the world [2], [3], [4]. The number of PCs and VoIP phones for the South African case was chosen based on these studies, as well as the number of possible subscribers at each of the telecentres. (The calculation for the number of possible subscribers is described below). The hospital has eight PCs, and it also hosts a telemedicine application. The number of VoIP phones was chosen such that people in the region don't have to wait in long queues to use the service. The VoIP requirements are discussed in more detail in section II B.

TABLE I
INFRASTRUCTURE AT TELECENTRES

Telecentre Type	**Number of PCs**	**Number of VoIP Phones**
Simple	6	4
Hospital	8	6
Mobile Clinic	2	1

The network infrastructure at the telecentres has been oversubscribed, in order to accommodate all possible subscribers. The possible subscribers at the simple telecentre are 2552 people. The hospital telecentre has 6380 possible subscribers. The possible subscribers at each of the clinic telecentres is 638 people. This was obtained using the following equation:

$$S = P\alpha\beta \quad (1)$$

where:

S is the number of people that are possible subscribers;

P is the total population of Ward 19 and areas around its perimeter. This is estimated to be approximately 6.72% of the population of Nongoma;

α is the fraction of the total population that lives in and around Ward 19 with access to the telecentre or within walking distance of the telecentre. It is estimated to be 20% for the simple telecentre and 50% for the hospital telecentre (since there is only one hospital in Nongoma). The fraction of the population with access to the clinic telecentres is estimated to be 5%;

β is the fraction of the population of Ward 19 locality that are possible subscribers, excluding the very young and the very old [1]. This is approximately 80% of the population;

A literature review of rural telecentres described in [2], [3] and [4] has given insight into the trends and the kinds of content and applications predominantly utilized by telecentres in developing countries such as South Africa. It further indicates that there is an overdue demand for telecommunications in these areas, and the need for affordable telecommunications is increasing. VoIP and e-mail are thus considered to be key applications. In addition a telemedicine service is offered at the hospital and clinic telecentres. This application holds the hope of providing revolutionary and innovative specialty care services to this developing rural community.

Based on these applications, a bandwidth estimate was developed. It includes current and growth values for the future. A time period of 2006-2014 was considered.

It is assumed that no other technology is used to solve the telecommunications problem in the region, thus a market share of 100% is assumed.

A. Data Bandwidth Requirements

The typical applications offered at each of the telecentres and their required bandwidth volumes were estimated over the eight-year period. The bandwidth measurements include uploads and downloads. The initial measurements in 2006 are considered as suitable for Greenfield rural markets. The total bandwidth requirement is dynamically increasing, depending on technological, social and economic factors [5]. Technologically, the complexity of web pages is increasing with additional graphics being included. Thus, typically a greater volume of data is being downloaded. Socially, as people begin to realize the value of the technology as well as its ease of use, they will utilize the telecentres more often. Thus, bandwidth requirements increase as user needs and perceptions change with time. As the economic position of the region improves, a faster growth in the number of subscribers will be seen.

An indication of how Internet user needs have changed in South Africa can be seen in the growth trend in [6]. The trend shows an initial slow uptake on the "arrival" of the technology. The subsequent years show a small "boom", with the following years pointing toward a maturity, showing smaller increases in number of users. Taking into account the technological, social and economic factors, it is assumed that a similar pattern will be followed in terms of bandwidth and data traffic increase for this network.

Table II below shows an example calculation of data transfer rates or bandwidth required per user, for the data applications in 2006:

TABLE II DATA TRANSFER RATE REQUIRED FOR AVERAGE SIZED APPLICATIONS

Application/Content	**Average Transaction Size (kB)**	**Data Transfer Rate (kbps)**
Documents/Government Forms	50	40
Formatted Email Text	2	1.6
Web-browsing	62.5	50

The tolerated delay by users to download times is inferred from [2] as approximately 10 seconds. Therefore assuming that no data compression is used, a minimum data transfer rate of 40kbps would be required to download a 50kB file in 10 seconds. The data transfer rates for the email and web-browsing applications was obtained similarly.

The average transaction or file size for each of the data applications is assumed to increase at the rates shown in Table III below. The growth values differ for the file sizes of the different applications. The email file sizes increase at approximately half the rate as the documents and web-browsing applications. These percentage growth values follow the trend of Internet user needs in South Africa. The file sizes of the documents exceed that of the web-browsing in 2012, for this case study. This is due to the fact that more government forms will be online in the years to come. Also, in the clinic and hospital telecentres, the transfer of medical documents, such as x-rays will increase with time.

The initial file size values for email and documents were selected from a telecentre case study in Australia [2]. Values were given for typical minimum, average and maximum file sizes. For the South African case, the minimum file sizes were chosen. The initial page size for web-browsing is obtained from a study on wireless networking in the developing world in [4].

TABLE III: AVERAGE TRANSACTION SIZE FOR DATA APPLICATIONS OVER THE PERIOD 2006 - 2014

Year	% Growth	Documents (kB)	% Growth	Web-browsing (kB)	% Growth	E-mail (kB)
2006		50		62.5		2.00
2007	10	55	10	68.7	5	2.10
2008	30	71.5	30	89.3	15	2.415
2009	50	107.2	45	129.5	25	3.019
2010	75	187.6	65	213.8	35	4.075
2011	80	337.8	55	331.4	33	5.399
2012	72	581.0	53	507.1	25	6.749
2013	65	958.7	50	760.6	20	8.099
2014	55	1486	45	1103	18	9.557

Thus, the data transfer rates for each of the applications were obtained. The following rule of thumb formula [2] was used to determine the bandwidth requirements for non-real time data:

$$BW = P * N * O \qquad (2)$$

where:

P is the number of PCs at a telecentre;

N is the bandwidth required. The maximum data transfer rate is used to support all of the non-real time applications, i.e. from 2006 to 2010, the data transfer rate of the web-browsing application was used and from 2011 to 2014, the data transfer rate of the documents was used;

O is the overbooking factor for bandwidth allocation. Typical ratio used is 0.4, given that number of users > 1[4];

The data application bandwidth requirements for each of the telecentres can be seen in the following graph:

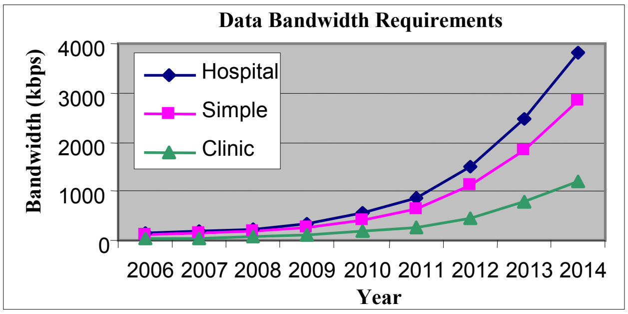

Fig. 2 - Data Bandwidth Requirements of each Telecentre

The values obtained can be considered conservative, when compared to [5], which draws a general conclusion that Internet traffic doubles every year.

B. Telemedicine and VoIP Bandwidth Requirements

Literature indicates that the data transfer rate or bandwidth required to meet medical diagnostic needs for telemedicine is 1.5Mbps. Telemedicine also assumes no oversubscription; therefore the bandwidth required is equal to the data transfer rate. The telemedicine bandwidth requirements are also found to increase exponentially over the eight year period.

The bandwidth requirements for VoIP were also dimensioned over the eight-year period. The type of codec used to carry voice over the IP network plays a key role in determining the amount of bandwidth used. The different codec's have different call qualities and different bandwidths.

The codec chosen for the Nongoma solution is the G.729. This codec is generally used as the most cost-effective codec to provide the toll call quality voice calls at low bandwidth utilization. Thus this codec is well suited to the rural Nongoma scenario.

Voice service generally has a lower oversubscription ratio than data and an oversubscription ratio of 0.17 is used in this research. This is approximately 1.5 times smaller than the ratio used for data.

By observing demand for public switched telephone network (PSTN) telephone access as well as taking into account social, technological and economic factors, an estimate of the growth for VoIP bandwidth requirements was obtained. The following equation was used to determine VoIP bandwidth requirements in bits/sec [8]:

$$\text{VoIP (bits/sec)} = EPCHV \qquad (3)$$

where:

E is the predicted telecentre traffic in Erlangs;

P is the coding rate for PCM coded voice (64kbps);

C is a factor for the codec compression in bits/sec. (The 8kbps G.729 was used). A value of 0.125 was used;

H is a factor for the compressed real time transport protocol (CRTP) header compression and layer 2 headers. A value of 3 was used. This compresses the headers by approximately 66%;

V is voice activity detection. A value of 0.6 was used;

The predicted telecentre traffic in Erlangs, E, was obtained as follows:

Taking the case of the simple telecentre for 2006, it is assumed that the average mean holding time for a call is 3 minutes. The number of possible subscribers (i.e. 2552 people) has been oversubscribed by a factor of 0.17, to obtain an active population of 425 people. It is assumed that each subscriber makes on average, 10 calls/month. Assuming an eight hour day for the simple telecentre, the traffic is 0.9Erlangs. The predicted telecentre traffic was obtained similarly over the eight year period for the hospital and clinic telecentres. It is assumed that these telecentres operate on twelve hour days.

Fig. 3. illustrates the VoIP bandwidth requirements dimensioned over eight years for each of the telecentres.

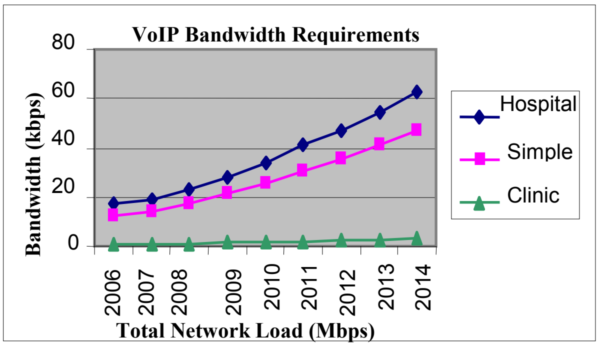

Fig. 3 – VoIP Bandwidth Requirements

C. Total Bandwidth Requirements

The estimated total bandwidth requirements for each telecentre over the specified time period, is a sum of the data application bandwidth, the telemedicine bandwidth, and the estimated VoIP bandwidth.

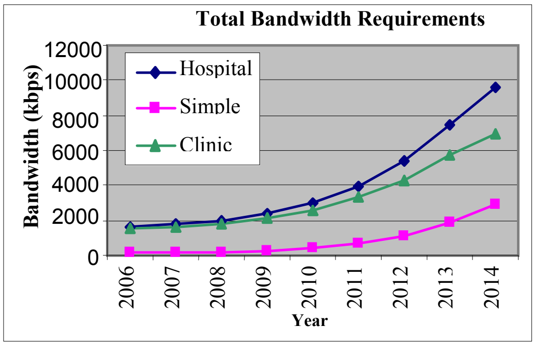

Fig. 4 – Total Bandwidth Requirements

The simulation scenarios are carried out using the Nongoma traffic profile over the eight year period. The network architecture of the system that was simulated is based on the relative locations shown in Fig. 1.

III. PERFORMANCE EVALUATION

A. The Contribution of WiMAX

The approach used in this research is to dimension a WiFi/WiMAX network for the Nongoma region using user specific data. WiMAX is used as backhaul technology and WiFi for access. Investigations were carried out on the proposed network through simulations in order to assess performance. The results obtained confirm that WiMAX is indeed a sustainable solution for rural regions in South Africa.

B. Related Work

Previous performance evaluation work on IEEE 802.16 MAC includes work done by Ekland et al [9]. Here two specific scenarios were considered; a residential scenario where only a best effort (BE) type of service was provided by the BS, and a Small Medium Enterprise (SME) scenario, where three types of services were investigated. A WiMAX simulator was used to investigate the above-mentioned scenarios. The study assumed an ideal channel in a fixed wireless point to multipoint (PMP) network. The load was increased by increasing the number of SSs. The average WiMAX connection delay results were presented. The results show the service differentiation in terms of delay between the data and multimedia traffic [9].

Work done by Cicconetti et al [10], is also a performance evaluation work on the IEEE 802.16 MAC. A PMPsystem was considered for the OFDM air-interface, although no packet corruption due to wireless channel impairment was considered. The scenarios investigated are for full-duplex SS's, and consider the BE, non real time polling service (nrtPS) and real time polling service (rtPS) scheduling services. All scenarios assume that each connection carries a combined traffic load from a variable number of data sources. The number of stations carrying the aggregate traffic from the data sources is also variable. The results are presented in terms of average WiMAX connection delay and throughput. The system performance is found to depend on factors such as frame duration and bandwidth request mechanisms.

The scenarios investigated in this study use the work presented Ekland et al [9] and Cicconetti et al [10], as benchmarks. The research for the Nongoma region investigates the performance of the different services based on the scheduling methods used in the IEEE 802.16 standard, namely; unsolicited grant service (UGS), rtPS, nrtPS and BE. A comparison is made between the system performance under ideal and non-ideal channel conditions. Ideal channel conditions imply no packet losses or corruption due to wireless channel impairments, such as fading. The system performance is also investigated when ARQ is enabled.

C. Simulation Results

OPNET Modeler 11.5A was the simulation tool used to implement the IEEE 802.11 and IEEE 802.16 standards for the Nongoma telecentre scenario. The simulation model is for a fixed wireless PMP network.

1) Ideal Channel Conditions

This investigation of the Nongoma telecentre scenario is under ideal channel conditions. The FTP application uses the nrtPS scheduling service. The nrtPS scheduling service is generally used for traffic types that have no stringent delay requirements, such as FTP. The email and web download traffic use the BE scheduling service, with VoIP in the unsolicited grant service (UGS) class. The UL and DL WiMAX connection delay results are presented below in Fig. 5 and Fig. 6 respectively, where the WiMAX connection delay is defined as the average time taken to send a packet from the WiMAX MAC of the SS/BS to the higher layer at the BS/SS.

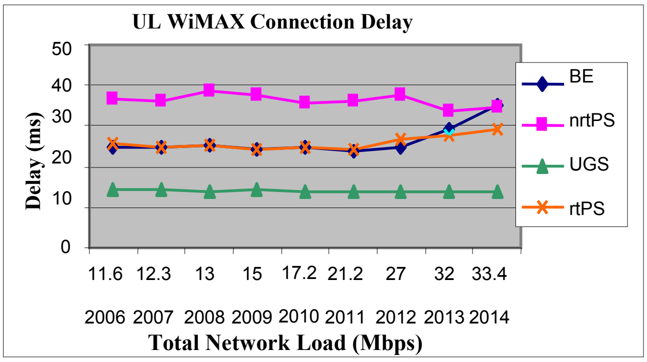

Fig. 5 - Average UL Delay vs. Total Network Load for each year

Fig. 6 above shows that in a lightly loaded system, (i.e. in the years preceding 2012), the nrtPS doesn't offer better service than the BE class, in terms of delay on the UL. This is not an intuitive result, and the conclusion that can be drawn from this result is that it takes longer for the nrtPS connections to request bandwidth than it does for the BE connections, in a lightly loaded system. It means that the time taken for unicast polls to reach the nrtPS connections is longer than the time taken to request bandwidth using contention.

This non-intuitive result corresponds to results obtained by Cicconetti et al [10], where a bandwidth request analysis was carried out. The study investigated the relative effectiveness of the BE and nrtPS bandwidth request mechanisms with data traffic. It was found that in a lightly loaded system, the nrtPS scheduling service did not improve the average delay performance of uplink connections.

The nrtPS connections are provided with unicast polls approximately every 15ms for a fixed SDU size of 1280 bytes. The unicast polls provided to the nrtPS connections take 10 times longer, than the unicast polls provided to the rtPS connections.

When the system starts to get congested (in year 2012 and beyond), BE effort delays are seen to rise faster than the nrtPs and the rtPS.

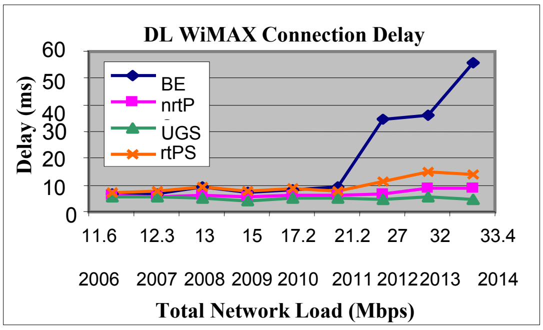

Fig. 6 – Average DL Delay vs. Total Network Load for each year

For the case of the DL delays, it can be seen that the videoconferencing delay is almost always higher than the nrtPS. The reason for this is that whether the system is lightly loaded or not, the amount of traffic using the rtPS is always higher. The amount of traffic using the rtPS is always more than 80% of the total network load. Thus, more bandwidth is reserved to this scheduling type. It can also be noted that the BE delay increases sharply. This is because, the BE traffic in the data queue at the BS, has to wait for the rtPS queues, and the nrtPS traffic queues to be empty before its data packets can be transmitted on the downlink.

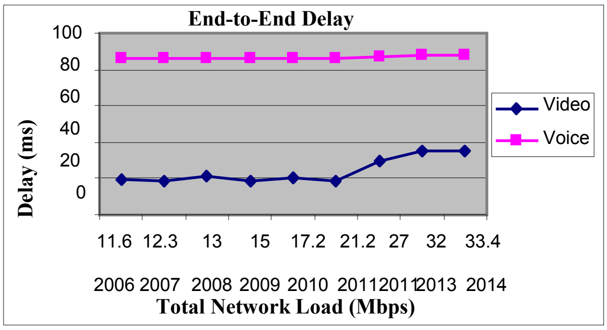

Fig. 7 - Average End-to-End Delay vs. Total Network Load

Fig. 7 illustrates end to end delays of videoconferencing and VoIP applications. It can be seen that the videoconferencing end-to-end delay does begin to degrade at the onset of congestion, but it is still within the end-to-end delay bound of 100ms as suggested by the ITU for interactive video. It should be noted that the network utilization is at approximately 84% in 2014. Voice end-to-end delay is maintained at a steady rate, also within its suggested ITU delay bound of 350ms. The voice end-to-end delay is also within the delay bound used in this research, i.e. 150ms. According to the TIA voice recommendation [11], the voice end-to-end delays correspond to an R-value above 90, and a MOS of 4.3, leaving users with high quality voice service.

2) *Non-Ideal Channel Conditions*

A non-ideal channel is considered, because an essential characteristic of wireless channels is that the signal strength varies randomly over time. OPNET uses a PDU dropping probability to emulate the PHY losses of the wireless channel. A PDU dropping probability of 5% was chosen. According to [12] this corresponds to a 25dB SNR, and literature indicates that a typical SNR for good link quality is considered to be above 25dB; typically averaging around 30 to 35dB most of the time, so a 5% packet loss is a fair choice for non-ideal channel conditions.

The non-ideal scenario found that introducing a 5% PDU dropping probability on the UL and DL for all the traffic types caused the total network load to decrease by approximately 11%. The most significant impact was seen on the download response times of the data traffic, which increased 10 times over.

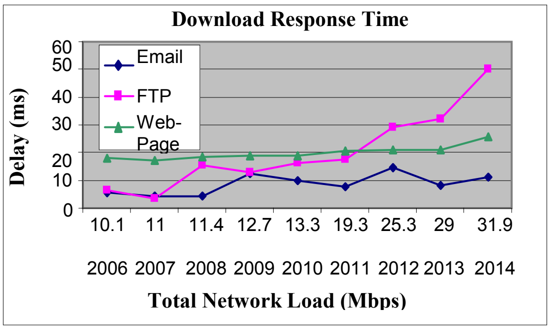

Fig. 8 also shows some delay variations. This is because data traffic arrival rate is unpredictable, this is even more so when there are packet losses due to channel impairments, and the variations in the delay can be attributed to the instability of the wireless channel.

This performance degradation can be explained by the fact that the email, FTP and Webpage traffic use TCP as the transport layer protocol. It was found that the average number of TCP retransmissions for the non-ideal case is approximately 25. This is five time higher than the number of TCP retransmissions for the ideal channel case. When this happens, TCP reacts by using it congestion control mechanism, thereby reducing the data rate and increasing the delay.

3) System Performance with ARQ

Further, ARQ was investigated, and for the sake of brevity these results are not included in this paper. It can be noted though, that the download response time decreased by 50%, but the packet loss was the same as for the non-ideal case, approximately 4%. This can be explained by the large amount of multimedia traffic on the network, also subject to the packet loss but don't have ARQ enabled. The amount of multimedia traffic on the network is in excess of 80%, thus, as a recommendation hybrid-FEC schemes could be used to improve the performance of multimedia traffic.

IV. CONCLUSION AND FUTURE WORK

Broadband wireless technology, such as WiFi and WiMAX was proposed as an affordable and equitable means to provide the infrastructure boost in the Nongoma region, based on poor existing telecommunication networks. The number of possible rural subscribers in Ward 19 and surrounding areas of Nongoma were estimated. A traffic estimate was also determined for data, Internet, voice and video applications over an eight year period namely, 2006 - 2014. The network growth was found to be exponential for all of the supported services. This growth was based on technological, social as well as economic factors.

Investigations conducted for the ideal WiMAX channel showed the positive effect service differentiation has on service performance, between data (using the BE scheduling service) and multimedia traffic (using the UGS and rtPS scheduling services). This is because the scheduling done at the BS uses fair scheduling algorithms based on traffic.

The voice and video end-to-end delays for all simulation scenarios were found to be within their suggested ITU limits and delay budget used in this research, i.e.100ms for video and 150ms for voice. Therefore it can be said that the values used in the network dimensioning is able to support the specified data and multimedia applications until 2014, thus indicating that WiMAX technology is suitable for rural backhaul.

Further research can be conducted in the use of hybrid-FEC schemes to improve the performance of multimedia traffic on a WiMAX network, in particular, the Nongoma telecentre system, with its user traffic profile. An investigation can be conducted to determine the packet loss improvement, when using this error correction method in a non-ideal channel.

The Nongoma telecentre scenario can be extended by using WiMAX mesh technology for the backhaul network. Further work can be conducted in this area, where economic modelling can be used to determine cost savings in first year and future years based on the traffic estimates for the entire Nongoma region.

Additional work can be conducted in the use of IEEE 802.16 centralized scheduling (CS) and distributed scheduling (DS) mesh modes for coverage extension, by means of a model network.

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