System performance evaluation of the IEEE 802.16e pico-base station in multihop-relay and mesh networks

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Abstract: - Paper proposes a new design and a simulation model for the pico base station based on IEEE 802.16e standard and evaluates its performance in a mutihop-relay and mesh networks. The proposed base station design allows multihop-relay communications and thus opens a possibility for the proposed base station to be an element of mesh networks. The conventional IEEE 802.16e base stations interconnected vie router or Ethernet switch are applied for point to point links and broadband wireless access. The design has been evaluated using proposed simulation model and the simulation tool OPNET Modeler for different scenarios that present real case deployment options for mesh networks thus allowing the multihop relaying that is to be supported only in the upcoming 802.16j standard, while the design is based on existing and well tested building blocks for conventional IEEE 802.16e base station.

Key-Words: - WiMAX, IEEE 802.16j, IEEE 802.16e, Pico base station, Simulation model, OPNET

1 Introduction

Broadband internet access either wired or wireless is available to majority of households in developed countries, while in developing countries a large percentage of population does not even have a basic internet access. Even in developed countries, there are rural areas with low population density and without internet access possibilities. These facts reveal a need for a technology that will cover the gap in internet access in developed countries and enable non expensive internet access to people in developing countries. For the last five years the wireless access based on IEEE 802.16 standards or its subset specified within WiMAX forum has appeared as a promising technology [1, 2].
Using wireless multihop networks in places round the world with insufficient, or even absent, infrastructure for the backhaul links should even increase the Wireless technologies possibilities for greater market shares [3]. Applying multihop relaying and mesh approach with the wireless technologies can extend current fixed infrastructure, which is currently mainly based on cooper and optical links [4].
Multihop wireless access networks are the subject of much interest at present. In the last few years they have moved from the domain of an interesting research topic to one having a significant impact on the commercial world [5].
There are a number of different types of multihop wireless networks, notably ad hoc networks, sensor networks, and wireless mesh networks. Each of these network types has different characteristics — mobility rates, power constraints, scale, form factor, and so on — which result in different system design (e.g., routing protocols, medium access control mechanisms). Another type of multihop wireless

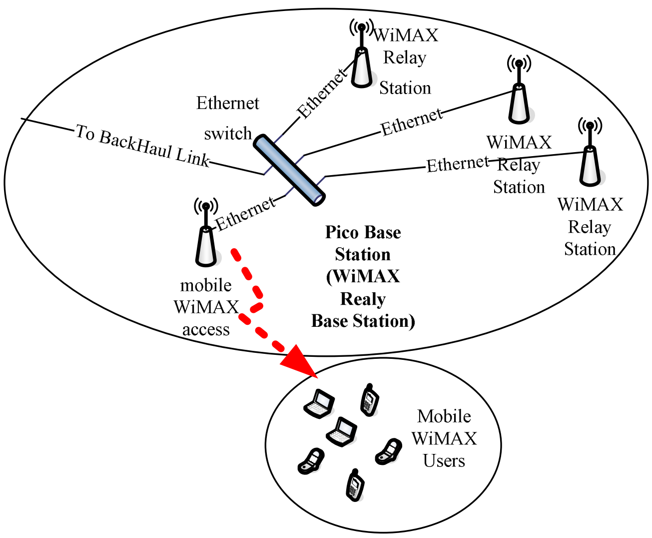


Figure 1: WiMAX pico base station concept

network that is the subject of some attention is based on a relay architecture [5], which is the focus of our paper. In developing countries, where the wired broadband infrastructure is weak or even absent, the WiMAX is increasing its market share. However, the lack of fixed backhaul infrastructure obstructs faster WiMAX penetration.

Though, WiMAX technology has not yet revealed all of its potentials as a wireless broadband access. The idea of using the WiMAX technology as a backhaul link for other technologies such as UMTS, GPRS and WiMAX is not new [6, 7]. The penetration potential for this technology will for sure improve with specifications for a new improved IEEE standard known as IEEE 802.16j [5]. The new standard aims at enhancing the coverage per user, throughput, and system capacity of IEEE 802.16e. In addition, the new standard will have much lower hardware complexity. Whilst its main advantage is the significant reduction of the deployment costs of the system since there are much lower demands for the wired backhaul: The IEEE 802.16j will support multihop relaying [8, 9].

In this paper a new concept for the IEEE 802.16e WiMAX pico base station is proposed, which is also able to connect to the neighbouring pico WiMAX base stations and form a mesh network and it can also act as an access point. The concept is presented in Figure 1.

The main characteristic of the model is that it is based on the IEEE 802.16e standard which does not specify multihop approach. The multihop support, as already mentioned, is to be supported only in the upcoming IEEE 802.16j standard. Naturally, at this early stage of standard development, there are no hardware and software components supporting IEEE 802.16j standard. The market needs have led even research community in to investigation for using already available IEEE 802.16e standard for the multihop-relaying purposes [10-12].

The paper evolves round pico base station, where firstly the theoretical concept is provided; the simulation model follows in Section 3, main parameters for the evaluation purposes are discussed in Section 4, while results and conclusions follow in Sections 5 and 6 respectively.

2 Multihop relay network

Relay-based systems typically comprise small form factor low-cost relays, which are associated with specific base stations (BSs). The relays can be used to extend the coverage area of a BS and/or increase the capacity of a wireless access system [13]. Typically, it is envisaged that they could be used in the early stages of network rollout to provide coverage at a larger scale and at lower costs than a BS only solution. In addition they can also be used for providing increased capacity in more developed networks as well as coverage to coverage holes such as areas in the shadows of buildings. [5]

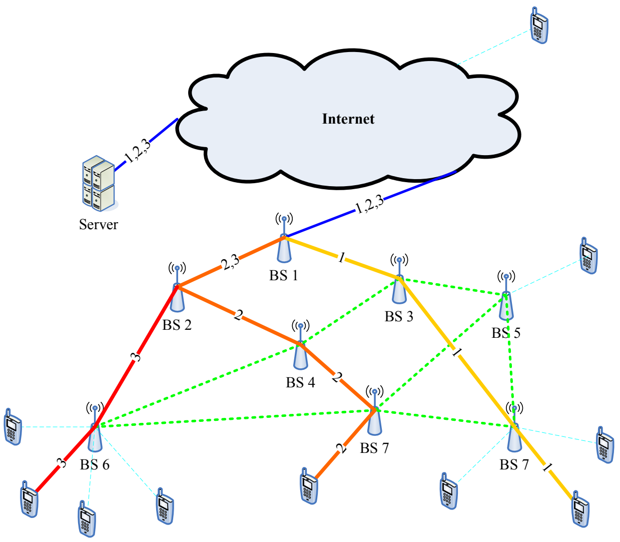


Figure 2: Three hop cellular network

Wireless mesh networks interconnect access points spread out over a large geographical area. Wireless terminals connect to the access points on their first hop. Then, their traffic is carried by the wireless mesh to the point of- presence where it can go to the Internet (Figure 2). The point of presence is the only node in the network connected to the Internet and can act as a base station (mesh coordinator) [14].

An example of a multihop-relay cellular network is presented in Figure 2. The network consists of pico base-stations that are interconnected with WiMAX point-to-point links, WiMAX last-mile network and internet network.

In the study three hop network is targeted deployment with the proposed pico base station. The following case studies are of our interest in a communication network which is limited to a maximum of three hops:

- End user inside the multihop network accesses the content in the remote server.
- Multiple end-users access simultaneously the same application in the remote server.
- End users communicate with each other inside the multihop network.

Since the IEEE 802.16j standard in most cases does not limit the number of hops in the multihop relay communications towards mobile station [15] it places greater responsibility in the hands of the network operator. Number of hops from end user to the remote server is in the case of "end user - end

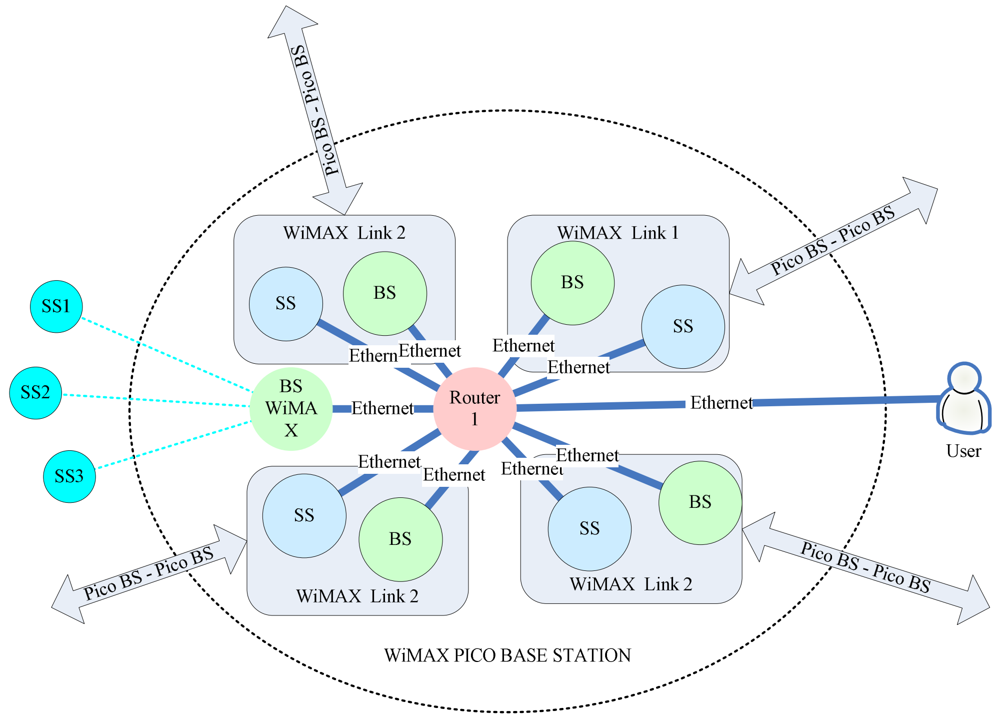


Figure 3: Detailed presentation of the WiMAX pico base station

user" communication doubled. This places constraints in the provision of the QoS demanding applications. The problem has already been noticed and proposals to decrease delay due to network hopping have already been proposed [16].
Looking deeper into the proposed communication study cases reveals that quasistatic tree shaped topology is sufficient for simulation model that allows analysis of the proposed interesting study cases. Temporal changes in the network, link breakdowns, traffic increase or decrease, adding new users to the network, starting new service, etc. can be modelled as a series of static scenarios that differ in the selection of input parameters.

2.1 Pico base station

The network model has been based on the pico base station which has been built using standard elements that have been roaming the market for a while and have been well tested.
The WiMAX pico base station has following features:

- four point to point connections based on the mobile WiMAX standard,
- the wireless access part based on mobile WiMAX standard,
- several Ethernet ports enabling wired connection and the router enabling routing traffic to and from all wired and wireless connections.

Figure 3 shows the basic element of the simulation model: the pico base station composed of the Ethernet switch or alternatively a router, WiMAX base station for the last-mile access for the end users, and four pairs of base stations and mobile WiMAX subscriber stations. Base station-mobile station pairs are placed there to simulate the radio relay point to point links. At these pairs we set the appropriate WiMAX relay parameters (e.g. the wireless links attributes such as capacity, stability, SNR, etc). Ethernet switch allows users to connect to the Internet via the standard Ethernet cable.

3 Simulation model

OPNET 15.0 PL3 [17] version supports the IEEE 802.16-2004 and IEEE 802.16e-2005 standards while simulation modelling of the 802.16j is at the moment not supported. Though, the solution proposed in this paper can be modelled using standard WiMAX OPNET models, allowing evaluation of custom scheduling algorithms for WiMAX base and subscriber stations, optimization of application performance by leveraging WiMAX QoS policies, predicting network performances for different MAC and PHY layer profiles, and visualizing live application performance over a simulated WiMAX network infrastructure.

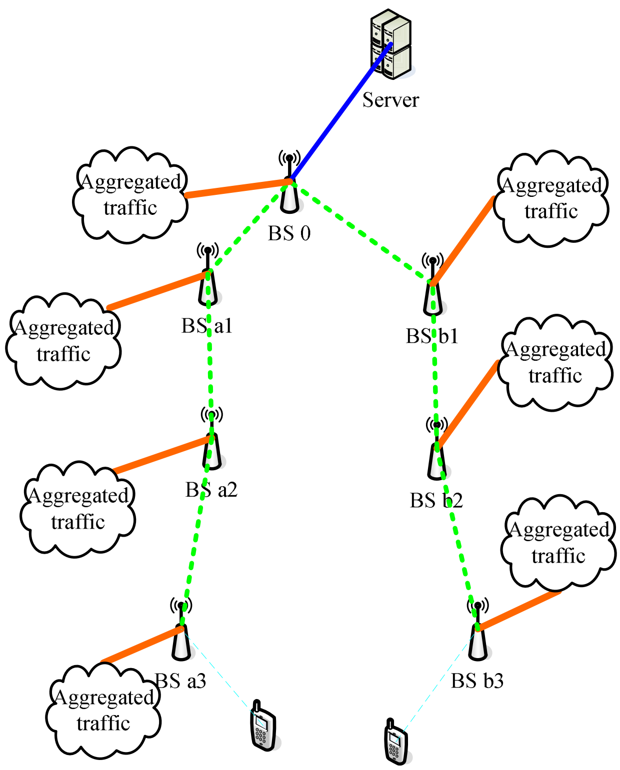


Figure 4: Simulation model of a three hop network

3.1. Pico base station simulation model

Similarly as a theoretical model presented in Section 2.1 the simulation model of the pico base station has all the basic elements from Figure 3. The radio relay links are modelled as a pair of subscriber and mobile WiMAX base station, which guarantee the duplex connection of the radio relay links. The wireless access part is a standard mobile WiMAX base station, while the router is a standard IP router. The proposed OPNET model of the WiMAX pico base station allows us to form a mesh network consisting broadband wireless and wired access part, duplex relay links based on mobile WiMAX connection and wired connection to the internet.

The interference between base stations is controlled by using different carrier frequencies at individual WiMAX relay stations.

Point-to-point connections between neighbouring WiMAX pico base stations are represented by four pairs of base – mobile station model. The proposed model allows analysis of:

- point-to-point duplex connection where download channel and upload channel are separated by using two different radio link carrier frequencies;
- point-to-point half duplex connection where in one WiMAX connection part of the frame is used for the downlink and part of the frame is used for upload connection.

Table 1: Main PHY parameters

Parameter	Value
CP length	1/8
BW (MHz)	10 MHz
Modulation	QPSK 1/2
Permutation	PUSC
Frame length (ms)	5
FFT size	1024
TTG (us)	105.7
RTG (us)	60
DL/UL ratio	29/18

Four WiMAX connections allow pico base stations to form a plain multihop ad-hoc network. By increasing the number of WiMAX connections we get only redundant elements. For instance an element with six connections is a cornerstone for forming a network in 3D space. Since terrestrial radio based networks are formed round the earth surface the four WiMAX connections are sufficient.

By using proposed approach we are able to set up parameters in the WiMAX MAC and PHY layer to:

- Model the capacity of the downlink and uplink channel, we can set up the appropriate ratio between the download and upload link capacity by modifying the coding and modulation schemata, changing the downlink upload ratio in one frame, and extending and narrowing the band of the channel.
- When we have a line of sight between the two parties, quality of the active connection can be modelled by receiver's and transmitter's antenna gain, receiver's sensitivity, and setting up the transmission power.
- Radio channel modelling is enabled by choosing environment (Vehicular, Pedestrian…) and the altitude of the pico base station.
- By setting up the carrier frequencies and zero sub-carriers in the OFDM schema one can model the size of the co-channel and adjacent channel interference.
- Individual applications can be scheduled differently through the WiMAX network. The simulator supports all the WiMAX defined QoS service algorithms (UGS, rtps, ertps, etc.)

3.2. Network model

As already discussed in Section 2 for modelling interesting scenarios the static topology is sufficient. Thus, in order to simulate various scenarios in WiMAX mesh network we propose to use a tree topology of the mesh network, which is depicted in Figure 5. It consists of seven proposed WiMAX pico base stations, from which only one is connected (through wired links) to the application server(s) and acts as an access point or point of- presence for other base stations in the network (see Figure 5).

Added network elements (to model relay stations) increase the network delay. The number of hops is therefore unlimited only theoretically. To provide users with expected QoS three hops network has been considered.

The traffic arriving from the other relay links and access network is modelled as an aggregated traffic entering each base station through Ethernet connection. One must keep in mind that this aggregated traffic loads the network but the QoS parameters (such as delay in VoIP application) should be interpreted correctly.

To make this discussion complete we have to point out the router element in the pico base station. Naturally its main function is to direct traffic correctly from end-users to routers.

3.3. Network traffic load

OPNET enables loading the network with simulations of application traffic. Generally, applications belong to different types of services and have different demands for quality of service (QoS). Applications also vary in their properties. Moreover, analyzing traffic in today's network operator reveals a large bucket of applications, thus, picking the representative applications/traffic is an important task.

We considered three types of traffic to be denoted as potentially the most interesting ones. In addition to that these three types of traffic cover the majority traffic diversity:

- Video Conference (VC) application represents bandwidth intensive, delay sensitive, video traffic and other video-rich applications. These video streams are typically encoded using MPEG-x codecs. For the simulation purposes this application has constant traffic flow.
- VoIP application represents majority of the traffic load in the network. Moreover, it represents the basic network functionality. It represents constant traffic flow.

Table 2: QoS service types settings for the used applications

QoS service type & application	Parameter	Value
UGS - Video conference	Maximum sustained traffic rate [kbit/s]	720
	Minimum reserved traffic rate [kbit/s]	720
	Maximum latency [ms]	10
ertps - VoIP	Maximum sustained traffic rate [kbit/s]	1000
	Minimum reserved traffic rate [kbit/s]	500
	Maximum latency [ms]	30
rtps - FTP	Maximum sustained traffic rate [kbit/s]	256
	Minimum reserved traffic rate [kbit/s]	128
	Maximum latency [ms]	30

- FTP traffic comes in bursts and represents all other traffic in the network. Due to low QoS demands it has the lowest priority of all the observed traffic types.

Loss-tolerant, performance of these traffic streams is inherently a function of available bandwidth, buffering, and delay characteristics of the underlying network [18].

When possible, we propose loading the network symmetrically. This means that we have the same throughputs in the download and upload direction. Though, real networks normally have their load in the download direction few times larger as compared to the upload load. Loading the simulation network in such a way will not affect the simulation results, but it will allow better control of the network occurrences.

The exposed applications differ in their demand to keep the delay or jitter below the certain number. The quality of the FTP application is evaluated by determining the response times in the download and upload direction. By loading the network with the selected applications and the measurements collected we can get enough information to evaluate the network performance.

4 Simulation scenario

Wide variety of specifications for channel coding and modulation schemes, duplexing methods, variations in the bandwidth and carrier frequency allow adaptation to various propagation environments. For the test purposes we are interested in providing the QoS for the end users in the simulated network.

The need for QoS arises when there are multiple data streams competing for the limited physical capacity of the transmission media or network devices. In the case of WiMAX, the limiting resource is the radio frequency bandwidth. When there are multiple data streams competing to use the same frequency bandwidth, a QoS policy is needed to determine which data stream has the priority to use the air interface. This QoS policy depends on the user applications that are characterized by QoS performance metrics [19].

WiMAX service classes capture the QoS requirements of service flows, where service flows represent traffic flows between the base station and the subscriber stations. For a given service class, the key parameters are minimum sustainable data and the media access control scheduler type, which enables WiMAX to provide QoS capabilities [18].

The simulation model allows setting up the complete seven layers OSI stack (i.e. from physical to application layer). To collect meaningful results from such a simulator one should have at least approximate knowledge on how the real deployed network will look alike. The complexity of setting up correctly the network can already be evaluated from the next example. The main parameters from the WiMAX MAC and PHY layer are presented in Tables 1 and 2. PHY layer parameters presented in Table 1 consider relatively poor propagation conditions for setting up the WiMAX point-to-point connection. QPSK ½ coding-modulation scheme has been foreseen. This scheme allows communication even with relatively low SNR. In the uplink that has been implemented for the relay-relay, relay-end user and base station – relay communication we have approximately 1.9 Mbps band available. This is even theoretically almost the worst case scenario from the throughput point of view and can only be improved. One can do so by increasing the transmission power at the transceiver, changing the UL/DL ratio and modifying the coding-modulation schemes.

MAC scheme, specifying the QoS service type, may be adapted only after the PHY parameters have been set. For the three applications from the section 3.3 three s QoS service types have been foreseen. The exact settings can be seen in Table 2.

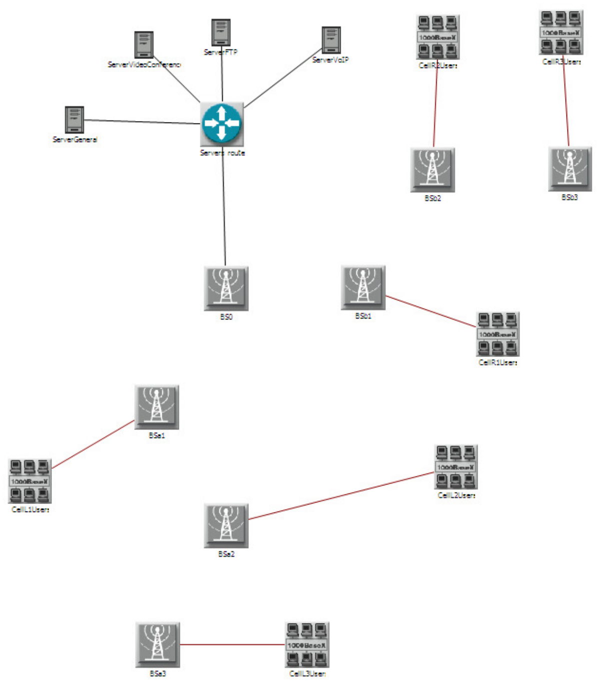


Figure 5: Screen shot of the network simulation model.

Using more than one QoS service type is appropriate solutions when network operators already have some knowledge on the end user behaviour. Generally the cost for using more than one s QoS service type is loosing some of the available bandwidth, since we have to arrange traffic in more than one queue. While the main benefit in using this approach is providing better QoS for different applications since the applications themselves generally do not interact with each other from the throughput perspective.

For Video conference calls we have reserved the UGS traffic QoS service. The Maximum sustained traffic rate parameter is set at the value to allow one Video conference call per branch. Regardless of the other applications load the network.

Second group of traffic is the VoIP traffic. We have allowed the VoIP traffic to make good use of almost all of the remaining bandwidth (the one not dedicated for the Video conference). The rtps QoS service has been chosen to set the upper bandwidth limit for the VoIP application. Furthermore, when the VoIP traffic throughput is between the minimum reserved traffic rate and the maximum sustained traffic rate the FTP application has the ability (using the best effort QoS service) can take advantage over the freed up capacity and increase its throughput, even if the maximum sustained traffic rate has been exceeded. When the VoIP application is using its dedicated bandwidth up to its limits the FTP application still has some bandwidth available to continuing its activities in the network.

5 Simulation results

5.1. Network analysis using various loads and three basic traffic types

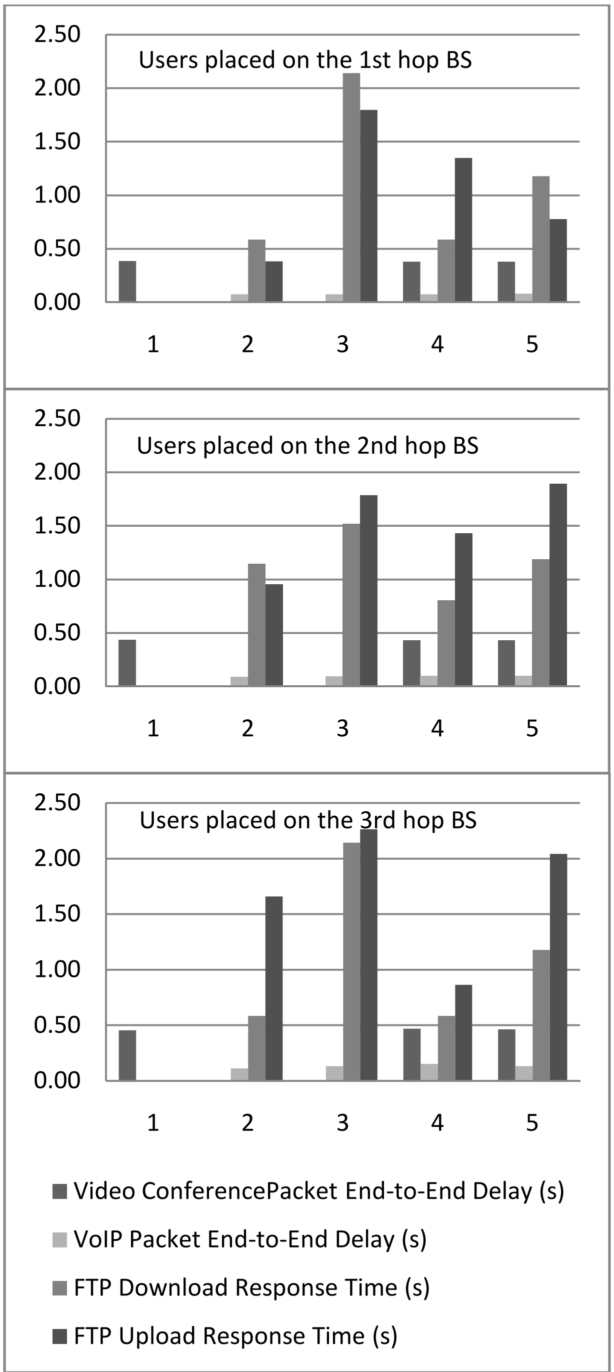
Goal of the scenario is to analyze the network using three different traffic types and three different scheduling types. The network is loaded with mint load, which never exceeds local nor global maximum network capabilities. We observe delays and throughputs while loading the network in different ways. The user distribution is summarized in table at the bottom of the Figure 6. All the users that use the application are placed at the same distance to the point of presence. For the first simulation run they are placed one hop away from the point of presence, for the second run they are placed two hops away from the point of presence and similarly for the third simulation: 3 hops away from the point of presence. All users are connected to the BS using wired (LAN) links.

Figure 6 present average delays or response time for the applications. Delay is measured individually for different number of hops. Each hop has five measurements that correspond to five cases that are explained at the bottom of figure. The top graph in Figure 6 represents results for when all users all one hop away from the point of- presence. The middle graph in the same Figure is for results when all the users in the network were two hops away from the point of- presence. In a same way we can conclude for the third graph in the Figure 6, where results for the users being three hops away from point of- presence are shown. From the mentioned results for Video conference (VC) application we can observe the:

- Packet delay grows with the number of hops.
- No significant influence of the FTP and VoIP load can be noticed from the measurements.
- For all the cases packet delay variation is close to zero (not shown in presented graphs).

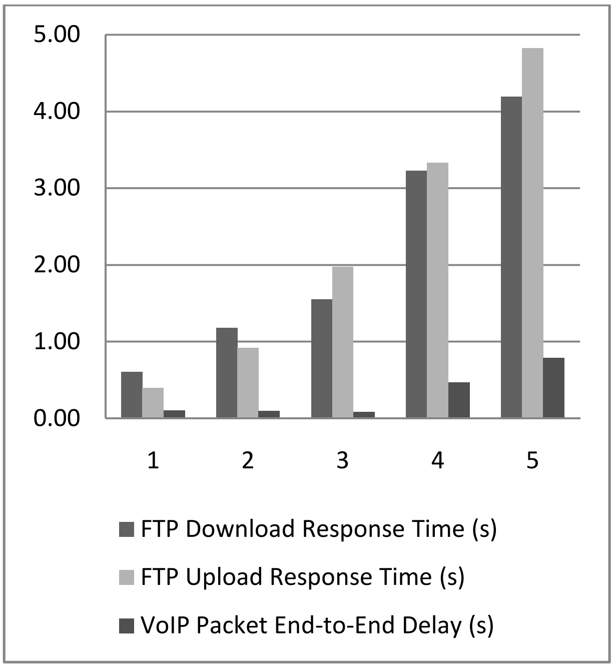
For the FTP traffic the results are different:

- Response time grows with the number of hops.
- Response time is also very dependent on the traffic load in the network. The FTP traffic has a limited amount of bandwidth reserved for it. With the growing load bursty FTP traffic has a big response time or has to wait



Case	Traffic load for the case scenario
1	1 Video conference user per branch
2	5 FTP and 5 VoIP users per branch
3	10 FTP and 10 VoIP users per branch
4	1 Video conference, 5 FTP and 5 VoIP users per branch
5	1 Video conference, 10 FTP and 10 VoIP users per branch

Figure 6: QoS evaluation parameters for the test applications. The upper graph presents results for users distant one hop to application server, middle graph for users distant two hops and the lowest graph for users that are placed three hops away from the application server. User distribution is explained in the table.



Case	Traffic load for the case scenario
1	1 FTP and 1 VoIP user per base station
2	3 FTP and 3 VoIP users per base station
3	5 FTP and 5 VoIP users per base station
4	10 FTP and 10 VoIP users per base station
5	15 FTP and 15 VoIP users per base station

Figure 7: QoS evaluation parameters for the test applications. Users were distributed equally through the complete network. The network load is defined by number of users that are explained for each case in the table at the bottom of the Figure

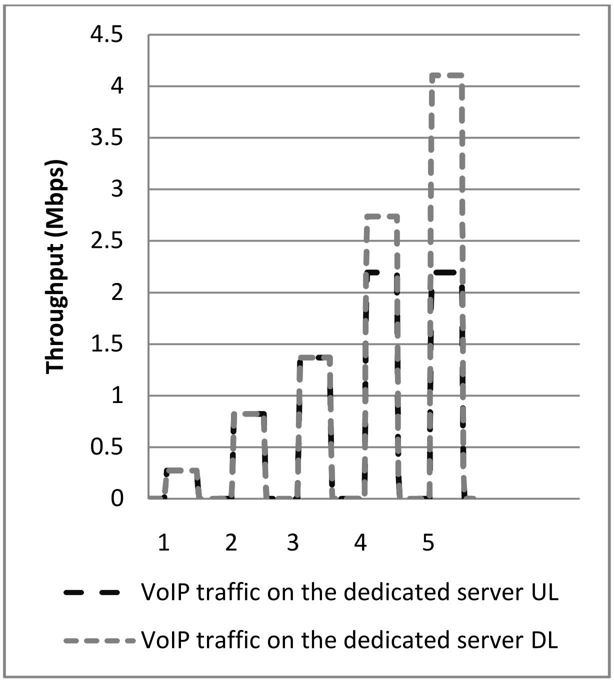


Figure 8: VoIP traffic load on the dedicated server. Load was symetric in the DL and UL direction.

for freed up spectrum from the VoIP application.

- VoIP application in the observed network and scenarios has the following significant properties:
- Response time grows with the number of hops.
- With the growing network load, also the increased delay can be noticed.

Values of the VC and VoIP application packet delay variation being low indicate that the network load is easy manageble by the system. Let us add at this point that the majority of delay for the VC and VoIP application represents appropriate coding of the stream.

In addition to measuring delays and response times we have double checked the application QoS by observing the throughput on the dedicated servers for each application. The rare packets that get lost in the network do not affect the performance of the application. The load is, as expected easily managed by the network, even for the delay intolerant application VC.

5.2. VoIP-traffic network-overload influence on the QoS

The goal of this scenario is to establish the maximum VoIP network load. In the case of dealing with overloaded network we can also observe which users in the network will be granted higher priority and will therefore gain (more) bandwidth.

Results from the previous scenario confirm that applications influence each other neglible. Therefore we have loaded the network using only VoIP and FTP applications. We have included the FTP applications because in highly loaded network the FTP application might be affected by the VoIP application (FTP application can temporarily use the freed up spectrum of the VoIP application-see Table 2).

Users were evenly distributed (in previous scenario they were distributed unevenly) in the network and their number was increased as specified in Table in Figure 7.

Figure 7 shows delay for the VoIP application and FTP response times. First three cases are within the range from the previous scenario. The delay is low as compared to fourth and fifth case. With 10 concurrent VoIP users per branch we can notice the significant increase of delays. Figure 8 clearly shows

the amount of VoIP traffic that can be transported through the network.
The MAC scheduling systems discards the packet that would raise the throughput per branch over the 1 Mbps.
The VoIP network overload also influences the FTP application. This can be read from the increasing response times (Figure 7). The response time increases when we have a big burst of FTP traffic in the network. In the mint loaded network, the FTP application could also use some of the band dedicated for the VoIP application. Let us point out once more that the UGS bandwidth (dedicated for the VC application) cannot be accessed by any other application.
By observing throughput of specific type of traffic on relays we wanted to establish weather users closer to the server have higher priority than the users with more hops to the server. The results have shown that all the users are treated the same at each hop.

5.3. Seven hop WiMAX network

The goal of this simulation block is to evaluate the network for the end user – end user communication within the same network. This scenario is applicable for purposes of emergency communications. The number of hops between the communication pair parties has been raised from three to seven. We do not expect the applications to run smoothly, but we are interested weather the seven hop network could be used at all in the cases of emergency where the lower quality of the network operability is acceptable if the network can be quickly established within the expected budget.
Three different applications and three different scheduling types are used in the same way as in the Section 5.1. The load per branch has not changed and we are interested weather the network can support three representative applications.
The server for the applications has been moved from the point of presence base station to BS b3 (as indicated in Figure 2). Users are now distributed only in the left branch of the tree network (BS a1, BS a2, BS a3).
The goal of this scenario is to load the network using moderate load, which implies using the network in normal conditions, even though the scenario is foreseen for the particular situations.
When loading the network in the unconventional way no engineer will be able to predict what is going to happen. The normal procedure would be to set up a test environment and do the measurements.
The results as presented in Figure 9 of the simulations are indeed interesting, showing

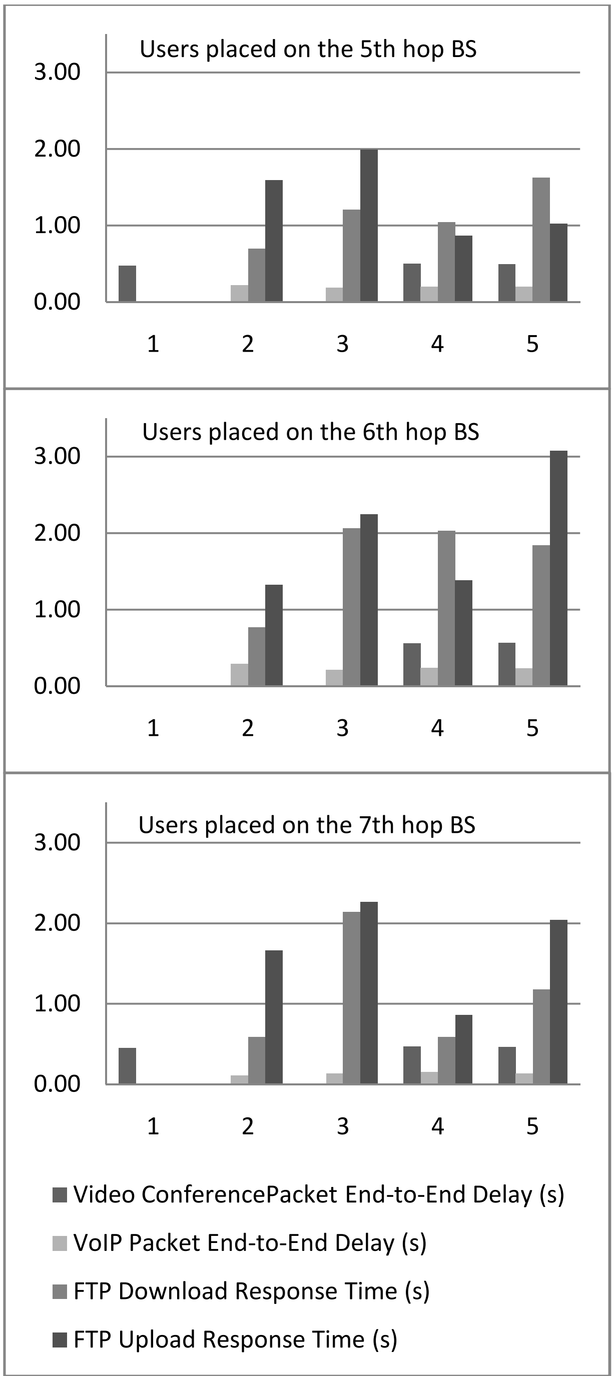


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Figure 9: QoS evaluation parameters for the test applications. The upper graph presents results for users distant one hop to application server, middle graph for users distant two hops and the lowest graph for users that are placed three hops away from the application server. User distribution is explained in table.

unpredictable behavior of the network. Similarly as in Section 5.1 the graphs in Figure 6 from top to bottom stand for different number of hops from the end users to the point of- presence (that is 5, 6 and 7 hops).

We will start with the analysis of the FTP and VoIP applications. These two applications work as expected. The delay time and response times have increased accordingly. The highest measured VoIP delay is just over the 0.3 s which makes the application still useful. The delays these size are already noticed by the user. In addition if the case is considered as an emergency communication system we can evaluate the network performance from the VoIP application point of view as outstanding.

Even for the use of the FTP application the results are (surprisingly) good. The response times have increased as compared to the reference scenario in the Section 5.1 but generally remain under the three seconds.

The VC application shows confusing results. We may claim that VC application still works for the users that are 5 hops from the dedicated server (upper graph in Figure 9). In this mentioned cases the delay has expectedly increased. But in addition to that there are no signs that the application is performing poorly. The throughputs show that the packets are not getting lost and that the throughput is comparable to throughputs in the reference scenario.

The explanation for the users on the 6th and 7th hop is straightforward. The application in some of the cases has not even started (the initialization packet was sent). We assume that the system did not start the application due to too high delays (the evaluation is done based on the initialization packet). From the results it looks like the application is also dependent on the other load in the network, though this is highly unlikely in the real world environment. We may conclude that there is a good chance that also a demanding application such as VC will work in such an unusually set network, though only the real test on the location of use will give the real conclusive answer.

5 Conclusions and further work

The model for WiMAX pico base station has been presented. Its main benefit is that it supports multihop relay communications that are not supported in the mobile WiMAX standard. All the base stations components are based on already existing and well tested equipment supporting the 802.16e standard. Therefore our model can be considered fully compatible with the 802.16e standard.

Main drawback for the proposed model is the limitation on number of hops between the end user terminal and point of presence, as we have also shown in the case scenario in Section 5.3.

The rest of the results presented in this paper show that the pico base station model is appropriate for real deployments, allowing three hop distance communication between the end user and the point of presence.

One may claim that the upcoming 802.16j standard is in addition to other improvements also no limit in number of hops. Even though this is a disadvantage for our proposed model, it is hard to overlook also the throughput limitations. The aggregated traffic in our modelled scenarios has quickly used the majority of bandwidth, thus placing a limit on number of hops not only due to delay reasons but also due to limited throughput.

It is unavoidable that in the near future mesh networks will extend current wired infrastructure for the last/first mile access. Thus the reduced time to market as offered by our model of pico base station might provide the great advantage for local vendors to penetrate the market early.

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