# ICT-601102 STP TUCAN3G

## Wireless technologies for isolated rural communities in developing countries based on cellular 3G femtocell deployments

## M52

## *Transport network architecture and interface to the access network*

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**Abstract:**

**Broadband connectivity in remote rural areas for backhauling small cells may be provided with wireless multi-hop transport networks based on WiFi, WiFi-based TDMA solutions or WiMAX. Satellite links may be used as the last alternative for links that are not feasible with other alternate technologies. The individual study of those technologies and the examination of several real scenarios permit to show the feasibility of this type of backhaul solution. However, QoS parameters may only be kept at acceptable values if IP routers control the traffic at every location. One of the considered alternatives, DiffServ, with the use of DSCP, is shown to be a feasible general solution for the differentiation of traffic classes. Other possibilities such as the use of MPLS would permit a higher level of control on the network performance. There are also different options studied for network monitoring. The HNB nodes may only trust on the backhaul network if they can query the transport network about its state and take admission control decisions based on that assessment. This document, conceived as an intermediate milestone, elaborates up the revision of alternatives in a research activity. The rest of the activity will permit to validate a definitive well-described proposal.**



**Keyword list: rural communications, heterogeneous backhaul networks, WiFi, WiLD, WiMAX, VSAT, satellite communications, long distance links, quality of service, admission control.**

**Document Revision History**

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| 10 Dec 2013 | V0.3 | Esteban Municio | State of the art completed |
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# Executive Summary

The provision of broadband connectivity in remote rural areas through heterogeneous wireless networks based on WiFi, WiLD (TDM/TDMA solutions based on WiFi) or WiMAX may be the low-cost solution that permits to take coverage to places where other more common alternatives cannot be considered. However, the way those technologies provide QoS support is heterogeneous, and suggests the use of IP advanced traffic control and management for an end-to-end coherent QoS support. In those cases where the terrestrial connection between the multi-hop transport network and the operator's core network is not feasible or it is too expensive, satellite links may be used as the last alternative for inaccessible nodes or networks.

The described type of network is firstly justified as the best alternative in many cases, and it is also demonstrated with several scenarios taken from the real life. The problem to solve is the enormous uncertainty about the end-to-end QoS figures in networks where each path has several hops and each hop may be shared with other paths. This suggests the need of an admission control system that gathers information about the state of the network continuously and takes decisions in order to prevent the network from overloading any of the systems.

Different alternatives are taken into account for both remote monitoring and advanced traffic control. The use of DSCP for traffic differentiation is seen as a first step that can give the whole network a common comprehension of the different types of traffic and the differentiated behaviour they require. Extra mechanisms such as MPLS are studied as a means to construct well characterized end-to-end paths. Also different solutions are considered to have a point to which HNB may query about the network state.

All these questions are presented, alternatives are studied and documented, and only a few high-level aspects of the network architecture are previously defined. For the rest, questions remain open and future work will continue by studying real mechanisms for the implementation of different techniques. The continuation of the activity will include real experiments and simulations, as well as a revision of real implementations of elements such as bandwidth brokers. All this is beyond the scope of this document.

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## List of abbreviations & symbols

| | |
|---|---|
| ABI | AN-BH Interface |
| ACK | Acknowledgement |
| AF | Assured Forwarding |
| AN | Access Network |
| BA | Behaviour Aggregate |
| BB | Bandwidth Broker |
| BE | Best Effort |
| BH | Backhaul |
| CAC | Call Admission Control |
| CBR | Constant Bit Rate |
| CBS | Commited Burst Size |
| CDR | Commited Data Rate |
| CIR | Commited Information Rate |
| CTS | Clear To Send |
| CW | Congestion Window |
| HDLC | High-Level Data Link Control |
| DSCP | Differentiated Services Code Point |
| ECN | Explicit Congestion Notification |
| EDCA | Enhanced Distributed Channel Access |
| EF | Expedited Forwarding |
| EXP | MPLS Experimental Bits Field |
| FEC | Forward Equivalent Class |
| FTP | File Transfer Protocol |
| GI | Guard Interval |
| HCCA | HCF Controlled Channel Access |
| HCF | Hybrid Coordination Function |
| HNB | Home Node B |
| HNB-GW | Home Node B Gateway |
| HTTP | Hypertext Transfer Protocol |
| IETF | Internet Engineering Task Forc |
| IP | Internet Protocol |
| IPFIX | IP Flow Information Export |
| ITU | International Telecommunications Union |
| LDP | Label Distribution Protocol |
| LLDP | Link Layer Discovery Protocol |
| LSP | Label Switched Path |
| MAC | Media Access Control |
| MCS | Modulation Coding Scheme |
| MIMO | Multiple Input Multiple Ouput |
| MOS | Mean Opinion Score |
| MPEG | Moving Pictures Experts Group |
| MPLS | Multi Protocol Label Switching |
| NRTPS | No Real Time Polling Service |
| NSIS | Next Steps in Signaling |
| OPEX | Operating Expense |
| OSI | Open Systems Interconnection |

| | |
|---|---|
| PBS | Peak Burst Size |
| PDR | Peak Data Rate |
| PHB | Per Hop Behaviour |
| PTP | Point to Point |
| QAP | Quality Access Point |
| QoS | Quality of Service |
| RFC | Request For Comments |
| RIP | Routing Information Protocol |
| RSVP | Resource Reservation Protocol |
| RSVP-TE | RSVP Traffic Engineering |
| RTCP | Real Time Control Protocol |
| RTP | Realtime Transport Protocol |
| RTPS | Real Time Polling Service |
| SCPC | Single Channel Per Carrier |
| SNMP | Simple Network Manager |
| TCP | Trasport Control Protocol |
| TDMA | Time Division Multiple Access |
| TLV | Type Length Value |
| TOS | Type Of Service |
| TXOP | Transmit Oportunity |
| UDP | User Datagram Protocol |
| UGS | Unsolicited Grant Service |
| UMTS | Universal Mobile Telecommunications Systems |
| VoIP | Voice Over IP |
| VSAT | Very Small Aperture Terminal |
| WILD | WiFi for Long Distances |
| WiMAX | Worldwide Interoperability for Microwave Access |
| WRED | Weighted Random Early Detection |

# 1 SCOPE OF THIS TECHNICAL REPORT

The first step in TUCAN3G WP5's research activity has been to study the expected performance of long WiFi and WiMAX links, as well as that of satellite links. The results of that first activity in WP5 have been presented in a technical report called “D51. Technical requirements and evaluation of WiLD, WIMAX and VSAT for backhauling rural femtocells networks” [TUCAN3G-D51]. Once the proposed technologies have been individually evaluated, the next step is to propose an architecture combining the three technologies for rural broadband transport networks. The interfaces between different segments in the transport network will be specified, as well as the interfaces between the access network, the transport network and the core network. The focus will be on the techniques introduced to ensure the required control on end-to-end quality of service (QoS) and to provide the information regarding the instantaneous performance of the transport network to the access network, so that an admission control mechanism may be implemented.

The methods for interfacing the access network and feeding it with QoS information will be technology agnostic, which means that the access network must work the same way regardless the specific transport technology it interfaces with.

A normal backhaul link for a classic base station is a high-capacity low-delay dedicated link. The backhaul is given enough capacity for the peak traffic generated by the base station's users (incoming + outgoing traffic). The delay is guaranteed to be very low unless a satellite link must be used, and even in that case the delay will be kept reasonably stable by using a dedicated carrier and enough capacity to avoid congestion. In our very special scenarios in TUCAN3G, several small femtocells are used to bring 3G/4G coverage to sparsely populated areas that are far away from urban areas. Moreover, there is a strong concern about cost in the project because only a low-cost solution could make TUCAN3G's proposals interesting for operators due to the reduced capacity to generate revenue from these rural populations. Hence, a multi-hop wireless network will be proposed instead, so that the closest location to the city becomes at the same time the relay that brings connectivity to the next location.

Hence, three technologies (four, considering proprietary WiLD solutions like Mikrotik NV2 as something different from 802.11) have been considered for one-hop connections, and now a multi-hop network will be considered to interconnect the urban area with all the locations in which femtocells are deployed. Several topologies can be considered, as well as several combinations of the different technologies. This document will firstly analyze what are the most determinant characteristics of each technology and the most reasonable use for it in a multi-hop heterogeneous network. Secondly, a mechanism will be proposed to make each link to perform well within the performance limits that are foreseen for it at the network planning stage. Last, elements and mechanisms will be introduced to make possible that the end-to-end QoS is controlled and monitored both for QoS support and for assessing admission control mechanisms in the access network.

The proposals in this document will be realistic and robust, but not necessarily optimal. The importance of realism is great in rural networks because the experience shows that only existing solutions will be eventually available as the low demand of these low populated areas is not strong enough to generate market for new technologies, or for implementing technologies that have not been implemented for greater markets. The optimization of the proposed solution in terms of both performance and power consumption will be faced in the next activity and is out of the scope of this document.

# 2 STATE OF THE ART

## *2.1 Scientific literature on end-to-end QoS in networks combining WiFi and WiMAX*

The integration of different wireless technologies within the same multi-hop wireless network is commonly needed in many scenarios. Some examples that illustrate this affirmation follow:

- A user receiving broadband connectivity at home through a WiMAX link is likely to use WiFi for several devices to get connected to the WiMAX terminal.
- A VSAT terminal that is shared for several neighbourhoods is likely to be accessed through WiMAX or another broadband technology.

Hence, the problem of integrating these technologies is not new. The integration is not a matter of basic compatibility: all these technologies are prepared to exchange IP packets over Ethernet or Fast-Ethernet interfaces. However, the way packets are differentiated or prioritized, as well as the way those systems may report their performance and be controlled remotely, may be fairly different.

By the time WiMAX was standardized and the first commercial devices were implemented (2004-2008), a few practical experiences of WiFi multihop rural networks where already being tested, such as the Silvia network [Rendon05], CuzcoSur network [Simo06] or the Napo network [Rey11].

When WiMAX came to scene, the first papers proposing a heterogeneous 802.16 / 802.11e architecture appeared immediately [Gakhar05, Haffajee05, Frattasi06]. These works already proposed mappings between WiMAX services and EDCA's access categories, but without any practical analysis or results. Some authors [Berlemann06, Kumar08] proposed the integration of 802.11e HCCA and 802.16 with spectrum sharing, but this research line was not very successful because the industry clearly chose not to implement HCCA and focused on EDCA. Later on, some authors proposed hybrid routers that include the functionality of a WiMAX user station and an EDCA QAP [Ghazisaidi09]. Others [Myounghawan10] also introduced the idea of complementing EDCA prioritization mechanisms with DiffServ traffic control capabilities to obtain a QoS support equivalent to that of the WiMAX side. However, all those works are mostly descriptive of a proposed architecture, and few also contain basic simulations.

Lately some studies [Pan08, Elayoubi10] have proposed to solve this problem by trying to model the integration between WiFI/WiMAX and developing new delay assurance algorithms for DiffServ[Lee09]. [Chieng11] proposes novel models on scalability of WiFi/WiMAX integrated networks. Although some real test-beds have been deployed in [Gracias11] and [Kakien12] shedding light on the feasibility of their basic proposals, none of them has crossed the line to propose specific methods for implementing those integration principles in an efficient way, and none of them has tested the integration experimentally. That is why [Zhang10] defines this problem as an open one, underlining the great interest to real priority applications like telemedicine.

From a different approach, a novel solution has been proposed to homogenize heterogeneous wireless networks by introducing a MPLS layer between IP and MAC layers. This is a step forward of the Diffserv point of view, in which the use of MPLS would give independence of OSI layers 2 and 3 and would give a better control over the network resources and give the IP flows a IntServ-like behaviour. [Sarraf13] gives an updated overview about this concept as well as other publications give a more accurate mapping QoS classes between MPLS and WiMAX [Khanzadi07] and between MPLS and WiFi [Oubaha08] and [Oubaha11]. Furthermore, [Cerutti07] and [Sameh10] propose advanced methods to distribute MPLS labels using RSVP-TE for both WiMAX and WiFi in order to get for DiffServ domains the QoS guarantees that are typical in IntServ.

Finally, a series of publications [Kretschmer10], [Niephaus11], [Kretschmer11] and [Niephaus12] implement this concept of integration wireless technologies with MPLS and perform experimental results in real heterogeneous backhaul network.

After carefully revising the state of the art, it is well known that WiFi, and specially EDCA, cannot be compared to WiMAX in terms of QoS support. However, with the right mappings of traffic classes to access categories and a strong traffic management at the IP layer (or MPLS layer), it seems feasible to provide a certain level of QoS support in a multi-hop wireless network that integrates WiFi and WiMAX.

Finally, WiFi-based TDMA solutions and VSAT links have not been studied in the literature in combination with WiFi and WiMAX in the same terms, as far as we know. This is probably because proprietary solutions are dominant in these technologies, and their QoS support use to be restricted to the IP layer. Hence, their integration in a heterogeneous architecture for end-to-end QoS support will be a matter of configuration of specific parameters and of IP QoS strategy. All the equipment revised in both technologies supports DSCP traffic differentiation and many of them have several functionalities for advanced IP traffic control.

### 2.2 State of the art on backhaul networks supporting QoS

Backhaul networks aim to link access networks with core networks. This is usually made using oversized high capacity links in which the congestion or saturation is rarely a problem. However, the scope of the TUCAN3G project and this document is focused in low-cost networks to support femtocell networks, where backhaul constraints are significant. Thus, the congestion of the rural backhaul network is an important issue we have to deal with. This problem has been reported by several authors like [Fitzpatrick11]. In this work, a WiFi-based backhaul network is studied to support VoIP for femtocell networks, concluding that it is necessary to include admission control mechanisms (e.g. Call Admission Control) in order to guarantee certain QoS levels to the VoIP flows, especially in those which WiFi links are used. This becomes very important in our femtocell based context.

From this starting point, a global approach must be taken in order to choose the most convenient strategies to design backhaul networks in isolated areas with a convenient admission control mechanism. Previous works like [Seungjoon06] have already highlighted the problems associated with QoS in generic backhaul networks and proposed new deterministic models for the admission control from the point of view of the delay and the topology. Also, admission control studies for local wireless links have been published like [Liu09] for WiFi and even WiMAX/WiFi integration for end-to-end QoS like [Carvalho09] and [Cicconetti07]. So far, there is no study which has made a realistic implementation of admission control mechanisms for heterogeneous backhaul networks. However, some papers have approached in a nearby way to these topics from different points of view.

In one hand, [Olariu12] and [Olariu13] studied an admission control mechanism for femtos based on real-time Mean Opinion Score (MOS) measurement using Call Admission Control. Similarly to this approach the work in [Tarii12] is also based on real-time QoS measurements, but in this case learning mechanisms are used to set temporary QoS patterns in order to take admission control decisions. [Hariyanto11] proposes a backhaul-aware admission control model in which femtocells can decide which algorithm they use to take decisions. These papers are focused on a distributed admission control mechanism in which femtocells are the elements that measure the network state and take decisions accordingly.

Last, following these distributed admission control point of view, the work in [Rattaro10] proposes an admission control mechanism based on an active throughput prediction using statistical learning. This consists of sending small amounts of data in order to infer the network state without barely affect its performance.

On the other hand, other approaches like [Lakkakorpi08] and [Chowdhury09] propose the use of a traditional bandwidth broker located in the backhaul network in order to help the access network, or the edge elements in the backhaul network, take decisions in the admission control process. Many papers like [Kalatunga04], [Bouras09] or [Bouras09b] study bandwidth brokers and offer different views about implementations (centralized, distributed and hybrid) and its performance in different scenarios. The previously cited works [Kretschmer10], [Niephaus11], [Kretschmer11] and [Niephaus12] also give solution for monitoring backhaul networks using different techniques of monitoring and signalling.

A deeper analysis of the admission control and monitoring (if any) mechanisms might be discussed subsequently in future TUCAN3G documents, such as D52 and D53, in order to choose the most appropriate alternatives for the project.

# 3 DEFINITION OF A HETEROGENEOUS BACKHAUL NETWORK BASED ON VSAT, WILD AND WIMAX

In this section a high-level architecture of heterogeneous backhaul networks will be proposed. Firstly, the different components will be examined and evaluated in order to find out whether it is convenient to use them or not. Then, the architecture itself will be proposed, and finally the interfaces and interactions will be detailed.

## *3.1 Role and limitations of each technology*

The previous technical report entitled "D51. Technical requirements and evaluation of WiLD, WIMAX and VSAT for backhauling rural femtocells networks" [TUCAN3G-D51] examined in detail the different wireless technologies being considered in this project. Now, we are going to extract the essential characteristics that must be considered for each technology from the results in that document and from latter experiments. As an example of what this means, several versions of WiFi have been evaluated, with several physical bitrates in each, several PHYs in some of them, … but only one will be retained as valid when the others are clearly worse. Let's see what elements have to be taken into account for our network architecture.

### 3.1.1 IP routers

As mentioned before, IP packets are going to be exchanged between femtocells and the operator's core network. Hence, IP packets will pass through the network, some with DSCP marks that femtos will use to differentiate packets belonging to different traffic classes. IP routers are nodes in the networks that have more than one network interface (either wired or wireless) and may receive IP packets, classify them and forward them to their destination following any rules that are previously established for queuing, priorities, traffic shaping or any other advanced traffic control actions.
IP routers may be used at any location that is the starting point of two or more links. It is also possible not to use IP routers in such locations when IEEE 802 frames are exchanged, just connecting link terminals directly or through a Level-2 bridge. Using IP routers in link interconnections has the disadvantage of introducing additional equipment and processing, and the advantage of strong management capabilities for both traffic monitoring and control.

### 3.1.2 WiFi links

Several WiFi standards have already been evaluated in [TUCAN3G-D51], and IEEE 802.11n has been shown to exhibit the best performance in all cases. Hence, we are going to ignore the other standards for further analysis.

At the MAC layer, we consider that EDCA is available and the four access categories will be used to differentiate traffic classes. The CoverageClass option will be used to adapt the range to the physical distance (typically up to 15 km) and the SlotTime, ACKTimeout and CTSTimeout will be adapted consequently to the distance as shown in [TUCAN3G-D51] for PtP links.

At the PHY layer, both 2.4 GHz and 5.8 GHz bands will be considered with 20 MHz channels. 40 MHz channels will not be considered in general, as only one 2.4 GHz 40MHz-wide channel or two 5.8GHz 40MHz-wide channels can be used in the same location without any overlapping. In our architecture, "WiFi" will be considered to use 20 MHz channels except for very specific scenarios which permit (and require) wider channels. Frame aggregation will be used systematically. The performance has been evaluated for different frame aggregation sizes, showing that short aggregated frames drive to lower delays and much lower throughput though long aggregated frames drive to higher delays and much higher throughput. In a typical case, 8 kB frame aggregation size and 800ns GI duration will be considered.

Provided that we are considering technologies for backhauling rural femtocells, we need a high level of control on the network performance. [TUCAN3G-D51] has shown that the performance varies importantly in the proximity of the saturation point (i.e. the operation point in which the highest throughput is achieved as the offered load is increased) and that low delays of a few milliseconds are only possible if external elements prevent the offered load from surpassing a certain threshold. MIMO2x2 is considered as an available solution through cross-polarity dual parabolic antennas.

Hence, WiFi links will have to be protected in order to guarantee their operation in unsaturated conditions, and they will be configured for using the highest transmission mode that may operate stably for a given link budget[1]. The rest of options must be adjusted as described here.

### 3.1.3 NV2 or alternative WiFi-based TDMA solutions

There are tens of manufacturers producing wireless solutions that use WiFi hardware but replace the CSMA/CA MAC layer for a TDMA MAC layer. As none of the manufacturers publishes the details of their MAC layer protocol, comparisons are only possible through extensive tests. In [TUCAN3G-D51], only Ubiquiti AirMAX and Mikrotik NV2 have been compared. Other alternatives exist from manufacturers such as Alvarion, Redline, Proxim, Radwin and others, that have not been tested in this project. However, from those being compared, NV2 showed better performance than AirMAX. Therefore, NV2 will be used as the representative of WiFi-based TDMA solutions within this document, acknowledging the possibility of getting similar or better performance with any of the solutions that have not been tested.

As in WiFi, MIMO2x2 will be considered as an available solution through cross-polarity dual parabolic antennas. In addition, 20 MHz channels will be considered except for very specific environments that require wider channels.

The highest transmission rate will be considered for which the link budget ensures the stability. In the case of NV2, it is possible to select frame duration between 1 ms and 10 ms [TUCAN3G-D51]. Different frame duration values will be considered depending on the acceptable maximum delay for each link in the network design.

### 3.1.4 WiMAX

WirelessHUMAN is considered by default (5 GHz band) with 10 MHz-wide channels and possibility of MIMO 2x2.

WirelessMAN is known to be an available alternative when non-licensed bands cannot be used due to regulatory restrictions, but will not be explicitly considered in this document, as it does not present any advantage in performance compared to WirelessHUMAN.

Frames are variable between 2.5 ms (the shortest), with lower delay and lower throughput, and 20 ms (the longest) with higher delay and higher throughput. Different options will be considered as the maximum per-hop delay changes (see [TUCAN3G-D51]).

### 3.1.5 VSAT

By default, satellite systems will be considered to be SCPC. Obviously, when a scenario permits its replacement for TDMA alternatives, the latter will be preferred in order to reduce the OPEX.

[1] Based on the current practices for the planning and deployment of terrestrial links, we consider in this document that a long link is stable for a given link budget if the average received power level is at least 15 dB higher than the receiver sensitivity, provided that the link operates at a frequency band under 6 GHz and with line of sight.

Only geostationary satellites are considered, using as much bandwidth as needed with 1 bps/Hz of efficiency and one-way delay around 260 ms.

Satellite gateways are expected to have DSCP differentiation capabilities, so that they can handle the traffic consistently with the QoS strategy implemented in the network.

### 3.1.6 Comparison of technologies for network links

First of all, VSAT links cannot be seriously compared with the other alternatives. Due to the OPEX and to the extremely high delay, VSAT links are only considered as gateways to the operator's core network when the rural network is too far from urban areas and a terrestrial multi-hop network is not a reasonable alternative.

In order to achieve the fairest comparison between the three technologies WiMAX/WiFi/WiFi-based-TDMA we have start from the premise of equal per hop delay. Thereby, when a heterogeneous backhaul network is designed, it is possible think of all these technologies as valid alternatives. As this project supposes that there may be paths in a backhaul network with more than one hop, the per-hop delay must not exceed 5-20 ms depending on the maximum number of hops. Therefore, only two cases will be analyzed, backhaul links with 5 ms and 20 ms per hop delay. Other values of per hop delay will not be considered in detail since these cases can be easily extrapolated from the upper and lower limits.

Achievable distances for each transmission profile are calculated by using typical 30dBi small parabolic antennas (around 60 cm of diameter), transmission power levels and sensitivities from real commercial devices of each type and path losses calculated with the Friis formula. A fading margin of 15dB is assured in all cases. Obviously, bigger antennas permit to achieve longer distances for all profiles. The considered sensitivity levels chosen are shown in Table1 and Table 2 for WiMAX and WiFi/NV2 (same equipment). These sensitivities can vary from one manufacturer to other, but variation is limited.

| WiMAX | Sensitivity |
|---|---|
| BPSK 1/2 | -92 dBm |
| QPSK 1/2 | -89 dBm |
| QPSK 3/4 | -86.5 dBm |
| 16 QAM 1/2 | -83.5 dBm |
| 16 QAM 3/4 | -80 dBm |
| 64 QAM 2/3 | -76 dBm |
| 64 QAM 3/4 | -74 dBm |

**Table 1: Sensitivity for different transmission schemes in a WiMAX system of the ARBA series by Albentia Systems.**

For a 5 ms per-hop delay, the achieved throughput for each technology is shown in Figure 1, where the link budget imposes a distance limit to each transmission profile. It is possible to observe that the highest throughputs are fostered by NV2 and WiFi for each modulation. It is also apparent that NV2 and WiMAX give constant throughput regarding the distance due to their TDMA nature, while WiFi throughput decreases significantly as the distance augments. In Figure 1, continuous lines correspond to WiFi values, dotted lines to NV2 and dashed lines to WiMAX.

The comparison is made from distance 0 km to 60 km. However, only IEEE 802.11n is hard-limited to around 60 km (unless new chipsets or products appear in the market that permit to modify ACKTimeout and CTSTimeout beyond those limits). WiMAX and NV2 have no MAC specific constraints regarding the distance limit.

| WiFI/NV2 | Sensitivty |
|---|---|
| MCS8 | -96 dBm |
| MCS9 | -95 dBm |
| MCS10 | -92 dBm |
| MCS11 | -90 dBm |
| MCS12 | -86 dBm |
| MCS13 | -83 dBm |
| MCS14 | -77 dBm |
| MCS15 | -74 dBm |

**Table 2: Sensitivities for different transmission schemes in WiFi/WiLD systems by Mikrotik**

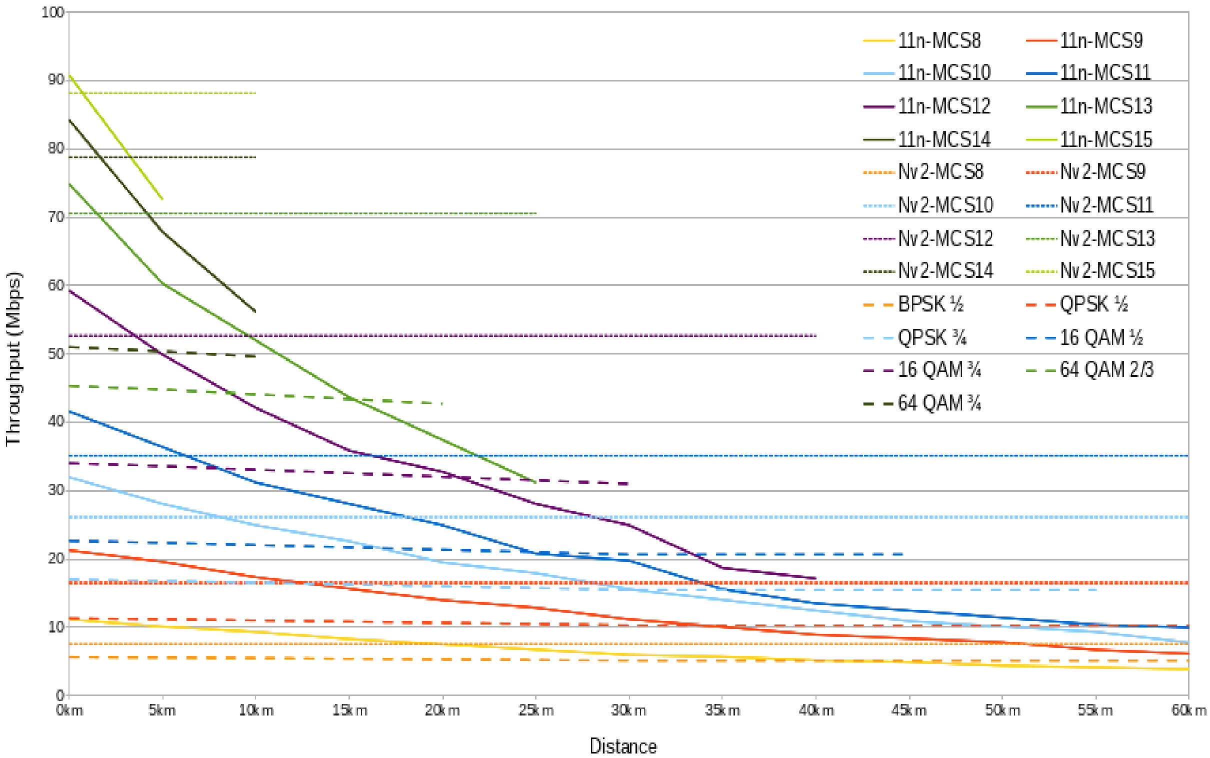



**Figure 1: Throughput vs distance for each technology when a per hop delay is limited to 5 ms.**

Figure 1 shows that WiFi gives the highest throughput only for short distances (d < 5km). For the rest of the distances NV2 gives better values.

Similar results are obtained for 20 ms of per-hop delay (see Figure 2), although higher values of throughput are obtained for each technology. For the case of WiFi and NV2, this is due to the higher maximum offered load that corresponds to higher per-hop delay limit. For the case of WiMAX, longer frame durations increase the effective throughput but also the delay. As in Figure 1, WiFi values are represented by continuous lines, NV2 by dotted lines and WiMAX by dashed lines.

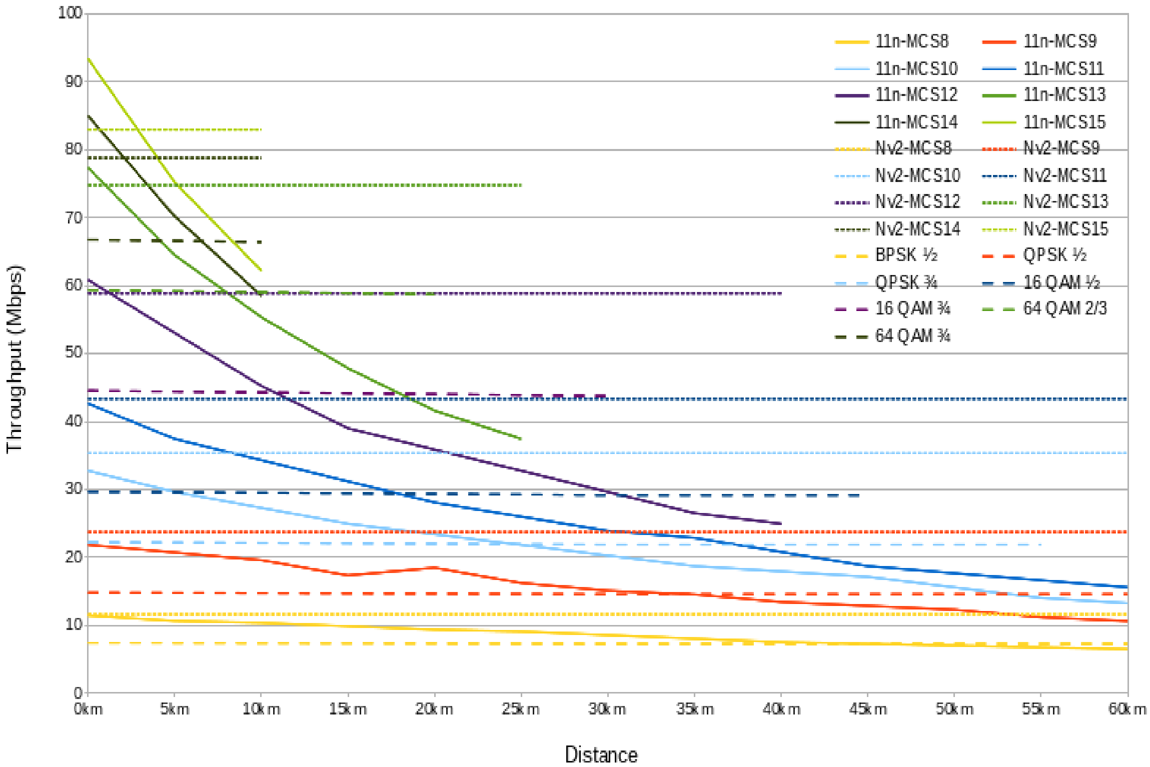



**Figure 2: Throughput vs distance for each technology when a per hop delay is limited to 20 ms.**

Similarly, 802.11n is shown to be the best choice only for 'short' shots of less than 5 km. Longer links get better performance using solutions like NV2. Regarding WiMAX, even though it looks worse than NV2 in the comparison, it should be noted that this is due to the channel bandwidth. WiMAX uses 10 MHz-wide channels, as this is the maximum established in the standard for WirelessHUMAN, while other alternatives in the comparison are using 20 MHz channels. In equal conditions of spectrum use, WiMAX performs better than any other alternative, since it shows better spectrum efficiency.

### 3.2 Appropriateness of a multi-hop solution for backhaul of rural 3G/4G access networks

The goal of this work is to define the architecture of a multi-hop network that acts as the backhaul for rural 3G/4G femtocells to the telecommunications operator's network. Several femtocells may be spread out over a remote area where wired connections are neither advisable nor feasible, hence wireless links are the reasonable options for backhauling. The three basic strategies that can be considered are presented in Figure 3.

- A wireless backhaul link may be used for connecting each small cell to an edge node in the operator's core network, as represented in part a) in the figure. This is the classic way to solve the backhauling, but may not be reasonable if the distance from that edge node to the small cells is much higher than the distances among small cells. In our case, this option may be considered only if:

 - The furthest locations are in the range of WiFi, WiMAX or WiFi-based TDMA links starting in the urban area. This means that (i) the maximum distance is still in the range of the preferred technology (which in turns depends on how much bandwidth we need), (ii) there is line of sight between ends of all the potential links, and (iii) the number of links allocated to the rural area is smaller than the number of available non-overlapping channels.
 - This solution requires higher towers in several locations in order to ensure the line of sight.
 - The offered load generated in small cells is so small that does not justify the investment in dedicated links at higher costs.

- Part b) in the figure shows the multi-hop alternative. One of the cells (the closest to the urban area) must be connected to an edge node in the operator's core network. Then that node can be used as the relay node to bring connectivity to other nodes, which in turn may be used as relay nodes that bring the connectivity to other ones in further locations. Although this approach implies several disadvantages such as the higher complexity for controlling the end-to-end performance experienced by each small cell, it is a reasonable and cost-effective alternative in many scenarios of TUCAN3G.
- Part c) in the figure represents the same alternative as b) when the distance between the urban area and the closest small cell is too long to consider the possibility of terrestrial broadband connectivity, even chaining several links. In this case, a two-hop link is always available through satellite with remarkable increases on the OPEX and the communication delay (as high as 260 ms one way).

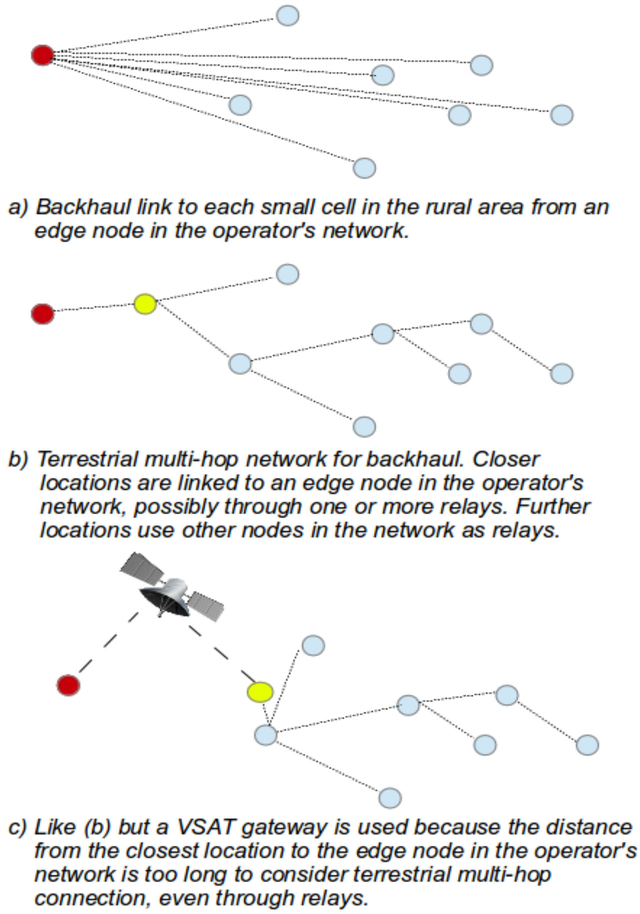
Despite of the disadvantages mentioned, the use of VSAT gateways may be essential in many scenarios due to accessibility conditions. Hence, the first decision in the backhaul is related to the use of the VSAT gateway. This decision may be stratified as follows:

- An accurate comparison between CAPEX and OPEX should be the main strategy to choose the right approach. If a terrestrial wireless link or a chain of terrestrial wireless links connecting the closest small cell to the operator’s core network ensure a delay smaller than 500 ms, the decision of using a VSAT gateway can be considered purely for economic reasons.
- The use of a VSAT gateway is compulsory in networks where the connection of the closest small cell to the urban area through terrestrial wireless links is unfeasible.
- Similarly, single small cells or groups of cells might be directly connected to the operator’s core network by means of a VSAT gateway when the distance to neighbour nodes or the topography makes impossible to connect with them through terrestrial links.

On the other hand, let us consider the cases where rural locations may be connected to the urban area through terrestrial wireless links. The next question to answer is whether there are situations in which a multi-hop wireless network is a better solution than straight one-hop links from all the locations to the urban area.

The possible advantages or disadvantages of each alternative are related to: cost (essentially due to the different height of towers required for line-of-sight), capacity (links in one-hop backhaul links carry only the traffic of one HNB, while links in multi-hop networks carry aggregated traffic to/from several location, so they require higher capacity) and delay (multi-hop delay use to be significantly higher).

In this analysis, it is straightforward to see that the cost is generally just a utility function that we would like to minimize.



*a) Backhaul link to each small cell in the rural area from an edge node in the operator's network.*

*b) Terrestrial multi-hop network for backhaul. Closer locations are linked to an edge node in the operator's network, possibly through one or more relays. Further locations use other nodes in the network as relays.*

*c) Like (b) but a VSAT gateway is used because the distance from the closest location to the edge node in the operator's network is too long to consider terrestrial multi-hop connection, even through relays.*

**Figure 3: Three different strategies for backhauling in remote small cells.**

The maximum delay that can be supported in the backhaul is a restriction. Each backhaul path will impose a total delay that is a summation of different components: a per-link delay associated to each hop and a routing delay (essentially due to queuing and scheduling) associated to each intermediate router, the edge router connected to the HNB and the edge router in the operator's network. If the designed multi-hop solution can overcome this restriction, it is no longer needed to consider it.

The minimum capacity required per backhaul path imposes another restriction. Each HNB in the access network generates a variable amount of traffic that can be characterized in general and for the busy hour. Many links in the multi-hop network carry simultaneously traffic for several HNBs, which means that some links must support much more traffic than in the case of one-hop straight PtP links. On the other hand, when the per-hop distance in the multi-hop solution is shorter than end-to-end distances in the other solution, typical adaptive coding and modulation schemes permit to achieve higher capacities. For example, if a network has two chained links of 20 km instead of one link 40 km long, the path-loss is 6 dB lower in average in the first case, driving to increments of 25%-80% in the throughput depending on what modulation and coding scheme is used in either case. As the capacity required from the backhaul by each HNB is a result of the access network planning, in case those requirements may be satisfied by a multi-hop solution, it is no longer needed to consider the capacity as a restriction.

Hence, the “classical” solution for linking each HNB to the urban area with straight links should only be considered when the two previous restrictions cannot be met by a multi-hop alternative.

Consequently, multi-hop terrestrial wireless transport networks present the best alternative for the backhaul of rural small cells in the most general case, and the other alternatives (VSAT links or one-hop backhauling) are restricted to specific scenarios that fit in the described conditions.

## 3.3 Comparison of technologies designing heterogeneous backhaul networks in practical scenarios

In order to get a practical comparison of the previously analyzed technologies, three archetypical backhaul networks will be analyzed. This will allow us to get some conclusions about the heterogeneous backhaul network design and provide a useful comparison tool that may help us to decide which technology must be chosen.

These three scenarios have been chosen to try to identify typical networks located in rural or isolated areas, representing different topologies, amount of users served, and accessibility. Since there is a lot of possible combinations in designing the backhaul network, we have restricted the design limiting the total backhaul delay to 50 or 60 ms. Many combinations can be obtained comparing the per hop delay of each technology, so in order to simplify, we will consider same per hop delay in each technology. In subsequent studies other configurations with different per hop delays will be analyzed.

The considered technologies are the ones described in Chapter 3.1 except VSAT, which is not justified in these scenarios. However further analysis will study when the use of VSAT is recommended.

### 3.3.1 Linear topology with few hops: Paranapura Network

The Paranapura network is an example of linear topology network that is implemented typically to reach isolated areas with minimum cost. Nodes are frequently located in river basins, especially in flat scenarios where no mountains can be used to take advantage of the altitude to provide line of sight. However, rivers offer other advantages like easier deployment, since the river itself is a way of communication, and proximity of villages. The network scheme is presented in Figure 4:


**Figure 4: Paranapura Network.**

Using [TUCAN3G-D41] as an input to obtain the backhaul traffic requirements, the viability of the usage of each technology has been calculated. As seen in Figure 4, there are only 3 wireless links which carry the traffic from the 3 last locations, Paranapura, San Gabriel and San Juan, as a chain to Yurimaguas. The performances that WiFi, WiMAX and NV2 could offer for each link are shown next, assuming 5 ms delay per hop in Table 3 and 20 ms delay per hop in Table 4. The green color means that the offered capacity is higher than the throughput required by the link using that technology.

| Link | Distance | Throughp. required (Kbps) | WiMAX (Kbps) | | WiFi (Kbps) | | NV2 (Kbps) | |
|---|---|---|---|---|---|---|---|---|
| Balsapuerto - San Gabriel | 21.2 Km | 8012.8 | 16QAM3/4 | 31527.7 | MCS13 | 31200 | MCS13 | 70598 |
| San Gabriel - San Juan | 19.3 Km | 13382.4 | 64QAM2/3 | 42728 | MCS13 | 37440 | MCS13 | 70598 |
| San Juan - Yurimaguas | 27.2 Km | 15110.4 | 16QAM3/4 | 31009.4 | MCS12 | 24960 | MCS12 | 52656 |

**Table 3: Capacity offered by different technologies in the Paranapura Network with a 5 ms per-hop delay.**

| Link | Distance | Throughp. required (Kbps) | WiMAX (Kbps) | | WiFi (Kbps) | | NV2 (Kbps) | |
|---|---|---|---|---|---|---|---|---|
| Balsapuerto - San Gabriel | 21.2 Km | 8012.8 | 16QAM3/4 | 43893.6 | MCS13 | 37440 | MCS13 | 74751.5 |
| San Gabriel - San Juan | 19.3 Km | 13382.4 | 64QAM2/3 | 58697.6 | MCS13 | 41600 | MCS13 | 74751.5 |
| San Juan - Yurimaguas | 27.2 Km | 15110.4 | 16QAM3/4 | 43764.1 | MCS12 | 29640 | MCS12 | 58851.3 |

**Table 4: Capacity offered by different technologies in the Paranapura Network with a 20 ms per-hop delay.**

As it is shown, WiMAX, WiFI and NV2 links can easily support the demand of the access networks, for both 5 ms and 20 ms per-hop delay in each bakchaul link of the Paranapura Network. For 20 ms per-hop delay, the offered capacity is higher while the total delay of the network is still under limits for most of the services. However, when the backhaul consists of many hops, a lower per-hop delay must be chosen in general to keep the total delay below the limit.

Since the three technologies considered are equally valid, their different combinations are not considered. It does not make any substantial difference whether the choice for each link is WiMAX, WiFi or NV2, as long as the backhaul requirements are satisfied. Future works will determine which combination is optimum for each scenario in terms of performance and costs.

### 3.3.2 Linear topology with many hops: Napo Network

The Napo Network can be seen as an extension of the Paranapura Network, as it is also a linear topology network deployed following a river basin (see Figure 5: Napo Network.Figure 5). The only substantial difference among them is the number of hops.

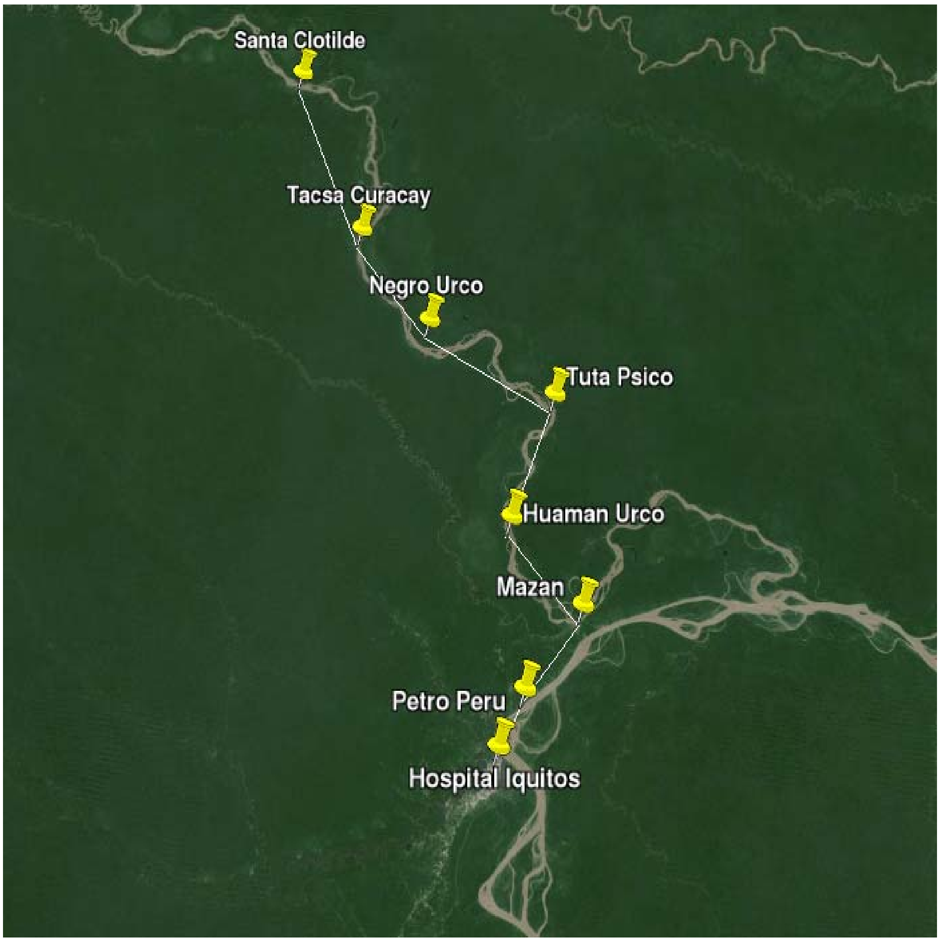



**Figure 5: Napo Network.**

In this case, more hops means that more access nodes are being served. The designs of this kind of networks usually try to take advantage of the infrastructures already deployed in the area, in order to reach as many users as possible. As calculated for Paranapura Network, Table 5 shows the performances of these technologies in each wireless link. In this case, only low per hop delay must be analyzed because of the size of the network, being 7 the maximum number of hops. Using longer frame durations in WiMAX or NV2, or increasing the offered load in WiFi might result in a total backhaul delay higher than 50 or 60 ms. This would mean that non-high delay tolerant services like VoIP could not be provided in the network.

| Link | Distance | Througput required (Kbps) | WiMAX (Kbps) | | WiFi (Kbps) | | NV2 (Kbps) | |
|---|---|---|---|---|---|---|---|---|
| Santa Clotilde - TC | 39.1 Km | 6412.8 | 16QAM1/2 | 20672.9 | MCS12 | 17160 | MCS12 | 52656.4 |
| TC – Negro Urco | 25.5 Km | 9248 | 16QAM3/4 | 31009.4 | MCS13 | 31200 | MCS13 | 70598.6 |
| Negro Urco – Tuta Pisco | 32.2 Km | 12083.2 | 16QAM3/4 | 31010.4 | MCS12 | 24960 | MCS12 | 52656.4 |
| Tuta Pisco - HU | 26.5 Km | 14918.4 | 16QAM3/4 | 31527.7 | MCS13 | 31200 | MCS13 | 70598.6 |
| HU – Mazan | 22.3 Km | 17753.6 | 16QAM3/4 | 31527.7 | MCS13 | 31200 | MCS13 | 70598.6 |
| Mazan - Petro | 19.9 Km | 24486.4 | 64QAM2/3 | 42728 | MCS13 | 37440 | MCS13 | 70598.6 |
| Petro – Hospital Iquitos | 11.7 Km | 24486.4 | 64QAM2/3 | 43419 | MCS13 | 43680 | MCS13 | 70598.6 |

**Table 5: Capacity offered by different technologies in the Napo Network with a per hop delay of 5 ms.**

Table 5 shows that all three technologies can meet the throughput backhaul requirements with 5 ms per hop delay. A higher per-hop delay is discarded due to exceeding the total delay limit. Although the three technologies are interchangeable as long as the demand is met, it is clearly that NV2 gives the best result in terms of higher throughput.

### 3.3.3 Tree topology: Cusco Network

The last scenario consists of a tree topology network located in a highland environment. This particular environment takes advantage from the elevation of peaks, where relay stations can mounted on small towers and still have LOS. In addition, better coverage can be assured easily, thus extending the number of villages that can be reached with similar budget. When it is necessary to reach many sparse villages, the tree-like topology is considered to be the best option. However this kind of topology is more prone to create bottlenecks in the links that are closer to the gateway because they carry traffic for several access nodes. Also, further strategies like channelization must be considered to merge multiple links in the same node. The Cusco Network scheme is shown in Figure 6.

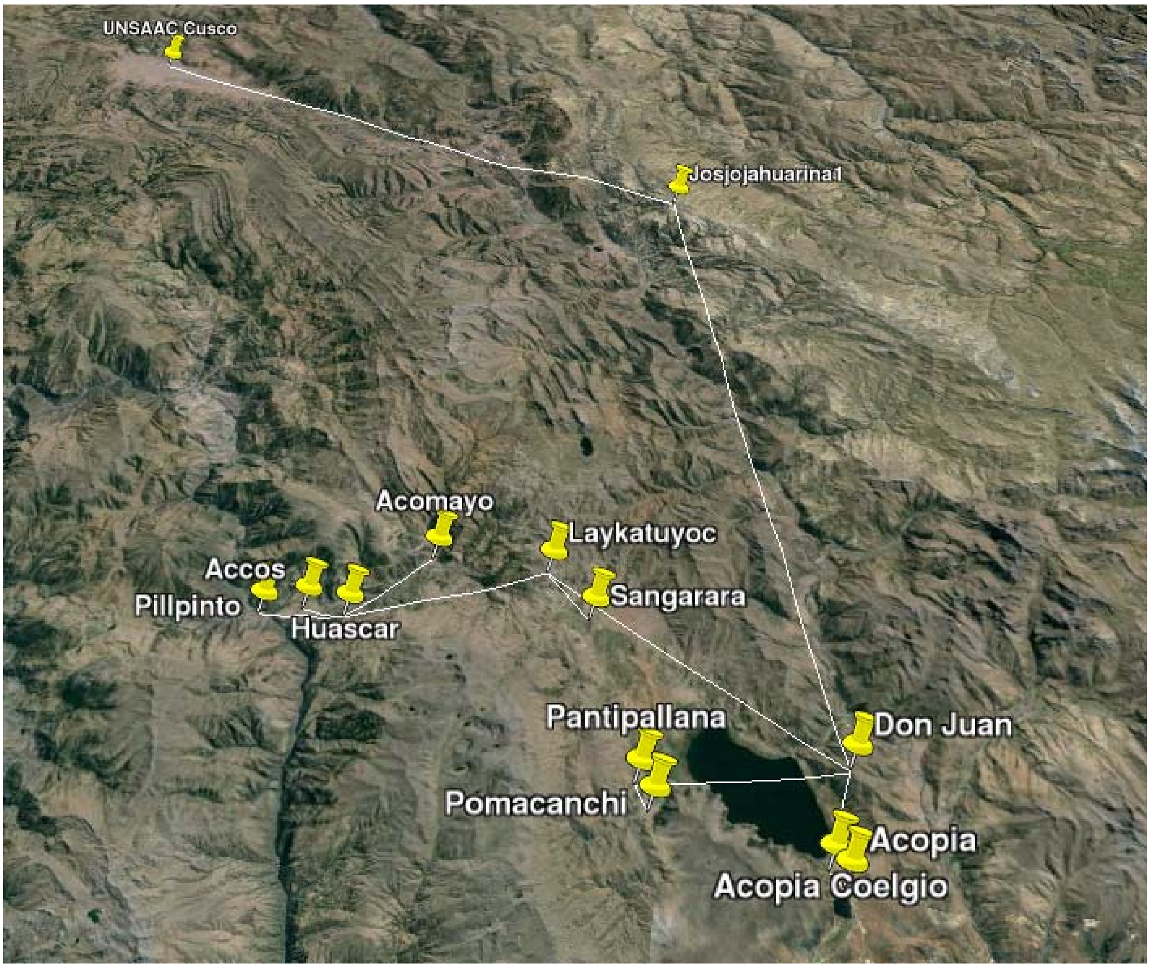



**Figure 6: Cuzco Network.**

The Cusco Network offers service to higher number of users, so its backhaul should bear more traffic. This is due to the higher population density, as compared with the previously studied networks. As in Napo Network, many hops inhibit use high per hops delays. In this case, the maximum number of hops is 5 in order to assure the total backhaul delay above to 50 ms or 60 ms. Table 6 gives numerical data of the throughput demand for the backhaul and presents the performances of the considered technologies.

| Link | Distance | Througput required (Kbps) | WiMAX (Kbps) | | WiFi (Kbps) | | NV2 (Kbps) | |
|---|---|---|---|---|---|---|---|---|
| Acopia - Acopia C | 4.58 Km | 6412.8 | 64 QAM3/4 | 50401.2 | MCS15 | 72600 | MCS15 | 88150.8 |
| Acopia C - Don Juan | 0.9 Km | 6412.8 | 64 QAM3/4 | 50401.2 | MCS15 | 72600 | MCS15 | 88150.8 |
| Pomac - Pantipallana | 9.48 Km | 16025.6 | 64 QAM3/4 | 49623.8 | MCS15 | 57000 | MCS15 | 88150.8 |
| Pantipallana – Don Juan | 1.44 Km | 16025.6 | 64 QAM3/4 | 50401.2 | MCS15 | 72600 | MCS15 | 88150.8 |
| Sangarara - Laykatuyok | 3.34 Km | 11065.6 | 64 QAM3/4 | 50401.2 | MCS15 | 72600 | MCS15 | 88150.8 |
| Acomayo - Huascar | 5.34 Km | 12825.6 | 64 QAM3/4 | 50401.2 | MCS15 | 72600 | MCS15 | 88150.8 |
| Acos – Huascar | 2.28 Km | 6412.8 | 64 QAM3/4 | 50401.2 | MCS15 | 72600 | MCS15 | 88150.8 |
| Pillpinto - Huascar | 4.43 Km | 3744 | 64 QAM3/4 | 50401.2 | MCS15 | 72600 | MCS15 | 88150.8 |
| Huascar - Laykatuyok | 10.2 Km | 22982.4 | 64 QAM3/4 | 49623.8 | MCS15 | 57000 | MCS15 | 88150.8 |
| Laykatuyok – Don Juan | 17.5 Km | 34048 | 64 QAM 2/3 | 42728.0 | MCS13 | 37440 | MCS13 | 70598.6 |
| Don Juan - Josjohauarina | 41 Km | 56486.4 | 16 QAM ¾ | 20672.9 | MCS12 | 17160 | MCS12 | 52656.4 |
| Josjojahuarina - Cusco | 42.3 Km | 56486.4 | 16 QAM ¾ | 20672.9 | MCS12 | 17160 | MCS12 | 52656.4 |

**Table 6: Capacity offered by different technologies in the Cusco Network with a per hop delay of 5 ms.**

In this case, the last two links are both the closest the gateway and the longest. This is translated that the throughput required for the backhaul is not satisfied at first view. In Table 6, green colour means complete viability, orange means that the throughput demand cannot be accomplished with the normal configuration described in Chapter 3.1, and finally red means that the required throughput cannot be provided with that technology for that link, no matter what configuration is chosen. As can be seen in Table 6 the throughput offered for WiFi, NV2 and WiMAX by the longest links is below of the network demand (red and orange). The reason of this is twofold: firstly, limiting the per-hop delay to 5 ms reduces the available per-hop throughput, and secondly, long-distance links require robust modulations that work stably with low received signal power levels at the cost of a low link capacity.

There is no an immediate way to fix this for WiMAX since neither higher MIMO configurations (i.e. 3x3) nor increased bandwidths (i.e. 20Mhz) are supported by existing commercial products. Even though certain installation practices may improve the link budget in order to use higher modulation and coding schemes, it is still not enough to provide the required throughput.

On the other hand, the required throughput can be provided by WiFi or NV2 just with small changes in the network design. These changes could be:

- **Increase the bandwidth to 40 MHz**. The available bandwidth in the 5 GHz band suffices for 2 channels with 40 MHz bandwidth. Hence, locations using only two wireless interfaces may operate with 40 MHz channels.

- **Improve the SNR of the longest links**. Improving the link budget can help to increase the offered throughput. However, while additional 3dB would be enough for NV2, WiFi's link budget should be increased 12 dB in order to meet the requirements.

- **Reducing the GI duration**. Although it is possible to reduce the GI in order to get better throughput in the link for both technologies, this could affect the link performance since the multipath interference protection would be reduced. Further studies in each specific scenario should determine whether reducing the GI is advisable or not.

In conclusion, Cusco Network can carry the traffic foreseen for TUCAN3G services only if the last two links are implemented by NV2 or WiFi, and only if specific configurations are used to increase the performance. Otherwise, none of the technologies can provide the required service level to the given amount of users with the specific traffic demand given by [TUCAN3G-D41] without either changing the standard configuration, or reducing the number of users, or decreasing the traffic per user in the network.

### 3.3.4 Conclusions

These three backhaul analysis make visible that many factors should be considered during the backhaul network planning.

The Napo and Paranapura Networks are examples of how a small/medium rural backhaul network can be implemented, using the proposed technologies in a way that meets the access network requirements. We can see that, in this kind of backhaul networks, the choice among WiMAX/WiFi/NV2 for most of the links is essentially a matter of costs.

On the other hand, Cusco Network shows that very long links should be avoided in the network planning when possible, especially near the gateway.

As conclusion, it is possible to announce that for each backhaul network, there is always a specific threshold for number of users, above which the network cannot be deployed using standard configuration. However, after analysing case by case, significant performance increases can be achieved by adapting the network configurations to the access networks demands. This can be done by setting the link distance accordingly to the load, and choosing among WiMAX/WiFI/NV2 per link depending on the specific throughput, delay and cost requirements.

## *3.4 High level architecture for an heterogeneous rural network based on WiLD, WiMAX and VSAT*

Excluding VSAT, all the technologies considered in this document for the backhaul may transport several Mbps. Their adaptive nature implies that they have a variable capacity that depends on the distance and the antennas chosen. Moreover, some technologies have to operate significantly below the saturation point (i.e. 802.11n) in order to keep the delay low in that link. On the other hand, excessing the offered traffic increases the packet-loss probability. Hence, links must be offered a controlled amount of traffic in order to keep the delay, the jitter and the packet-loss under control.

In the case of a multi-hop network, the maximum aggregated traffic offered to some links easily exceeds their maximum capacity, especially in any link supporting a high number of end users (no matter if it is the backhaul for a populated location or it aggregates the traffic to/from many small villages). The most reasonable and common way to control the amount of offered traffic by each individual link is to insert an IP router between any pair of hops in the network.

However, the use of IP routers implies the insertion of IP queues which increase the delay and eventually may cause packet-drops. The only way to operate the whole multi-hop network with low end-to-end latency and negligible packet-drop probability is to introduce an admission control mechanism that limits the traffic offered by each access node to the transport network.

To facilitate the understanding of this section, some definitions follow. IP routers to which the HNB nodes are connected will be referred to as “edge routers”. The router connecting the backhaul network with the operator's core network will be referred to as the “transport network gateway”. Any other IP routers in the transport network are referred to just as “core transport network routers”.

At any location, the “node” is made up with several communications systems interconnected. A transport network router (gateway, edge or core) is always present. One or more communication systems (that can be WiFi, WiMAX or WiFi-based TDMA) are the near ends of links connecting that node with others. If the node is the gateway node, a system connected to the core network is present, or alternately a VSAT terminal connects to the core network through satellite. If the node is an edge node, there is a HNB. The physical interconnection between any pair of systems is likely to be an Ethernet link, either with a direct cable or with a switching device. The capacity of the Ethernet segment between any pair of elements must be high enough to never limit the link capacity, so that it remains “transparent” in terms of performance. Hence, Fast-Ethernet or Gigabit-Ethernet should be considered depending on the speed of systems and links being bridged. These Ethernet connections are not going to be detailed in the architecture.

Hence, the general architecture for the transport network is represented in Figure 7. Interfaces are given a name in order to avoid ambiguous references within this document. Each place in which communications equipments are installed is called a Location ($L^k$). Each location has a Router ($R^k$) which controls all the traffic originated in / destinated to / passing through location $L^k$. All communications equipments (femtocells $C_i^k$ or WiFi/NV2/WiMAX/VSAT systems $W_i^k$) in $L^k$ are connected to $R^k$ through an Ethernet link (Ethernet, fast-Ethernet or Gigabit-Ethernet as needed; as mentioned before, this interface is supposed not to be a bottleneck in any case). Interfaces between $W_i^k$ and $R^k$ are given a name $I_{Wi}^k$, and interfaces between $C_i^k$ and $R^k$ are called $I_{Ci}^k$ instead. Wireless links are also given a name related to the upstream location: $l^{k,j}$.

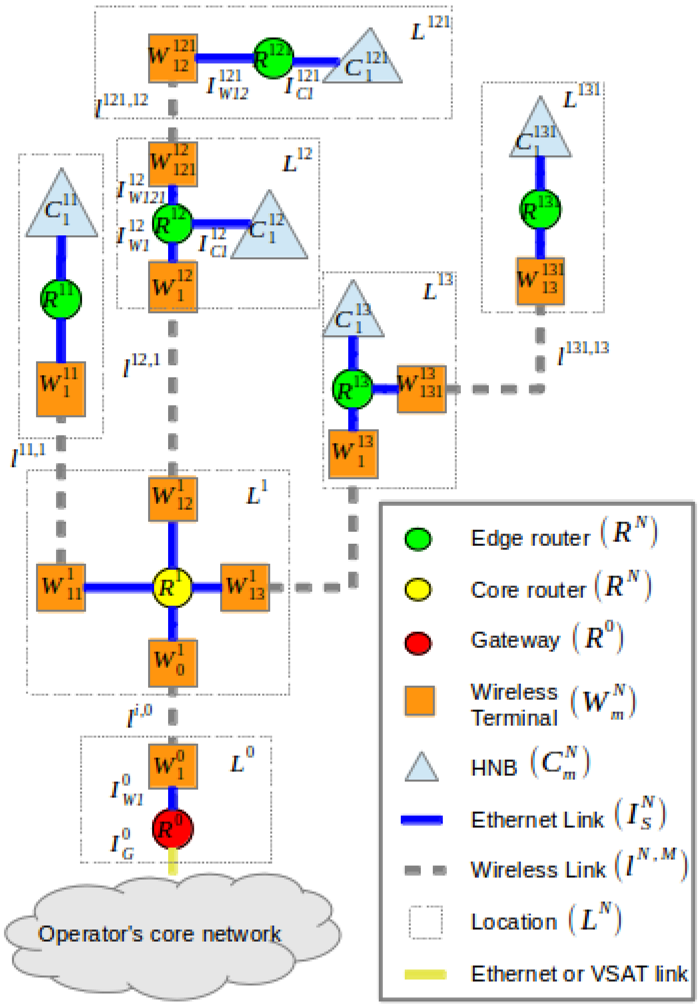



**Figure 7: Example of the general high-level transport network architecture for multi-hop backhaul.**

The following rules must be followed in the network planning phase:

– Limited end-to-end delay. Consider an arbitrary cell $C_i^k$ in location $L^k$. Let's call $D_{Ci}^k$ the expected maximum delay between the gateway ($R^0$) and the cell $C_i^k$, be $D^k$ the delay introduced in $R^k$ caused by queuing and scheduling, and be $D_l^{k,j}$ the delay introduced by the communication between $W_i^k$ and $W_i^j$ (linked by $l^{k,j}$). If the path between $L^k$ and $R^0$ goes through locations $L^k$, $L^j$, $L^i$, …, $L^a$, $L^0$, then

$$D_{Ci}^k \geq D^k + D_l^{k,j} + D^j + D_l^{j,i} + \ldots + D_l^{a,0} + D^0 \qquad (1)$$

– Enough capacity in every link. Let's call $S^{k,j}$ the expected capacity for link $l^{k,j}$ . Then,

$$S^{k,j} \geq \sum_{\forall x} S^{x,k} \qquad (2)$$

In the previous equation, x indexes all the locations in the network but $S^{x,k}$ only makes sense for x referring to locations that are one hop upstream from k, that is, locations for which k is the relay towards the gateway. For x referencing any other location not matching that condition, $S^{x,k} = 0$. Note that we speak about “expected capacity”. The real capacity for a link must be higher (or equal), but the relationship must be accomplished only with the expected capacity.

– We have already seen that the studied wireless technologies may offer different delays and different capacities depending on the operation conditions. If $S_R^{k,j}(t)$ is the real capacity of link $l^{k,j}$ , and $D_R^{k,j}(t)$ is its real delay, they should satisfy the following conditions at any time: $P\{S_R^{k,j}(t) \geq S^{k,j}\} \geq \chi_s$ , and $P\{D_R^{k,j}(t) \leq D_l^{k,j}\} \geq \chi_d$

$\chi_s$ and $\chi_d$ are design parameters that represent the network availability, that is, the probability of any link offering acceptable values of capacity and delay at any time. If the three conditions can be accomplished with any combination of the studied technologies, the multi-hop transport network is feasible. For the rest of the document, we consider that the studied transport network satisfies these conditions and therefore it is feasible. We will define the interfaces, the interactions and the mechanisms for monitoring and controlling the network.

## *3.5 High-level description of the interfaces and interactions*

The interfaces to be described are the following:

### 3.5.1 HNB to edge router interface ($I_{Cn}^{m}$)

Physically this interface will be supported by an Ethernet cable connecting the HNB to an edge router, as already explained in the previous section. IP packets are exchanged through the interface. IP packets coming from the HNB are source-marked with DSCP, while those addressed to the HNB have been previously classified and marked with DSCP at the gateway router. The maximum expected traffic over this interface $(S_{Cn}^{m})$ is defined in the network planning phase. The corresponding ingress block in $(R^{m})$must colour the traffic, marking each packet internally as needed so that the egress block can use that information for scheduling and traffic shaping.

### 3.5.2 Router (gateway, core or edge) to wireless terminal interface ($I_{Wk}^{m}$)

The wireless link may be VSAT, WiFi, WiFi-based TDMA or WiMAX. In principle, point-to-point links will always be used unless it is absolutely clear that a point-to-multipoint link is advantageous in a very specific scenario. In those cases where one end acts as “master” and the other one as “slave”, the master will always be the system closer to the gateway.
Router $(R^{m})$ and wireless terminal $(W_k^{m})$will be connected with a fast-ethernet or gigabit-ethernet cable as needed. The egress block in the router will ensure that priorities are applied as required in the network, and the traffic is shaped so that the offered load to the wireless terminal is always under the link capacity $S^{m,k}$ . On the other hand, this process might cause long queues and eventually packet dropping. A mechanism to monitor the state of queues must be implemented to prevent HNB from generating more traffic when any router in the path to the gateway is close to a congestion status.

# 4 QUALITY OF SERVICE PROVISIONING IN HETEROGENEOUS BACKHAUL NETWORKS BASED IN VSAT, WILD AND WIMAX

The heterogeneous multi-hop transport network used for backhaul must ensure a minimum quality of service, especially for voice communications and signalling. Hence, this transport network is likely to require a traffic control system that is independent from the technologies used for the different communication links. As already justified, this control must be exercised at the IP layer in order to do an homogeneous end-to-end treatment to the traffic over heterogeneous technologies, and also in order to prevent links from operating in saturation conditions.

In previous sections, different strategies to ensure QoS have been analysed. The proposal described in this section is based on DiffServ, associated with an Admission Control Mechanism.

## 4.1 Use of WiMAX+IP and WiLD-EDCA+IP to provide end-to-end QoS support

On one hand, WiFi-EDCA [IEEE 802.11-2007] presents a QoS prioritization mechanism where, after setting some MAC parameters, MAC frames are classified in up to four access categories (traffic classes) which in turn implies a higher or lower priority accessing the network. The four access categories defined in the standard are: AC_VO (voice), AC_VI (video) AC_BE (best-effort) and AC_BK (background). The parameters that characterize the transmission mode of each category are:

- AIFS (Arbitrary Inter-Frame Space Number): Time interval between the instant when the channel enters the idle state and the beginning of contention window.
- $CW_{min;i}$ (Minimum Contention Window): Upper limit for the number of time slots given to the contention window the first time a frame is going to be transmitted.
- $CW_{max;i}$ (Maximum Contention Window): Maximum upper limit for the number of time slots given to the contention window, no matter how many times the frame has been retransmitted.
- $TXOP_i$ (Broadcast Opportunity): Maximum duration that a station may keep the exclusive access to the channel once the contention has been won.

Then, when a station requires the channel for the transmission of a frame with maximum priority, it is likely to get a low AIFSN, low $CW_{min}$ and low $CW_{max}$, and in some cases it may be required to get a high value of TXOP. The opposite can be said for lower priority frames. Default values for these parameters for the different access categories are given in Table 7.

| AC | CW_min | CW_max | AIFSN | TXOP limit | | |
|---|---|---|---|---|---|---|
| | | | | For PHYs defined in Clause15 and Clause 18 | For PHYs defined in Clause17 and Clause 19 | Other PHys |
| AC_BK | aCWmin | aCWmax | 7 | 0 | 0 | 0 |
| AC_BE | aCWmin | aCWmax | 3 | 0 | 0 | 0 |
| AC_VI | (aCWmin+1)/2 -1 | aCWmin | 2 | 6.016 ms | 3.008 ms | 0 |
| AC_VO | (aCWmin+1)/4 -1 | (aCWmin+1)/2 -1 | 2 | 3.264 ms | 1.504 ms | 0 |

**Table 7: Default EDCA parameters in [IEEE 802.11].**

For the case of WiMAX, the [IEEE 802.16-2009] standard basically defines two different types of elements: the base station (BS) and subscriber stations (SS). The BS is in charge of managing communications and network resources. This standard uses a special mechanism at the MAC layer called Request /Grant to provide QoS support, which performs a deterministic planning to distribute network resources among existing connections.

In this method, each SS keeps requesting the bandwidth required for each connection (Request) and then the BS allocates resources for each SS (Grant) depending on availability and the characteristics of each connection. Then a (Grant) refers to an assignment of one or more slots in the uplink subframe. Meanwhile, the BS manages the downlink, so it allocates the resources on its own as needed.

In order to supply different levels of QoS support, each connection must be associated with a service flow. Considering the different requirements on delay, flow rate, jitter and others, 802.16 defines five types of service (see also Table 13 in the next section):

- Unsolicited Grant Service (UGS): Designed to support data streams in real time (with strict delay requirements), with fixed size data packets, transmitted at regular intervals of time. When a UGS service is assigned to a SS, the BS ensures the defined bandwidth, without requiring a prior request. It is recommended for constant-bit-rate flows such as VoIP without silence suppression
- Real-Time Polling Service (rtPS): Designed to support data streams in real time (with less stringent delay requirements, compared with the previous) that generate variable-length packets transmitted periodically. In this case, the SS has a slot reserved for bandwidth request, specifying the desired size for the transmission interval. Such services are dynamic in nature, such as MPEG (Moving Pictures Experts Group) video or VoIP with silence suppression.
- Extended Real-Time Polling Service (ertPS) is a planning service that is based on the advantages of UGS and rtPS. In this case, the BS can allocate bandwidth to a SS without request, as in UGS, but in contrast with UGS, in ertPS the allocation can be variable-sized (upon request from the station) while UGS is fixed-sized. This service is designed to support service flows that generate real-time variable-sized packets in a periodic form, such as VoIP with silence suppression. The type of ertPS service is optional and therefore is not implemented in all systems.
- Non-Real-Time Polling Service (nrtPS): Designed for service flows which are not real-time, generating bursts of variable-sized data packets, such as FTP (File Transport Protocol) flows. Typically, the services carried in these connections are tolerant to longer delays and are practically insensitive to jitter.
- Best Effort (BE): Designed for data streams that do not require a minimum service level and can be transmitted when there is available bandwidth, these flows do not provide any guarantees that if the data are delivered. For example, the HTTP communication.

Hence, for a good QoS support in WiMAX, it is essential to identify the different traffic flows that must be differentiated and do a proper planning about resource consumption. An accurate configuration of equipments according to this will permit to get the expected QoS.

### 4.1.1 Expected QoS and limitations

As already mentioned, both WiMAX and WiFi-EDCA have a method for providing some QoS support, provided that they always operate below their maximum capacity. However, they differ substantially in the treatment they give to differentiated packets. NV2 is still a quite different solution in terms of QoS support, because the traffic differentiation seems to be supported only at the IP layer. Hence, it is not straight-forward to obtain a reasonable end-to-end behaviour in a heterogeneous environment that incorporates different technologies.

Hence, the integration of WiFi and WiMAX links within the same network presents a challenge from a functional perspective. At a first glance, it is necessary to specify how to map different traffic classes between access categories in WiFi and the services flows in WiMAX. This specification must include the classification mechanism. Beyond this, it is clear the necessity of monitoring the network and implementing an access control method which ensures that data flows admitted by the network will have all the required resources.

Finally, after making a proper planning of the network, it must be able to fulfil at least the minimum QoS requirements established by the ITU (International Telecommunication Union). Table 8 shows the services classification established by the ITU. Table 9 shows the recommendation on the QoS parameters for such services. The backhaul is not the only segment contributing to delay and jitter, or limiting the throughput. Therefore, for the rest of the document it will be admitted that the end-to-end capacity must be enough permanently in normal conditions, and the end-to-end delay and jitter may achieve up to 50% of the values agreed by ITU for the different services, letting other segments contribute with the other 50%.

| ITU Classes | Applications features | Examples of Applications |
|---|---|---|
| 0 | Real time, jitter sensitive, bit rate variable and constant | VoIP, multimedia, tele or videoconference |
| 1 | Real time, jitter sensitive, interactive, variable and constant bit rate | |
| 2 | Transactional data, signaling, highly interactive | Signaling, transactional |
| 3 | Transactional data, interactive | Transactional |
| 4 | Sensitive to losses, short transactions, bulk data, continues flow, variable bit rate | Audio/video streaming |
| 5 | Traditional applications in IP networks | Web navigation, internet traffic |
| | | e-mail and ftp transfers |

**Table 8: Service types defined by the ITU [Y1541].**

| Network performance parameters | QoS Classes | | | | | |
|---|---|---|---|---|---|---|
| | Class 0 | Class 1 | Class 2 | Class 3 | Class 4 | Class 5 Unspecified |
| **Mean delay** | 100 ms | 400 ms | 100 ms | 1 s | | |
| **Mean jitter** | 50 ms | 50 ms | | | | |

**Table 9: ITU Recommendations for QoS parameters [Y1541].**

### 4.1.2 Interactions and configuration mapping

A heterogeneous network is made up of two or more technologies with different characteristics. Hence, it requires that each technology along the path provides a mapping for the QoS required by a packet being transported. Extending the concept of PHB (per-hop behavior) that DiffServ uses for IP routers to links, each technology needs to provide the means to implement a "per-hop behavior" that satisfies the different QoS requirements.

For this particular case, the technologies that have been considered are 802.16 and 802.11e (and, in some cases, Mikrotik NV2 as a representative of WiFi-based TDMA solutions). Due to the incompatible philosophies for QoS support, the mechanisms for interoperability must be implemented at the IP layer. In consequence, it is suggested that the mechanism of traffic classification used by both architectures is based on the Differentiated Services Code Point (DSCP) as defined in the DS byte [RFC2474] of the IP packet header. DSCP gives the support to create a hierarchy of service priorities for the network traffic. Both routers and wireless communications systems use DSCP marks to adequate their behavior accordingly.

Considering the service types defined in WiMAX [IEEE 802.16-2009], and the access categories in WiFi-EDCA [IEEE 802.11-2007], a maximum of four types of network traffic can be differentiated in both cases: VoIP, Video, Data and Signaling. Hence, we need to do a triple mapping between DSCP, EDCA and WIMAX service flows. The case of NV2 is implicitly included because it does the traffic differentiation at the IP layer, and DSCP is one of the supported mechanisms for traffic classification.

The traffic mapping proposed in [Mendiola11] fulfills this project's requirements and is shown in Table 10:

| DS field | DSCP Values | DSCP Classes | EDCA Access Category |
|---|---|---|---|
| 0b00000000 / 0x00 | 000000 / 0x00 | Default | AC_BE |
| 0b00001000 / 0x08 | 000010 / 0x02 | CS1 | AC_BK |
| 0b00100000 / 0x20 | 001000 / 0x08 | CS1 | |
| 0b00101000 / 0x28 | 001010 / 0x0A | AF11 | AC_VI |
| 0b10100000 / 0xA0 | 101000 / 0x28 | CS5 | |
| 0b11000000 / 0x30 | 110000 / 0x30 | AF11 | AC_VO |
| 0b10001000 / 0x88 | 100010 / 0x22 | AF41 | |
| 0b10111000 / 0xB8 | 101110 / 0x2E | EF | |
| 0b11100000 / 0xE0 | 111000 / 0x38 | CS7 | |

**Table 10: Mapping TOS codes to EDCA access categories [Mendiola11].**

Finally, Table 11 shows the mapping with WiMAX.

| DSCP Class | EDCA AC | WiFi Parameters | WiMAX Class | WiMAX Parameters | Examples |
|---|---|---|---|---|---|
| BE | AC_BE | Peak Data Rate, User Priority | BE | Maximum Sustained Traffic Rate, Traffic Priority | Internet traffic, HTTP |
| CS1 | AC_BK | Minimum Data Rate, Peak Data Rate, User Priority, Burst Size | NrtPS | Minimum Reserves Traffic Rate, Maximum Sustained Traffic Rate, Traffic Priority, Maximum Traffic Burst | FTP |
| CS5 | AC_VI | Minimum Data Rate, Peak Data Rate, Delay Bound, Burst Size | RtPS | Minimum Reserves Traffic Rate, Maximum Sustained Traffic Rate, Maximum Latency, Maximum Traffic Burst | MPEG, VoIP with Silent Suppression (VBR Traffic) |
| EF | AC_VO | Peak Data Rate, Delay Bound, (Calculated Jitter) | UGS | Maximum Sustained Traffic Rate, Maximum Latency, Tolerated Jitter | VoIP without Silent suppression (CBR Traffic) |

**Table 11: Proposed traffic mapping between WiFi and WiMAX [Mendiola11].**

### 4.1.3 Other considerations for end-to-end QoS provisioning

The following tasks generate a traffic overload that impacts the QoS support and must be taken into account:

a) Measuring/monitoring traffic.
b) Monitoring nodes' states.
c) Exchanging specific information required by access control mechanisms.

The CPU capacity required in IP Routers to provide the advanced tasks proposed in this document must be estimated carefully and taken into account for device selection.

The procedures and algorithms required for each node in the network to support QoS must be defined in the next deliverable D52.

The communication protocol used to collect the traffic information from all network nodes needs to be defined. One option to consider here is SNMP, but others may be studied.

The specific requirements of each traffic class (i.e. telephony) in terms of throughput, delay and jitter need to be considered at the network planning phase and the designed mechanisms must be enough to guarantee those requirements.

### *4.2 Other solutions to provide QoS support*

As mentioned in Chapter 2, there are approaches which propose add a new MPLS layer between IP and MAC layers in order to improve the QoS support in heterogeneous wireless backhaul networks. Although a complex mechanism of traffic engineering is required, the use of MPLS DiffServ [RFC3270] gives some additional advantages comparing when using only DiffServ mechanisms. Some of them are:

- Circuit switching is emulated by using a flow-oriented mechanism for packet switching. Traffic Trunks (TT) can be created on demand and can be managed dynamically. This gives a more deterministic and stricter control over the network resources.
- Independence of OSI layers 2 and 3 gives a homogenizer view to heterogeneous networks.
- Additional routing mechanism based on labels. This way, routes are not only defined by IP protocol issues but also by QoS criteria.

The implementation of MPLS in a backhaul network structured as explained in this document is feasible by building an MPLS domain that coincides with the whole backhaul network and that exchanges plain-IP packets between edge nodes and HNB and between the gateway and the operator's core network. The architecture is represented in Figure 8, where links between nodes symbolize wireless links based in WiFi/WiLD/WiMAX technologies.

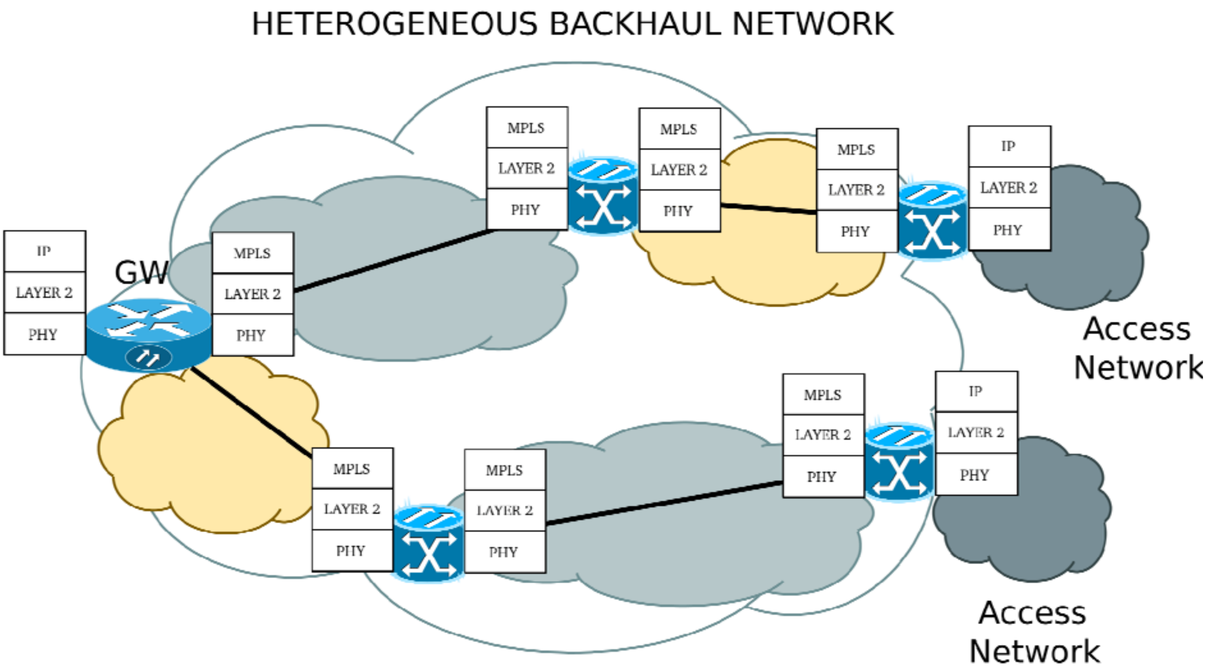



**Figure 8: MPLS implementation in a heterogeneous backhaul network when using only MPLS to provide QoS support.**

Hence, MPLS is used as OSI layer 3, together with DiffServ techniques in the edge routers, which are responsible for proper mapping between IP and MPLS.

In the State of the Art analysed in Chapter 2.1, several works mentioned the importance of use DiffServ independently of other mechanisms of QoS like EDCA [Simo12] or MPLS [Oubaha08]. This is because MPLS does not define new QoS architectures, but uses the DiffServ architecture. Hence, the use of DiffServ jointly with MPLS and the other QoS mechanisms in OSI layer 2 seems to be the configuration which better fits in our scenario.

As seen in Chapter 4.1, a special configuration is needed to adapt IP to different OSI 2 layers in order to achieve an end-to-end QoS support. When MPLS and DiffServ are used in the backhaul network, these configurations must be extended also to layer 3.

Since DSCP field is not directly visible to MPLS routers, IP DiffServ information must be made visible using the EXP and Label field in the MPLS header. Hence, edge routers and the gateway must classify packets coming from outside the MPLS domain by using DSCP, and then those nodes must map the DSCP into the MPLS EXP and Label fields, according to the Forwarding Equivalent Classes (FEC). There are two ways to do that. multiple Behaviour Aggregates (BA) can be mapped to single LSP, or a single Behaviour Aggregate is mapped to single LSP. In the first method, the EXP field in MPLS is used to specify a Per Hop Behaviour (PHB) and it is called EXP-Inferred-PSC LSP (E-LSP). In the latter, a single BA is mapped to a single LSP and its called Label-Only-Inferred-PSC LSP (L-LSP).

The process of mapping the DSCP value to the EXP is related as follows in Table 12:

| | DSCP Value (6 bits) | EXP Value |
|---|---|---|
| Expedited Forwarding | 101110 | 101 |
| Assured Forwarding 1 | 001010 / 001100 / 001110 | 001 |
| Assured Forwarding 2 | 010010 / 010100 / 010110 | 010 |
| Assured Forwarding 3 | 011010 / 011100 / 011110 | 011 |
| Assured Forwarding 4 | 100010 / 100100 / 100110 | 100 |
| Best Effort | 000000 | 000 |

**Table 12: IP DiffServ - MPLS DiffServ mapping.**

E-LSP can support up to 8 PHB. A higher number of PHB requires that EXP field and Label field are used together. In E-LSP, all packets take the same explicit path, with a different priority treatment. In L-LSP, separate LSP can be established for each traffic class. There are several protocols that can be used to establish LSPs. The most important one is Label Distribution Protocol (LDP), which supports the establishment of LSPs through some QoS criteria using Constraint-based LSP (CR-LSP). The traffic characteristics of a path are described in the traffic parameters TLV of distributed messages, in terms of peak rate, committed rate, and service granularity. Other protocols can be used such as RSVP-TE which provides an IntServ-like functionality. Once the path is established, the backhaul routers (Label Switching Routers or LSR) will manage the traffic according DiffServ MPLS-based mechanisms, without using IP. But this DiffServ must be translated to OSI layer 2 through mechanisms that will vary according the specific wireless technology.

For WiFi, the only known practical way to support some QoS is using EDCA since no real implementation of HCCA have been found up to date. For this reason each LSP will be mapped in different Access Categories (ACs). Since only 4 ACs are defined, for WiFi networks, only using E-

LSP would be sufficient to map each FEC AC combination. EDCA cannot provide strict guarantees for QoS parameters. An additional analysis must be made in the future to dig more into this topic.

WiMAX defines four types of service flows, each one with different QoS requirement. MPLS QoS parameters must be mapped to these types of service flows to support the WiMAX QoS. This association are listed in Table 13:

| WiMAX Service flow | Paramteres | CR-LDP Parameters |
|---|---|---|
| UGS | Maximum Sustained Traf. Rate | PDR and PBS |
| | Maximum Latency | Frequency |
| | Tolerated Jitter | Frequency |
| | Minimum Reserved Traf. Rate | CDR and CBS |
| rtPS | Maximum Sustained Traf. Rate | PDR and PBS |
| | Maximum Latency | Frequency |
| | Minimum Reserved Traf. Rate | CDR and CBS |
| nrtPS | Minimum Reserved Traf. Rate | CDR and CBS |
| | Maximum Sustained Traf. Rate | PDR and PBS |
| | Traffic Priority | Used for Queue Priority |
| BE | Maximum Sustained Traf. Rate | PDR and PBS |
| | Traffic Priority | Used for Queue Priority |

**Table 13: WiMAX service flows - MPLS DiffServ mapping. Where: PDR=Peak Data Rate, PBS=Peak Burst Size, CDR=Committed Data Rate, CBS=Committed Burst Size, Frequency=8 bit integer code with the values of 0 (Unspecified), 1 (Frequent), 2 (Very Frequent) and 3-255 (Reserved). The frequency field is used for delay and jitter specification in terms of rate availability regarding the CDR during measurements in specific time intervals.**

Finally, this analysis could be extended in a similar way for NV2. Although it is a proprietary solution, it is known that TDMA techniques are used at layer 2 and IP is used at layer 3, with DSCP differentiation and prioritization available as needed. So, theoretically there would be no problem in mapping the MPLS QoS parameters to the specific NV2 QoS implementation if the previous mapping between DSCP and MPLS has been consistent.

Since the general description of the solution for the wireless backhaul network has not been defined yet, further studies must be made in order to analyse the effects of MPLS in this kind of networks and also if MPLS is a proper alternative to implement them. Especially, the study about the possibility of using MPLS over VSAT technologies will determine whether MPLS can be used as a homogenizer solution for heterogeneous wireless backhaul networks.

# 5 INTERFACE DESCRIPTION BETWEEN THE ACCESS NETWORK AND THE HETEROGENEOUS BACKHAUL NETWORK

This section discusses the design of the interface between the access network (AN) and the backhaul (BH). Since both networks are investigated in different work packages (WP4 for the AN and WP5 for the BH), the interface is closely related with the work developed in both milestones M43 and M52, which contain sections dealing with this issue. Therefore, this section has some contents that overlap with those in Section 5.2 of M43.

## *5.1 Interface overview: elements and procedures involved*

### 5.1.1 Introduction

The state of the backhaul has a great impact in the overall network performance. Traditionally, 3GPP Home NodeB's (HNB) are connected to the HNB Gateway (HNB-GW) in the core network through an ADSL (or similar) link, which usually provides a reliable connection with enough bandwidth for preserving QoS requirements. Hence, no explicit interactions between the access network (AN) and the backhaul network are needed, and typical femtocells are designed to be independent of the backhaul. However, in TUCAN3G scenario a heterogeneous wireless network is considered, and bandwidth over-provisioning cannot be *a priori* assumed. Therefore, a certain degree of interaction between AN and BH is necessary, which is enabled by the AN-BH interface (ABI).

According to the inputs provided by WP4, at least three types of interactions are needed in the ABI in order to provide end-to-end QoS. First, BH should be able to preserve UMTS-QoS requirements for data exchanged between the HNB and the core network. Mechanisms to request the appropriate QoS services and techniques to provide them are explored in Section 5.2. Second, algorithms for packet scheduling and admission control in the AN shall take into account BH conditions. The information needed to characterize the BH state are investigated in WP4 and described in M43. The mechanisms to collect this information are analysed in Section 5.3. Third, the joint optimization of the AN and BH would require a procedure for transferring additional information from the AN to the BH. This will be briefly discussed in Section 5.4.

In order to implement an interface that enables these interactions, a formal interface based on a simple protocol that is able to transmit simple messages (like service primitives) will be described. This formal interface will include requests, responses, confirmations and control commands, and will detail exchanged information. This is discussed in Section 5.5.

### 5.1.2 Architecture and standardization

The overall network architecture is shown in Figure 9, where the interfaces between the AN and the BH are highlighted. Two key elements in the interface between both networks are the edge routers and the gateway router, which shall be placed back-to-back with HNB and the HNB-GW respectively. In practice, the ABI will be implemented between each HNB and its corresponding edge router, and between the HNB-GW and its corresponding edge router (referred to as gateway router in previous sections).

Several technical specifications of the 3GPP are involved in the task of defining the ABI. The end-to-end link between the HNB and the core network that is represented in Figure 9 corresponds to the Iuh interface defined in [TS25467]. The Security Gateway is assumed to be co-located with the HNB-GW, and packets in the ABI are assumed to fulfil 3GPP security requirements, including the encapsulation with IPSec [TS33320]. The structure of the transport layers in the Iuh (based on ATM or IP) is defined in [TS25444]. Finally, the end-to-end QoS architecture for UMTS networks is described in [TS23207]. A brief discussion on the solutions provided in this technical specification is given in milestone M43.

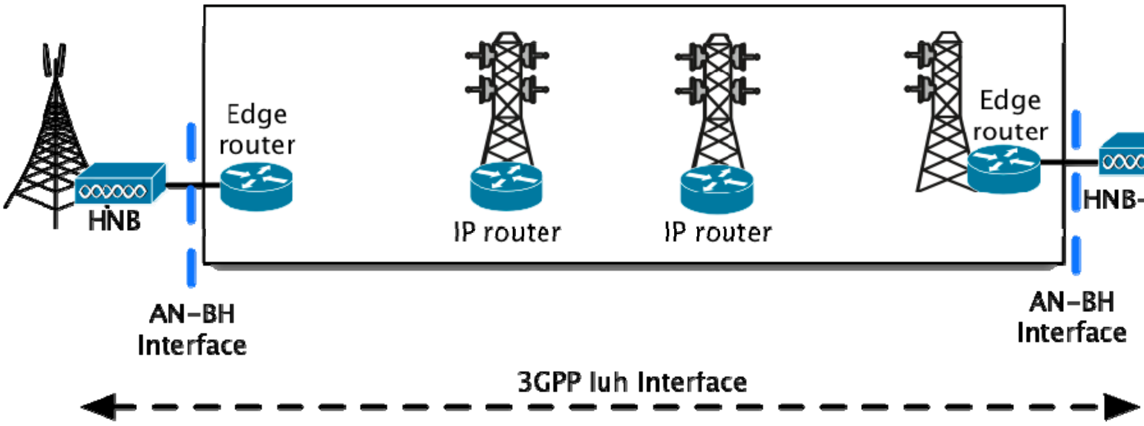



**Figure 9: Network architecture.**

#### 5.1.3 Scope and limitations of the analysed solutions

The HNB that will be considered in this project are likely to have two limitations: (i) no capability for exchanging non-standard information with a non-3GPP device, and (ii) very limited storing and processing capabilities. These constraints deeply influence the design of the ABI. Regarding the first limitation, if the BH collaborates with the AN in the task of collecting BH-state information, an information exchanging mechanism must be implemented in the HNB and the edge router.

Furthermore, in this task two different solutions will be investigated for each interaction: a general theoretical solution that would provide the best performance in each case, and a limited practical solution that can be implemented considering the actual limitations of the HNB and the rest of the hardware used in TUCAN3G WP6.

Finally, normal functioning of 3GPP signalling procedures imposes certain constraints to the ABI design. For example, if the admission control procedure needs to request BH-state information to the edge-router, a very stringent upper bound on the response time is needed. Hence, the AN requirements for the interface shall also be identified and considered in its design.

### *5.2 QoS mechanisms to request/provide QoS to/from the BH*

According to deliverable D41 [TUCAN3G-D41], the BH must support at least three types of QoS, corresponding to three traffic classes: control, voice and data traffic. More QoS types may be supported if specified in WP4. Each QoS class requires a different QoS level, mainly defined by rate, delay and jitter parameters, and some of them have strict QoS requirements. Both QoS types and parameters have to be defined by WP4 so that the BH is able to manage the traffic flows properly. In D41, the requested bandwidth for each type of service has already been identified.

For the backhaul to be able to guarantee the appropriate QoS for each service, several strategies can be considered, namely: Integrated Services (IntServ) based on Resource Reservation Protocol (RSVP) [RFC2205][RFC2210] and its evolution NSIS Signalling Layer Protocol for QoS Signalling [RFC5974], Differentiated Services (DiffServ) based on DSCP (Differentiated Services Code Point) marking [RFC2474], and DiffServ with Multiprotocol Label Switching (MPLS) [RFC3031].

1) IntServ. The main idea behind IntServ is to provide quantitative QoS services based on a resource reservation procedure that precedes the connection establishment. For the resource reservation procedure several protocols are available. The best known is RSVP, which provides signaling to request and confirm a set of QoS parameters (called *flowspec*) for an individual traffic flow. Each node in the path must accept or reject the data flow based on the

QoS parameters specified in the *flowspec*. Once a flow is accepted, each node reserves resources for it, and uses a specific filter (called *filterspec*) to identify the packets belonging to the flow. The main advantage of this alternative is that it allows guaranteeing a quantitative QoS level and providing a simple admission control mechanism. Indeed, [TS23207] proposes to use RSVP combined with DSCP to deal with non-3GPP transport networks. However, RSVP has a critical drawback since most wireless devices do not support it.

2) DiffServ. It is a network architecture that provides mechanisms for classifying data flows and for providing different QoS levels to them. Packets are marked using the DS field in the IP header, which contains the 6-bit DSCP value. Several classes of QoS behaviors and types of dropping priorities are defined using those 6 bits. The per-hop behaviors are: default (typically best effort), expedited forwarding (for low-loss, low-latency traffic), assured forwarding (provides assurance of delivery if the traffic does not exceed the negotiated rate) and class selector (for backward compatibility). All together, the different QoS classes enable a way of differentiating different types of traffic in terms of priority and packet dropping probabilities. Hence, it does not support quantitative QoS services.

3) MPLS. It is a mechanism for providing virtual links between end-point nodes that avoids the need of routing in the network layer. Virtual flows are identified with a label. Each packet with a particular label will have a predefined path to the destination, so long routing tables are no longer necessary for packet routing. Moreover, each flow can be associated with a particular QoS set of parameters. Labels are distributed across the network using the Label Distribution Protocol (LDP) [RFC3036].

In the next deliverable D52, the feasibility of the three alternatives will be evaluated.

## 5.3 BH state information collection

### 5.3.1 AN algorithms' requirements

The algorithms for BH aware admission control and packet scheduling require knowing the conditions of the BH. The required information has to be defined, and may include available rate, current delay and jitter, congestion level, status of the BH nodes' batteries and the network topology. This information may be required to be collected with a different frequency and accuracy, for individual links or for end-to-end path, and part of the information may be flow dependant or aggregated. Therefore, a detailed characterization of the information needed by the AN procedures will be completed in WP4. M43 discusses this issue.

3GPP signalling procedures impose certain constraints to the ABI design. For example, if the admission control procedure needs to request instantaneous BH-state information from the backhaul, a very stringent upper bound on the response time is needed. Due to HNB processing limitations, computational complexity of the proposed algorithms may also have an impact on the ABI. Then, it is necessary to characterize the requirements for each procedure. This is explained in M43 and will be carried out in WP4.

### 5.3.2 Information collection methods

The AN algorithm requirements mentioned in the previous section will have an impact on the design of the interface and the procedure to collect the information. In addition, the HNB limitations must be considered in that design. In milestone M43, three methods are considered for obtaining the BH state information.

1) Non-collaborative methods: the AN collects the state information without the participation of the BH. Two techniques are proposed: one based in the information provided by 3GPP procedures and the ratio of dropped packets, and the other one based on the information provided by Real Time Control Protocol (RTCP). These methods are discussed in M43.

2) Collaborative methods: the BH must collect state information and pass it to the AN through the ABI. Three steps are needed: (1) the information must be obtained in each node (and some information directly on the edge routers); (2) the information must be centralized and aggregated in an external agent; and (3) the information must be passed to the AN. In M43 two options for step (3) are discussed. The first two steps of this procedure are discussed later in this section.

3) Hybrid methods: with methods based on IntServ architecture, a small amount of information can be collected. A typical example of this is a HNB using RSVP to figure out if there exists enough bandwidth in the BH for a connection.

#### *5.3.2.1 BH state monitoring*

In order to measure the BH state, two non-exclusive approaches can be considered: end-to-end measurements and node-by-node measurements.

In the first case, end-to-end parameters can be acquired, like total delay and jitter in the BH, end-to-end congestion level and available bandwidth. These measurements would be performed by the edge routers, and several alternatives can be used:

1) Of-the-self measurement software. There exist several software tools to measure the performance of a network based on traffic injection, the most typical being D-ITG [Botta12] or Iperf [Tirumala]. With these tools bandwidth is easily measured, and delay can be obtained even if end nodes are synchronized (for example, with Network Time Protocol). The main drawback is that the amount of traffic needed is too high. Since these measurements need to be taken frequently these options could produce congestion in the network. Alternately, passive software tools that only monitor the traffic may also be used in every node.

2) Ad-hoc measurement software. In [Rattaro10] a procedure for measuring a network state is designed that do not require high bandwidth consumption. Both congestion state and end-to-end delay are obtained.

3) Explicit Congestion Notification (ECN). ECN is defined in [RFC3168] and allows end-to-end congestion notification without the need of dropping packets. If both edge-routers are configured to support it, it provides reliable congestion measurements.

4) Rate and queue length measurements. In the edge-routers specific software can be developed to measure transmitted rate in any interface and the length of the queues.

In the second case, node-by-node measurements provide detailed local information that must be subsequently collected and aggregated. In each node, the delay, jitter and congestion state can be measured per traffic class. Additionally, other information like the battery level can be collected for optimization purposes. The alternatives described for end-to-end measurements can also be applied here.

Finally, specific software should be used for topology discovery. The IEEE protocol LLDP (Link Layer Discovery Protocol) and its Linux implementation (OpenLLDP) can be used for this purpose. In addition, standard management tools based on SNMP (Single Network Management Protocol) are available.

These alternatives will be qualitatively evaluated according to their limitations and benefits. Some of them will be tested in the laboratory.

#### *5.3.2.2 Information collection and aggregation*

The second step of the information collection process is transferring the state information of each node to a centralized node. The IETF defines de entity Bandwidth Broker (BB) [RFC2638] as an element that has knowledge about the network state and is able to take decisions on resources allocation. BBs have several key functionalities, like admission control. For the BH state information collection this entity can be useful since (1) a BB needs knowledge about the network state; (2) BB architecture can consider several transit-domain; and (3) access network may require support from the BB to make admission control decisions.

In Section 2.2 of this document, different architectures based on BB are mentioned. Specifically, a centralized or distributed BB architecture may be designed, which respectively consist of one central BB having the whole state information, or a group of BB, each one having partial state information. For TUCAN3G project, both alternatives are possible: a central BB placed in a strategic point, or a group of BB, each one placed in each edge router. However, the last alternative presents one important advantage, since once the information is in the edge router, passing it to access network is faster and do not consume wireless resources.

Several alternatives are available to transfer the measured information to the BB. The IETF standardized protocol IPFIX (Internet Protocol Flow Information Export) provides a way to export network measurements from individual metering nodes to one or more collectors [RFC3917]. Furthermore, tools based on SNMP allow supervising the network load. Simple agents may be embedded in all IP routers in order to acquire and forward state information regularly.

Finally, a procedure to aggregate the information from the nodes of a specific path must be defined for each parameter. For example, the delay will be the addition of all the delays in the path, but the throughput can be computed as the minimum throughput of all the hops.

These alternatives will be evaluated according to the available scientific literature and their suitability for the project. When possible, those alternatives that are suitable will be benchmarked in the laboratory.

### *5.4 Support for AN-BH joint optimization*

One of the tasks in WP4 addresses the problem of the joint optimization of AN and BH networks. Not only the state of the BH affects the decisions of the AN, but also the contrary may be true. For example, if very few connections are established by the AN in a particular HNB, the nodes connecting only that HNB may reduce their output power and switch to a slower modulation and codification scheme. If the joint optimization algorithm is run by the AN, any decision affecting the BH shall be transmitted through the ABI. For this purpose, a set of configuration commands and parameters should be considered in the ABI design. Then, the edge routers can retransmit the configuration changes to the intermediate nodes using standard SNMP commands.

The control commands, their parameters, and the specific communication method will be designed according to the requirements defined by WP4, and only if necessary.

### 5.5 Formal definition of the interface

A simple communication protocol will be defined to implement the ABI. This protocol will define a standard frame to send commands between the HNB and the edge router. This frame will accommodate a set of primitives and commands in both directions. The set of primitives needs to be defined in this task, but in general, it will contain the following types of messages:

- Requests: if the AN needs information about the BH state, it will send a request including the required information. The message may also include a parameter to define the request. As an example, the admission control mechanism can request information about the availability of certain amount of throughput, with a request like this: *REQUEST_AVAILABLE_BW(REQ_RATE, PATH, ID).*

- Indications: in order to provide a response for a request, an indication command can be used. In the previous example, the answer for the request could be a simple accept or deny: *INDICATION(RESPONSE, ID)*.

- Confirms: in order to confirm packets, an ACK frame would be added. In order to confirm a control command, a CONFIRM message may be used.

- Control commands: in order to set a configuration parameter in the BH, the AN may use a control command. As an example, the joint optimization algorithm may conclude that the transmit power in the BH nodes can be reduced. This could be transmitted to the AN with a message like: *SET(PATH, PARAMETER, VALUE, ID)*, where *PARAMETER* would be set to *TX_POWER* and *VALUE* to a power value in dBm.

**¡Error! No se encuentra el origen de la referencia.**10 shows three examples of the interactions in the ABI. Note that the exact message types and their fields are not defined yet, and that these figures are only examples. **¡Error! No se encuentra el origen de la referencia.**(a) represents a request from the AN to figure out if there is enough available bandwidth for a connection of 100 Kbps to destination node 10.10.1.1. The messages of these exchanges are identified with an ID field containing a "1". Since there is enough bandwidth in the BH, the response is an accept messages. **¡Error! No se encuentra el origen de la referencia.**(b) shows an example of a request from the AN to know the end-to-end delay from the HNB to the node 10.10.1.1. The response indicates the value of the delay. In **¡Error! No se encuentra el origen de la referencia.**(c) the AN sends a SET message to nodes in path 10.10.1.1 to reduce their transmit power.

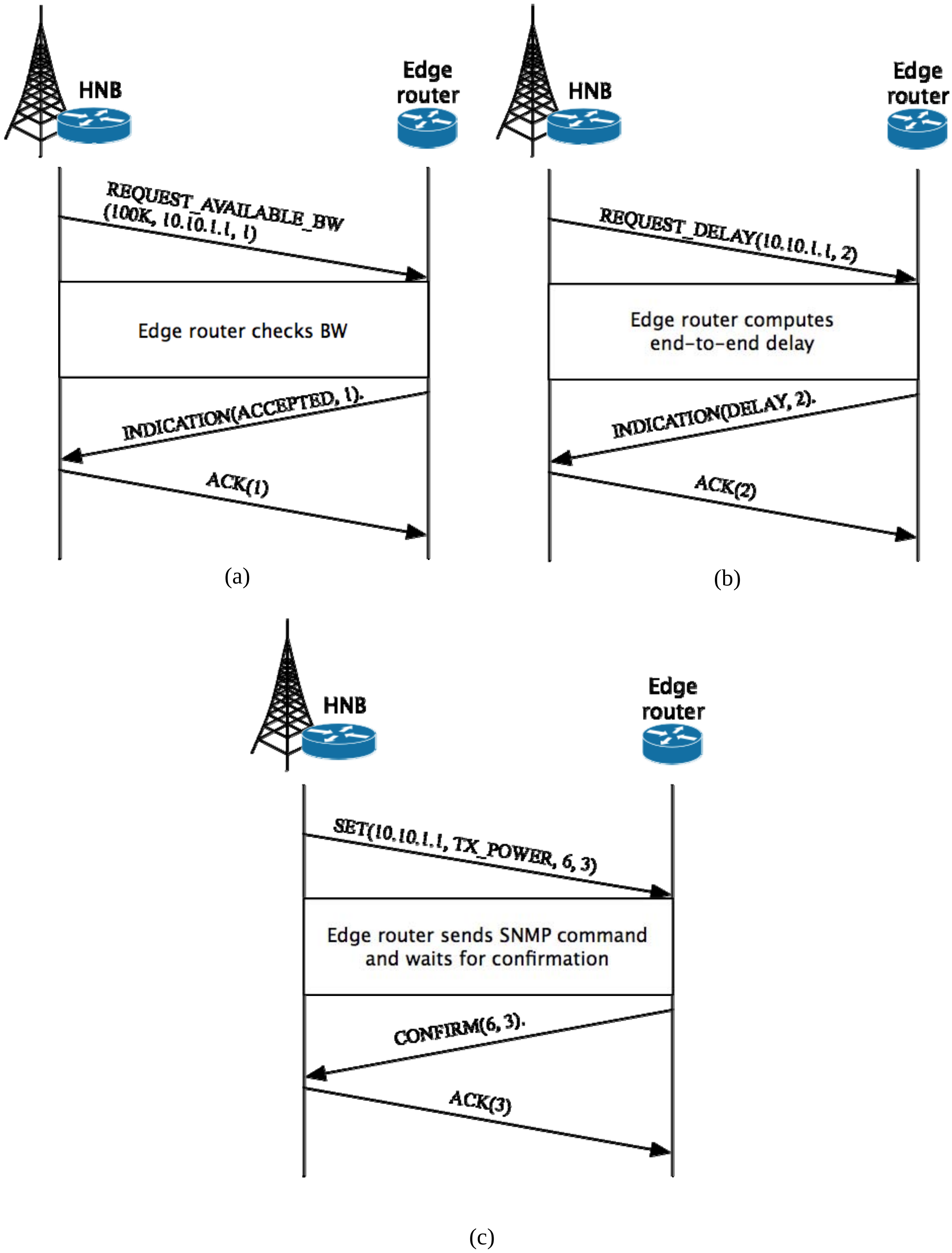



**Figure 10: Examples of the message exchanging in the ABI: (a) an available bandwidth request, (b) a delay request and (c) a control command to set the transmit power.**

# 6 VSAT ROLE IN THE OPTIMIZATION OF THE QOS THROUGH THE ACCESS NETWORK AND THE HETEROGENEOUS BACKHAUL NETWORK

## *6.1 Gateway role description*

The objective of the satellite links in TUCAN3G is to serve as IP Gateway between backhaul network and the operator's core network, mainly where the distance between gateways and operator's network is too long to use another type to wireless connectivity.

Satellite link will be the last hop between the group of other wireless hops that compose the Backhaul Network, linking it to the Operator's Core Network, as illustrated in Figure 11.

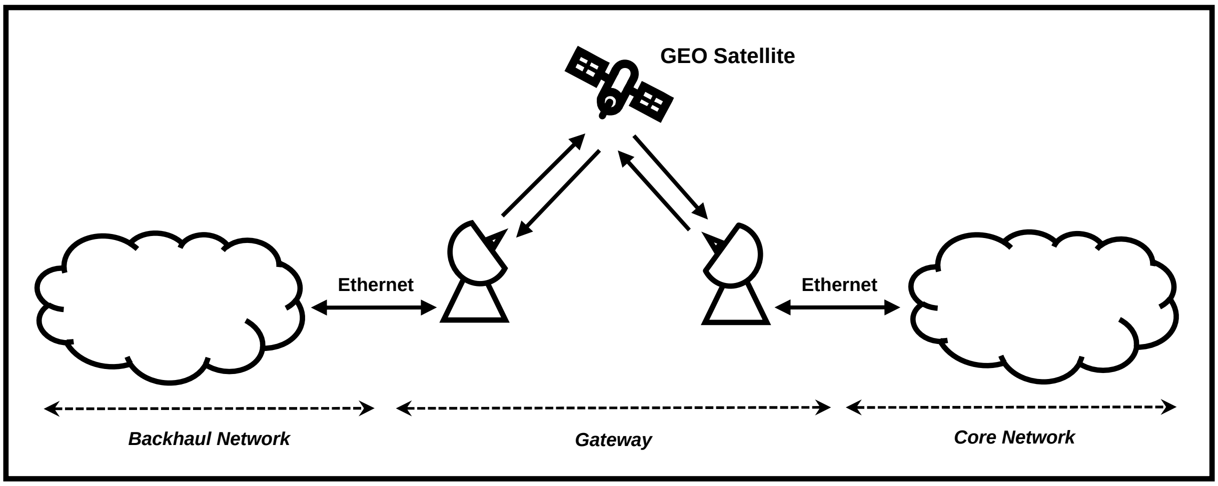



**Figure 11: Typical situation of a satellite link in the backhaul architecture.**

From its own point of view, the satellite link will have to carry Iuh traffic (signalling, voice and data) between several Home Node-B (HNB) distributed on the Backhaul Network and one Home Node-B Gateway (HNB-GW) located in the Core Network.

In addition to Iuh traffic, it is expected to be also "management" traffic for the monitoring and control of the end-to-end system itself.

Due to the different traffic types, sources and destinations, proper QoS need to be provided by the satellite link, in coordination with the other elements of the end-to-end network. On section **¡Error! No se encuentra el origen de la referencia.** the possibilities of providing proper QoS within the satellite link are presented and analysed.

The satellite link, as indicated on **¡Error! No se encuentra el origen de la referencia.**, will be by default a point-to-point SCPC. SCPC, in comparison with TDMA alternative, can provide minimum, stable and predictable delay, as well as guaranteed throughput.

Satellite link will be based on satellite modems with 100Base-Tx Ethernet interface and IP processing/routing capabilities. Satellite modems on both ends of the satellite link will have the same functionalities and are expected to be identical in terms of hardware manufacturer (make and model), to assure proper working.

Main differentiation of the Backhaul-side vs the Core-side of the satellite link will be the available bandwidth on each way, as the SCPC satellite link is composed on the satellite spectrum on two different carriers, and then it be can be configured to be asymmetrical. This has to be taken into consideration when sizing the satellite link, to minimize and optimize the bandwidth use.

### *6.2 Interface with the backhaul and with the core network*

Interfaces with backhaul and core networks can be analysed as a single one, since the satellite modems need to be equal on both sides of the link, and must provide the same functionalities.

Satellite modem interface will be a 100Base-Tx Ethernet interface. Depending on the selection of manufacturer (mark and model), there are different functionalities that the modems can provide and be used to optimize QoS for traffic carried by the satellite link:

- Bridge vs Router
- Traffic prioritization and QoS
- Encapsulation and compression
- Link occupation and traffic congestion

As the satellite link will be based on SCPC architecture, delay and jitter are predictable and can be considered equal to all traffic types. In addition, available bandwidth will be fixed and maximum capacity of the link will be known in advance.

Application of available QoS techniques must be focused on prioritization of different traffic types according to available bandwidth.

**Bridge vs Router**

First differentiation that must be done when designing the IP satellite link is regarding the so called “working mode” of the Ethernet/IP layer of the modems. Most of the manufacturers provide at least two different possibilities:

- Bridge Mode: Satellite link works as an L2 Ethernet bridge between the Ethernet ports of the two satellite modems. There is no need to configure routing, and traffic types other than IP are also supported. As disadvantages, IP addresses of Ethernet ports of both modems must be on the same subnet, and under the combination of some configurations and manufacturers, the overhead traffic is increased and so the link losses efficiency. However, although this mode is easier to be configured, it is not recommended if traffic control and proper QoS need to be provided.

- Router Mode: Satellite link works as an IP Router, where each satellite modem can be considered as a router with two interfaces: the Ethernet port and the satellite port. Basic routing possibilities are present, like static routing configuration and RIP compatibility. Also, additional functionalities like traffic prioritization that sometimes are not available when working on basic bridge mode, are also possible with router mode. This is the recommended mode for advanced and complex configurations.

**Traffic prioritization and QoS**

Most of the SCPC IP satellite modems provide traffic prioritization and QoS, with some possibilities:

- Simple packet prioritization according to IP protocol or source/destination address/port.
- QoS Rules based on priority and maximum bandwidth.
- QoS Rules based on minimum-maximum bandwidth without prioritization.
- QoS Rules based on DiffServ.

The most interesting possibility under the scope of the TUCAN3G project is QoS based on DiffServ, as it allows the development of a standard QoS prioritization mechanism compatible with other parts of the end-to-end network.

Most manufactures provide inside the IP router of the satellite modem a QoS engine that can be fully compliant to the DiffServ standards.

Typically, DiffServ is implemented on satellite modems using exclusively Class Selector DSCP or exclusively Expedited and Assured Forwarding DSCP. Some modems are fully DiffServ compliant and can work with either DiffServ implementation or even with a combination of both.

As an example of possibilities and flexibility, these are the implementations and default priorities for QoS engine included in the Comtech CDM570-IP:

- Class Selector DiffServ Code Points (DSCP). Some implementations of DiffServ prioritize traffic by Class Selector assignment. This is defined in the DiffServ Code Points (DSCP) within the IP header. The first three bits of the DSCP define the Class Selector Precedence (or Priority), as shown in Table 14: DSCP in Comtech CDM570-IP.

| Class Selector | DSCP | Satellite Priority (configurable) |
|---|---|---|
| None / Default | 000 000 | 9 |
| Precedence 1 | 001 000 | 7 |
| Precedence 2 | 010 000 | 6 |
| Precedence 3 | 011 000 | 5 |
| Precedence 4 | 100 000 | 4 |
| Precedence 5 | 101 000 | 3 |
| Precedence 6 | 110 000 | 2 |
| Precedence 7 | 111 000 | 1 |

**Table 14: DSCP in Comtech CDM570-IP, using only 3 bits.**

- Expedited Forwarding and Assured Forwarding DSCP. Another implementation of DiffServ uses all six bits of the DSCP to define Expedited and Assured Forwarding, as shown in Table 15: DSCP in Comtech CDM570-IP, using all 6 bits..

| DiffServ Type | Class Selector | DSCP | Satellite Priority (configurable) |
|---|---|---|---|
| Expedited Forwarding | Precedence 8 | 101 110 | 3 |
| Assured Forwarding – Class 1 | Precedence 8 | 001 xx0 | 4 |
| Assured Forwarding – Class 2 | Precedence 8 | 010 xx0 | 5 |
| Assured Forwarding – Class 3 | Precedence 8 | 011 xx0 | 6 |
| Assured Forwarding – Class 4 | Precedence 8 | 100 xx0 | 7 |

**Table 15: DSCP in Comtech CDM570-IP, using all 6 bits.**

Expedited Forwarding (EF) DSCP – This defines premium service and it is mostly used for real time traffic applications.

Assured Forwarding (AF) DSCP – This defines four service levels and also uses the last three bits of the DSCP to define the Drop Precedence (Low, Medium or High). The Drop Precedence determines which packets will most likely be dropped during periods of over congestion, similar to Weighted Random Early Detection (WRED). As a result, each of the four AF service levels also have three Drop Precedence levels, for which the QoS engine of the satellite modem provides 12 separate queues.

For each of the four Assured Forwarding classes it is possible to define a minimum and a maximum bandwidth. Minimum bandwidth allows a committed information rate (CIR) to be applied to any class of traffic to guarantee the reservation of bandwidth to any particular flow. Maximum bandwidth can be assigned to any class of traffic to restrict the maximum bandwidth that any particular flow will utilize.

**Encapsulation and compression**

While encapsulation and compression are not QoS functionalities, they can be used, if available, to minimize bandwidth consumption, and then free capacity to allow more traffic to be carried.

Modifications of the HDLC (High-Level Data Link Control) standard have been historically used by satellite modem manufacturers to encapsulate and transmit different traffic types over satellite. These encapsulation techniques are very robust, but they lack of excessive overhead for small packets, like the ones usually present on VoIP or cellular backhauling.

Some of the satellite modem manufacturers have developed new encapsulation techniques focused on efficient transmission of small packets, and these functionalities must be taken into consideration in case of bandwidth restrictions.

As an example of the improvement in new encapsulation techniques, Table 16 shows overhead for different IP packet sizes when using the two encapsulation options available on Comtech CDM570-IP modem, the old HDLC and the new one also called “Streamline” (see Table 16).

| Packet Size (bytes) | Overhead (%) for CDM570-IP with “HDLC” encapsulation | Overhead (%) for CDM570-IP with “Streamline” encapsulation |
|---|---|---|
| 32 | 18,8 | 7,4 |
| 64 | 10,9 | 4,3 |
| 128 | 7,0 | 2,7 |
| 256 | 5,1 | 2,0 |
| 512 | 4,1 | 1,6 |
| 1024 | 3,6 | 1,4 |
| 2048 | 3,4 | 1,3 |

**Table 16: Overhead with two different encapsulation options in Comtech CDM570-IP.**

Same criteria apply to compression techniques. Although they are not a QoS feature, they can be used to minimize bandwidth consumption and allow more traffic to be carried over the satellite link.

Most of the satellite modem manufacturers provide functionalities to compress both header and payload for different traffic types and protocols.

Depending of hardware manufacturer and implementation, header compression is possible for:

- Ethernet headers: IEEE 802.3, IEEE 802.2, VLAN-tag and MPLS-tag.
- Layer 3-4 headers: IP, TCP, UDP, RTP.

As an example of the performance of the header compression mechanism, a G.729a voice call operating at 8 kbps, that occupies 32 kbps once encapsulated into IP at the Ethernet port of the modem, can be transmitted using 11 kbps over the Satellite WAN, using IP/UDP/RTP header compression.

Payload compression efficiency depends on the type of traffic. Some traffic types are already compressed or coded, so compression of payload is not possible. Payload compression techniques are usually based on LZS and compatible with RFC 2395 (IP Payload Compression Using LZS).

**Link occupation and traffic congestion**

Another feature that has to be analysed is the possibility of monitoring the occupation of the satellite link, to use that information to develop the bandwidth management and congestion prevention mechanisms. Most of the satellite modems can provide information regarding link occupation using SNMP get/response queries.

Depending on the modem manufacturer, this information is presented as a percentage (%) of occupation of the link or as traffic rate (kbps) transmitted/received in the moment of the query. This information can be obtained by polling the modem trough SNMP and then used to evaluate the availability of free capacity at the satellite link and the possibility of establish a new voice or data connection from the HNB to the HNB-GW.

### *6.3 Considerations related with femtos in the access network*

As explained in previous deliverables of the project, for cellular backhauling there is a difference in performance of satellite solutions based on TDM/TDMA and SCPC architectures.

SCPC provides minimum delay and very stable jitter, which are critical for voice quality and high speed data performance, while TDM/TDMA usually offers a less expensive connection at the cost of increasing delay and jitter.

Tolerance of the HNB to delay and jitter need to be analysed and taken into consideration prior to use a TDM/TDMA link.

### *6.4 Conclusion*

When selecting satellite SCPC solution for Gateway role under the scope of the TUCAN3G project, main issues that have to be considered and analyzed are compatibility of the satellite modems with Differential Services QoS RFC standards and SNMP options to monitor link occupation. As a second need, encapsulation and compression options can also be analysed to optimize the bandwidth consumption.

# 7 CONCLUSIONS

The provision of broadband connectivity in remote rural areas at a reasonable cost for backhauling small cells often requires the use of wireless multi-hop transport networks. Although many wireless technologies are eligible for linking any pair of nodes in such networks, the cost may be lowered dramatically by using WiFi, WiFi-based TDMA solutions or WiMAX. The choice among these three technologies must be done link by link based on the required capacity and acceptable delay. In those cases where the terrestrial connection between the multi-hop transport network and the operator's core network is not feasible or it is too expensive, satellite links may be used as the last alternative for inaccessible nodes or networks. The type of network proposed with an adequate configuration has been shown to have enough capacity and good enough QoS indicators for backhauling rural HNB.

All those technologies have some sort of QoS support, but very heterogeneous in nature. Additionally, the wireless links may exhibit a good performance (enough capacity, low delay, low jitter, negligible packet loss) if they are prevented from getting saturated. Both reasons suggest that nodes must have IP routers terminating both ends of any point-to-point link, so that the traffic can be controlled and monitored. This ultimately permits to implement admission control mechanisms. The traffic differentiation capabilities in the wireless technologies and in the IP nodes must also be used in a coherent way. DSCP has been shown to be a basic mechanism to received marked traffic from the AN and deal with it in a coherent fashion throughout the network. Additionally, different paradigms may be adopted for network QoS management, being DiffServ or MPLS the most simple and promising solutions.

Three basic traffic types must be differentiated in the backhaul network: signalling, voice and data. The whole backhaul network must be configured in order to exhibit a consistent traffic differentiation and per-hop behaviour for those three traffic classes. However, in those cases in which the backhaul network is shared with other private uses, additional classes may be used in order to differentiate the backhaul traffic from the rest of traffic.

There are also different ways to monitor the state of routers in order to prevent them from approaching a saturation state and control them, as well as the wireless links. It has been seen that a bandwidth broker might be a good solution for a concentration point where the state of any path on the network may be consulted. Other alternatives may exist, such as informing periodically to each edge node about the state of its path to the gateway.

At this point, the general high-level architecture is clear and the alternative for several mechanisms are open. The following activities will be oriented to conduct experiments and generate the conditions to decide among the different alternatives in those questions that remain open. This will eventually permit to propose a closed complete solution, which will be presented in deliverable D52.