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

M53

Strategies for the optimization of communications resources under energy constraints

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Abstract:

Transport networks serving as backhaul for rural 3G femtocells have been specified in previous deliverables generated in TUCAN3G. These networks are initially planned based on the expected traffic generated to/from several rural access nodes, and the transport network planning ensures that all links offer a high enough capacity to bear the expected maximum throughput. However, the static situation described in the network planning phase is just an initial point. The dynamic operation of the network is subject to continuous changes. Some may be positive, because capacity in excess along a path may be used to offer access nodes more capacity than initially assigned. Some others may be negative, when the capacity of one or several links decreases due to temporary environmental conditions. The transport network must be able to distribute in either case the positive or negative margin among the access nodes in a controlled way. Another situation that the transport network must manage efficiently is battery shortage. In exceptional situations, it may be better for a system to worsen its performance in order to get a longer life. This document studies all these situations, proposes a basic formal description of the expected behaviour of the transport network and explores the strategy to be followed for the transport network optimization. The complete development of this strategy, including the formal definition of optimization problems and their resolution, will be contained in deliverable D53.

Keyword list: transport network optimization. Dynamic backhaul operation, interface between backhaul and access network.

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Executive Summary

Transport networks serving as backhaul for rural 3G femtocells have been specified in previous deliverables generated in the TUCAN3G project. These networks are initially planned based on the expected traffic generated to/from several rural access nodes, and the transport network planning ensures that all links offer a capacity high enough to bear the expected maximum throughput. However, that static situation described in the network planning phase is just an initial point. The dynamic operation of the network is subject to changes in that initial situation. Some changes may be positive, because capacity in excess along a path may be used to offer access nodes more capacity than initially assigned. Some others may be negative, when the capacity of one or several links decreases due to temporary environmental conditions. The transport network must be able to distribute in either case the positive or negative margin among the access nodes in a controlled way. Another situation that the transport network must manage efficiently is battery shortage. In exceptional situations, it may be better for a system to worsen its performance in order to get a longer life.

This document studies all these situations. Firstly, the aspects to be considered at the network planning stage are studied. Each of the proposed technologies is analysed to identify the significant factors that impact on the cost, performance and/or power consumption in each of them. Also the state of the art on network planning optimization is studied, although there is little room for optimization at that stage for TUCAN3G's transport networks. The objective of this part is to settle the foundations for any optimization proposal to be developed in deliverable D53.

Then, the dynamic of the transport network operation is studied. The operation is formally described in order to provide a good understanding on the type of optimization problems that could be formulated, and the state of the art is also studied. Based on this, a basic formulation and optimization strategies are proposed. The complete development of this strategy, including the formal definition of optimization problems and their resolution, will be the content of the next deliverable D53.

Finally, the document reports the results of an initial exploration for tools and techniques that permit to harvest state information in a real implementation.

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List of abbreviations & symbols

ACM	Adaptative Coding and Modulation
AUPC	Automatic Uplink Power Control
AWGN	Additive White Gaussian Noise
BH	BackHaul
BUC	Block Up Converter
CAPEX	Capital Expenditures
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DL	DownLink
EIRP	Equivalent Isotropically Radiated Power
FBW	Fixed Broadband Wireless
GEO	Geostationary Orbit
GPIO	General Purpose Input/Output
HNB	Home Node B
IP	Internet Protocol
LOS	Line Of Sight
LNB	Low Noise Block
MAC	media access control
MCMCF	Minimum Cost Multi Commodity Flow
MCS	Modulation and Codification Scheme
MCPC	Multiple Channels Per Carrier
MIMO	Multiple Input Multiple Output
MINLP	Mixed Integer Linear Program
MPLS	Multi Protocol Label Switching
NJRC	New Japan Radio
NP-HARD	Non-Polynomic Hard
OPEX	Operational Expenditures
PNO	Physical network operators
QoS	Quality of Service
RF	Radio Frequency
RSSI	Received Signal Strength Indicator
SCPC	Single channel per carrier
SLA	Service Level Agreement
TDM	Time Division Multiplexing
TDMA	Time Division Multiplexing Access
TX	Transmission
UL	UpLink
VNO	Virtual network operators
VSAT	Very Small Aperture Terminal

1 INTRODUCTION

Previous deliverables generated by WP5 in the TUCAN3G project [D51][D52] have shown that a combination of WiLD (WiFi for Long Distances) [IEEE 802.11-1999], WiMAX [IEEE 802.16-2009] and VSAT links can be used to build a rural multi-hop heterogeneous network that may serve as backhaul for 3G femtocells deployed over a rural area. A backhaul network architecture has been proposed that uses traffic control nodes connected in a tree topology with WiLD or WiMAX point-to-point links, while VSAT links are used in extreme cases when the other alternatives are not valid due to the distance or topographic obstacles. The traffic control nodes are intended to shape the traffic presented to links so that all the links in the network operate under saturation conditions. More specifically traffic control nodes must ensure that wireless links operate under a well determined traffic load level that corresponds to a certain delay threshold. Additionally, traffic control nodes must differentiate traffic classes and assure different priorities to telephony, signalling and data traffic. Two alternatives were tested for the traffic control in the backhaul: MPLS, which permits a high level of end-to-end traffic control but limits the advantages of traffic aggregation in the network, and DiffServ IP routing. Nodes belonging to the backhaul network that are in contact with the access network are called “edge nodes” and have some special functions. An edge node is configured to limit the incoming traffic, so that the backhaul network does not permit incoming traffic in excess of what was initially foreseen. This behaviour protects the “legal” traffic from high delays or packet losses caused by unexpected traffic peaks, ensuring that the offered quality of service is good under normal circumstances.

Up to this point, the backhaul network was intended to be static. The requirements for the backhaul are supposed to be defined initially, the network is planned, the required capacity for all the links is calculated and the technologies and configurations for all the links are carefully chosen in order to ensure that the whole backhaul network may bear the expected traffic. However, this static situation is not realistic and is far from being optimal. On one hand, one may think of many situations in which a network may accept temporarily more traffic than initially expected from/to a given HNB without any negative impact, provided that the edge nodes have enough information about the network state. On the other hand, wireless links may be impacted by the weather or other environmental conditions and unexpectedly change the available capacity, requiring temporary changes in the limitations imposed to ingress traffic. Beyond that, the possibility of changing parameters dynamically in the network depending on the network state must be examined in order to decide whether there are optimisation techniques that may foster the performance or reduce the cost.

This document introduces the characterisation of the different elements in the backhaul network in terms of performance, and the optimisation strategy. Further work will drive to Deliverable D53, proposing solutions to well-defined optimisation problems. The document is structured in four sections, being this introduction the first and the conclusions the last one. The other two sections consider the backhaul network in two steps: the initial planning and configuration (Section 2) and the real-time optimization of the network (Section 3).

2 OPTIMAL BACKHAUL NETWORK PLANNING AND CONFIGURATION

Before addressing any optimization problem for a specific network, it is necessary to define the network scenario and the different variables we can consider when planning and deploying it. The network design will be determinant to the final performance of the network, since generic aspects and parameters such as distance between nodes, number of nodes, power transmission, technologies used, etc. are primary decisions. After studying what parameters can be configured and optimized for each technology, it is possible to address the optimization in the planning stage before study the optimization in the operation stage. Sections 2.1 and 2.2 characterize VSAT, WiFi and WiMAX technologies in terms of parameters that can be adjusted for optimization. Section 2.3 will address different approaches to optimum planning and deployment of rural networks for consideration in D53.

2.1 Characterization of VSAT systems for performance optimization with QoS and energy constraints

As previously set in other documents, the objective of the satellite links in TUCAN3G is to serve as IP transport network between gateways and the operator's core network, mainly where the distance to the closer transport network's node is too long or the topography does not permit to connect with terrestrial links.

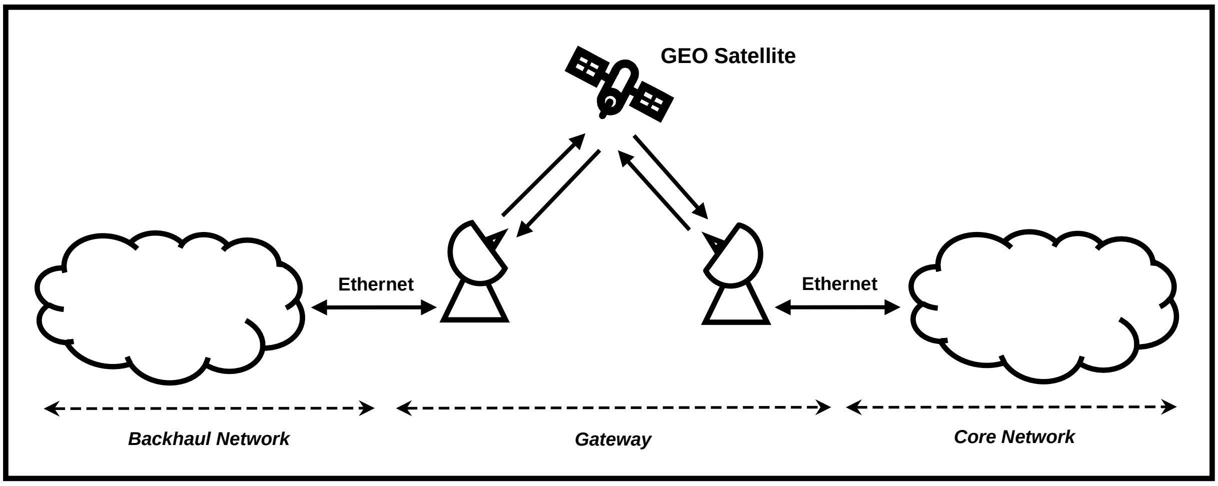

Figure 1: Role of a satellite communications link in the TUCAN3G backhaul.

In this section, several variables that may be considered in the installation of a satellite communications station are going to be discussed. The objective of this qualitative analysis is to determine what considerations must be done in order to obtain an efficient and cost-effective system. The main variables under discussion are the energy consumption, the transmission power, the antenna gain and the cost of the installation.

The discussion of energy consumption for satellite links acting as gateways in TUCAN3G applies mainly to the satellite stations connected to the backhaul network side, as the other ones, connected to the operator's core network side, will be usually located in a satellite teleport where energy supply is not an issue.

Energy consumption is not always a main driver in the design of a satellite link budget for a commercial service, as there are other issues considered as key drivers for network dimensioning: antenna size and RF transmitter power. Proper selection of antenna size and RF transmitter power (minimizing cost of both of them), according to particular satellite specifications to obtain optimum bandwidth usage and desired availability, is the way a link budget is usually done, since the bandwidth is a very expensive resource in satellite systems.

Energy consumption is treated as a secondary need to fulfil, and only when satellite stations are installed in very remote areas without proper continuous energy sources, and solar panels and/or batteries are the only energy source that it is feasible.

There are approaches than can be studied to minimize and optimize power consumption, some of them fixed in the initial design of the links and other ones than can act dynamically, if available, according to the traffic demand.

The first approach usually considered to reduce energy consumption is to modify the initial link budget: to increase antenna size (passive amplification, without energy consumption) and to reduce RF transmitter power (active amplification, with energy consumption). This modification can be usually achieved without affecting the bandwidth efficiency and maintaining the target availability, but it has a cost: The fact that in these cases the satellite stations are installed in very remote areas make difficult to justify the increase of the antenna size, as the costs of the transportation and the installation, plus the cost of the antenna itself, increase significantly. Depending of the particular case of the satellite link, it can be possible to make a change of 3dB in the balance (+3dB on the antenna, -3dB on the RF), but only if the initial size of the antenna reflector, as result of the link budget, is small.

As an example, changing from 1.2m to 1.8m for a Rx/Tx Ku antenna (+3db approx.) can increase the antenna cost from 250,00 US$ to 500,00 US$, and changing the BUC (Block-Up-Converter, the RF transmitter) from 4W to 2W (-3dB approx.) can reduce the cost of the RF transmitter from 500,00 US$ to 250,00 US$, resulting in the same cost for the hardware kit of the satellite remote station. But the weight of the hardware kit is increased in 50 Kg and its volume is increased in 0.5 m^3. Increase of cost for transportation of this new hardware kit will depend of how remotely the installation area is and what transportation ways are available. Installation cost is also increased but not expected to have a significant impact, as civil works and labour hours are very similar for the installation of 1.2m and 1.8m antennas.

Transportation and installation costs start to increase exponentially from 2.4m (+3db approx. from 1.8m), 3.8m (+3db approx. from 2.4m) and so on, because of the weight/volume of the antennas and the need of more expensive civil works for the installation. Increase of cost of the antenna itself is also significant starting with 2.4m (1.2m: 250 US$; 1.8m: 500 US$; 2.4m: 1.500 US$, 3.8m: 10.000 US$).

Power saving obtained with this simple approach is significant, as the element with more power consumption is the RF transmitter. Following two examples of a SCPC satellite station use the same modem (Comtech EF Data CDM570L-IP) and different BUC types from same manufacturer (NJRC), to show impact of consumption of RF transmitter and possibilities of energy saving:

Configuration	**Power Consumption**	**Power Saving**
SCPC CDM570L-IP Ku-Band 1.2m + 8W	116 W	36 %
SCPC CDM570L-IP Ku-Band 1.8m + 4W	74 W	
SCPC CDM570L-IP C-Band 1.8m + 10W	112 W	24 %
SCPC CDM570L-IP C-Band 2.4m + 5W	85 W	

Power consumption of CDM570L-IP (widely used SCPC modem with IP module) is 37W, including power consumption of LNB (Low Noise Block, the amplifier for the RF reception). The modem has also an integrated power supply to feed the BUC, with a maximum power consumption of 90W. Selected BUCs for this exercise are the ones with more RF power according to power consumption limitation of 90W, and the ones with -3dB power, assuming it is possible to make a +3dB change in the antenna size (from 1.2m to 1.8m on Ku-Band, and from 1.8m to 2.4m on C-Band).

NRJC Model	**Band**	**RF Power**	**Power Consumption**
NJT5118N	Ku	8W (+39dBm)	79W
NJT5307N	Ku	4W (+36dBm)	37W
NJT5762N	C	10W (+40dBm)	75W
NJT5669	C	5W (+37dBm)	48W

As a result, estimation for power consumption savings is 25-35%, reducing RF transmitter power in -3dB and increasing antenna gain in +3dB. Depending on the way the terminal is powered, the impact of the energy savings is on the CAPEX or on the OPEX. In case of using solar photovoltaic system, the energy savings supposes that the CAPEX is reduced due to the reduction in the number and size of the solar panels and batteries. This savings may be higher or lower than the increase of the CAPEX due to the size of the parabolic antenna. In other cases, the energy savings means a reduction in the OPEX, which may be clearly convenient for a long-term cost optimization.

Other approaches to reduce and/or optimize power consumption will depend on the network topology and technical solution selected. There are two alternatives considered as feasible for deployment under TUCAN3G project as satellite links with a GEO satellite:

- SCPC, with point-to-point (or point-to-multipoint) topology and leased bandwidth.
- TDM/TDMA, with star-topology and shared bandwidth.

On common **SCPC** systems, the available bandwidth is fixed, reserved for the service, and aggregate traffic rate is guaranteed. Initially, power consumption is the same no matter if there is traffic to transmit or not, either with high or low priority, because the carrier is always in the air and with the same EIRP (Equivalent Isotropically Radiated Power). Most advanced SCPC satellite modems can make use of two functionalities that impact on both the performance and the power consumption:

- **AUPC. Automatic Uplink Power Control.** This functionality allows to increase transmit power (and so, energy consumed) when the other side of the link detects a significant decrease in the level of the signal received, or when a local monitor of a test carrier (usually the beacon of the satellite) also detects a decrease. This functionality is usually deployed on SCPC satellite links in Ku-band, to mitigate the attenuation effect of the rain fading. It is less used on satellite links in C-band, as rain fading attenuation effect is minimal on these cases. To deploy AUPC you need, in addition to the support of the functionality in the satellite modems, the possibility to have extra power available on the RF transmitter. Because the cost of the RF transmitter increases as its power is greater, it is not expected to have more than 3 or 6 dB of available extra power, unless this possibility was explicitly included as a driver in the design of the link budget. It is possible to save energy when this functionality is available and it has been included in the design of link budget: The link can be designed to have less protection margin against rain fading on nominal level (so, lower transmission power is needed and lower energy is consumed) and get the maximum transmit power temporary activated only when it is really needed and not all the time.

Nowadays, AUPC functionality is included in the SCPC satellite modems as a standard, with no extra cost, so it is easy to make use of it. For cases on Ku-Band links deployed on areas with heavy rain patterns, a reduction in -3dB on nominal power can reduce up to 50% of power consumption of the RF transmitter during the periods without raining.

- **ACM. Adaptive Code and Modulation.** This is another functionality designed to deal with adverse weather conditions, but it works in a different way. In this case, what the modem can do when it detects that it is under a rain fading condition, is to change modulation and coding rate (ModCod), so it is able to transmit the payload with more robustness, relaxing ModCod to use one with lower Eb/No requirement. For the energy saving point of view, use of this functionality allow to keep the link operational, reducing traffic rate when a rain fade is occurring, without the need of more transmit power, or avoiding the link to be down as the margin of protection against rain fading is over reached. If proper sizing is done, and congestion monitor techniques are applied, it is possible to fine tuning the link to minimize the possibilities of having the link with ACM active and peak demand of traffic at the same time, so user’s experience is like having always the link with maximum capacity available and protected against rain fading. For the cases when congestion occurs and available traffic rate is less than needed, QoS allows prioritizing signalling over voice and voice over data, so the impact is only noticed on data service.

  Another theoretical use of ACM would be to maintain the link in nominal operation with a relaxed ModCod while the demand of traffic allows serving all of them without maximum rate available, and activating the most optimized ModCod only when maximum demand is needed. This integration between ACM and traffic monitoring is not implemented on commercial satellite modems, and the implementations of ACM made by the manufactures do not modify output power when a change of ModCod is done, so there is no application for energy savings purpose.

  Nowadays, ACM is still considered as an option for a SCPC satellite modem. It is not included as a standard and its cost vary from 1.000,00 to 3.000,00 US$ per modem (depending of manufacturer and maximum traffic rate supported).

  Some references of implementation of ACM of SCPC satellite modem manufacturers:

http://www.comtechefdata.com/technologies/acm

http://www.comtechefdata.com/files/articles_papers/WP-CDM625_ACM_White_Paper.pdf

A third functionality available on some SCPC modems can be considered in the analysis of energy saving possibilities:

- **Dynamic bandwidth allocation for SCPC**. Sometimes called "Dynamic SCPC". This functionality is sometimes available and can be deployed on SCPC links that operates in point-to-multipoint topology, where one central station transmit a MCPC carrier sharing traffic to several remote sites, and each remote site transmits each own SCPC returning carrier to the central station. Dynamic SCPC allow a remote site to request bandwidth according to its traffic needs, so the SCPC return link carrier is dynamically switched to increase or decrease its capacity. Management of the bandwidth is always controlled from the central station. The bandwidth assignment and remote satellite modem control are done automatically and on-line through a pre-programed system that manages priorities and assures that all the transmission are done according to link budgets, available bandwidth and possibilities of the remote stations.

  From the energy savings and QoS point a view and under TUCAN3G scope, Dynamic SCPC can be used to keep the satellite link using a minimum bandwidth (and so, low transmit power and low energy consumption) for signalling and voice needs, while demanding more bandwidth only when a peak demand is needed, basically when 3G data traffic increases.

  Implementation of Dynamic SCPC feature is an advanced option available on a reduced number of modem manufactures, and an expensive option: In addition of the cost for each remote satellite modem, there is a high invest cost for equipment in the central station, and a recurrent cost for annual support contract of the technology manufacturer.

On **TDM/TDMA**, the bandwidth is shared between several remote stations. Traffic rate may not be guaranteed 100% at all the time for the different traffic classes, because there is oversubscription. Initially, power consumption varies according to the traffic transmitted, as the TDMA carrier is only active on bursts as needed. Latest use of linear-type BUCs instead of saturated-type ones, also reduces energy consumption.

On most of the newest TDM/TDMA solutions, there are also possibilities of using techniques like AUPC and ACM, with the same benefits and considerations as the SCPC case, making TDM/TDMA deployments better energy saving solutions if compared to SCPC ones.

In addition, as TDM/TDMA solutions are usually cheaper than SCPC ones and are the selected option for deployments of broadband access in remote rural areas, some of the hardware manufacturers have made developments to enhance energy saving:

- There are manufactures with stations specially designed to consume as low as 20W for bi-directional traffic, helping to minimize solar or other alternative energy sources often required in rural areas:

  http://www.gilat.com/dynimages/t_brochures/files/SkyEdge%20System%20Brochure%202011-09.pdf

- Also, there are manufactures that can put the satellite modem into a "sleep mode" after a period of time with absence of traffic to transmit. This can be used to save energy from batteries on nights, when there is no demand of traffic, but the process of "waking-up" when the traffic appears can take some minutes (powering up + Rx synchronizing and demodulator lock + Tx synchronizing) and produce a significant delay in the activation of the femtocell.

The availability and performance of these functionalities will depend on the decision made by the satellite service provider to have them included in their deployed commercial platforms. The fact that the technology manufacturer has a given functionality does not guarantee that the service provider is making use of it.

2.2 Characterization of WiLD and WiMAX systems for performance optimization with QoS and energy constraints

In general terms, the use of either WiFi or WiMAX in multi-hop backhaul networks is feasible if and only if LOS is guaranteed between the two ends of every link. There could be exceptions to this rule in particular cases, but existence of LOS will be assumed in this document.

A second assumption here is the use of a non-licensed band, which conditions the authorised transmission power and the antenna gain[1]. This assumption, together with the context of long-distance links, permits us to assume that systems will be planned for operation at the maximum transmission power permitted. There could also be exceptions for the case of WiMAX, and in this case the limits imposed to the transmission power can be relaxed and the optimization problem may become more complex because the transmission power may not be set necessarily to the maximum.

Under the previous assumptions the scenario is very clearly defined for these technologies. Locations having one or more end communications systems need to have a mast or a tower on which they will be installed. The basic structure of costs of a whole infrastructure deployed in a location was already analysed in [D51], including the mast or tower itself, the powering subsystem, the electrical protection and the communications subsystem. For most scenarios, the cost of towers, including structure, lightning protection and grounding, is very dominant over all the other cost components, because the LOS requirement implies the use of large supporting structures that make possible the placement of antennas at the right elevation. In general terms, the longer is the link, the higher the towers need to be because of the Earth's curvature and the higher number of obstacles. However, the consequences of this trend in each particular scenario are diverse: while in mountainous regions the position of each station is very much limited by the orography, flat regions impose limitations related with accessibility and obstacles such as buildings and trees. This makes almost impossible to do any general optimization of any real value based on the trade-off between cost of infrastructures and number of locations. The most reasonable approach is to determine the appropriate locations for communications systems based on the network planning with constraints such as accessibility and security of candidate locations. Once the locations are determined, the size (and the cost) of the structures is determined by the elevation required for the antennas.

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[1] The conditions for using non-licensed bands differ from one regulatory domain to another. For example, the FCC permits to transmit up to 1W in 5.8 GHz without any penalty in the antenna gain up to 27dBm. This has been assumed in many Latin American countries as the reference, but other regions may have different restrictions.

Besides the impact of supporting infrastructures on the cost, other elements with minor impact on the CAPEX are:

- The antennas: the more gain the antenna has, the higher is the cost. For big antennas there might be and additional cost for the supporting infrastructure.
- The communication system: depends on the technology and model chosen.
- The powering system: the higher is the power consumption, the higher is the cost of solar panels and batteries.

Although accurate expressions can be obtained to establish a relationship between antenna gain and size for parabolic antennas, the cost cannot be associated to the antenna gain with a formal law. However, the antenna gain cannot be chosen very high because the installation on top of high structures has other limitations. While a parabolic antenna for a satellite communications system is supported by a solid short structure, a WiFi or WiMAX system with LOS requires a mast or tower that exposes the antenna to changes of position due to winds and temperature variations. A high antenna gain requires a precise positioning that cannot be assured under these conditions. Hence, the short range of possibilities in terms of antenna gains and the typical prices at that range (under $500 USD) imply that this variable will have little impact in the overall cost.

The communications systems considered are in a range of prices between $1000 USD and $3000 USD for a pair of systems (case of PtP links) and there is not a proportional law between performance and cost. Based on the results obtained in the previous deliverables, the selection of a particular technology and system tends to be for WiFi-based TDMA systems unless a point to multipoint setup is required in a leaf of the backhaul tree, in which case WiMAX may provide more control on the individual performance of each HNB. From this point of view, the selection of technology is mostly a matter of network planning and design and can be ignored here.

In terms of performance, the better is the link budget, the higher is the performance. Once the best possible antenna is chosen for each communications system, the link budget mainly depends on the link length. As already seen in [D51], the capacity-distance law is a stairs-shaped curve because both WiFi and WiMAX are adaptive technologies with several MCSs that can be chosen depending on the RSSI.

For WiFi, the values of Bandwidth, Guard interval, Frame Aggregation Threshold, can be adjusted in order to achieve the highest throughput. Setting the highest possible capacity, a short GI and a high frame aggregation threshold, the throughput can be increased without increasing the delay.

For WiMAX: Bandwidth and Cyclic Prefix duration can be adjusted to obtain the optimum throughput without increasing the delay.

In both WiMAX and WiFi-based TDMA solutions, there is a throughput-delay trade-off that depends on the frame duration. Delay limitations determine the maximum frame duration that can be used. This generally is determined by the number of hops: the backhaul will be allowed to introduce a maximum one-way delay (in this work package we have considered 60 ms) that imposes a limit to the sum of all the one-hop delays along a path.

Finally, the use of MIMO techniques can also improve the performance in a one-hop link at expenses of increasing slightly the infrastructure costs. MIMO can be used for both diversity and spatial multiplexing. Although both alternatives are interesting and must be analysed carefully in each scenario, usually higher revenue of performance will be achieved using spatial multiplexing.

However the most critical factor which will determine the performance and cost issues will be the number of hops. A higher number of hops implies lower towers, lower costs per location, but a higher number of locations along a path. It also has performance consequences. A higher number of hops implies shorter links, with higher RSSI (received signal strength indicators) that permits to operate at more efficient MCS (modulations and coding schemes) and hence to obtain a better performance, especially in terms of throughput. The delay, jitter and packet-loss probabilities are also influenced by the number of hops, but will be considered per-traffic-class constraints, as explained in subsection 2.1.

In general, the eligible locations in a rural backhaul are very much conditioned by the topography and the physical accessibility. Hence, from a technology-specific perspective, most of the variables considered in this subsection don’t really present any trade-offs in general. The characterisation of WiFi and WiMAX suggests that the network planning determines the locations to be connected in first place. Then, it may be required to add the minimum set of relay stations that are needed to deploy a reliable tree-topology multi-hop network. Then, the selection of equipment and antennas, permit to ensure certain maximum per-hop capacities that may be compared with the access network requirements. Bottlenecks must be identified and, when possible, solved with MIMO 2x2 configurations, wider channels or even higher antenna gains. When there is not a better solution, an extra relay station may be added to divide a link in two shorter paths that may increase the capacity conveniently. This design process do not present loops or clear trade-offs in general, though each particular case must be studied carefully.

However, the quantitative study for these relationships among cost and performance indicators will be further developed in deliverable D53.

2.3 Previous approaches for optimum planning and deployment

The network planning is critical when optimum performance is desired. Although the characterisation made in the previous subsection seems to leave little room for optimization in this phase, we are going to review how other works have faced this problem.

[Liu2008] presents an energy constrained linear backhaul network, and proposes an efficient deployment scheme which involves location management, routing, and power management. The deployment optimization problem is addressed with a greedy deployment scheme and a closed-form relationship among different design parameters such as number of nodes, desired life time, and coverage distance is revealed. The objective here is to find a deployment to cover the maximum distance given the number of nodes and the heuristic presented performs close to the optimal.

Also in [Ting2011] and in [Ting2012] the optimum deployment of a heterogeneous multihop wireless backhaul network is addressed. First in [Ting2011] the capacity and coverage in 802.11n for rural networks is analysed and then in [Ting2012] the general optimization for the same scenario is presented. However, no standard formulation is given, only specific algorithms for topology, access channel and power optimization.

[Islam2014] tries to do joint optimization of node placement, power allocation, channel scheduling, and routing to optimize a wireless backhaul network. A standard formulation of an optimization problem is presented based on a Mixed Integer Non-Linear Program (MINLP) and capturing the different interference and multiplexing patterns in the sub-6GHz band. To solve the MINLP, a linear relaxation based in the branch-and-bound algorithm is studied and particularized in an example urban network, but there is not any important reason preventing from applying this methodology to rural areas.

Finally, in [Chieng2010] a general optimization of the network planning is made in terms of CAPEX+OPEX through several inputs parameters related with the design options, environment conditions and cost. The optimization is addressed through the adjustment of the node density and clustering against target data rate and range. A series of algorithms based in the Tabu search meta-heuristic are proposed, and some interesting keys in network planning are obtained.

In the next deliverable D53 these ideas in the network planning will be considered for the particular case of the transport network as proposed in the TUCAN3G project.

3 DYNAMIC OPTIMIZATION OF THE PERFORMANCE OF THE BACKHAUL NETWORK

3.1 General description of the optimization goals

The proposed backhaul network architecture is by far more complex than a typical backhaul link that connects a base station to the operator's network. However, its purpose is the same and it must provide certain guarantees in order to meet the requirements of the access network. In this proposal, the use of wireless links operating in non-licensed bands implies that the exposure to fading and to interferences is much higher than it is in a classical backhaul approach. Moreover, the multi-hop approach means that certain links in the backhaul network are shared by different HNB. These differences render the design more complex and make advisable to identify accurately the conditions that the backhaul must accomplish to perform its function adequately, so that the proposed architecture is not only appropriate for the context of rural isolated areas, but also a valid replacement for other traditional alternatives from a technical point of view.

The backhaul must bear the traffic exchanged between HNBs and the operator's network preserving the required QoS for each traffic class and, at the same time, must do it optimally to permit the operator to obtain the maximum benefit from a given infrastructure. Provided that the backhaul must transport and differentiate three different traffic classes: real-time voice traffic from telephony, signalling and data, a first approach to the problem could be formulated with the following clauses:

C1. Voice traffic must be given maximum priority all along its path through the backhaul network, and must experience a delay $D_V \le D_V^{max}$, a jitter $\sigma_V \le \sigma_V^{max}$, and a packet loss $L_V \le L_V^{max}$. Typical values for those thresholds may be: $D_V^{max} = 50ms, \sigma_V^{max} = 15ms, L_V^{max} = 1\%$, but this can change depending on the context.

C2. Signalling traffic must be given high priority all along its path through the backhaul network, and must experience a delay $D_S \le D_S^{max}$, and a packet loss $L_S^{maz} \approx 0$. Typical values for that threshold may vary depending on the implementations, as the recommendations from ITU for the delay of signalling are in the same order of magnitude as for voice, but most manufacturers will certainly prepare their equipment to support much higher delays in order to make them compatible with VSAT links. This is the case of IP.Access HNBs and controllers, which support $D_S^{max} \sim 1s$, but this can change depending on the context. A seen in deliverable D52, the intensity of signalling traffic is extremely low, so its requirements are better preserved if the highest priority is given to this traffic, with negligible impact on the QoS offered to voice traffic.

C3. Data traffic must be given “the best possible” quality of service, but no thresholds will be defined for its QoS parameters. While voice and signalling consume limited resources for a given number of active users, data traffic will use the rest of available resources with lower priority, and the available resources must be maximized while preserving clauses C2 and C1 as restrictions. One additional restriction will be added for data traffic, whose end-to-end average packet loss probability must not exceed L_D^{max} ($L_D \le L_D^{max}$).

C4. Each HNB '*i*' is authorised to generate a maximum throughput of $\hat{S}_{V_i}^{UL}[n]\,\hat{S}_{X_i}^{UL}$ in the uplink and $\hat{S}_{X_i}^{DL}$ in the downlink, where $X \in \{V, S, D\}$. $\forall$ node i, if $S_{X_i}^{UL} \le \hat{S}_{X_i}^{UL}, S_{X_i}^{DL} \le \hat{S}_{X_i}^{DL}$, the traffic belonging to each traffic class obtains the same priority and shares the resources in equal conditions with the traffic of the same class belonging to other nodes that accomplishes the same condition. Traffic in excess must be discarded in edge nodes before it can generate delay to other packets, or alternatively can be coloured, so that it can be discarded later if necessary.

C5. If the network cannot accomplish clause C2, the network is considered in failure condition.

C6. If the network can accomplish C2 but cannot accomplish C1 for one or more HNB, the bottleneck must be identified, the gap between the available resources and the required resources must be measured, the gateway node and any edge node connected to a HNB 'X' affected by the bottleneck must be informed about the measurement, and then it must consider temporary new values $\hat{S}_{X_i}^{UL}[n] < \hat{S}_{X_i}^{UL}$ and $\hat{S}_{X_i}^{DL}[n] < \hat{S}_{X_i}^{DL}$ consequently as maximum thresholds. In this temporary situation, clause C4 is redefined temporarily replacing the maximum values with the temporary values. The original thresholds must be recovered as soon as the conditions permit it.

C7. If a HNB '*i*' can be given higher throughput thresholds $\hat{S}_{X_i}^{UL}[n] > \hat{S}_{X_i}^{UL}$ and $\hat{S}_{X_i}^{DL}[n] > \hat{S}_{X_i}^{DL}$ without compromising C1-C4 for all other HNBs, the gateway node and its edge node may modify those thresholds temporarily while the previous conditions are met. In this temporary situation, clause C4 is redefined temporarily for HNB '*i*', replacing the maximum values with the temporary values. This temporary situation can be maintained as long as C1-C4 are not compromised for other stations.

C8. If any link may save energy by reducing its capacity without compromising C1-C4 for HNBs that use it in their path to the gateway, it can change its state temporarily while the previous conditions are met. This clause may conflict with C7, and the network policy must determine clearly which of those two clauses has priority over the other depending on the situation.

C9. Permanent changes in throughput thresholds are subject to a new network planning.

From this general description of the optimization goals, we address the optimization problem, first analysing and considering the state of the art in network optimization and then formulating a specific solution.

3.2 Theoretical approach for optimization problems

Depending on which our goal is, we can formulate different optimization problems. This document considers two points of view:

- Maximum throughput optimization. The objective is to maximize the capacity offered by the backhaul to the set of HNBs, given a specific Service Level Agreement (SLA) in terms of QoS constraints. This approach looks at the real-time performance of the network in order to dynamically assign resources in a way that preserves the SLA and, at the same time, maximizes the use of the available resources. This point of view neglects the power consumption and raises the issue of how to deal with fairness.

- Minimum power consumption optimization. The objective here is to minimize the power consumption through the management of the either the TX power or the TX rate, subject to certain traffic requirements. This case considers a power saving mode for the nodes. It is advisable to apply this point of view for any node experiencing energy shortages. From this point of view, the capacity in excess will be used to reduce de TX power and/or the transfer rate.

This document is going to deal with both approaches separately. However further studies can address the multi-objective optimization. This would consider a Pareto-optimal region in which the objectives throughput and power consumption are in a trade-off situation, as improving one of them may worsen the other in terms of rewards and costs for the network operator.

3.2.1 Previous approaches for the optimization problem

Since the graph theory was developed, there have been many studies about how to get the better performance in a network through the optimization of the variables such as maximum throughput, delay, congestion, etc. using the concept of the graph.

One of the most famous problems in network optimization is the Maximum Flow Problem. This problem and all its variants may be solved with very efficient algorithms, such as Ford-Fulkerson, Edmonds-Karp or Dinitz Blocking Row.

Also other methods such as Linear Programming and Dynamic Programming may give decent results. The Multi-commodity Flow Problem is a derived problem which could resemble to this backhaul optimization problem. Depending on which is the optimization objective, some variants can be formulated, such as maximize throughput, minimize costs, or maximize usage percentage. The most extended formulation is the MCMCF problem (Minimum Cost Multi Comodity Flow). For real solutions this convex problem can be solved by Linear Programming in a polynomial time. However, if the flows are considered as integer numbers the problem becomes NP-hard (or NP-complete if it is a decision problem).

In a generic formulation, the problem is defined as follows:

Given a flow network G(N, A) with N nodes and A edges, there are *k* flows (o commodities) for each , and each flow k has an associated cost $c^{k_{ij}}$. This cost would be a variable to be optimized, such as money, delay, power consumption, etc. When "associated cost" is considered, the optimization would consist of minimizing the objective function. In those problems in which the goal is to maximize the objective function, the "associated reward" r_{ij}^{k} would be used instead of the associated cost. Finally, each flow *k* is defined by an origin and by a destination (source and sink). Multiple sinks can be considered in those cases which multicast is present.

is the amount of traffic generated by node *i* of the flow type *k* in the *n* instant. Depending on the role of the node, if it is a node which injects traffic of this type in the network, if it is a node which absorbs traffic of this type, and if it is a neutral node in the inner network which only routes the traffic.

is the decision variable which determines the amount of traffic of type *k* that each transports. As said before, it use to be a real or an integer number.

$\vec{S}_{ij}[n]$ It is the maximum capacity allowed for a specific link (i,j) at time *n*.

Then, a generic objective function would be:

$$max \sum_{k\in K} \sum_{(i,j)\in A} x^{k}{}_{ij} \cdot c^{k}{}_{ij}$$

subject to:

$\sum_{k\in K} x^{k}{}_{ij} \leqslant \vec{S}_{ij}[n]$ for each $(i,j) \in A$ (capacity restrictions)

$\sum_{k\in K} x^{k}{}_{ij} - \sum_{(i,j)\in A} x^{k}{}_{ji} = S^{k}{}_{i}[n]$ for each $i \in N$and $k \in K$ (flow conservation restrictions)

$x^{k}{}_{ij} \geq 0$ for each $(i,j) \in A$ and $k \in K$ (non-negativity restrictions)

From this generic formulation, it is possible adapt many network optimization problems by adding new restrictions or changing the objective function. Also, different objectives can be achieved assigning different meanings to the cost/reward parameter and transforming the problem to more complex versions of itself. Some aspects such as the congestion level in edge nodes, number of blocked users in the femtocells, aggregated power consumption in the path or delay in each link can be used in order to model the cost/reward parameter. In order to do so with fairness and assign different weights to different variables, positive or negative efficiency can be assigned to the cost/reward parameter using polynomial or logarithmic functions.

When adapting this formulation to our context, it is necessary to bear in mind that the whole state of the network must be known by one or more nodes. Also a dynamic nature of the network operation must be considered, so the capacity restrictions and some of the flow restrictions must be instantaneous and time-dependent. Other restrictions can be averaged instead.

The graph theory and different formulations of the multicommodity flow problem for backhaul networks are used and studied by several authors.

[Ghatee2011] study the QoS optimization problem as an integral multicommodity flow problem in which the target is to jointly minimize the delay and the congestion. This problem is known to be NP-Hard, since the variables to be optimized are integers. The study proposes to extend the traditional mathematical programming with meta-heuristics such as genetic algorithm in order to yield reasonable results in a low number of iterations.

Another work that models the problem as a MCMCF is [Coudert2008]. This study addresses the power consumption minimization choosing which traffic flows are permitted and hence which power transmission and modulation scheme is selected for each link. As said before, this results in large scale integer linear programs, so a linear relaxation program model is introduced. In order to achieve this, a piecewise linear cost function is introduced and the MCMCF is rewritten, and the convexity of the energy cost over the throughput in the radio link is exploited through a heuristic algorithm.

Also [Caillouet2013] consider the network optimization problem as an integer linear model. This paper considers the network optimization in terms of revenue in the fixed broadband wireless network (FBW). These networks operate licensed frequency bands and usually are shared between PNOs (Physical network operators) and VNOs (Virtual network operators), so increasing the profit in FBW is capital in order to use them as an effective backhaul solution. The paper uses the statistical programming approach (robust optimization) mixed with the integer linear programming to study this trade-off between revenue maximization and the allowed level of uncertainty in the stochastic traffic demands subject to a prescribed SLA (service level agreement) presented as end-to-end delay. In this case, time or efficiency is not considered but the robustness of the model against stochastic events.

[Mannweiler2013a] and [Mannweiler2013b] are similar and introduce the multi-objective optimization for wireless mesh networks. The optimization is made based on several parameters such as network capacity, energy consumption, efficiency, reliability, etc. through dimensioning the degree of meshing of the network. [Mannweiler2013a] introduce the concept of multi-objective, proposing a non-linear integer program, while [Mannweiler2013b] presents a linearization of this problem and formalize a backhaul topology optimization algorithm that generates a Pareto-optimal backhaul topology which reduces power consumption while keeping network capacity and user outage at satisfactory levels. Other similar works, such as [Viswanathan2006], also consider the meshing degree and address the routing and scheduling problem within the framework of variable-rate transmissions dependent of the interference power through linear programming optimization. Since the TUCAN3G project considers a tree topology for the transport network (with none or very low degree of meshing in the backhaul) as the most cost-effective topology that fits into most real scenarios, these papers move away slightly from the context of this document.

Finally, another approach for the optimization problem is to design a specific heuristic algorithm which can address the problem from a realistic, implementable and deployable solution. Usually, if the heuristic is well defined, it can be proved that the global optimum can be reached and that the solution converges to the standard formulation solution. In the same way the heuristic of a standard formulation can be obtained in few steps [Gutjahr2002]. Since the TUCAN3G project is very scenario-dependent, besides the standard optimization problem formulation also a heuristic or iterative algorithm may be proposed.

3.3 Strategy for the dynamic optimization of a multi-hop heterogeneous backhaul network with end-to-end QoS requirements and energy constraints

Once the different elements of the backhaul network (WiMAX, WiLD, TDMA-WiFi and VSAT) have been characterized in terms of performance, infrastructure costs and QoS constraints, it is possible to formulate and characterize the dynamic backhaul network operation problem. Taking into account the previous optimization approaches, the first step is the clear definition of the parameters involved in the optimization of the multi-hop heterogeneous backhaul network.

- <u>QoS parameters</u>:

The following definitions are assumed for characterizing the backhaul networks in terms of QoS, based on the previous descriptions for one-hop links made in Sections 2.1 and 2.2. Delay, jitter and packet-loss are conditioned as follows:

- Voice traffic			
· Delay:	D_V	Maximum delay:	$D_V \leq D_V^{max} = 50ms$
· Jitter:	σ_V	Maximum jitter:	$\sigma_V \leq \sigma_V^{max} = 15ms$
· Losses:	L_V	Maximum losses:	$L_V \leq L_V^{max} = 1$
- Signalling traffic:			
· Delay:	D_S	Maximum delay:	$D_S \leq D_S^{max} = 50 - 1000ms$
· Jitter:	σ_S	Maximum jitter:	∄ Not defined
· Losses:	L_S	Maximum losses:	$L_S \leq L_S^{max} \approx 0$
- Data traffic:			
· Delay:	D_D	Maximum delay:	∄ Best effort
· Jitter:	σ_D	Maximum jitter:	∄ Best effort
· Losses:	L_D	Maximum losses:	∄ Best effort

These parameters are highly dependent of the values of capacity and offered load in the network. Although they are influenced by multiple factors, their main contributions are related directly with the level of congestion in the network. For this reason, capacity and offered load values are more complexly defined as follows:

- <u>Traffic load parameters</u>:

- Maximum Guaranteed Throughput:

$$\begin{array}{ccc} \hat{S}_{V_i}^{\mathrm{UL}} & \hat{S}_{S_i}^{\mathrm{UL}} & \hat{S}_{D_i}^{\mathrm{UL}} \\ \hat{S}_{V_i}^{\mathrm{DL}} & \hat{S}_{S_i}^{\mathrm{DL}} & \hat{S}_{D_i}^{\mathrm{DL}} \end{array}$$

These parameters are the maximum guaranteed throughput in DL or UL links for the HNB *i* for each traffic type: voice (V), signalling (S) and data (D). This differentiation is made since asymmetrical traffic is expected and each type of traffic will be treated in a different way. These values are fixed from the initial network dimensioning and backhaul requirements.

Since the following definitions are the same for each traffic type and for each direction of the flow, henceforth only notation for the UL Voice flow will be cited. For each equation given below exclusively for the UL voice flow, there would be other five similar expressions for the other flows.

- Maximum Dynamic Throughput: $\hat{S}_{V_i}^{UL}[n] = \hat{S}_{V_i}^{UL} + \hat{M}_{V_i}^{UL}[n]$

This parameter is the current maximum throughput allowed by the edge router for the HNB *i* at time *n* for voice traffic in the uplink. It depends on the fixed term Maximum Guaranteed Throughput $\hat{S}_{V_i}^{\mathrm{UL}}$ and the variable term Dynamic HNB Margin $\hat{M}_{V_i}^{UL}[n]$. This dynamic margin can be greater, equal or less than zero, so the Maximum Dynamic

Throughput could be temporarily greater, equal or less than the Maximum Guaranteed Throughput.

- Current Generated Throughput: $S_{V_i}^{\mathrm{UL}}[n]$

This parameter corresponds to the actual throughput injected by the HNB *i* at time *n* for this type of flow to its corresponding edge router. The corresponding edge routed will discard the excess traffic from the HNB, upper bounding the Current Generated Throughput to the Maximum Dynamic Throughput ($S_{v_i}^{UL}[n] \leq \hat{S}_{v_i}^{UL}[n]$).

- Local Link Capacity: $\vec{S}_l^{\mathrm{UL}}[n]$

This parameter represents the throughput capacity of the link *l* at time *n* for the aggregated traffic in the UL direction when the delay is bounded to the maximum link delay D_l [D51]. The capacity $\vec{S}_l^{\mathrm{UL}}[n]$ will depend mainly on the modulation level used as well as other technology specific parameters (detailed in deliverable D51). The real capacity will be always higher than this parameter but the link will never work in this load curve zone since the performance regarding delay, losses and jitter is very poor. The D_l value will be determined by the size of the network in the dimensioning and planning stage (i.e number of hops) but also will depend of the frame duration for those links in which a TDMA solution has been selected. It is important to notice that only in TDMA technologies a UL/DL differentiation will be made, since in CSMA/CA WiFi systems a contention protocol is used and both ends of a link contend for the channel.

Regarding the backhaul dimensioning, it is necessary to design the network so that all the backhaul requirements can be accomplished. This can be translated in the following statement:

$$\vec{S}_l^{UL}[0] \geq \sum_{\substack{i \in l \\ x \in \{V,S,D\}}} \hat{S}_{x_i}^{UL}$$

where $i \in l$ are the HNBs whose traffic passes through the link *l* in its way to or from the gateway, and $x \in \{V,S,D\}$ represents the three traffic types. For both directions, DL and UL, each wireless link must be capable to transport all the traffic detailed in the initial planning, i.e, the Local Link Capacity at time *n* = 0.

The $\vec{S}_l^{\mathrm{UL}}[n]$ parameter can vary in time. Depending of the optimization goal, it is possible increase the modulation level in order to transport more traffic or reduce it in order to reduce the power consumption. Also, if eventual increment of fading or interferences exists, this capacity must be automatically reduced in order to avoid work above the saturation point in the specific link *l*.

- Dynamic Link Margin: $\vec{M}_l^{UL}[n]$

This parameter is the available throughput in a specific link *l* in the direction UL at time *n*; and represents the difference between the Local Link Capacity of the link *l* and the traffic demand on this link *l*. and one of the first decision to take is how to define this margin.

If this Dynamic Link Margin is calculated as follows:

$$\vec{M}_l^{UL}[n] = \vec{S}_l^{UL}[n] - \sum_{\substack{i\in l\\ x\in\{V,S,D\}}} \max\left(\hat{S}_{x_i}^{UL}, S_{x_i}^{UL}[n]\right),$$

where $i \in l$ are the HNBs whose traffics pass through the link *l* in its way to or from the gateway, and $x \in \{V,S,D\}$ represents the three traffic types; the link can be underused because we are saving link capacity to transport $\hat{S}_{x_i}^{UL}$ even when $\hat{S}_{x_i}^{UL} > S_{x_i}^{UL}[n]$. If the Dynamic Link Margin is calculated only taking into account the Current Generated Throughputs, we are doing a better use of the link but we must take other actions to guarantee the Maximum Guaranteed Throughputs.

When this Local Link Margin is greater than zero, it represents that the value Local Link Capacity is enough to transport all the current flows in the link and the optimization problem consists of how to distribute this excess of margin among all the HNBs *i*.

Usually when there is a malfunction in the network (interferences, high level of fading, etc.), the Local Link Capacity can decrease and this Local Link Margin is less than zero. It indicates that the traffic injection must be reduced to maintain the level of QoS in the network. In this case, the optimization problem consists on how to distribute this reduction of capacity among all the HNBs *i*, decreasing their Dynamic HNB Margins.

Note that, with severe malfunctions, a wireless link can be unable to transport all the traffic detailed in the initial planning:

$$\vec{S}_l^{UL}[n] < \sum_{\substack{i\in l\\ x\in\{V,S,D\}}} \hat{S}_{x_i}^{UL}$$

That case leads to negative Dynamic HNB Margins, which cuts down the Maximum Guaranteed Throughput to maintain the level of QoS in the surviving communications.

Note also that no offloading techniques are being considered in these definitions. However, using traffic offloading would increase the Local Link Margin and a most efficient use of the network would occur.

Considering all the previous definitions, the dynamic optimization of the multi-hop heterogeneous backhaul network consists of the fair distribution of the Dynamic Link Margins of the network among the Dynamic HNB Margins to maximize the throughput in the network. This optimization must consider the offered traffic by the HNBs and is subject to maintaining the required QoS.

This optimization implies several open questions that will be considered in the future deliverable D53. We name the next issues as examples of these open questions:

1. What information is available?
   The optimal solution to the optimization problem requires a perfect knowledge of all the network parameters at each instant of time (including throughputs, margins, offered load, delays...). However, the knowledge of all this information for all the involved routers may be unfeasible (in distributed solutions) or, simply, someone of these parameters could not be measured through feasible methods (even in centralized solutions).

2. How often this information is collected?
   Collect all the information in short periods improves the optimization results but implies an increase of signalling traffic in the network.

3. Who performs the margin calculations?
   We can consider a centralized solution where a supervisor node (may be the gateway) collects all the information, performs the optimization calculus and informs to all the edge routers of their corresponding Maximum Dynamic Throughput. Or consider a distributed solution where several nodes (may be the edge routers or the inner routers) collect partial information to calculate the Maximum Dynamic Throughput.

The optimization problem can be tackled either using heuristic techniques that leverage the operating conditions of the particular deployment, or under a more formal optimization framework. Based in all the previous definitions and open questions, in the future deliverable D53 we will explore two approaches to the dynamic optimization of the multihop heterogeneous backhaul network:

- Approach 1: Total knowledge of the network state.
  Considering the full knowledge of all the network parameters, we will formulate the optimization problem as a MCMCF problem in which the objective function will be maximized or minimized regarding the cost/rewards strategies. The output of this problem will be the optimum flow configuration of the network and it can be calculated in two ways. In a centralized mode, in which a core node gathers the network information, solves the optimization problem and sets the edge nodes policies regarding the output of the problem. Also it can be formulated in a decentralized version, where each edge node gathers the network information, solves the optimization problem and applies for himself the output of the problem.

- Approach 2: Partial knowledge of the network state.
  Considering only partial knowledge of the networks parameters, we will explore the implementation of distributed and iterative algorithms that converge to near optimal solutions. The difference here is that only information of the path of each edge node is needed in each edge node to perform the iterative algorithm in a distributed form, so a centralized implementation is not considered.

With this Approach 2, we are obtaining promising results in our preliminary researches so far. It is based on that the Local Link Margin of a given link causes modifications in the policy rules in the edge routers when the optimization objective is to maximize the traffic carried by the network. This Local Link Margin may be positive or negative, but in either case it must have a specific influence in the edge routers, allowing them to adjust the admitted traffic consequently. Since each edge router has a specific amount of users (HNB flows), it is necessary to define a distribution strategy, so that all edge routers affected by a specific Local Link Margin may update their traffic policy rules. One very simple but robust alternative is that each HNB gets a proportional portion of the margin, either if it is positive or negative. This way the distribution would be done according the planning design, giving more to those which has more traffic demand. This case can be defined as:

$$\hat{M}_{V_i}^{UL}[n] = \min_{l\in(i\rightarrow gateway)} \left(\frac{\hat{S}_{V_i}^{UL}}{\sum_{\substack{i\in l \\ x\in\{V,S,D\}}} \hat{S}_{x_i}^{UL}} \cdot \vec{M}_l^{UL}[n] \right)$$

where $(i \rightarrow gateway)$ $i \in i \rightarrow$ gatewayare the HNB's whose traffic passes through the link *l* in its way to or from the gateway. It can explain as: the margin assigned to HNB *i* at time *n* for the voice traffic in Uplink is the minimum of the $\vec{M}_l^{UL}[n]$ weighted with its demand. Similar expressions may be given for the downlink, and for the other traffic classes in both uplink and downlink.

Our preliminary results show that this simple algorithm converges to a near maximum network throughput, but may produce unfair states because this statement favours those HNBs which are using all its assigned capacity. When other HNBs want to use their entire assigned capacity, an unfairness situation arises related to the way the excess of margin is distributed. Only when the first HNB which uses all his assigned bandwidth has a traffic demand reduction may the other HNBs get an increment of Maximum Dynamic Throughput. To avoid this unfair performance, we will study the introduction of penalties in the assignation of margins to HNBs that are transmitting well above its initial Maximum Guaranteed Throughputs.

3.4 Techniques to make possible the dynamic adaptation of the transport network

The previous subsection has proposed a theoretical approach to studying the dynamic adaptation of the transport network. This subsection focuses on the possible techniques that may harvest the parameters required to implement any optimization strategy.

Summarizing, from a practical point of view the strategy is summarized as follows:

- The end-to-end state of the path between each edge-router and the gateway must be monitored. Ideally, several parameters should be measured on a per-hop basis: delay and jitter, queue status, available bandwidth (or congestion level) and battery levels.
- This information shall be provided to the edge router (and maybe to the gateway). Then, a mechanism to transport this information is required.
- The transport network may be temporary unable to provide the expected QoS due to environmental changes that make the performance differ from the one expected in the original design. In this case, the edge routers must modify their policing and traffic conditioning actions as appropriate.

- Also the downlink traffic (from the gateway to each edge router) must be taken into account. Two alternatives are considered:
    1. The gateway also receives the state information from all the nodes in the transport network. Hence, it performs actions for all the downlink flows similar to the ones that each edge node performs for its specific uplink flows.
    2. Since one gateway may support a high number of flows, the previous option might not scale. In this case, no change in the traffic shaping or queues is carried out in the downlink. Instead it is expected that, since most services are bidirectional, the constraints imposed to the uplink will in turn produce a proportional effect on the downlink traffic.

3.4.1 Measurement of state parameters in the transport network nodes

There are three types of parameters that should ideally be measured:

- Node parameters (related to the state of each node): batteries and queues.
- Link parameters (related to the state of each hop): uplink and downlink rate (transmitted and available), uplink and downlink congestion state, uplink and downlink one-way delay, uplink and downlink jitter, and two-way delay.
- End-to-end parameters (related to the path between each edge-router and the gateway) uplink and downlink rate (transmitted and available), uplink and downlink congestion state, uplink and downlink one-way delay, uplink and downlink jitter, and two-way delay.

For measuring battery levels, an ad-hoc solution to obtain a voltage lecture in all nodes is needed. For example, if there is a GPIO port in the devices that are used as routers, it can be used to obtain the voltage directly. Other alternatives may be studied that permit each node to get a voltage measurement periodically.

The state of the queues is a useful measurement of the congestion state. When studying a path in the transport network, two different devices have to be considered separately in each node: the wireless device that receives the outgoing traffic and the IP router itself. With the traffic management policy explained in [D52], measuring the queues in the routers does not make any sense, since the connection between the router and both wireless devices will always have enough bandwidth and the router's queues will normally be empty. Then, the queues in the wireless devices should be measured. However, there is not a simple general solution for this purpose since the wireless devices to be used are heterogeneous (Wi-Fi, WiMAX, VSAT, etc.). Hence, there are two alternatives: (1) not measuring the queues; (2) using device-dependant management software to query each device. Although the second option will be investigated, the first option is preferable if the optimization solutions may go without this information.

In order to measure the rest of parameters, there are many existing tools that will be tested. Table 1 enumerates the main ones. The approach in [Rattaro10] with an extension to infer the one-way delay will also be investigated.

Name	**Rel.**	**Platform**	**Information/code**
BPROBE	1996	Linux	http://www.cs.bu.edu/~crovella/src/bprobe/Tools.html
CPROBE	1996	Linux/C	http://www.cs.bu.edu/~crovella/src/bprobe/Tools.html
PATHCHAR	1997	Linux	http://www.caida.org/tools/utilities/others/pathchar/
CLINK	1999	Linux/C	http://allendowney.com/research/clink/
RTPL	2000	JAVA	http://staff.science.uva.nl/~jblom/rtpl/index.html
NETTIMER	2001	Linux	https://www.usenix.org/conference/usits-01/nettimer-tool-measuring-bottleneck-link-bandwidth
PATHCHIRP	2003	Linux/C	http://www.spin.rice.edu/Software/pathChirp/
STAB	2003	Linux/C	http://www.spin.rice.edu/Software/STAB/
SPROBE	2003	Linux/C	http://sprobe.cs.washington.edu/
DIETTOP	2004	Linux	doi=10.1.1.330.965
PCHAR	2005	Linux, C++	http://www.kitchenlab.org/www/bmah/Software/pchar/
THRULAY	2005	Linux/C	http://thrulay-hd.sourceforge.net/
PATHLOAD	2006	Linux/C	http://www.cc.gatech.edu/fac/constantinos.dovrolis/bw-est/pathload.html
PATHRATE	2006	Linux/C	http://www.cc.gatech.edu/~dovrolis/bw-est/pathrate.html
IGI	2006	Linux/C	http://www.cs.cmu.edu/~hnn/igi/
PTR	2006	Linux	http://www.cs.cmu.edu/~hnn/igi/
IGI	2006	Linux/C.	http://www.cs.cmu.edu/~hnn/igi/
ASSOLO	2009	Linux/C	http://netlab-mn.unipv.it/assolo/
IPERF	2011	Most	http://sourceforge.net/projects/iperf/
YAZ	2011	Linux	https://github.com/jsommers/yaz
NETPERF	2012	Linux/C	http://www.netperf.org/netperf/NetperfPage.html
OWAMP	2012	Most	http://software.internet2.edu/owamp/

Table 1. Tools to measure network performance.

4 CONCLUSIONS

This document includes all the information required to model the proposed technologies in a transport network for performance optimization. The factors that impact on cost, performance and power consumption have been qualitatively discussed.

The dynamic operation of the transport network has also been formally described, and the state of the art for the performance optimization of a network of this type has been studied. The basic strategy for such optimization has been developed, including formulation and definition of the optimization goals. Also the strategies and tools to use for practically gathering information in real implementations have been explored.

All the previous achievements are the basis for the definition and solution of optimization problems, which will be the content of deliverable D53. Also some results will be provided in that deliverable for the strategy definitely proposed for the access network-transport network interface.