FEDERAL UNIVERSITY OF PARÁ
INSTITUTE OF TECHNOLOGY
POST GRADUATE PROGRAM IN ELECTRICAL ENGINEERING

FABRÍCIO DE SOUZA FARIAS

DESIGNING COST-EFFICIENT TRANSPORT SOLUTIONS FOR FIXED AND MOBILE BROADBAND ACCESS NETWORK

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Doctoral Thesis submitted to the examining committee of the Post Graduate Program in Electrical Engineering from Federal University of Pará as a requirement to obtain the title of Doctor in Electrical Engineering.

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DESIGNING COST-EFFICIENT TRANSPORT SOLUTIONS FOR FIXED AND MOBILE BROADBAND ACCESS NETWORK

AUTHOR: FABRICIO DE SOUZA FARIAS.

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God is wonderful!

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SUMMARY

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ACRONYMS

ADSL2+ - Asymmetric Digital Subscriber Line

AFR - Annualized Failure Rate

AP - Access Point

BM - Brownfield Migration

CAPEX - Capital Expenditure

CDMA-IS95 - Code Division Multiple Access - Interim Standard 9

CO - Central Office

DF - Distribution Fiber

DSL - Digital Subscriber Line

DSLAM - Digital Subscriber Line Access Multiplexer

EARTH - Energy Aware Radio and Network Technologies

FF - Feeder Fiber

FP7 - Seventh Framework Programme for Research and Development

FS - Fiber Switch

FTTB - Fiber-To-The-Building

FTTC - Fiber-To-The-Curb

FTTH - Fiber-To-The-Home

FTTN - Fiber-To-The-Node

FFTX - Fiber-To-The-X

GD - Greenfield Deployment

GES - Gigabit Ethernet Switch

GSM - Global System for Mobile Communications

HetNets - Heterogeneous Networks

ITU-T - International Telecommunications Union - Telecommunication Standardization Sector

LOS - Line of Sight

LTE - Long Term Evolution

METIS - Mobile and Wireless Communications Enablers for the Twenty-Twenty Information Society

MN - Metro Network

MON - Maintenance Cost Of Network

MTTR - Mean Time to Repair

MW - Microwave

NGOA - Next Generation Optical Access

OLT - Optical Line Terminal

ONU - Optical Network Unit

OperaNet - Optimizing Power Efficiency in Mobile Radio Networks

OPEX - Operational Expenditure

PC - Personal Computer

PMP - Point-To-Multipoint

PON - Passive Optical Network

PTP - Point-To-Point

QoS - Quality of Service

RAN - Radio Access Network

RN - Remote Node

SFP - Small Form-Factor Pluggable

SFP+ - Small Form-Factor Pluggable Plus

SLA - Service Level Agreement

TCO - Total Cost of Ownership

TDM - Time Division Multiplexing

UMTS - Universal Mobile Telecommunication System

VDSL2 - Very-high bit rate DSL

WAN - Wide Area Network

WDM - Wavelength Division Multiplexing

WIMAX - Worldwide Interoperability for Microwave Access

LIST OF SYMBOLS

α - Impact Factor that Measures the Reputation Losses from the Telecommunication Operators

$\alpha(t)$ - Average Daily Traffic Variation in Terms of Percentage of Active Users for a given Time *t*

β - Parameter that Defines the Number of Business Clients

τ - Minimum Capacity Provided to the End-User

ρ - Population Density in the Area

η - Femto Penetration Rate

γ - Impact Factor that Controls the Price per Extra Gbps accordingly to the Extra Traffic Requested

A – Area

A_{cab} - Standard Size for Cabinets

A_{hub} - Area of a Microwave Hub

Cab_M - Maintenance Cost of Cabinets

Co_M - Maintenance Cost of Central Offices

C_{macro} - Maximum Transmission Capacity of a Macro Base Station

$C_i^{penalty}$ - Penalty Costs at State *i*

C_i^{repair} - Related Costs of Failed Equipment Repair at State *i*

$D_{Building \rightarrow RN}$ - Distance from a Building to the Remote Node

$D_{DFS \rightarrow RN}$ - Distance from a Distribution Fiber Step to the Remote Node

$D_{FFS \rightarrow CO}$ - Distance from a Feeder Fiber Step to the Center of Scenario

$D_{PDFS \rightarrow RN}$ - Distance from a Protection Distribution Fiber Step to the Remote Node

$D_{PFFS \rightarrow CO}$ - Distance from a Protection Feeder Fiber Step to the Center of Scenario

$D_{RN \rightarrow CO}$ - Distance from a Remote Node to the Center Office

l - Distance between Buildings

l_{df} - Distance between Buildings

L_{Fiber}^{DF} – Distance to Distribute the Fiber Links to Connect the Edge-Equipment

L_{Fiber}^{PTP} - Distance to Feed the Fiber Links to Connect the Splitters

l_{ff} - Length of a Street Block

L_i - Length of Each Cable Section in Kilometers

L_{Fiber}^{PTP} - Total Length of Fiber to be Fed

M_{Co}^{cost} - Fixed Cost to be Paid for Hardware Upgrade, and for Replacing Some Materials in the Central Office

M_{Cab}^{cost} - Cost to be Paid for Hardware Upgrade, and Replacing Some Materials in the Cabinet

MW_M - Maintenance Cost of Microwave Links

n - Number of Buildings or Houses in a Row

N - Number of Remote Node in a Row

$N_{active/macro}$ - Number of Active Users that can be Served by a Macro BS

N_{ap} - Total Number of Apartments in the Area

$N_{Ap/floor}$ - Number of Apartments per Floor

N_{bf} - Number of Buildings with Femto Base Stations

N_{BS} - Number of Base Stations in the Area

N_j^{cab} - Number of Cabinets in Year *j*

N_i^{Co} - Number of Central Offices

n_{df} - Number of Buildings Connected in Each Local Exchange

$N_{Direction}$ - Number of Antenna Directions

N_{DSLAM} – Number of DSLAMs

n_{ports}^{DSLAM} – Number of Ports per DSLAM

N_{Rack}^{Eq} - Number of Equipment per Rack

N_{type}^{eq} - Number of Equipment Types

N_i^{Eq} - Number of Pieces of Equipment of Type *i*

$N_i^{\frac{Eq}{Co}}$ - Number of Pieces of Equipment located in the inside the Central-Office Racks

n_{ff} - Number of Fiber Connections

N_{floors} Number of Floors per Building

n_{ports}^F – Number of Ports of a FS

N_s^F – Number of FSs Aggregating Indoor Traffic

N_{ul}^F – Number of Uplink Connections Towards FS and MN

NB_{sub}^{fail} - Number of Business Subscribers Affected by Failure

NR_{sub}^{fail} - Number of Residential Subscribers Affected by Failures

N_{sub}^{failed} - Number of Failed Subscriber in the Network

$N_k^{failuredEq}$ - Number of Failure Equipment *k*

$N_{avg}^{failureEq}$ - Average Number of Failure Equipment

N_{femto} - Number of Deployed Femto Base Stations

N_{i}^{fiber} - Number of Fibers per Cable in the Location of Failure that needs to be spliced

n_{ports}^{GES} - Total Number of Ports of the GES

N_{hub} - Total Number of Hubs

N_{i}^{node} - Total Number of Nodes

$N_{j}^{MacCell}$ - Number of Macro Cells with High Importance in Year *j*

N_{macro} - Total Number of Macro Base Stations

N_{s}^{MW}- Total Number of Fiber Switches (FSs) Inside the Hubs

N_{ul}^{MW} – Total Number of Uplink Connections between FS and MN

N_{MWant}^{Mh} - Yearly Man-Hours Required for the Maintenance of each Microwave Antenna

N^{MWLink} - Number of Microwave Links Used for the Backhaul

N_{Co}^{Mh} - Man-Hours Required for the Maintenance of Each Central Office per Year

N_{Cab}^{Mh} - Man-Hours per Cabinet

N_{op} - Number of Mobile Operators in the Area

n_{cards}^{OLT} - Number of OLT Cards

N_{OLT} - Number of OLTs in the Network

$N_{failured}^{ONU}$ - Expected Number of Failed ONUs during Analysis Time

N_{i}^{Port} - Number of Ports to be Installed

$N_{SmallBlocks}$ - Number of Local Exchanges

$n_{ports}^{Splitter}$ - Number of Ports per Splitter

N_{tech} - Number of Technicians required to Repair a Failure

P_{bh}^{arch5} - Power Consumption of Architecture 5

P_{bh}^{arch4} – Power Consumption of Architecture 4

P_{bh}^{arch3} - Power Consumption of Architecture 3

P_{bh}^{arch2} - Power Consumption of Architecture 2

P_{bh}^{arch1} - Power Consumption of Architecture 1

Pr_{bus} - Business Penalty Rate Agreed in SLA

$P_{i}^{cost/h}$ - Penalty Rate per hour

P_{DSLAM} - Power Consumption of a DSLAM

P_k^{Eq} - Power Consumption of the Equipment k

Pr_i^{Eq} – Equipment Price

$Pr_{perKm}^{FiberLease}$ - Cost to Lease one Km of Fiber

Pr_{Fiber} - Price to Feed Fiber per Km

P_s^F - Power Consumption of a FS

P_{GES} - Power Consumption of a GES

P_{high-c} - Power Consumption of a Microwave Antenna in High Capacity Mode

P_h - Horizontal Position

Pr_{Gbps} - Price per Gbps Secured with the Operator

Pr_{Gbps} - Price per Extra Gbps

Pr_{fiber}^{inst} - Price to Install Fiber per Km

Pr_k- Price of the Failed Equipment

Pr_i^{kWh} - kWh Price

$Pr_{CostperKm}^{LeaseAcquisition}$ - Cost Acquisition to Secure a Contract for the Next Years

Pr_{link} - Price of One Link to Communicate the Base Station with the Aggregation Node

P_{low-c} - Power Consumption of a Microwave Antenna in Low Capacity Mode

P_s^{MW} - Power Consumption of a Fiber Aggregation Switch

Pr^{MWLink} - Microwave Link Price

P_{modem} - Power Consumption of a VDSL2 Modem

P_{ONU} - Power Consumption of an ONU

P_{OLT} - Power Consumption of an OLT

Pr_i^{Out/m^2} - Yearly Rental Fee Paid by an Operator for Outdoor Areas

Pr_{res} - Residential Penalty Rates Agreed in SLA

P_{SFP+} - Power Consumption of a SFP+

P_{SFP} - Power Consumption of a SFP

Pr_{Tech} - Salary of a Technician per Hour

$Pr_{Trenching}$ - Price to Trench per Km

P_v - Vertical Position

$\mathrm{Pr}_{Rack}^{Ind/m}$ - Yearly Rental Fee Paid by an Operator for Indoor Areas

$R(t)$ - Daily-Generated Traffic over a given Area

$r_k^{ordinary}$ - Hourly Average Data Rate of an Ordinary User

r_k^{heavy} - Hourly Average Data Rate of a Heavy User

r_k - Average Data Rate

$\bar{r}$ - Average Data Rate Requirement per Active User

Sal - Crew Salary

SR - Splitting Ratio

s_k - Fraction of the Subscribers Using Terminal Type k

SW_{lic} - Yearly Fee Paid for the Software Licenses

t - Time of Analysis in Hours

$Tot_{InstCost}^{CopperEq}$ - Cost for Installing Equipment of Copper

T_D - Desired Time Interval in Hours

$Tot_{InstCost}^{DFProtection}$ - Total Cost to Install Protection in the Distribution Fiber

$Tot_{trenchCost}^{DFProtection}$ - Total Cost to Trench the Protection in the Distribution Level

Tot_{Trench}^{DF} – Distance to Trench the Paths from the Splitters up to the ONUs

Tot_{Cost}^{Eq} - Equipment Cost

$Tot_{InstCost}^{Eq}$ - Total Cost for Installing Equipment

$Tot_{instCost}^{Fiber}$ - Fiber Installation Cost

$Tot_{instCost}^{FFProtection}$ - Cost to Install Protection in the Feeder Fiber

$Tot_{trenchCost}^{FFProtection}$ - Total Cost to Trench the Protection Fiber in the Feeder Fiber

$Tot_{InstCost}^{Fiber}$ - Total Cost to Feed and Distribute the Fiber Over the Area

$Tot_{InstCost}^{FiberEq}$ - Total Cost for Installing Equipment of Fiber

Tot_{cost}^{FlSp} - Floor Space Cost

$Tot_i^{kWh/y}$ - Yearly kWh Consumed by Equipment

Tot_{Cost}^{M} - Total Maintenance Cost

$Tot_{InstCost}^{MWEq}$ - Cost for Installing Equipment of Microwave

$Tot_{LeaseCost}^{PTP}$ - Total Leasing Cost of a PTP Infrastructure

$Tot_{LeaseCost}^{PON}$ – Total Leasing Cost of a PON Infrastructure

$Tot_{InfraCost}^{PTPLease}$ - Total Cost for PTP Infrastructure

$Tot_{InfraCost}^{PONLease}$ - Total Cost for PON Infrastructure

$Tot_{InfraCost}^{Trench}$ - Total Cost for Trenching the path from the Central Office up to the Remote Node and User-Premises

$Tot_{rent}^{TrafficExceeded}$ - Total Cost Associated with Failures that are over the Expected Average of Failures in the Network

$Tot_{cost}^{TrafficRent}$ - Traffic Rent Cost

$Tot_{FiberTrench}$ - Distance to be Trenched to Connect all Infrastructure

Tot_{Cost}^{infra} - Total Infrastructure Cost

$Tot_{Cost}^{TrafficRent}$ - Total Cost of Traffic Rented

$Tot_{Cost}^{TrafficExceeded}$ - Traffic Exceeded Cost

$Tot_{Cost}^{SpectrumRent}$ - Total Cost of Microwave Spectrum Leasing

$Tech_i^{sal}$- Hourly Salary of Each in Year i

$T_{MWant_i}^{trav}$ - Travelling Time to the Location of each Antenna

$T_i^{InstallPort}$ - Total Time to Install an Equipment Port

T_i^{inst}- Time to Install

Tot_{Cost}^{Energy} – Total Energy Cost

$Tech_{team}$ - Number of Technicians per Team

T_{sp}- Time of Splicing per Fiber

TT - Troubleshooting Time

T_{trav} - Travelling Time to the Location of the Failure

$unAv_{ij}$ - Number And Connection Unavailability of Backhaul Link to the Macro Cell i.

$UnAv_{fiber}$ - Fiber Unavailability per Kilometer

μ_{ONU} - Failure Rate of ONU

$\frac{dis_i}{vel}$ - Travel Time to the Equipment

$\left\lceil \frac{n^2}{SR} \right\rceil$ - Number of Splitters in One Block

List of Papers

List of papers included in the thesis:

I. M. Fiorani, S. Tombaz, **F. Farias**, L. Wosinska, P. Monti, "Joint Design of Radio and Transport for Green Residential Access Networks", IEEE Journal on Selected Areas in Communications (JSAC), Special Issue on Energy-Efficient Techniques for 5G Wireless Communication Systems, to appear, 2016.

II. Lopes, Albert Richard Moraes; **Farias, Fabricio S.**; Costa, João Crisostomo Weyl Albuquerque. Evaluation of the Energy Impact on Indoor Small Cells and Backhaul. International Journal of Future Computer and Communication, v. 4, p. 152-159, 2015.

III. Lopes, Albert Richard Moraes; **Farias, Fabricio S.**; Costa, João Crisostomo Weyl Albuquerque. An Energy Efficiency Assessment for Indoor Small Cells Using Copper-Based Backhaul. International Journal of Future Computer and Communication, v. 4, p. 170-174, 2015.

IV. Fernandes, A. L. P.; **Farias, F. S.**; Santos, I. M.; Costa, J. C. W. A. Economic Analysis on Passive Optical Networks Using Markov Chain and Monte Carlo Simulation. In: XXXIII Simpósio Brasileiro de Telecomunicações, 2015, Juiz de Fora. Anais do XXXIII Simpósio Brasileiro de Telecomunicações, 2015.

V. S. Tombaz, P. Monti, **F. S. Farias**, M. Fiorani, L. Wosinska, J. Zander, "Is Backhaul Becoming a Bottleneck for Green Wireless Access Networks?," In *IEEE International Conference on Communications (ICC)*, Sydney, vol., no., pp.4029,4035, 10-14 June 2014.

VI. **Farias, F.S.**; Monti, P.; Vastberg, A.; Nilson, M.; Costa, J.C.W.A.; Wosinska, L., "Green backhauling for heterogeneous mobile access networks: What are the challenges?," *Information, Communications and Signal Processing (ICICS) 2013 9th International Conference on* , vol., no., pp.1,5, 10-13 Dec. 2013.

List of related papers not included in the thesis:

I. Mate, D. M.; **F. S. Farias.**; Costa, J. C. W. A. Estudo da Interferência do Sistema PLC no DSL. In: XXXIII Simpósio Brasileiro de Telecomunicações, 2015, Juiz de Fora. Anais do XXXIII Simpósio Brasileiro de Telecomunicações, 2015.

II. Mate, D. M.; **F. S. Farias.**; J. C. W. A. Costa. Digital Television Interference on the LTE System in the 700 MHz Band. In: XXXIII Simpósio Brasileiro de Telecomunicações, 2015, Juiz de Fora. Anais do XXXIII Simpósio Brasileiro de Telecomunicações, 2015.

III. Dércio M. Mathe; Lilian C. Freitas; **Farias, F.S.**; J. C. W. A. Costa. "Interference Analysis between Digital Television and LTE System under

Adjacent Channels in the 700 MHz Band," Journal of Information Technology & Computer Science (IJITCS), v. 13, p. 42-50, 2014.

IV. Dércio M. Mathe; Lilian C. Freitas; **F. S. Farias.**; J. C. W. A. Costa. "Performance Analysis of LTE under Interference of Digital Television in Adjacent Channel," In: The 2nd Radio and Antenna Days of the Indian Ocean (RADIO), 2014, Mauritius. Radio and Antenna Days of the Indian Ocean RADIO 2014, 2014.

V. **Farias, F. S.**; Borges, G. S.; Monteiro, W. B.; Silva, D. L. L.; Costa, J. C. W. A."Noise estimation in DSL systems using linear regression, " In: 2013 International Conference on Advanced Technologies for Communications (ATC 2013), 2013, Ho Chi Minh. 2013 International Conference on Advanced Technologies for Communications (ATC 2013), 2013. p. 291.

VI. **F. S. Farias**, G. S. Borges, R. M. Rodrigues, A. L. Santana, J. C. W. A. Costa, "Real-time noise identification in DSL systems using computational intelligence algorithms," *Advanced Technologies for Communications (ATC)*, 2013 International Conference on , vol., no., pp.252,255, 16-18 Oct. 2013.

THESIS STRUCTURE

This thesis is divided in 5 chapters.

Chapter I introduces the main concepts about heterogeneous networks, transport schemes, i.e., mobile backhaul and protection schemes. Moreover, it constitutes of both related literature and hypothesis. This chapter uses information from Paper I, II, III, IV, V and VI.

Chapter II presents the main base station technologies available in market and the different options of access medium to transport next year's traffic. This chapter used information from Paper VI.

Chapter III introduces the proposed assessment methodology, based on Greenfield or Brownfield backhaul deployment. In this chapter all math models are presented and described, e.g., traffic model, backhaul models, etc. Additionally, a case study and results are presented. In this chapter, it was used information from Paper I, V.

Chapter IV introduces the proposed passive optical network protection schemes. Furthermore, it demonstrates all the models developed to obtain the main resolutions. Finally, a case study and its results are presented. In this chapter, it was used information from Paper IV.

Chapter V discusses the overall conclusions and future work.

ABSTRACT

This thesis undertakes a techno-economic evaluation of transport solutions for fixed and mobile broadband access. In the case of future mobile access networks, it is proposed to make use of backhaul architectures using fiber and microwave applied to Greenfield deployments and a copper-legacy backhaul infrastructure based on Brownfield migration, i.e. finding a way of using a legacy infrastructure to its full capacity. At the same time, protection deployments based on fiber-wireless schemes are recommended for future fixed broadband. The main contribution made by this thesis is to carry out a research investigation into the total investment cost of the broadband transport infrastructure. This will be determined by employing two sets of models to assess the capital and operational expenditures, (CAPEX and OPEX respectively), of mobile and fixed broadband access network operators. First, this involves a set of models for mobile broadband that are summarized in a general methodology that aims at providing: traffic forecasting, wireless deployment, mobile backhaul deployment and total cost assessment. It was found that, fiber-based backhaul through a Greenfield deployment is the most energy-efficient option. Furthermore, Brownfield reveals that copper-based backhaul can still play a key role if used up to its full capacity and sharply reduces the investment costs in infrastructure. Additionally, there is an examination of the main differences in cost and energy values between Greenfield and Brownfield. Finally, a methodology is employed for fixed broadband based on network dimensioning, failure costs and an assessment of the total cost of ownership. The models are used to assess five architectures that represent different protection schemes for fixed broadband. This research shows the economic benefits of using a hybrid protection scheme based on fiber-wireless architecture rather than fiber-based protection options and a sensitivity analysis is conducted to show that the extra CAPEX invested to protect the infrastructure might be recovered through the OPEX after a number of years. The results obtained in the thesis should be useful for network operators to plan both their fixed and mobile broadband access network infrastructure in the future.

Keywords: Fixed broadband, Mobile backhaul, Capital Expenditure, Operational Expenditure.

RESUMO

Esta tese se concentra na avaliação técnico econômica de soluções de transporte para acesso banda larga fixa e móvel. Para futuras redes de acesso móvel, propõem-se arquiteturas de backhaul usando fibra e microondas baseado no desenvolvimento de redes de acesso wireless verde e infraestruturas legadas de backhaul baseada em cobre para migração *Brownfield*, ou seja, usando infraestrutura existente até o limite de capacidade suportada, enquanto para redes de banda larga fixa são propostas implantações de proteção baseadas em esquemas híbridos, ou seja, fiber+wireless.

As principais contribuições desta tese estão relacionadas ao campo de pesquisa do custo total de investimento em infraestrutura de transporte banda larga. Em termos de custo total de investimento, são propostos dois conjuntos de modelos para avaliar as despesas de capital e de operação, CAPEX e OPEX respectivamente, de operadoras de redes de acesso banda larga fixa e móvel. Primeiramente, para banda larga móvel, é apresentado um conjunto de modelos condensado em uma metodologia geral que visa fornecer: previsão de tráfego, implantação de rede sem fio, implantação de backhaul móvel e avaliação do custo total. É mostrado que o backhaul baseado em fibra considerando acesso sem fio verde é a opção mais eficiente em termos de energia. Além disso, *Brownfield* mostra que o backhaul baseado em cobre ainda pode desempenhar um grande papel se utilizado até a exaustão de sua capacidade e reduz drasticamente os custos de investimentos em infraestrutura. Adicionalmente, são apresentadas as principais diferenças de custos e valores de energia entre redes de acesso sem fio verde e *Brownfield*. Finalmente, para banda larga fixa, é proposta uma metodologia baseada em dimensionamento de rede, custos associados à falha e avaliação do custo total por assinante. Os modelos são utilizados para avaliar cinco modelos que representam diferentes esquemas de proteção para arquiteturas de banda larga fixa. Esta pesquisa revela os benefícios econômicos do uso de esquema de proteção híbrido baseado em arquitetura fiber+wireless comparado com a opção de proteção baseada totalmente em fibra e é também apresentada uma análise de sensibilidade para provar que o investimento adicional em CAPEX para proteger a infraestrutura pode ser recuperado em alguns anos através da economia em OPEX.

Os resultados obtidos na tese podem ser úteis às operadoras de rede para planejar tanto suas infraestruturas de redes de acesso fixas quanto móveis.

Palavras chaves - Rede de Banda Larga Fixa, Backhaul, CAPEX, OPEX.

CHAPTER I

INTRODUCTION

This chapter sets out the main research challenges that transport network operators, (i.e., mobile and fixed), are facing during the period of network dimensioning. Its objective is to demonstrate to the reader the importance of finding techno-economic solutions in the telecommunication field. Finally, two hypotheses that are raised and these are validated in the following chapters.

1.2.1 Main Research Projects on Mobile Backhaul

Recently, the popularization of new Internet devices such as modern laptops, tablets and smartphones has caused an unprecedented growth in the demand for data traffic [1][2][3]. Studies have shown that this data growth has a direct impact on network dimensioning, i.e., by sharply increasing the amount of equipment, (e.g., transport or radio equipment to meet the increasing demand) [4][5][6]. The introduction of extra equipment in the network access layer increases the need for investment. This, leads to a reduction in profits on the side of the operator [7] and forces operators to introduce protection schemes to guarantee reliable services anytime and anywhere.

The reduction in revenue has forced operators to find both energy and cost-efficient alternatives to handle the upcoming traffic demand, e.g., by investing in renewable energy [8], base stations with standby technology for discontinuity [9], and Heterogeneous Networks (HetNets) [10][11]. Among all the attempts to define the access layer through reducing energy consumption and Total Cost of Ownership (TCO), HetNets have proved to be the most attractive option [11][12].

HetNets use macro base stations, which guarantee full coverage of the area, and small cells, (e.g., micro-, pico- and femto base stations), to ensure a sufficiently high capacity to meet traffic demands. Moreover, HetNets are able to reduce the energy consumption of mobile access networks by replacing a number of energy-demanding macro cells with small cells [13][14].

Although HetNets have the benefits mentioned above, there are some drawbacks related to their use, e.g., owing to the densification of the number of small cells in the

HetNets, the energy consumption and operational costs of mobile backhaul have begun to represent a significant proportion of final bill [4]. Mobile backhaul is a term used to describe the connectivity between base stations and metro aggregation node in cellular systems in a wide range of transport media, (e.g., fiber and copper) [15] and the impact undergone by the backhaul is mainly caused by the "explosion" of the number of devices (switches, digital subscriber line access multiplexers, microwave antennas, etc.) that are required to connect all the macro base stations and small base stations through the access layer to the metro aggregation node.

The increasing amount of backhaul equipment raises new challenges/questions for the operators regarding profit margins and cost efficiency and how these problems must be solved. For example, the operators might decide either to deploy a new backhaul network (Greenfield) or upgrade an existing infrastructure (Brownfield) to transmit the traffic generated in the radio access networks. In the Greenfield scenario, the infrastructure is built from scratch and is usually chosen when the operator migrates from an incompatible technology or when a new contract is secured, thus forcing a general capacity upgrade [16]. On the other hand, Brownfield scenarios involve situations when the operator exploits the opportunities created by the legacy infrastructure, e.g., based on copper that is used to its full capacity and reuses the available infrastructure as much as possible to reduce the amount required for extra investment. The Brownfield solution raises the problem of defining at what point it is energy-efficient and profitable to make use of an old infrastructure.

To the best of our knowledge, most of the projects and papers related to HetNets and mobile backhaul subjects entail energy-efficient and Greenfield deployment [10][11][17][18][19][14][20][21]. In addition, there is no overall TCO methodology for evaluating different backhaul options in terms of costs and energy which employ both Greenfield and Brownfield strategies.

Among the main projects, Energy Aware Radio and Network Technologies (EARTH) consortium [17] adopt an approach aimed at reducing costs and minimizing the energy consumption of Long-Term Evolution (LTE) networks, which provide solutions at each level from the lowest level up to the system level. The Optimizing Power Efficiency in Mobile Radio Networks (OperaNet) project [18] adopts a general approach which takes account of a complete end-to-end system after it has optimized cooling systems, a terminal design, an energy recovery system in base stations, etc. The GreenHaul [22] project focused on the task of understanding how different backhaul technologies and architectures may affect the total backhaul power consumption and then applying the knowledge to devise HetNet deployment strategies for the overall broadband segment; the aim of this is to reduce the total power consumed by the mobile wireless access and backhaul segments combined. Finally, there is the project involving Mobile and Wireless Communications Enablers for the Twenty-twenty Information Society (METIS) [23], an integrated scheme that was partly funded by the European Commission under the Seventh Framework Programme for Research and Development (FP7) framework [24]. METIS was set up by leading telecommunications companies in order to address the technical challenges arising from the avalanche of increasing traffic, upsurge of connected devices, and wide range of services and information requirements for the connected society beyond 2020. The "technology components" as well as the "horizontal topics" needed to build the next generation mobile system, ("5G"), which form the main bricks of METIS, are fully investigated in this project.

In terms of papers, [19] investigates the effect of small cell deployments on urban and dense urban areas from the perspective of energy consumption. The authors use a parametric power model for legacy macro cell networks and new emerging small cells. The study quantifies the power reduction gained by deploying HetNets that consist of a blend of both technologies mentioned. As a part of the study, a framework was established to determine the optimal network architecture in terms of a combination of small cells and macro cells. The results obtained are based on the traffic demand data measured from the urban area of Wellington, NZ. Additionally, the paper investigates the impact of future traffic growth and provides a 5-year forecast of the network energy consumption. The numerical results confirm that a considerable reduction in power was achieved from deploying small cells. Furthermore, the study suggests that improving the power consumption in idle mode of small cells, is one key area that can make a significant reduction in the total power. The authors in [11] and [13] employed methodologies to evaluate the impact of different backhaul architectures on the overall mobile network power consumption. In particular, the authors in [11] assessed the power consumption of backhaul networks based on fiber (with point-to-point topology) and microwave (with point-to-point, ring and star topology), and showed that backhaul networks are responsible for a significant part of the overall power consumption in the case of HetNet deployments. To conclude, the backhaul network should be carefully included in any deployment strategy with the aim of minimizing the total mobile network power consumption. With this in mind, paper [20] investigates the relationship between energy efficiency and densification with regard to the network capacity requirements. The authors propose a framework that takes account of interference, noise and backhaul power consumption. The numerical results show that deploying smaller cells significantly reduces the transmitted power at the base station, and thus shifts the key elements of energy consumption to idle and backhauling power. Additionally, paper [25] analyses the possibility of exploiting the load balancing between the base stations to improve the backhaul capacity utilization. Load balancing is performed through cell selection algorithms that take into account both the radio interface and backhaul conditions. The obtained results show that the proposed algorithm can achieve a higher rate of backhaul resource utilization than the traditional cell selection schemes while providing the same radio interface performance. Finally, in [13] the impact of backhaul energy consumption on future green HetNets was investigated at different user-equipment traffic levels and with different backhaul technologies. The results confirm that the backhaul plays a significant role in the total HetNet power consumption, and more importantly, that its role becomes more prominent when there is an increase in traffic generated by the user-equipment.

While the papers mainly mentioned above, tended to only focus on power consumption, more recently there have been studies aimed at assessing and minimizing the TCO of the backhaul networks in HetNet deployments [4][5][26][4][27][28][29]. In [26] a techno-economic model was proposed to compute the TCO of radio networks, i.e., macro and femto base stations, and backhaul. The results show that it is possible to reach up to 70% cost savings when using indoor small cell deployments instead of traditional macro deployments in urban areas. The works in [4][27] studied various wireless architectures (both homogenous and heterogeneous) and assessed the impact of backhaul on the entire TCO. The results suggest that the backhaul solution represents a considerable portion of the TCO in the femtocell deployment scenarios, when compared with the case of macrocell deployment. In [28], the authors evaluated microwave backhaul in terms of cost-efficiency for rapid outdoor deployment. The results showed that point-to-point microwave is the most cost-efficient technology for providing high backhaul capacity in short deployment times. The authors in [29] and [5] assessed the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) of several 4G Greenfield deployment scenarios. In particular, paper [29] assessed the economic impact of fiber and microwave backhaul solutions for low and high traffic demands, while paper [5] set out a comprehensive cost evaluation model to compute the TCO of mobile backhaul networks, including a detailed breakdown of CAPEX and OPEX.

To the best of our knowledge, only Greenfield backhaul deployment scenarios have been considered in the literature. Greenfield scenarios do not take into account the existing legacy infrastructure in the field. Currently, most households are still connected through copper cables, e.g., using Digital Subscriber Line (DSL) technology. DSL is the most popular last-mile fixed broadband technology and about 3/4 of the FTTX (Fiber-to-the-X = node/cabinet/building) solutions rely on DSL to connect to the end-users [30][31]. Legacy DSL solutions can be used when combined with other technologies for backhauling small cells, especially those situated indoors. This solution is referred as Brownfield. In the first part of this thesis, there is an examination of both Greenfield and Brownfield scenarios with the aim of providing a TCO assessment methodology that can help mobile operators to plan and deploy their backhaul infrastructures for HetNet, particularly with regard to the traffic levels and expected costs of current and future users.

1.2.2 Main Research Studies and Projects on Protection Schemes for Passive Optical Networks

Among the traffic and transport technologies, fiber is the best suited to meeting future traffic demands. Additionally, Passive Optical Networks (PON) is the most viable solution for deployment in the last mile segment owing to its potential very high capacity and long reach [32][33]. PON technologies are able to meet and handle the high traffic demands expected today and in the near future [34]. As a result of this increase in traffic requirements, the operators will be dealing with new customers, (e.g., business/commercial), and this will be even more demanding and costly in terms of penalties. The new customer profile has driven operators to invest in reliable solutions, e.g., protection topologies for Feeder Fiber (FF) and Distribution Fiber (DF), which will strictly comply with the Service Level Agreement (SLA), as a means of reducing failures and undesired losses in revenue [6][35][36].

Protection schemes for transport networks are an important means of avoiding service failures and improving PON reliability and survivability. The following protection schemes are specified in [37][32][38]: *(i)* feeder fiber protection - this scheme protects the feeder fiber by means of a spare fiber that is situated between the

Optical Line Terminal (OLT) and the passive optical splitter/combiner at the remote node, and is thus attached to the feeder fiber via optical switches; *(ii)* OLT and feeder fiber protection - in this scheme, an additional OLT is used to provide both OLT and feeder fiber protection; *(iii)* full duplication - this approach protects all the Optical Network Units (ONUs) as well as OLT and both the feeder and distribution fibers.

In the literature, the paper [39] proposed a 1:1 protection scheme designed to ensure there was a backup path between the distribution fibers of a Wavelength Division Multiplexing (WDM) PON. In this architecture, ONUs are equipped with optical switches and filters. Additionally, a bidirectional connection between each pair of ONUs is provided by using additional optical fiber links. In [40], the survivability of a WDM PON was investigated and a new survivable architecture was proposed and then experimentally examined. In the proposed optical 1:1 protected WDM PON, automatic protection switching with in-service fault location was performed by the ONUs. A 1:W shared protection scheme (using W working and 1 protecting resources) was put forward and investigated. The proposed architecture provides self-protection and automatic traffic restoration capability for the distribution of cut fiber. Although the above mentioned protection techniques provide protection for OLT and/or ONUs as well as feeder and/or distribution fibers, using full optical protection methods is cost-prohibitive for cost-sensitive access networks. In this context, paper [41] carries out a comprehensive assessment of CAPEX and OPEX to evaluate a cost-efficient protection for Time Division Multiplexing (TDM) PONs based on sharing FF ducts between OLT and Remote Node (RN) with backup fibers. The results confirm the benefits of the proposed method of providing protection, which leads to a significantly greater reduction of TCO, i.e., CAPEX and OPEX, than the unprotected case in all of the examined scenarios (rural, urban, and densely-populated urban). Paper [42] conducts a comprehensive cost analysis for fiber access networks including both CAPEX and OPEX. The results show that for business users the TCO in protection topologies may be lower than in some unprotected topologies.

Paper [43] examines some new protection schemes based on WDM Next Generation Optical Access (NGOA) networks. Additionally, a cost comparison is made between two different NGOAs within a densely-populated urban scenario. The results show the importance of offering protection to the feeder fiber level so as to significantly reduce the TCO per ONU when penalties are applied. An additional result of this paper is the influence of the fiber layout (in particular the FF layout owing to its high failure rate) on the penalty cost: it should be noted that the fewer streets containing FF (i.e., the more concentrated the FF layout), the lower the penalty costs. Moreover, it was found that with regard to the proposed fiber layout, the increase in investment for offering protection is a low percentage of the TCO.

In contrast, papers [41], [42] and [43] based their analysis on static models and did not take account of dependencies between failures, i.e., the static models were not able to reflect the dynamism of the network because of the strong failure mode assumptions and the repairs that were necessary to allow them to be characterized.

Paper [6] assessed OPEX for PONs in terms of both expected repair costs and expected penalty costs using the Markov model with costs, which is based on a geometric model that describes the area of study. The results show that the expected penalty cost accounts for the main part of these OPEX, and sharply increases in sparse scenarios and when business clients are involved. However, in [44] the authors evaluated the CAPEX in different PON protection schemes by taking account of the design of the physical layout. The results show that protection at the feeder levels is almost mandatory to reduce the risk of large failures, while protection at the distribution level has little effect on them. In [36], the authors conducted a detailed cost analysis of PONs, that included CAPEX and the dependability-related OPEX. With regard to the failure-related OPEX, the cost of the repairs and penalty were taken into account. The results suggested that the most cost-efficient protection scheme for PONs should protect the feeder fibers as well as the OLT components.

Despite the fact that these papers mainly focused on protection schemes that only used optical fiber, there are studies that aim at providing full protection by means of hybrid fiber-wireless topologies in [45][46]. The authors in [47] and [46] proposed protection schemes for the hybrid Wireless-Optical Broadband-Access Network (WOBAN) which involved routing the signals through backup ONUs and wireless routers. The numerical results from [47] show that the proposed protection scheme is much more cost-effective than employing self-protecting PON architectures.

The results from paper [46] show that the delay via the wireless routers can be even more than 5 ms when the traffic load is high. Furthermore, it can cause approximately 30% packet loss if a failure occurs at the OLT, which might be acceptable for residential users, but could be a serious problem for mobile backhauling, particularly future 5G mobile services. Since the author wished to reduce packet losses, paper [48] proposed a hybrid fiber and microwave protection scheme for PON-based mobile backhauling. The novel architecture relies on a microwave connection which is used to protect the distribution and feeder levels. The results show that microwave backhaul can be used in protection schemes. Additionally, they demonstrate that fiber and microwave protection can provide better levels of reliability and availability than protections schemes that are entirely based on fiber. However, the study did not take into account how the usage of hybrid protection topologies affects the TCO. In the second part of this thesis, a Greenfield deployment with different protection schemes for PONs is set out with the objective of providing a TCO assessment that can help operators to plan and deploy their infrastructure for fixed broadband.

1.3 PROPOSALS

Given the challenges that transport network operators are facing to guarantee the level of data traffic that will be required by new applications and services in the future, and the attempts to address this problem found in the literature review discussed above, it is clear that the choice of a cost-efficient radio architecture is an important matter. In view of this, the hypotheses put forward in this thesis will be examined in the following subsections.

1.3.1 Assessment of backhaul deployment based on Greenfield and Brownfield scenarios

Operators are currently making huge investments in new backhaul infrastructures. However, the high initial cost of deploying fiber-based transport backhaul directly affects profits which are low in the short-term. The hypothesis raised in this study is that copper-based technologies can still be regarded as a suitable alternative to backhaul the traffic respecting overall costs and energy consumption. In order to validate the first hypothesis, this thesis employs an assessment methodology which involves the implementation of a total cost of ownership for mobile backhaul that assumes different backhaul architectures such as Greenfield and Brownfield scenarios.

1.3.2 Assessment of protection schemes for Passive optical networks

When a protection scheme is planned for PON the concerns are associated with the high CAPEX and OPEX. The second hypothesis is based on the assumption that a wireless mobile broadband infrastructure can provide reliable protection for unprotected optical fiber at a low investment cost, i.e., the operator either leases the capacity (Giga Byte) or owns the mobile transport infrastructure. This hypothesis can be validated by employing an assessment methodology for a total cost of ownership that follows three stages, i.e., Network Dimensioning, Failure-Associated Costs, and an assessment of the Total Cost of Ownership. Afterwards, different protection architectures for PON are included in the methodology to determine the most cost-efficient option.

CHAPTER II

MEDIUM ACCESS TECHNOLOGIES

2.1 INTRODUCTION

The objective of this chapter is to provide a description of the types of base station used in a HetNet deployment and also to outline the technological options available for transporting the fixed broadband and backhaul segments, (see Figure 2.1). To start with, there is a description of the various types of base station (i.e., macro, micro, pico, and femto) that usually form a part of a HetNet deployment. After this, the most popular access medium is described: Fiber, Microwave and Copper.

2.2 BASE STATIONS

Macro base stations (deployed outdoors, at over-rooftop level) are capable of covering a vast area and supporting a very large number of users. Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) are high due to their price, their site acquisition/rental costs, and their energy consumption levels. Macro base stations can provide 2G, 3G and 4G services. Legacy 2G (i.e., GSM, CDMA-IS95) sites are usually backhauled and use copper, while 3G (i.e., UMTS, CDMA-2000) and newly deployed 4G (i.e., LTE, WIMAX) base station sites use fiber and/or microwave for backhaul.

Micro base stations are also deployed outdoors, but at below-rooftop levels (e.g., lamp posts, or outside walls) to cover a specific area (e.g., to provide high traffic capacity in crowded streets and built-up areas). Their size, cost and effective radiated power levels are lower than those of macro base stations. They are usually backhauled via microwave [16][28].

Pico base stations have lower coverage than *macro* and *micro* and hence need a lower transmission power. They are often deployed to remedy the coverage/capacity holes in a given area, i.e., they work as *hot-spots* to guarantee connectivity for special events, such as concerts and parades, where several people are concentrated in the same area. When deployed indoors, *pico* base stations are usually backhauled through an existing broadband infrastructure that provides enough capacity (i.e., Fiber-to-the-

Home/Curb combined with Ethernet), while *pico* base stations deployed outdoors are mostly backhauled via microwave.

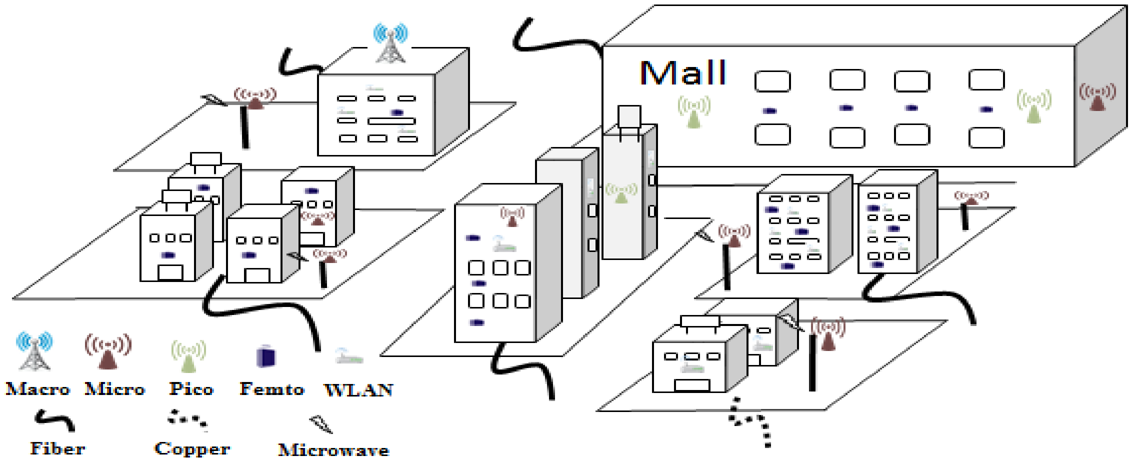


Figure 2.1: Possible HetNets deployment with relative backhaul in densely populated urban areas.

Table 2.1 - Base station types and characteristics.

Type	Coverage	Radiated Power [W]	
		Outdoors	Indoors
Macro	< 35Km	5-40	-
Micro	< 2Km	0.5-2	-
Pico	< 200m	0.25-2	0.1
Femto	10-15m	-	< 0.1

Femto base stations are the cheapest and most energy-efficient equipment. However, they have the worst performance and coverage. Unlike the other base station types, *Femto* is not an industrial grade system, but it is made for end-user connection and improving indoor traffic capacity. Their role is similar to *pico* base stations, i.e., to provide extra capacity where needed, but their power consumption is lower due to their proximity to the user and their short coverage range (i.e., limited to a few tens of meters). They are usually backhauled by a fixed broadband infrastructure, which means mainly legacy copper and fiber, i.e. Digital Subscriber Line (DSL), Ethernet, Fiber-to-the-Building and Fiber-to-the-Home. Additionally, Table 2.1 summarizes the main characteristics of the different base stations.

2.3 FIBER

Fiber technology is able to provide virtually unlimited capacity to end-users and to offer long-term support with respect to the demand for capacity growth [49], but fiber comes today at a relatively high deployment cost, i.e., CAPEX. However, a high investment in cost and time to deploy, backhaul based on fiber can support any unexpected increase in future capacity requirements, especially in dense urban areas. Regardless of the fact that fiber is an alternative, the time to either deploy or upgrade this technology can be too long, while the backhaul traffic is already a serious problem. For this reason, alternative kinds of backhaul technology, i.e. microwave and copper, also play key roles.

Optical access networks comprise three areas: Central Office (CO), local exchange, and end-user premises. The CO stores the Optical Line Terminals (OLT), which aggregate the network traffic and send it through its uplink to the Wide Area Network (WAN). Splitters, Arrayed Wavelength Grating (AWG) or Optical Network Units (ONU) are usually connected to the OLT downlink ports. Figure 2.2 illustrates the possible alternatives. Figure 2.2 (a) depicts an architecture where OLT is connected to splitters or AWG. The connection between them is called feeder fiber and the part from the splitter to the ONU is called Distribution Fiber (DF). This architecture, which consists of the FF and DF, is called Passive Optical Network (PON). PON is the most common architecture in use that provides high capacity through full end-to-end fiber connection from the CO to the end-user’s home. In this architecture an OLT is connected to a splitter, which serves a number of ONU. The splitter is usually deployed to replace DSLAMs during the migration process from Fiber-To-The-Node (FTTN) towards Fiber-To-The-Home (FTTH). Currently, there are several types of PONs, depending on the data multiplexing scheme in use. In this investigation, the Time Division Multiplexing (TDM) PON is adopted and operates where traffic from/to multiple ONUs are TDM multiplexed onto the upstream/downstream wavelength. However, this is only a general scheme and if it is decided to deploy a WDM PON architecture, it is only necessary to replace the splitter with AWG [40][50]. Figure 2.2 (b) describes the infrastructure without splitters, which is known as Point-To-Point (PTP) architecture. In the PTP architecture, there is has a direct link from the OLT to the ONU.

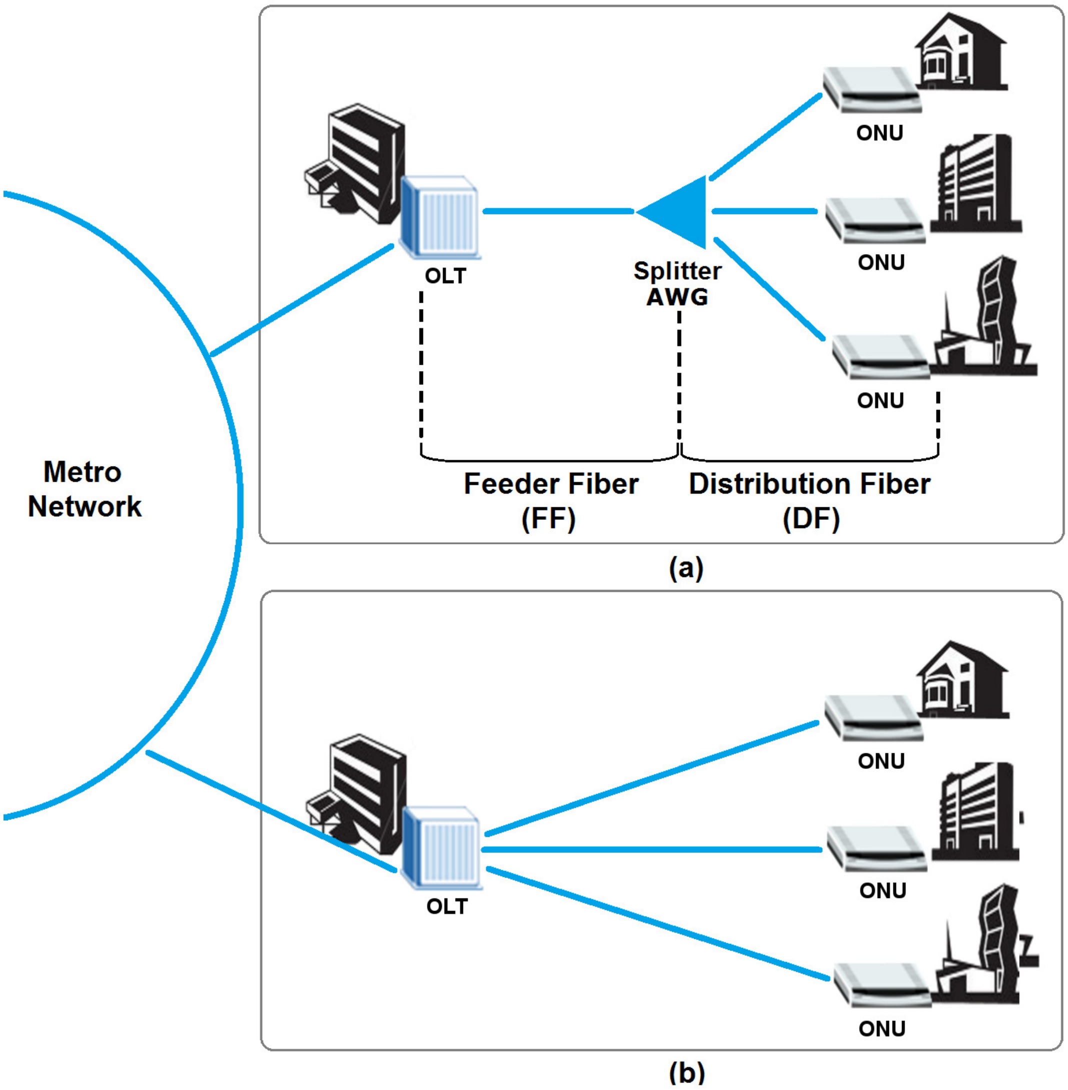


Figure 2.2: Fiber-to-the-home backhaul infrastructures. (a) Passive optical network. (b) Point-to-point fiber architecture.

2.4 MICROWAVE

Microwave is the most widespread backhaul technology in urban and rural regions [51][52][53]. The main reason for the success of microwave can be attributed to the short time and low CAPEX for deploying. Moreover, microwave-based backhaul is attractive in terms of short time-to-market, low investment in infrastructure and simple deployment [51]. On the other hand, this backhaul technology compels the operators to pay for a very high OPEX due to high costs of energy and spectrum leasing. Microwave backhauling can be divided into two main categories: Microwave PTP and Microwave Point-To-Multipoint (PMP), each of which incurs a different energy and spectrum leasing costs [29].

The first is *Microwave Point-To-Point (PTP),* depicted in Figure 2.3. PTP requires a dedicated link (in the 2-30 GHz range) to connect each Radio Access Network (RAN) site to a hub node that is sequentially connected to the metro/aggregation segment. If the RAN site is too far from the hub, or if there is no Line of Sight (LoS) connectivity, the backhaul may include multiple hops [29].

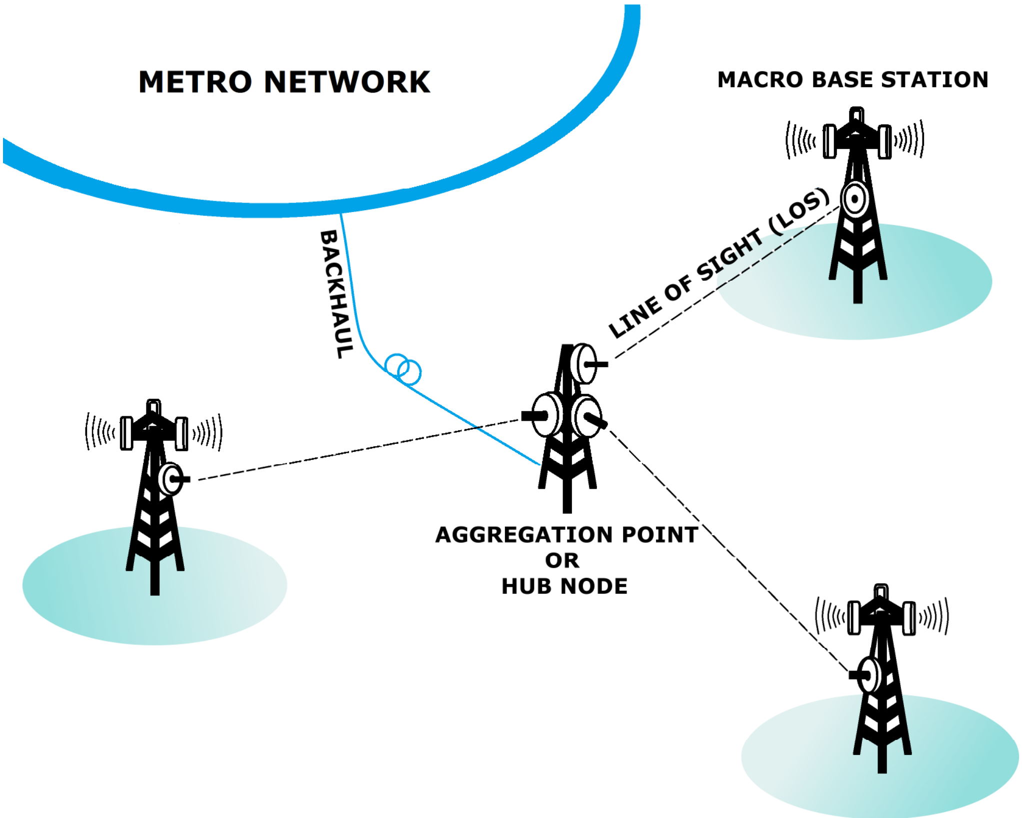


Figure 2.3: Point-to-point microwave backhaul communication.

The *Microwave Point-to-Multipoint (PMP)* links, depicted in Figure 2.4, allows one Access Point (AP) in the hub be connected simultaneously to multiple RAN sites thus reducing the number of required dedicated links. This provides obvious CAPEX and OPEX savings in terms of radio equipment and fewer dedicated microwave links respectively.

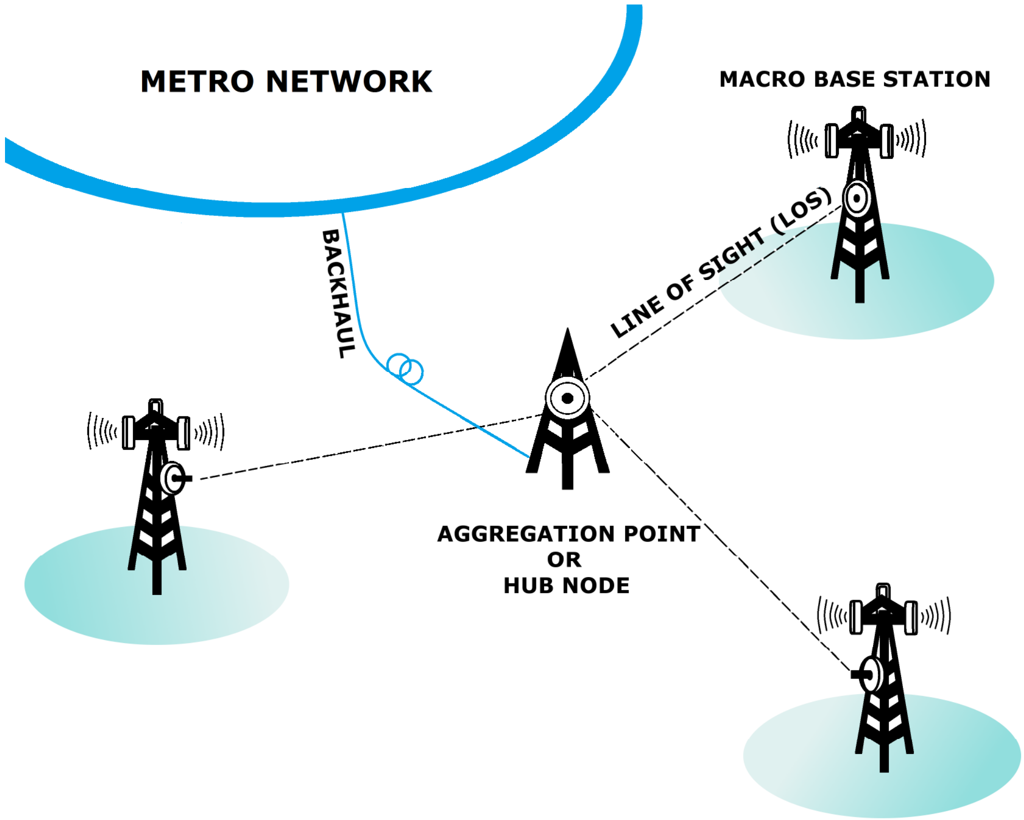


Figure 2.4: Point-to-multipoint microwave backhaul communication.

2.5 COPPER

Digital Subscriber Lines (DSLs) might be still appealing in the presence of an existing copper infrastructure, bearing in mind their limited capacity [54]. The infrastructure makes use of fiber transmission links from the CO to the local exchange. Digital Subscriber Line Access Multiplexers (DSLAM) are stored in the local exchange to establish Internet connection over twisted-pair copper cables with the end-user, as illustrated in Fig. 2.5, which can be referred to as hybrid fiber-copper [55].

Copper is the legacy technology that has been most widely used in recent decades to provide fixed broadband connectivity (i.e., Asymmetric Digital Subscriber Line 2 (ADSL2+) standard International Telecommunication Union (ITU-T) G.992.5 [56], Very-High-Bit-Rate Digital Subscriber Line 2 (VDSL2) standard ITU-T G.993.2 [57], etc.). Copper has also been used to backhaul traffic in the early generations of mobile services (i.e., 2G and 3G).

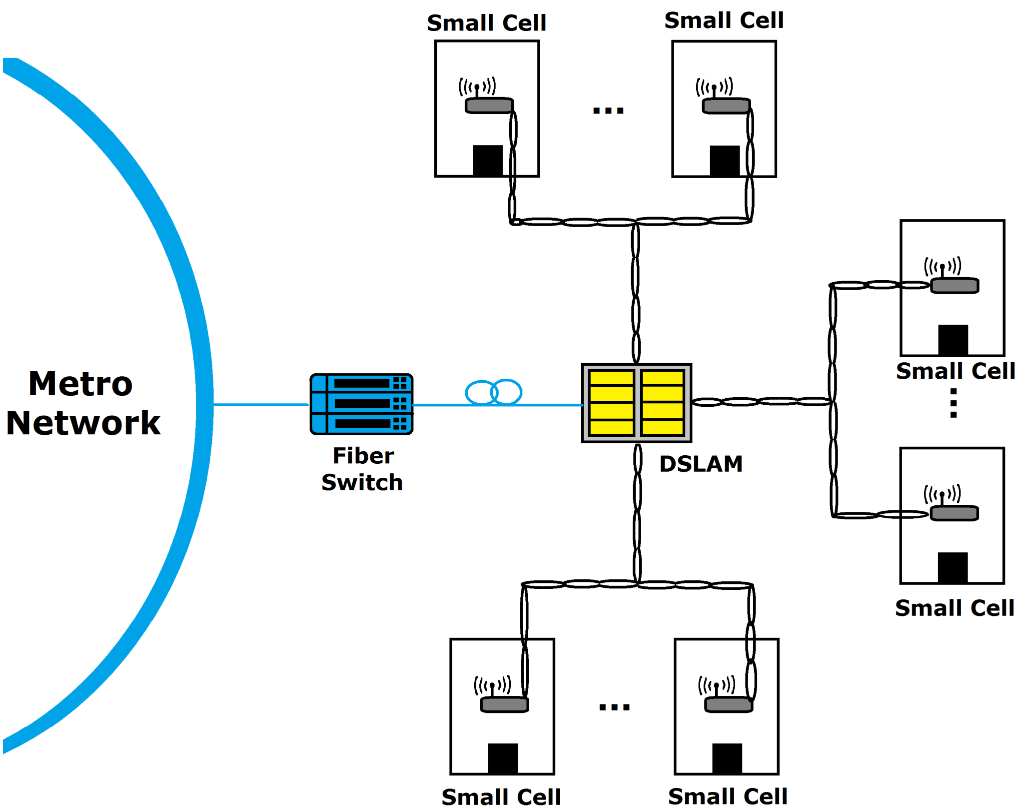


Figure 2.5: Copper-based backhaul communication.

It is known that copper is the most widespread broadband technology and that there are approximately 1.3 billion copper phone lines all over the world [30]. It also remains an attractive option for a number of backhauling indoor scenarios [58], especially in the short term, while more capacity efficient backhaul solutions (i.e., based on fiber or microwave) are being deployed to both enhance the existing copper-based backhaul and to cater for longer term traffic requirements. For example, in a Fiber-To-The-Cabinet (FTTC) or Fiber-To-The-Building (FTTB) scenario, mobile operators may still benefit from making use of an already deployed copper-based infrastructure, especially to backhaul small base stations (i.e., Pico and Femto) traffic, where the aggregated bandwidth is not huge. On the other hand, this technology has a serious drawback which is its inability to provide a high capacity over long distances.

Among the copper-based transport technologies, the ADSL2+ can provide maximum capacity of 24Mbps for users [59][56]. Additionally, the ADSL2+ operates in the band from 26.075 kHz to 137.825 kHz, and is used for upstream communication, while 138 kHz – 1104 kHz is used for downstream communication. Another technology in use is the VDSL2, which is a DSL variant that provides hundred Mbps to users and extends the performance of existing applications in Internet access, video-conferencing and provision of digital video [59]. VDSL2 is an extension of the existing ADSL technology, and generally operates within the frequency band of 25 kHz up to 30 MHz; however, the higher bit rates provision can only be carried out over shorter distances [57], in fact, it only has the capacity to perform with a good speed of up to 300 meters. Finally, G.fast access to subscriber terminals (G.fast) is a new standard from ITU-T that is aimed at providing up to 1 Gbps over short links, i.e., up to 100 meters (as illustrated in Figure 2.6), using a frequency range of up to 212MHz [60][61]. In other words, new G.fast technology is able to provide fiber-like speeds over the last mile and this reduce capital expenditure. Additionally, G.fast allows network operators to offer a high speed service with no need to enter and rewire homes, offices and buildings.

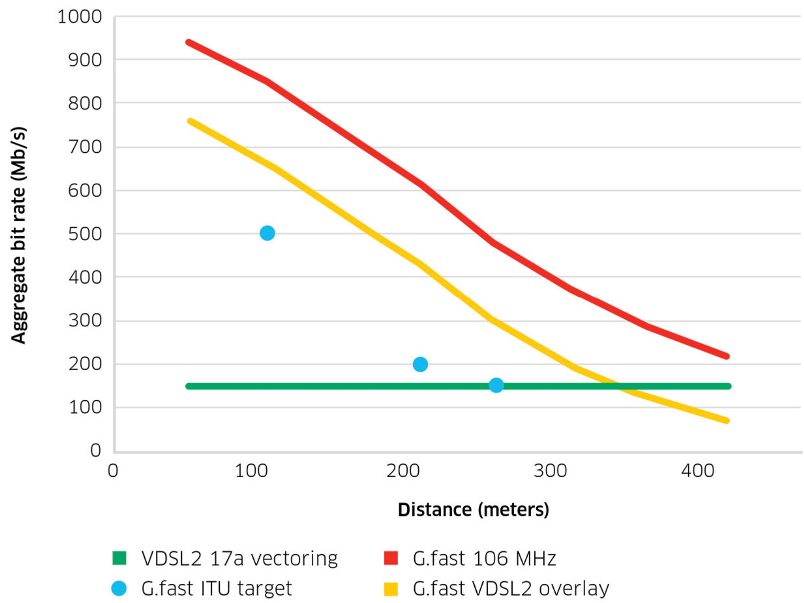


Figure 2.6: Beyond VDSL2: G.fast delivers fiber speeds over short copper loops [65].

The high capacity of G.fast cannot be maintained over long distances, so the best approach is to use a combination of two technologies, i.e., G.fast and VDSL2 vectoring when G.fast is out of range. G.fast is ideal for applications that bring fiber closer to the home and uses very short copper loops to cover the last few meters, e.g., distributed transport and antenna systems [62][63][64], while VDSL2 vectoring remains the best technology for longer distances, i.e., up to 400 meters [65].

G.fast must be deployed in conjunction with fiber rollouts, but it is possible to leverage its existing assets. FTTH operators can use the PON to backhaul G.fast-enabled ONUs and traditional FTTx operators can use G.fast to increase bit rates without having to extend the fiber all the way to the home.

2.6 CONCLUSION

This chapter introduced the main types of base stations and the different access medium technologies that can be used to transport traffic from base stations and the fixed-user. The main features of the base stations were described, e.g., coverage and capacity, and from the transport access medium, e.g., the maximum reachable capacity and main topologies.

CHAPTER III

ASSESSMENT OF THE TOTAL COST OF OWNERSHIP FOR MOBILE BACKHAUL

3.1 INTRODUCTION

This chapter introduces a methodology for assessing the Total Cost of Ownership for mobile backhaul, which is divided into five phases. Figure 3.1 summarizes the phases. The proposed methodology is used to determine the most suitable backhaul and relies on two key factors: Greenfield, i.e., deployment of a new transport network infrastructure to serve mobile clients in a certain area, or Brownfield, i.e., legacy backhaul usage to transport network infrastructure up to its full capacity and also serve mobile end-users. In the Brownfield, the migration to a new transport network technology, e.g., fiber and microwave, is carried out by reusing the previous infrastructure, e.g., ducts and trench.

The demand estimation of traffic is used to compute the expected traffic requirements in the area for a given year. It uses as inputs, the expected data for network and service usage, such as population density, number of active mobile subscribers, user profile (e.g., heavy or ordinary), number of mobile operators in the area, variation in daily traffic volume and penetration rate of mobile terminals (e.g., tablets, smartphones and laptops). Following this, with the aid of a long-term traffic model, it estimates the average user demand and the traffic demand in an average area.

The wireless deployment phase is used to determine the number of base stations in the area. In this case, the number of buildings and apartments in the area are taken as input, together with the type and capacity of macro and small base stations, and the penetration rate of the small base station. Accordingly, it is possible to obtain the number of macro and small base stations required to cover the area and satisfy the average traffic requirements in a given year.

In the backhaul deployment and migration phases, the amount of backhaul equipment required to serve the macro and small base stations in the area is determined. During this deployment, the inputs are the peak capacity of macro and small base stations, the backhaul architecture and the transmission and switching capacity of the backhaul equipment. On the other hand, in the backhaul migration, the already existing infrastructure can also be taken as input. The output of this phase is to calculate the number of devices (e.g., microwave antennas, fiber cables, and modems) that need to be installed.

Finally, in the last phase, i.e., the evaluation of the total cost of ownership, the overall TCO is calculated in accordance with the models examined in Section 3.5. The inputs of this phase are the backhaul design (e.g., deployment or migration), cost of equipment and available services (e.g., energy consumption, fiber trenching and spectrum leasing). The CAPEX and OPEX of the backhaul architectures are calculated on the basis of the inputs and a tailor-made TCO model.

It is should be noted that the methodology employed was validated during the research project called GreenHaul [22], which was a cooperative venture between wireless@KTH, TeliaSonera and Transmode.

In the following sections, there is a description of the math models adopted during the assessment methodology. First, there is a detailed account of the traffic estimation model; then, the proposed wireless and backhaul architectures; and finally, the TCO model.

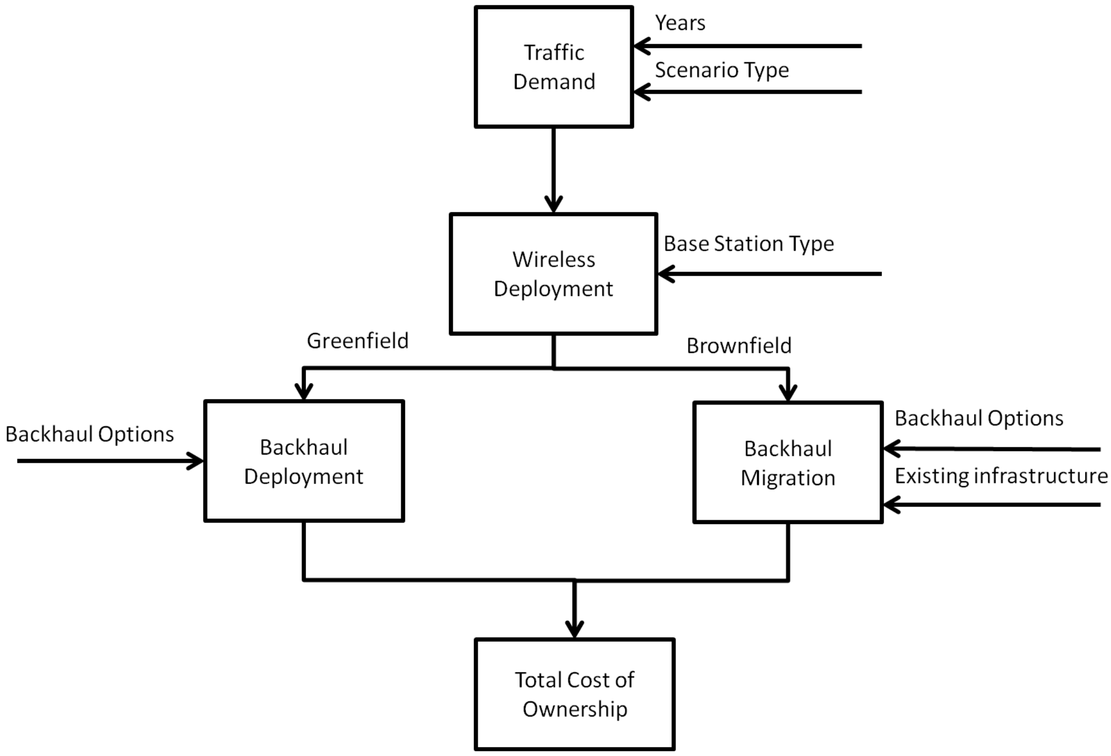


Figure 3.1: Assessment methodology.

3.2 TRAFFIC DEMAND

When predicting the traffic demand, i.e., traffic forecast for the next *T* years, the first stage is to define the type of scenario among urban, suburban and rural sectors. In this case, a model is designed for the urban scenario. The main inputs are: area (in km^2), population, number of mobile subscribers, user types, (i.e., defined as heavy or ordinary), and the penetration rate of the different devices, e.g., tablets, smartphones and laptops. The following outputs can be obtained from this: population density, user demand, and traffic demand.

a) A Long-Term Large-Scale Traffic Model

This study involves, a densely-populated urban scenario and a referenced traffic model, (as shown in [66]), to estimate the area traffic demand. Since data volumes per subscriber do not depend on a specific deployment scenario, the daily-generated traffic $R(t)$ over a given area can be defined by Eq. (3.1):

$$R(t) = \frac{\rho\alpha(t)}{N_{op}}\sum_{k} r_k\, s_k, \qquad [Mbps/km^2] \tag{3.1}$$

where ρ represents the population density in the area. $\alpha(t)$ represents the average daily traffic variation in terms of percentage of active users for a given time *t*. The term *k* indicates the terminal type (i.e., laptop, tablet or smartphone). N_{op} represents the number of mobile operators in the area. Finally, r_k and s_k represent the average data rate and the fraction of the subscribers using terminal type *k*, respectively. The daily peak traffic is used to represent the broadband request.

As in [66], three different terminal types are included: Personal Computer (PC), tablet and smartphone. On average, it is assumed that a PC user will generate two and eight times more data traffic than a tablet and a smartphone user, respectively [66]. The users are divided into two groups (i.e., heavy and ordinary users) where the capacity requirements of an ordinary user are 1/8 of those of a heavy user [66]. Based on the assumption that $h\%$ of the subscribers are classified as heavy users, the average daily rate of demand for data for terminal *k* can be defined as Eq.(3.2).

$$r_k = \frac{\left[h r_k^{heavy} + (100 - h) r_k^{ordinary}\right]}{45000} \qquad [Mbps] \tag{3.2}$$

where r_k^{heavy}[MB/hour] and $r_k^{ordinary}$[MB/hour] represent the hourly average data rate of a heavy and an ordinary user, respectively.

Using Eq. (3.1) in combination with the forecasted values of h, the fraction of the subscribers using the three terminal types (i.e., s_{pc}, s_{tablet}, $s_{s.phone}$), and the average data rate requirements for a heavy user r_k^{heavy} [1][66], it is possible to calculate the peak area traffic demand at the busy hour as $\mathcal{T}$[Mbps/ km^2] = $max_t(R(t))$, which corresponds to the case of $\alpha(t) = \alpha_{max}$ [66].

3.3 WIRELESS DEPLOYMENT

On the basis of the traffic demand, it is possible to determine the most suitable wireless deployment for indoor and outdoor environments. Here, an attempt is made to define which type of base station is more suitable for each scenario and the required traffic demand. There are alternative base stations (i.e., macro, micro, pico and femto) that are usually a part of the HetNet deployment. In this thesis, a deployment scenario is designed with outdoor macro and indoor femto base stations.

3.3.1 Macro + Femto Deployment

In the case of wireless network dimensioning, it is assumed that the mobile operator deploys the macro base stations on the rooftops. In contrast, the femto base stations are randomly deployed by the end-users in their apartments. The number of deployed femto base stations (N_{femto}) is given as a function of the femto penetration rate (η) and the total number of apartments (N_{ap}) in the area: $N_{femto} = N_{ap}\eta$. It is assumed that the apartments are uniformly distributed in N_b buildings. Since the macro-cellular network must serve the remaining active users (i.e., those which are not served by the femto base stations), the required number of macro base stations can be computed by Eq. (3.3):

$$N_{macro} = \frac{\rho \, \mathrm{A} \, (1-\eta) \, \alpha_{max}}{N_{active/macro}} \tag{3.3}$$

where A is given in $[km^2]$ and represents the area under consideration Additionally, $N_{active/macro}$ denotes the number of active users that can be served by a macro base station and is given by Eq.(3.4):

$$N_{active/macro} = \frac{C_{macro}}{\bar{r}} \quad (3.4)$$

where C_{macro} and $\bar{r}$ represent the maximum transmission capacity of a macro base station and the average data rate requirement per active user, respectively.

3.4 BACKHAUL DEPLOYMENT AND MIGRATION

In this Section, there is a detailed account of the backhaul architecture dimensioning along with its power consumption models, which will later be evaluated.

3.4.1 Architecture 1: Microwave Backhaul

The first backhaul architecture is shown in Fig. 3.2, and is based on microwave star topology [11]. Among different Microwave-based backhaul architectures, Microwave (MW) based on Point-To-Point (PTP) highlights in terms of energy efficiency and cost savings [29]. Moreover, due to the low time to deploy and low effort to setup, the MW technology became the main outdoor backhaul architecture that provides high capacity in the order of Gbps for macro, micro and Picocells [28].

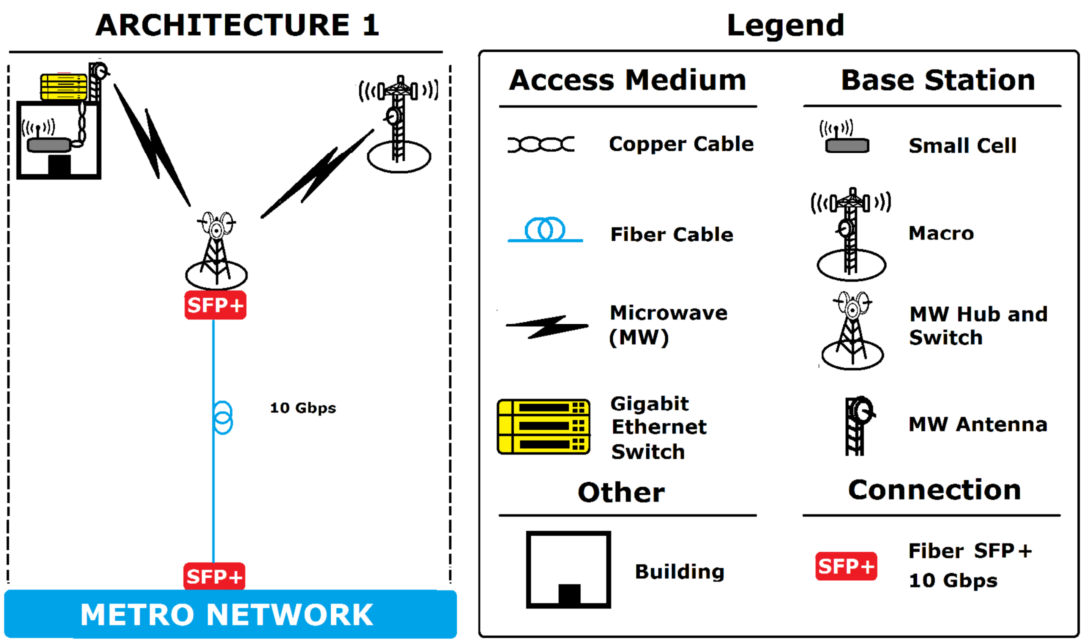


Figure 3.2: Microwave to femto and macro base stations.

The outdoor macro base stations backhauled by MW are equipped with microwave antennas, which are directly connected to a hub using a dedicated microwave link. At the same time, the femto base stations inside a building are connected to a Gigabit Ethernet Switch (GES) using copper cables (e.g., CAT 5/6/7). The GES aggregates the traffic from the femto base stations inside a building and provides connectivity to a microwave antenna placed on the rooftop. The antenna is in turn connected to a hub using a dedicated microwave link. The microwave links can operate, for instance, in a range of between 5 and 80 GHz, which is most suited to dense urban areas [3]. The hubs are equipped with switches that are responsible for aggregating the traffic from the microwave antennas and connecting them to the Metro Network (MN). The transmission within the MN occurs though optical point-to-point links and Small Form-Factor Pluggable Plus (SFP+) transceivers which are used for transmitting and receiving the optical signal. The power consumption of the architecture, i.e., P_{bh}^{arch1}, can be expressed as:

$$\begin{aligned} P_{bh}^{arch1} = & \left(N_{bf} + N_{macro}\right)P_{low-c} + N_{bf}P_{GES} + N_{hub}P_{high-c} \\ & + 2N_{ul}^{MW}P_{SFP+} + N_{s}^{MW}P_{s}^{MW} \end{aligned} \tag{3.5}$$

where N_{bf}, N_{macro}, N_{hub}, $N_{s}^{MW}$and N_{ul}^{MW} are the number of buildings with femto base stations, macro base stations, hubs, total number of Fiber Switches (FSs) inside the hubs and total number of uplink connections between FS and MN, respectively. On the other hand, P_{low-c} and P_{high-c} represent the power consumption of a microwave antenna in low and high capacity mode, respectively (according to the power model described in [11]). Finally, P_{GES}, P_{SFP+}, P_{s}^{MW} show the power consumption of a GES, SFP+ and fiber aggregation switch, respectively. It can be observed that N_{hub} is a function of the maximum number of links supported by a hub (n_{max}^{MWlink}), i.e., $N_{hub} = \left\lceil \frac{N_{bf}+N_{macro}}{n_{max}^{MWlink}} \right\rceil$. Finally, N_{ul}^{MW} depends on the total aggregate traffic collected at the FSs, i.e., Agg_{tot}, and the maximum transmission rate per uplink interface ($Max_{Trans/Link}$). N_{ul}^{MW} can be computed as follows: $N_{ul}^{MW} = max\left(\left\lceil N_{s}^{MW}; \frac{Agg_{tot}}{Maex_{Trans/Link}} \right\rceil\right)$.

3.4.2 Architecture 2: Fiber-To-The-Node + Microwave Backhaul

The Fiber-To-The-Node (FTTN) architecture provides the end-user with high capacity through existing copper pairs. Depending on the copper technology in use, it can theoretically achieve a maximum capacity of 1Gbps up to 100 meters, 100Mbps up to 300 meters or 24Mbps up to 1 kilometer using G.fast, VDSL2 or ADSL2+, respectively [65][67][68]. In FTTN, data is backhauled to the metro aggregation through a hybrid topology, where dedicated fiber is provided from a fiber switch located at the CO to a DSLAM in a local exchange, (usually a cabinet placed on the street corner, close to the end-users). Copper-based technologies are used from the DSLAM to the user-modem.

The FTTN+Microwave, is shown in Fig. 3.3, and includes a hybrid architecture that employs both fiber and copper for indoor femto cells and microwave for outdoor macro base stations. Here, the femto base stations are backhauled by means of VDSL2 links, which have a frequency range of up to 30 MHz and provide a maximum downlink capacity over copper cables of 100Mbps up to 300 meters. Each femto base station is connected to a VDSL2 modem that is in turn connected to a DSLAM using a high speed connection through copper. The DSLAM is located at a remote node usually placed inside a street cabinet close to the user's premises. The DSLAMs are connected to a number of FSs using point-to-point optical links. Small Form-Factor Pluggable (SFP) transceivers are used for transmitting and receiving the optical signal from the DSLAM to the FS. In contrast, the macro base stations are connected to the FSs using microwave links (already described for Architecture 1). The FSs aggregate the traffic coming from the wireless network before sending it towards the MN via optical links and SFP+ modules. The power consumption of the second architecture, i.e., P_{bh}^{arch2}, is obtained through the following formula:

$$\begin{aligned} P_{bh}^{arch2} = {} & N_{femto}P_{modem} + (P_{DSLAM} + 2P_{SFP})N_{DSLAM} \\ & + N_s^F P_s^F + N_{macro}P_{low-c} + N_{hub}P_{high-c} + N_s^{MW} P_s^{MW} \\ & + 2P_{SFP+}(N_{ul}^F + N_{ul}^{MW}) \end{aligned} \tag{3.6}$$

where P_{modem}, P_{DSLAM}, P_{SFP} and P_s^F are the power consumption values of a DSL modem, a DSLAM, a SFP and a FS. Moreover, N_{femto}, N_{DSLAM}, N_s^F, N_{ul}^F are the respective number of femtos, DSLAMs, FSs aggregating indoor traffic and uplink connections to FS and MN. N_{DSLAM} is a function of the number of ports per DSLAM (n_{ports}^{DSLAM}), i.e., $N_{DSLAM} = \left\lceil \frac{N_{femto}}{n_{ports}^{DSLAM}} \right\rceil$. Similarly, N_s^F is based on the number of ports of a FS (n_{ports}^F), i.e., $N_s^F = \left\lceil \frac{N_{DSLAM}}{n_{ports}^F} \right\rceil$. Finally, N_{ul}^F and N_{hub} can be computed as $N_{ul}^F = max\left(N_s^F; \left\lceil \frac{Agg_{tot}}{Max_{TransLink}} \right\rceil\right)$ and $N_{hub} = \left\lceil \frac{N_{macro}}{n_{max}^{MWlink}} \right\rceil$ respectively.

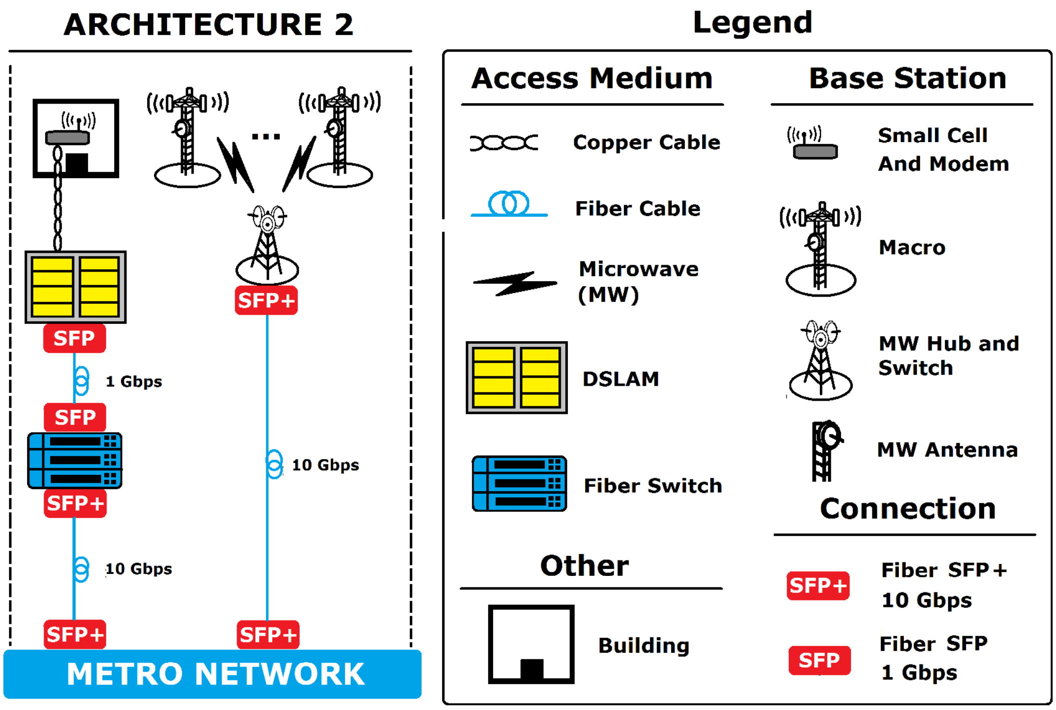


Figure 3.3: Fiber-to-the-node for the femto and microwave to the macro.

3.4.3 Architecture 3: Fiber-To-The-Building + Microwave Backhaul

Fiber-To-The-Building (FTTB) Point-To-Point (PTP) architecture provides dedicated fiber link connection between the fiber switch, located at the CO and attached to the metro aggregation, and the GES located inside the end-user building. Owing to the lack of local exchanges, FTTB can guarantee realistic capacity of 1Gbps per building and about 100Mbps per GES downlink port, which are directly connected to small cells. The GES can be used to backhaul small-cell data traffic and provide fixed broadband at the same time. This enables the power consumption of GES to be calculated in accordance with the number of ports that have small cells connected.

The main drawback of the FTTB is the high deployment cost incurred by the initial investment in infrastructure which includes fitting each building with fiber technology and renovation of equipment. These items usually discourage operators to immediate migrate to this backhaul alternative.

The third backhaul architecture, referred to as FTTB+Microwave, is shown in Fig. 3.4. As in the case of Architecture 1, the femto base stations inside a building are connected to a GES through copper cables. The GES is in turn connected to a FS with optical point-to-point links. The SFP transceivers are used at the GES and FS to transmit and receive an optical signal. The FSs are connected to the MN by means of optical links and SFP+ transceivers. Moreover, the macro base stations are backhauled through the same microwave infrastructure previously described. The power consumption of Architecture 3 can be computed by the following formula:

$$P_{bh}^{arch3} = (P_{GES} + 2P_{SFP})N_{bf} + N_s^F P_s^F + N_{macro}P_{low-c} \\ + N_{hub}P_{high-c} + N_s^{MW} P_s^{MW} + 2P_{SFP+}(N_{ul}^F + N_{ul}^{MW}) \tag{3.7}$$

where N_s^F is given by $N_s^F = \left\lceil \frac{N_{bf}}{n_{ports}^F} \right\rceil$. Additionally, N_{hub} and N_s^{MW} are computed as in Architecture 2.

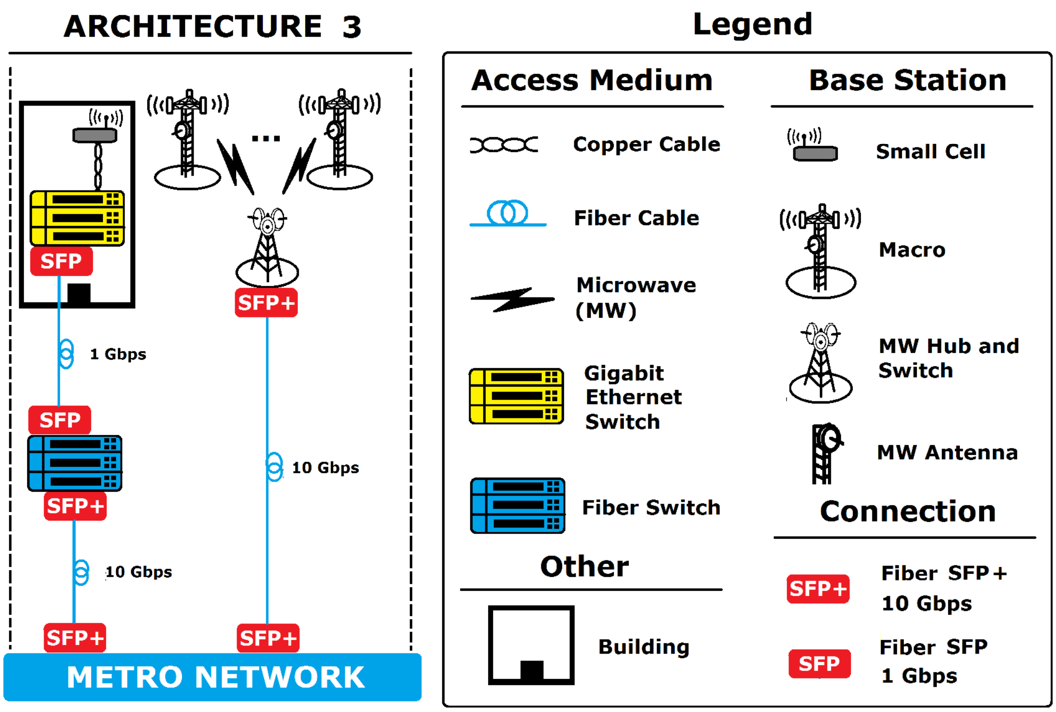


Figure 3.4: Fiber-to-the-building for the femto and microwave to the macro.

3.4.4 Architecture 4: Fiber-To-The-Home + Microwave Backhaul

Fiber-To-The-Home (FTTH) is the architecture which depends on Passive Optical Networks (PONs) to provide the fastest and most reliable backhaul solution.

The fourth backhaul solution, referred to as Fiber-To-The-Home (FTTH)+Microwave, is shown in Fig. 3.5. In this architecture, the indoor femto base stations are backhauled with the aid of PON. Each femto base station inside a building is directly connected to an ONU. The ONUs are then connected to OLTs through passive optical splitters. The OLTs are connected to the MN using optical links and SFP+ transceivers. However, the macro base stations are backhauled by means of the same microwave network with star topology shown in the previous architectures. The power consumption of Architecture 4 can be defined by as the following Eq (3.8):

$$P_{bh}^{arch4} = N_{femto}P_{ONU} + N_{OLT}P_{OLT} + N_{macro}P_{low-c} + N_{hub}P_{high-c} + N_s^{MW}P_s^{MW} + 2P_{SFP+}(N_{ul}^{F}+N_{ul}^{MW}) \tag{3.8}$$

where P_{ONU} and P_{OLT} represent the power consumption of an ONU and an OLT, respectively. The number of ONUs corresponds to the number of femto base stations (N_{femto}). At the same time, N_{OLT} represents the number of OLTs in the network, which is a function of the number of ports per splitter ($n_{ports}^{Splitter}$) and the number of OLT cards (n_{cards}^{OLT}), i.e., $N_{OLT} = \left\lceil \frac{N_{ONU}}{n_{cards}^{OLT} n_{ports}^{Splitter}} \right\rceil$. Finally, the MW dimensioning for outdoor macro BSs is similar to Architecture 2.

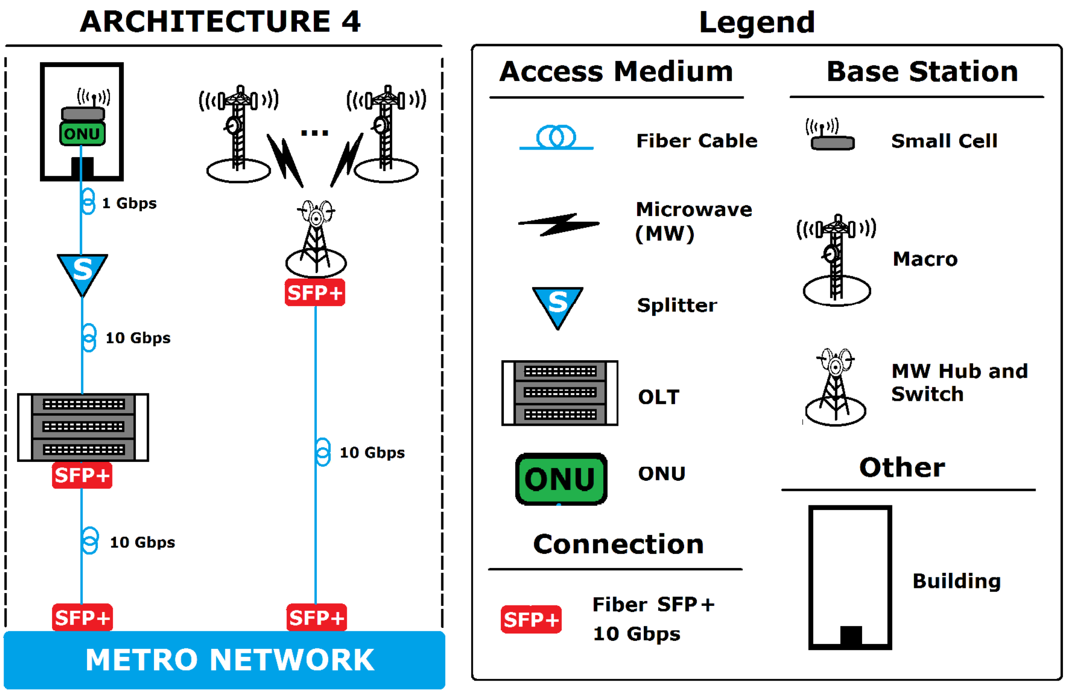


Figure 3.5: Fiber-to-the-home for the femto and microwave to the macro.

3.4.5 Architecture 5: Fiber-To-The-Home Backhaul

In terms of power consumption, the Backhaul Architecture 5, represented by FTTH backhaul, is the most energy-efficient option. However, due to high footprint costs, including Greenfield deployment, (i.e., starting from scratch), this architecture might not be financially viable for much of the time.

The last proposed backhaul solution, referred to as Fiber-To-The-Home (FTTH) backhaul, is shown in Fig. 3.6 and is based on PONs for backhauling both femto and macro base stations. Here, each femto and macro base station is equipped with an ONU connected to an OLT via a passive optical distribution network. The power consumption of this architecture can be defined as Eq. (3.9):

$$P_{bh}^{arch5} = \left(N_{femto} + N_{macro}\right)P_{ONU} + N_{OLT}P_{OLT} + 2N_{ul}^{F}P_{SFP+} \tag{3.9}$$

where the total number of ONUs corresponds to the total number of base stations (i.e., femto and macro) in the area. Moreover, N_{OLT} is calculated as in Architecture 4.

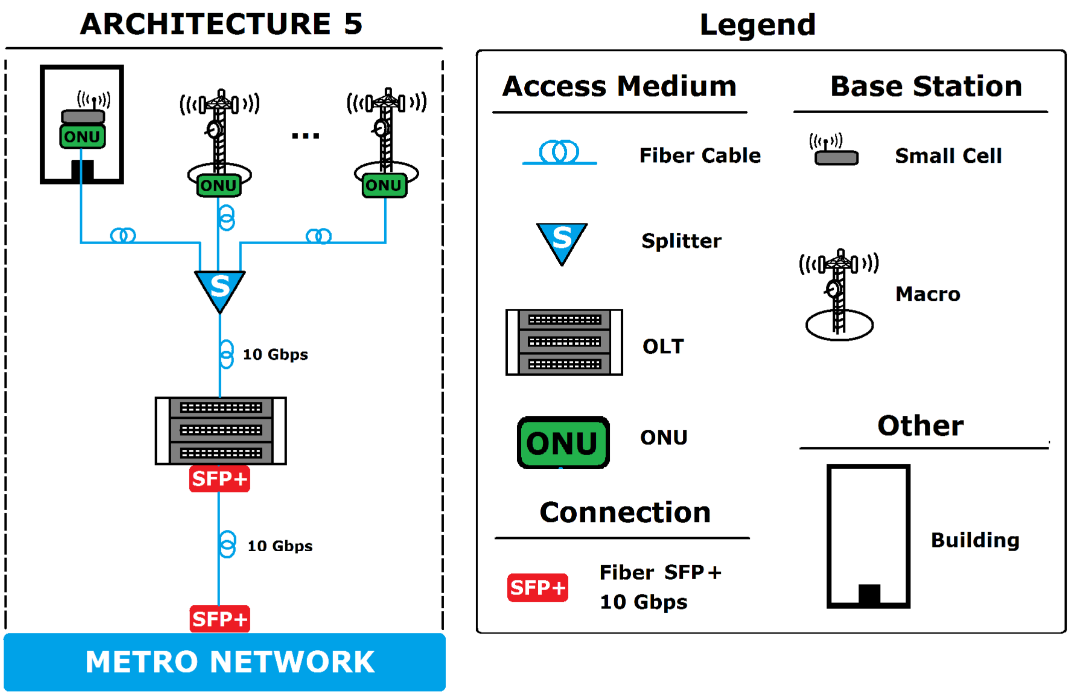


Figure 3.6: Fiber-to-the-home for the femto and macro base stations.

3.5 TOTAL COST OF OWNERSHIP

In this phase, there is an evaluation of the TCO of the backhaul architectures, starting from the dimensioning and the power models discussed in the previous section. The TCO is given by the sum of CAPEX and OPEX, which is illustrated in Fig. 3.7. The CAPEX is obtained as the sum of the costs for Infrastructure, Installation and Equipment. In this study, the Infrastructure costs refer to the fiber trenching costs (i.e., the cost of trenching one kilometer (km) of fiber times the number of km of fiber required to serve the area). Furthermore, the Installation cost includes the costs incurred by the installation and setup of the backhaul network equipment. When estimating the installation cost the total time to install the network equipment is computed and multiplied by the equivalent of a technician's salary, e.g., in US$/hour. Finally, the Equipment cost is the sum of the backhaul network equipment costs. OPEX contains the yearly expenses of the backhaul network operation. It is a sum obtained by adding up five key cost categories: Energy, Floor Space, Spectrum & Fiber Leasing, Maintenance and Fault Management. Energy costs refer to the total network energy consumption of the network and is expressed in kWh (they are estimated with the aid of the power consumption models from Section 3.4 and assuming that all the network equipment is active all the time) times the cost of energy (e.g., expressed in US$/kWh). The Floor space cost is calculated by multiplying the total area required to accommodate the backhaul equipment (e.g., expressed in square meters and including central offices, local exchanges, and antenna mounts) times the price to rent a space, e.g. in US$/m^2. Spectrum & fiber leasing costs cover the expenses to lease microwave spectrum (e.g., expressed in US$/Link), and dark fibers (e.g., expressed in US$/km). Maintenance costs represent the expenditure of monitoring, repairing and testing network equipment in the central office, the local exchange and microwave hubs. It also includes the annual license fee costs for the software. Finally, Fault Management includes the sum of the repair costs for each failure that occurs in the backhaul network. More details about TCO models for backhaul are available below.

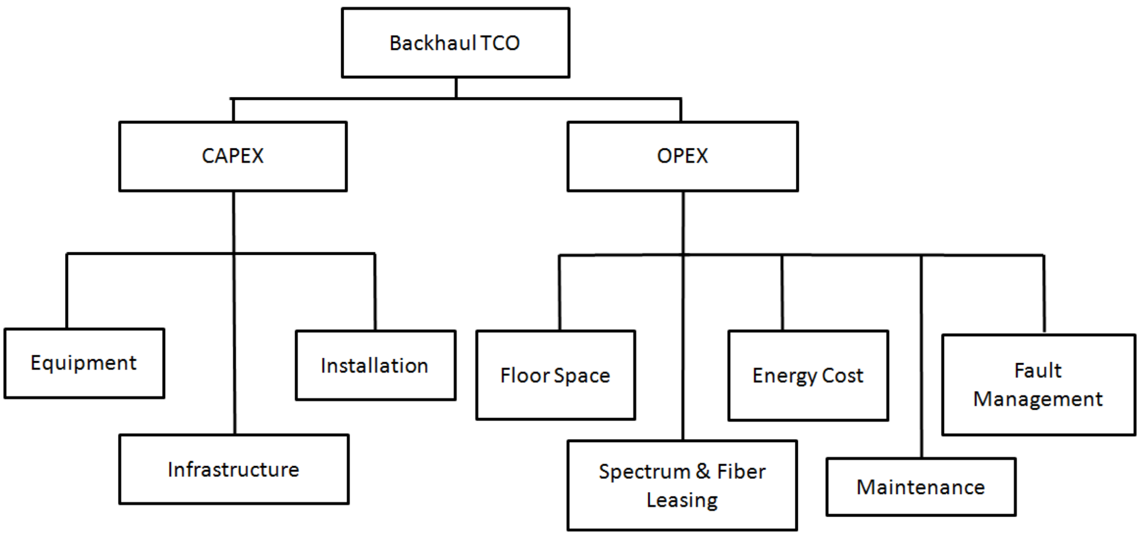


Figure 3.7: Backhaul techno-economic model.

3.5.1 CAPEX: Equipment Costs

The equipment cost (Tot_{Cost}^{Eq}) is given by:

$$Tot_{Cost}^{Eq} = \sum_{i=1}^{m} N_i^{Eq} Pr_i^{Eq} \tag{3.10}$$

where N_i^{Eq} and Pr_i^{Eq} are the sum of all the pieces of equipment and the price of each one, respectively.

3.5.2 CAPEX: Infrastructure Costs

The total infrastructure cost (Tot_{Cost}^{infra}) of a mobile backhaul segment corresponds to the investment needed to deploy the fiber infrastructure, either PTP or PON, as well as the cost of leasing fibers (when the fiber infrastructure has already been deployed by other providers and is available for leasing). Finally, Tot_{Cost}^{infra} also includes the expenses needed to install the microwave hubs, i.e., masts and antennas, where it is needed:

$$\begin{aligned} Tot_{cost}^{infra} &= Tot_{InfraCost}^{PTP} + Tot_{InfraCost}^{FF} + Tot_{InfraCost}^{DF} \\ &+ Tot_{InfraCost}^{LeaseFiber} + N^{MWHub} Pr^{MWHub} \end{aligned} \tag{3.11}$$

where $Tot_{InfraCost}^{PTP}$, $Tot_{InfraCost}^{FF}$, $Tot_{InfraCost}^{DF}$, $Tot_{InfraCost}^{LeaseFiber}$ are the total infrastructure costs to deploy, assuming the operator is the backhaul owner in the first three variables, point to point, feeder fiber and distribution fiber, and the total infrastructure cost when the operator leases dark fiber. Additionally, N^{MWHub}, Pr^{MWHub} are the number of microwave hubs and the price of each microwave hub, respectively.

3.5.2.1 OWNING THE INFRASTRUCTURE

Before they can own the backhaul infrastructure, the operators must deploy a topology in the network and end-user. In the case of the PTP infrastructure, the operator connects the OLT, located at MN, directly with the ONU, at the other edge.

$$Tot_{InfraCost}^{PTP} = Tot_{FiberTrench} Pr_{Trenching} + L_{Fiber}^{PTP} Pr_{Fiber} \tag{3.12}$$

where $Tot_{FiberTrench}$, $Pr_{Trenching}$, L_{Fiber}^{PTP}, Pr_{Fiber} are the total distance to be trenched to connect all the infrastructure, the price to trench per Km, the total length of fiber to be installed and the price to feed fiber per km, respectively.

The models were built by assuming a uniform distributed customer base over a symmetrical square area, as depicted in Fig 3.8. One site in the square contains n buildings containing a uniform distributed number of floors (N_{floors}) and apartments per floor ($N_{Ap/floor}$). Thus the square has $N_{Ap/floor}\ N_{floors}\ n^2$ apartments. The distance between two buildings is indicated by l. With regard to only the connection points of the buildings, the longest distance horizontally or vertically between the two most distant buildings is given by $(n-1)l$. The longest distance (horizontally or vertically) is nl and the square surface is defined as n^2l. The central office is located in the center of the scenario.

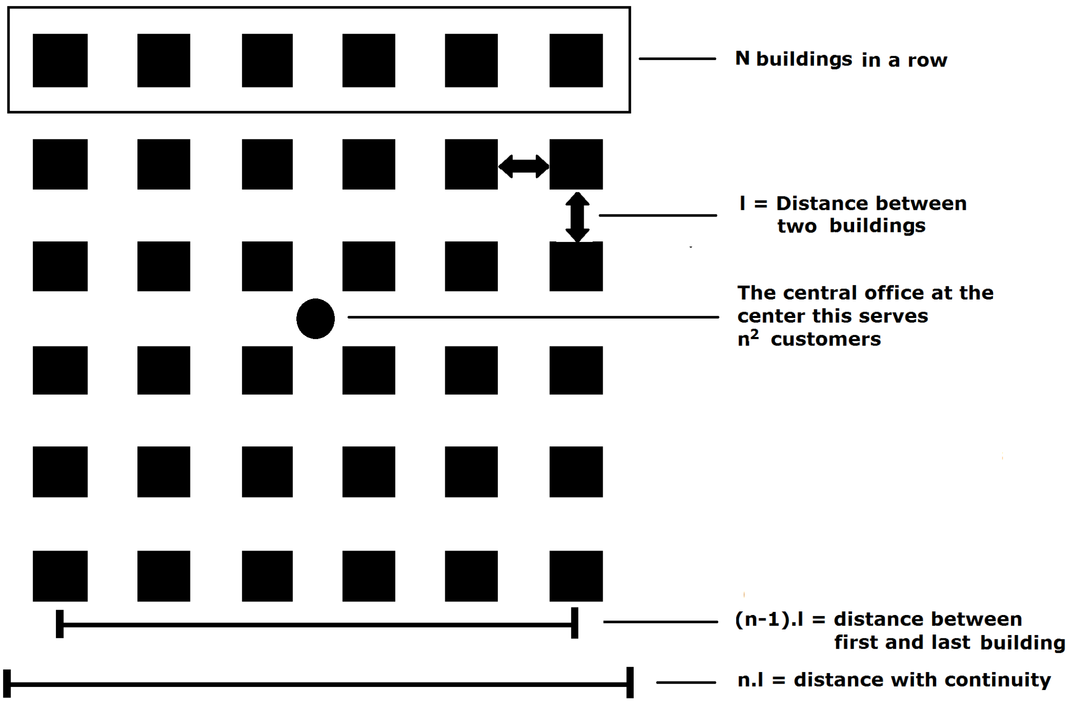


Figure 3.8: Schematic overview of the logical structure and parameters to obtain the trenching and installation distances.

In new deployments of residential and business areas the fully buried installation of fiber cables runs along the side of the streets to the premises of the end-user [69]. This model is called street length model and it follows one street and connects all the buildings through fiber cables located in the middle of the street, (as shown in Fig 3.9).

In this structure the trench length is defined grouping all buildings per 2 as indicated in Fig 3.9. A trench length of nl is used to connect all the pairs of buildings in

2 adjacent rows (one street). There are $\frac{n}{2}$ such adjacent rows and to connect these adjoining pairs of buildings into one fully connected street, a trench length of $(n-1)l$, is needed and again in $\frac{n}{2}$ adjacent rows. Finally, the connection to the central office occurs in the divider street that has a length of $(n-2)l$. The combination of all the elements for the $Tot_{FiberTrench}$ is given by:

$$\begin{aligned} Tot_{FiberTrench} &= \frac{n^2 l}{2} + \frac{n(n-1)l}{2} + (n-2)l \\ &= \left({n_{ff}}^2 + \frac{n_{ff}}{2} - 2\right) l_{ff} \end{aligned} \tag{3.13}$$

where n_{ff} and l_{ff} are the number of fiber connections, i.e., the number of ONU to be installed, and the length of a street block; while for the installation fiber, the buildings are grouped in categories, i.e., a = 2, b = 2, c = 2, d = 2, e = 2, f = 2. The grouping is per pair of buildings and the distance between two consecutive horizontal streets is $2l$. In the case of two categories, it is again grouped (a+b), (c+d), (e+f). For each of the new groups, the number of apartments is the same and the distance is twice the smallest + 1. Finally, all this information leads to the following L_{Fiber}^{PTP}:

$$L_{Fiber}^{PTP} = 4\, N_{Ap/floor}\, N_{floors}\, l_{ff} \sum_{i=1}^{\frac{n_{ff}}{2}-1} \left(2\, min\left(i, \frac{n_{ff}}{2} - i\right) \left[\frac{n_{ff}}{2} - 1\right] 4 + 1\right) \tag{3.14}$$

where i is the number of connections. i goes up to $\frac{n_{ff}}{2} - 1$ because each connection reaches the middle of the street blocks, and is thus able to connect with both sides of the street.

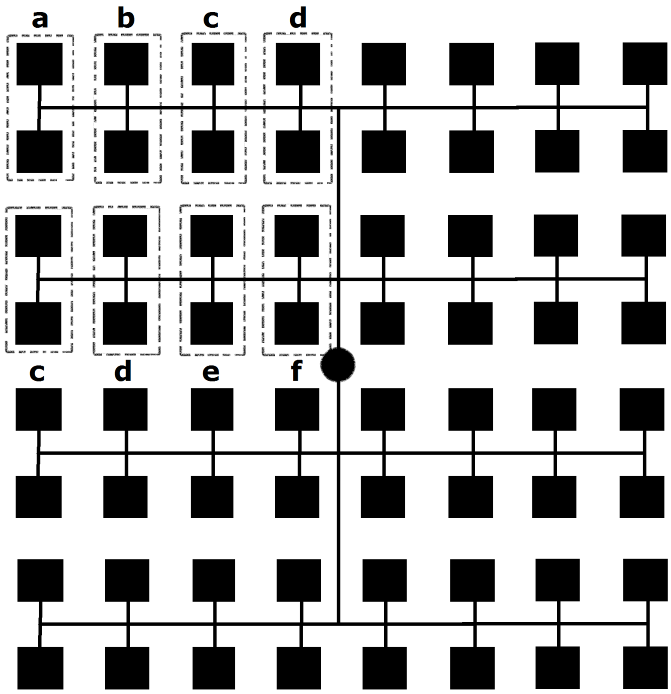


Figure 3.9: Logical structure for the fiber connections.

Unlike the PTP infrastructure, the PON has two levels, called the feeder and distribution fiber. The feeder fiber connects the network from the metro aggregation to the local exchange, while the distribution fiber connects the local exchange to the ONU. The model for $Tot^{FF}_{InfraCost}$ is similar to Eq. (3.13), but the n_{ff} element is replaced by the number of splitters ($n_{splitters}$) and Eq. (3.14) is adapted to Eq. (3.15):

$$L^{FF}_{Fiber} = 4\, l_{ff} \sum_{i=1}^{\frac{n_{splitters}}{2}-1} \left(2\, min\left(i, \frac{n_{splitters}}{2} - i\right) \left\lceil \frac{n_{splitters}}{2} - 1 \right\rfloor 4 + 1\right) \tag{3.15}$$

where $Tot^{DF}_{InfraCost}$ represents the distribution level of the PON, i.e., from the splitter to the ONU, and is described as follows:

$$Tot^{DF}_{InfraCost} = Tot^{DF}_{Trench} Pr_{Trenching} + L_{DistributionFiber} Pr_{Fiber} \tag{3.16}$$

where Tot^{DF}_{Trench} and $L_{DistributionFiber}$ are the distance to the trench paths from the splitters to the ONUs and the distance to distribute the fiber links to connect the ONUs with the splitters, respectively. Tot_{Trench}^{DF} is defined as follows:

$$Tot_{Trench}^{DF} = \left(n_{df}{}^{2} + \frac{n_{df}}{2} - 2\right) l_{df} N_{SmallBlocks} \tag{3.17}$$

where n_{df}, l_{df}, $N_{SmallBlocks}$ represent the number of buildings connected to each local exchange, the distance between the buildings and the number of local exchanges, respectively. L_{Fiber}^{DF} is defined by Eq. (3.18):

$$L_{Fiber}^{DF} = 4\, N_{Ap/floor}\, N_{floors}\, N_{SmallBlocks} l_{df} \sum_{i=1}^{\frac{n_{df}}{2}-1} \left(2 \min\left(i, \frac{n_{df}}{2} - i\right) \left[\frac{n_{df}}{2} - 1\right] 4 + 1\right) \tag{3.18}$$

3.5.2.2 LEASING THE INFRASTRUCTURE

PTP and PON are two alternative topologies for operators who wish to lease backhaul infrastructure. The general formula for leasing is given by:

$$Tot_{InfraCost}^{LeaseFiber} = Tot_{InfraCost}^{PTPLease} + Tot_{InfraCost}^{PONLease} \tag{3.19}$$

where $Tot_{InfraCost}^{PTPLease}$ and $Tot_{InfraCost}^{PONLease}$ denote the total cost for leasing PTP and PON infrastructure respectively. $Tot_{InfraCost}^{PTPLease}$ model is described as follows:

$$Tot_{InfraCost}^{PTPLease} = L_{Fiber}^{PTP} Pr_{CostperKm}^{LeaseAcquisition} \tag{3.20}$$

where $Pr_{CostperKm}^{LeaseAcquisition}$ is the acquisition cost to secure a contract for the following years, e.g., next 15 or 20 years; and $Tot_{InfraCost}^{PONLease}$ is described as Eq. (3.21):

$$Tot_{InfraCost}^{PONLease} = (L_{Fiber}^{FF} + L_{Fiber}^{DF}) Pr_{CostperKm}^{LeaseAcquisition} \tag{3.21}$$

3.5.3 CAPEX: Installation Costs

The Equipment cost ($Tot_{Cost}^{Install}$) is the sum of all the expenses related to installing the backhaul components in their specific locations:

$$Tot_{Cost}^{Install} = Tot_{InstCost}^{FiberEq} + Tot_{InstCost}^{MWEq} + Tot_{InstCost}^{CopperEq} \tag{3.22}$$

where $Tot_{InstCost}^{FiberEq}$, $Tot_{InstCost}^{MWEq}$ and $Tot_{InstCost}^{CopperEq}$ represent the total cost for installing fiber, microwave and copper equipment respectively. The fiber, microwave and copper equipment installation costs can be defined as:

$$\begin{aligned} Tot_{InstCost}^{FiberEq} = Tot_{InstCost}^{MWEq} = Tot_{InstCost}^{CopperEq} \\ = \sum_{i=1}^{m} \left(T_i^{InstallPort} N_i^{Port}\right) N_i^{Eq} Pr_{Tech} \end{aligned} \tag{3.23}$$

where $T_i^{InstallPort}$, N_i^{Port}, N_i^{Eq} and Pr_{Tech} represent the total time needed to install equipment port, the number of ports to be installed, the total amount of equipment costs and the technician's salary per hour. *i* represents the type of equipment, e.g., DSLAM, Switch.

3.5.4 OPEX: Energy Costs

The electricity bill is part of the OPEX. This cost (Tot_{Cost}^{Energy}) is obtained by adding up the energy costs of all the active equipment in the various backhaul locations (i.e., CO, cabinets, microwave sites).

$$Tot_{Cost}^{Energy} = \sum_{i=1}^{m} Tot_i^{kW/y} \, Pr_i^{kW} \tag{3.24}$$

where $Tot_i^{kW/y}$ and Pr_i^{kW} are the yearly kW consumed by equipment and the kW price respectively. *i* represents the type of equipment, e.g., Switch, DSLAM, modem.

3.5.5 OPEX: Spectrum and fiber leasing

The costs of spectrum and fiber leasing can be expressed by Equation (3.25):

$$Tot_{Cost}^{Lease} = \sum_{i=1}^{m}\sum_{j=1}^{t} N_{ij}^{MWlink} Pr_{ij}^{MWLink} + Tot_{LeaseCost}^{PON} + Tot_{LeaseCost}^{PTP} \tag{3.25}$$

where N^{MWLink} and Pr^{MWLink} denote the number of microwave links used for the backhaul, e.g., links of 100 Mbps, 1 Gbps, and the microwave link price of type *i* during year *j*, respectively. Additionally, $Tot_{LeaseCost}^{PON}$ and $Tot_{LeaseCost}^{PTP}$ are the total leasing cost of the PON infrastructure and of the PTP infrastructure, respectively. When leasing the fiber links, the operator is charged a yearly fee for the maintenance and repairs of the rented fibers in addition to the upfront expenses. Both costs are computed as follows:

$$Tot_{LeaseCost}^{PON} = (L_{Fiber}^{FF} + L_{Fiber}^{DF}) Pr_{perKm}^{FiberLease} \tag{3.26}$$

$$Tot_{LeaseCost}^{PTP} = L_{Fiber}^{PTP} Pr_{perKm}^{FiberLease} \tag{3.27}$$

where $\boldsymbol{Pr_{perKm}^{FiberLease}}$ is the cost of leasing one Km of fiber.

3.5.6 OPEX: Maintenance Costs

Regular routine maintenance is needed to keep a backhaul network active and running. This includes monitoring and testing the equipment, updating the software (including renewing licenses when needed), and renewing the support components such as batteries, etc. The total maintenance cost (Tot_{Cost}^{M}) is expressed by Equation (3.27):

$$Tot_{Cost}^{M} = Co_M + Cab_M + MW_M + SW_{lic} + Mon \tag{3.27}$$

where Co_M , Cab_M and MW_M reflect the maintenance costs of central offices, cabinets and microwave links, respectively. The annual license fee for the software is represented by SW_{lic}. Finally, *Mon* is the annual expenditure of the salaries of the technicians, who are responsible for monitoring the network.

The operators undertake several rounds of maintenance procedures for each central office depending on the number of users and services covered by each one. This expense can be expressed as follows:

$$Co_M = \sum_{i=1}^{L_n} (N_{Co}^{Mh}\, N_i^{Co} Tech_i^{sal} + M_{Co}^{cost} N_i^{Co}) \tag{3.28}$$

where N_{Co}^{Mh} , $N_i^{Co}$and M_{Co}^{cost} denote the man-hours required for the maintenance of each central office per year, the number of central offices and the fixed cost to be paid for upgrading hardware, and replacing some materials (e.g., batteries).

A similar expression can be derived for the maintenance of cabinets (Equation 3.29), where the number of man-hours per cabinet (N_{Cab}^{Mh}) is lower than those required for the central offices.

$$\begin{aligned} Cab_M = & \sum_{j=1}^{L_n} \sum_{i=1}^{N_j^{cab}} (N_{Cab}^{Mh} + 2T_{cab_i}^{trav})\, Tech_i^{sal} \\ & + M_{Cab}^{cost} \sum_{j=1}^{L_n} N_j^{cab} \end{aligned} \tag{3.29}$$

where N_j^{cab} represents the number of cabinets per year j and M_{Cab}^{cost} represents the cost to be paid for upgrading hardware, and replacing some materials (e.g., batteries).

The microwave links also require regular monitoring, because the antennas might tilt and lose their line of sight. This part of the TCO can be expressed by Equation (3.30).

$$MW_M = \sum_{j=1}^{L_n} \sum_{i=1}^{N_j^{MWlink}} \left(N_{MWant}^{Mh} + 2T_{MWant_i}^{trav}\right) Tech_j^{sal} \tag{3.30}$$

where N_{MWant}^{Mh} and $T_{MWant_i}^{trav}$ represent the annual number of man-hours required for the maintenance of each microwave antenna and the travelling time to the location of each antenna, respectively.

Eq. (3.31) reflects the monitoring costs of the backhaul network. It is assumed that every 10 nodes, (such as central offices), can be monitored with one team of technicians. Therefore dividing the total number of nodes (N_i^{node}) by 10, gives the number of required teams in time. $Tech_{team}$ and $Tech_i^{sal}$ represent the number of technicians per team and the hourly salary of each in year i, respectively. The monitoring cost per year is then calculated by multiplying these parameters by the number of hours per year.

$$Mon = \sum_{i=1}^{L_n} (24 \times 365) Tech_{team} \left(\frac{N_i^{node}}{10} \right) Tech_i^{sal} \tag{3.31}$$

3.5.7 OPEX: Fault Management

Fault management refers to the expenses incurred by the repairs of failures that might occur in a backhaul network. The total number of failures per year of each component type can be calculated by multiplying the Annualized Failure Rate (AFR) of each component with the amount of equipment for each type (N_i^{eq}).

$$\begin{aligned} Tot_{FM}^{cost} = \sum_{j=1}^{L_n} \sum_{i=1}^{N_{type}^{eq}} &((MTTR_i + 2T_{trav}) N_{tech}\, Tech_j^{sal} \\ &+ Eq_{ij}^{Cost})\; AFR_i \times N_i^{eq} + FM_{fiber} + Penalty \end{aligned} \tag{3.32}$$

where, $MTTR_i$, T_{trav}, N_{type}^{eq}, N_{tech}, Eq_{ij}^{Cost} represent the mean time to repair, travelling time to the location of the failure, the number of equipment types, the number of technicians required to repair a failure and the repair cost depends on the new component purchasing cost in a year *j* when needed, respectively.

As the repair failure of the fiber infrastructure differs from the network components, Eq. (3.33) is used to calculate the failure/repair costs related to the fiber cut in the backhaul segment.

$$\begin{aligned} FM_{fiber} = \sum_{j=1}^{L_n} \sum_{i=1}^{N_j^{cable}} & L_i \\ &\times unAv_{fiber} \left(TT + N_i^{fiber} T_{sp} \right) N_{tech} Tech_j^{sal} \end{aligned} \tag{3.33}$$

where L_i and $unAv_{fiber}$ denote the length of each cable section in kilometers and unavailability of fiber per kilometer, respectively. The latter parameter varies depending on the demographic data of the area. For example the probability of fiber cut in urban areas is higher than in rural areas since cables are buried at a lower depth in rural areas. When a fiber cut occurs, a certain time is needed to find the location of the failure and open up the ground to reach the cable; this time is referred to as troubleshooting time (*TT*). N_i^{fiber} and T_{sp} represent the number of fibers per cable in the failure location which need to be spliced and the time required for splicing per fiber

Finally, Eq. (3.34) defines the $Penalty$, which is the fine that operators have to pay to the customers when the interruption of service is longer than the threshold defined in the SLA (T_{tr}). In the case of mobile backhaul, the penalty is applied when the macro cells are out of service and leave lots of customers out of service. Thus, penalty cost for backhaul provider is imposed when the macrocell backhaul connectivity is lost due to a certain failure.

$$Penalty = \sum_{j=1}^{L_n} \sum_{i=1}^{N_j^{MacCell}} P_I^{cost/h} (unAv_{ij} \times 365 \times 24 - T_{tr}) \tag{3.34}$$

where $N_j^{MacCell}$, $unAv_{ij}$ and $P_I^{cost/h}$ represent the number of macro cells with high importance in a year *j*, the connection unavailability of the backhaul link to the macro cell *i* and the rate of penalty agreed in the SLA.

3.5.8 OPEX: Floor Space

The floor space cost (Tot_{cost}^{FlSp}) is an annual rental fee paid by an operator to store its equipment, i.e., to place components in the racks with standard size. The number of racks inside a central office is computed by dividing the amount of equipment per central office ($N_i^{\frac{Eq}{Co}}$) by the amount of equipment per rack (N_{Rack}^{Eq}). The total floor space cost can be defined as follows:

$$Tot_{cost}^{FlSp} = \sum_{j=1}^{L_n} \left((A_{Rack} \left(\frac{N_i^{\frac{Eq}{Co}}}{N_{Rack}^{Eq}} \right)) \mathrm{Pr}_{Rack}^{Ind/m} + A_{cab} N_i^{cab} \mathrm{Pr}_i^{Out/m^2} + A_{hub} N_i^{hub} \mathrm{Pr}_i^{Out/m^2} \right) \tag{3.35}$$

where $\mathrm{Pr}_{Rack}^{Ind/m}$ and Pr_i^{Out/m^2} are, respectively, the annual rental fee paid by an operator for indoor areas (e.g., CO) and outdoor locations where no storage is provided. Cabinets are usually built with a standard size A_{cab} regardless of the components inside them. A_{hub} shows the area required to install a microwave hub. The number of cabinets and hubs in year *i* is related to the number of backhaul equipment.

3.6 CASE STUDY

In this section, the methodology and math models discussed so far are employed for a European Urban Scenario. It is assumed that the area under consideration is A=100 km^2, with buildings uniformly distributed measuring 80x80 meters and a distance between them of 20 meters. The total number of buildings in the area is set at 10000 and each building has 5 floors and 2 apartments per floor (i.e., the total number of apartments N_{ap} corresponds to 100000). In addition, it is assumed that the population density is ρ =3000 users per km^2 and that a single operator serves the area. Moreover, the Manhattan street model [69] is employed to calculate the distances between the CO, local exchanges and end-users. In the following section, the TCO calculation is outlined in detail.

With regard to the traffic demand τ, it is assumed that 16% of the subscribers are active during the busy/peak hours (i.e., $\alpha_{max} = 16\%$) and that the capacity requirement of an ordinary user is 1/8 that of a heavy user [66]. Moreover, it is assumed that on average PC users generate two and eight times more data traffic than tablet and smartphone users, respectively. More details about the traffic demand can be found in [66][1].

It was assumed that in the year 2010 the area was served by a homogeneous wireless network based only on macro base stations, i.e., $\eta = 0$. In addition, after 2010 the wireless deployment evolves towards HetNets (i.e., it is based on macro + femto base stations) and there is a linear increase in the femto penetration rate of 5% every year. Regarding the backhaul network, it was assumed that in 2010 the macro base stations were backhauled by means of microwave point-to-point links.

In the Greenfield scenario, starting from the year 2011, the operator deployed a new backhaul infrastructure to support HetNets. The new infrastructure could either be based on microwave or fiber (it is assumed that the operator will not deploy a new infrastructure based on copper because of its limited capacity to provide high traffic over long distances). As a result, in the Greenfield scenario, the possible solutions for the operator (starting from year 2011) are the backhaul Architectures 1, 3, 4 and 5, described in Section 3.4.

On the other hand, in the Brownfield scenario the operator is able to leverage from the already existing fiber and copper infrastructure, i.e., the operator owns a backhaul infrastructure like that of Architecture 2. As a result, in the year 2011 the operator faced two options for a network upgrade. The first choice was to continue deploying MW based backhaul (i.e., relying on Architecture 1), and the second option was to migrate to new network architectures by reusing legacy ducts and the trench infrastructure. The migration can be executed by employing several different models. In the following, there is a description of some of the promising alternatives.

Gradual migration take-up (M1): In this migration model, the operator decides to exploit the copper infrastructure to backhaul the indoor femto cells. As a result, in the year 2011 the operator selected the Architecture 2. Afterwards, the mobile operator gradually migrated from Architecture 2 to Architecture 5. In particular, the operator started replacing the copper infrastructure with PON-based backhaul three years before the copper was used up (i.e, three years before the copper infrastructure is expected to be unable to support the increased traffic demand). This occurs when the traffic demand for fixed broadband access networks exceeds 100 Mbps per household, and is calculated on the basis of the traffic forecast model shown in [70]. In addition, the operator also gradually replaces the MW based backhaul with PONs, starting from three years before the time when the area traffic demand exceeds 1000 Mbps/km^2. The gradual migration is represented by a replacement starting from a rate of 20%, which in the next year increases to 50% of the infrastructure migrated to the new technology, and in the last year of migration rises to 80%. In the fourth year, i.e., one year after the gradual migration, 100% of the infrastructure is already represented by the new equipment.

Gradual migration take-up (M2): As in the case of the previous migration model, it is assumed that in the year 2011 the operator chose Architecture 2. Afterwards, the operator gradually migrates from Architecture 2 to Architecture 4. The copper infrastructure is replaced with PON-based backhaul (as described in the migration model M1). On the other hand, in this case the operator keeps relying on the MW-based backhaul for the macro BSs.

Immediate take-up (M3): In this migration model, the operator in 2011 decided to make a large investment to replace both the copper and the MW infrastructure with PONs immediately. Hence, in the year 2011 the operator migrates directly toward Architecture 5.

Immediate take-up (M4): The M4 migration model is similar to M3, but in this case the operator only replaces the copper infrastructure with PON-based backhaul, while keeping the MW infrastructure for backhauling the macro base stations. As a result, in the year 2011 the operator migrated directly toward Architecture 4.

No take-up (M5): This case is similar to migration model M1, where the operator chooses Architecture 2 and then migrates to Architecture 5. However, in this case the migration is not carried out gradually. In fact, the operator keeps the VDSL2 copper infrastructure until its capacity has been used up and only afterwards replaces it with PONs. Similarly, the replacement of the MW-based backhaul with PON is only carried out after the traffic demand exceeds 1000 Mbps/km^2.

No take-up (M6): This migration model corresponds to migration model 2 with the difference that the migration from copper to PON backhaul is not undertaken gradually. MW backhaul is always used for macro base stations.

Table 3.1 - Inputs for power consumption and investment costs.

Eq./Comp.	P (Watts)	Cost per Equipment/Service (US$)
DSLAM	85	1750
GES	50	2400
FS	300	3000
Hub Switch	53	2930
Antenna	37 or 92,5[1]	4472
OLT	105	3000
Splitter (32 ports)	0	140
ONU	4	146
Modem	5	30
SFP	1	37
SFP+	1,5	78
Fiber (km)	-	160
Trenching (km)	-	130000
Yearly spectrum leasing	-	204
Leasing upfront fee (km)	-	800
Yearly fiber leasing fee (km)	-	200
Yearly rental fee – Indoor (m^2)	-	287
Yearly rental fee – Outdoor (m^2)	-	249

[1] Depending on traffic demand

The TCO has been evaluated for all the options described above to define the most cost-efficient solution. The electric power consumption and cost values shown in Table 3.1, which were extracted from [4][70][71] [72][3][73], are drawn on for our calculations.

With regard to the MW backhaul technology, it is assumed that the MW antenna power consumption corresponds to P_{low-c} when the traffic at the antenna is lower than 500Mbps, otherwise it corresponds to P_{high-c}.

Fast Ethernet connections operating at 100Mbps are used inside the buildings to connect the femto cells to the GES (in Architectures 1 and 3). In addition, the femto base stations are distributed uniformly among the buildings and in the area. As a result, the number of GES (N_{GES}) is equal to the number of buildings if $\eta > 0$. In addition, it is assumed that the power consumption of a GES linearly scales with the number of ports that are used for backhauling the femto base stations: $P_{GES} = \left\lceil \frac{N_{femto}}{N_b n_{ports}^{GES}} \right\rceil P_{GES}^{max}$, $\forall\, \eta \geq 0.1$, where n_{ports}^{GES} is the total number of ports of the GES. Moreover, in the Greenfield scenario, two possible values are given for the maximum distance between the femto cells and the local exchanges, which are 300m and 1Km. On the other hand, in the Brownfield scenario, there is only a maximum distance of 300m between the femto cells and local exchanges. This is because VDSL2 technologies are not able to cope with distances longer than 300m (which means that architecture 2 could not be employed as a migration option).

For this study, a technician's salary is set at 72 US$/hour for the first year and energy costs (kWh) at 0.15 US$/kWh, with a yearly increase based on the geometric progression given by c_n=$c_1 q^{n-1}$. Where c represents either the technician's salary or the energy cost in the year n, and q = 1.03 is the increase in the ratio [5]. A fixed yearly depreciation is also specified for the network equipment cost corresponding to 5% (unless stated otherwise).

3.7 RESULTS

It is worth mentioning that the obtained models and results were validated during the GreenHaul project [22]. Figures 3.10 to 3.17 illustrate the results obtained from the analysis of the case study. It can be seen that Architecture 1 (i.e., MW-only) always shows the highest energy consumption. Hence, the results achieved with Architecture 1 are used as a benchmark for the discussion of the results for Greenfield and Brownfield scenarios discussed below.

3.7.1 An analysis of the Greenfield Deployment

Fig. 3.10 illustrates the total cost of power consumption per year respecting the traffic demand for architectures 1, 3, 4 and 5. When architectures 1 and 3 are compared, it is evident that fiber-based backhaul for femto cells can significantly reduce the overall backhaul energy consumption. On the other hand, when FTTH solutions (architectures 4 and 5) are employed, the power savings are even higher. In specific terms, the best results are obtained with the PON backhaul for both femto cells and macro base stations, i.e., Architecture 5. Moreover, it was observed that the power consumption for the scenario where the maximum distance between the local exchanges and the femto cells, is 300m; this is the same as in the case where the maximum distance is 1km (even if the total number of required local exchanges is higher when the maximum distance is set to 300m). The reason is that the local exchanges in architectures 3, 4 and 5 are always bypassed (Architecture 3) or equipped with passive components (Architectures 4 and 5).

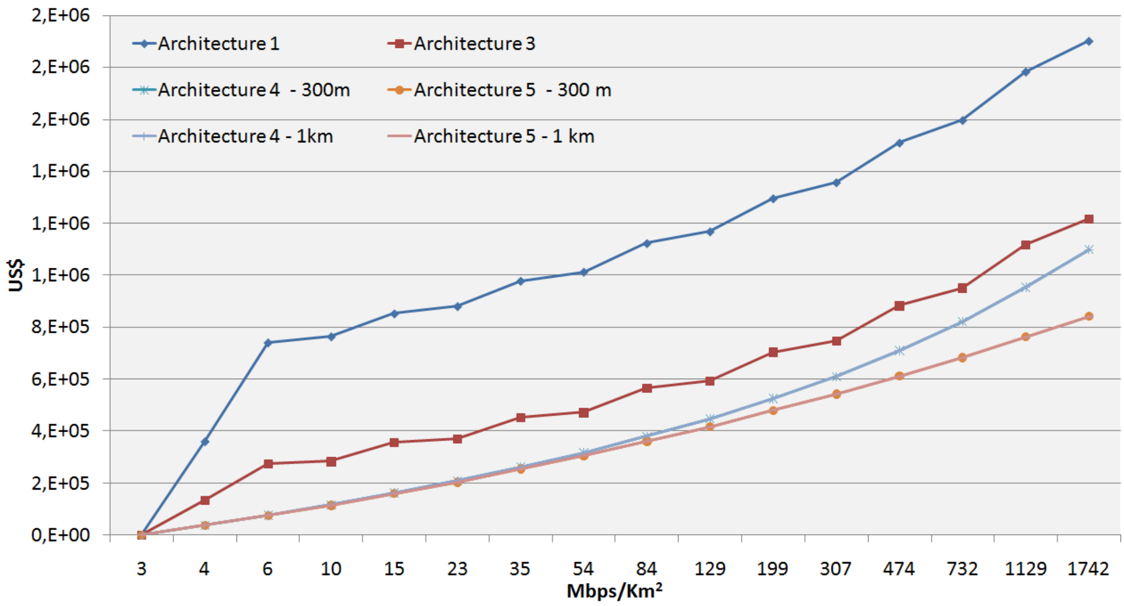


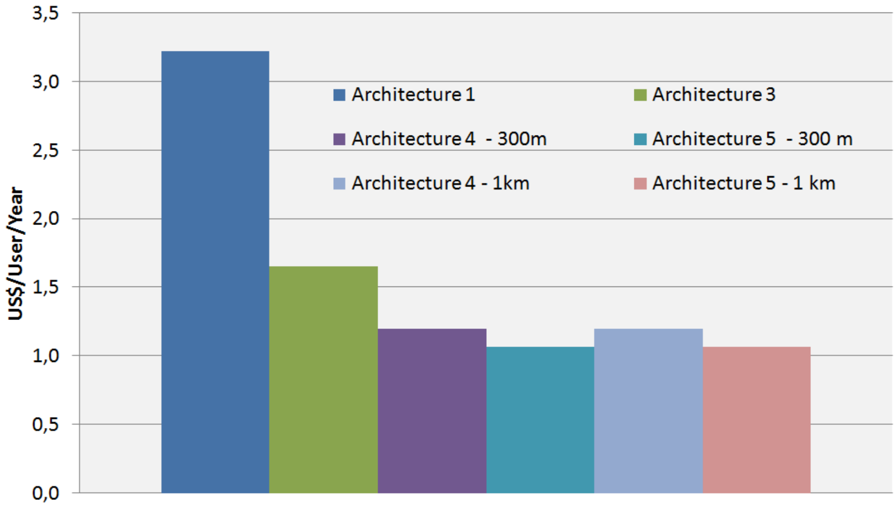
Figure 3.10: Greenfield deployment - Energy consumption for period *T* equals to 15.

Fig. 3.11(a) illustrates the average cost of energy consumption per user per year. It can be observed that the use of FTTH and FTTB technologies for backhauling the femto cells leads to a significantly greater reduction in energy costs than the MW-based solution. In particular, when Architecture 2 is used, it is possible to save up to 1.57 US$ per user per year with regard to Architecture 1, while Architecture 5 it is possible to save up to 2.16 US$ per user per year which is greater than Architecture 1.

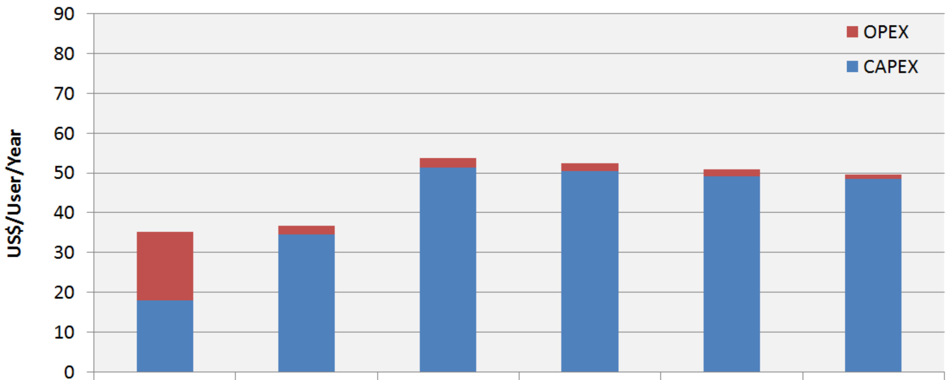
Figs. 3.11(b) and 3.11(c) provide a more complete picture of the cost analysis of the various architectures by showing the TCO for a period *T* lasting 15 years. The results that are obtained Fig. 3.11(b) are based on the assumption that the operator builds a new infrastructure, which means that in Architectures 3, 4, and 5 an investment must be made to pay for trenching the fiber cables to connect the end-users to the MN. The figure shows that, owing to this high investment, Architectures 3, 4 and 5 lead to a higher TCO than Architecture 1 (up to 16.13 US$ per user per year and higher in the case of Architecture 4). In fact, Architecture 4 is the most expensive and reaches a TCO as high as 58.48 US$ per user per year.

The results in Fig. 3.11(c) are computed by assuming that in architectures 3, 4 and 5, the operator leases dark fiber from an external entity (e.g., another network operator) to connect the transport radio access networks to the MN. Leasing dark fiber is an option to decrease CAPEX by avoiding the high financial investment required for trenching and faster deployment time. In this case, a contract is signed between the operator and the external entity, where the operator pays a yearly fee in return for the fiber connectivity.

Depending on the architecture, the dark fiber leasing might or might not be a useful alternative. Fig. 3.11(c) shows that leasing the dark fiber of Architecture 3 is the most attractive solution since it has the lowest TCO among all the considered cases (i.e., it is 15.8US$ lower than Architecture 1). In contrast, Architectures 4 and 5 are hardly feasible in terms of costs when the maximum distance between the femto cells and the local exchanges is 1km. This is due to the fact that the increase in terms of distance between the local exchange and end-user (to 1km) entails more fiber deployment in the distribution fiber path, which implies further costs and higher leasing. This differs when viewed from the stand point of energy consumption because in the case of the TCO of PONs, (i.e., when there are deployment of feeder fiber and distribution fiber paths), the location and number of local exchanges in the network really matters and are more attractive in financial terms, when the local exchange is closer to the end-user, e.g., 300 meters.

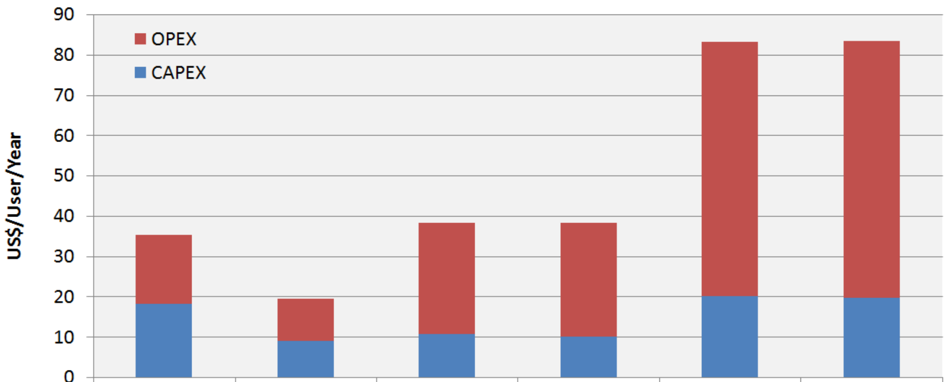


(a)



	Architecture 1	Architecture 3	Architecture 4 - 300m	Architecture 5 - 300 m	Architecture 4 - 1km	Architecture 5 - 1 km
OPEX	17,14131755	2,082810795	2,39090947	1,859669914	1,716347123	1,185107567
CAPEX	18,08986253	34,66434719	51,37660669	50,57210408	49,27199786	48,47937702

(b)



	Architecture 1	Architecture 3	Architecture 4 - 300m	Architecture 5 - 300 m	Architecture 4 - 1km	Architecture 5 - 1 km
OPEX	17,14131755	10,42521471	27,53076511	28,14438649	63,03324188	63,87596637
CAPEX	18,08986253	9,002224797	10,72131008	10,15430752	20,09028814	19,58269447

(c)

Figure 3.11: Greenfield energy consumption and total cost of ownership. (a) Energy consumption per user per year. (b) TCO assuming trenching. (c) TCO assuming leasing dark fiber.

3.7.2 An Analysis of the Brownfield Deployment

Fig. 3.12 shows the electric power consumption of the different migration alternatives described in the previous section. It is noticeable that the *immediate take up* approaches (M3 and M4) are the most energy-efficient solutions. On the other hand, the migration options that employ *no take up* (M5 and M6), i.e., that exploit copper-based backhaul until it reaches “exhaustion”, are the least energy-efficient. This is because M5 and M6 rely on the energy inefficiency of copper infrastructure for longer period of time. Moreover, the energy consumption achieved when adopting *gradual take up* measures (M1 and M2) lies in the middle of the previous cases. M1 and M2 solutions perform better in terms of energy consumption with regard to M5 and M6 because the energy inefficiency VDSL2 infrastructure begins to be replaced at an earlier time (i.e., three years before exhaustion of capacity). Finally, it is evident from Fig. 3.12 that all the considered migration options (M1-M6) achieve lower energy consumption with respect to the solution that is only based on MW (i.e., Architecture 1). In fact, using MW links for backhauling the indoor femto cells leads to higher power consumption than using the fixed line infrastructure (i.e., copper or fiber).

Fig. 3.13(a) shows the energy cost per user per year. The results show that among the Brownfield migration alternatives, M3 is the most energy-efficient solution since it leads to an energy cost of 1.06 US$/User/Year. This low cost is due to the fact that the upgrade towards PON (i.e., Architecture 5) already occurred in the year 2011, i.e., when indoor base stations are first deployed.

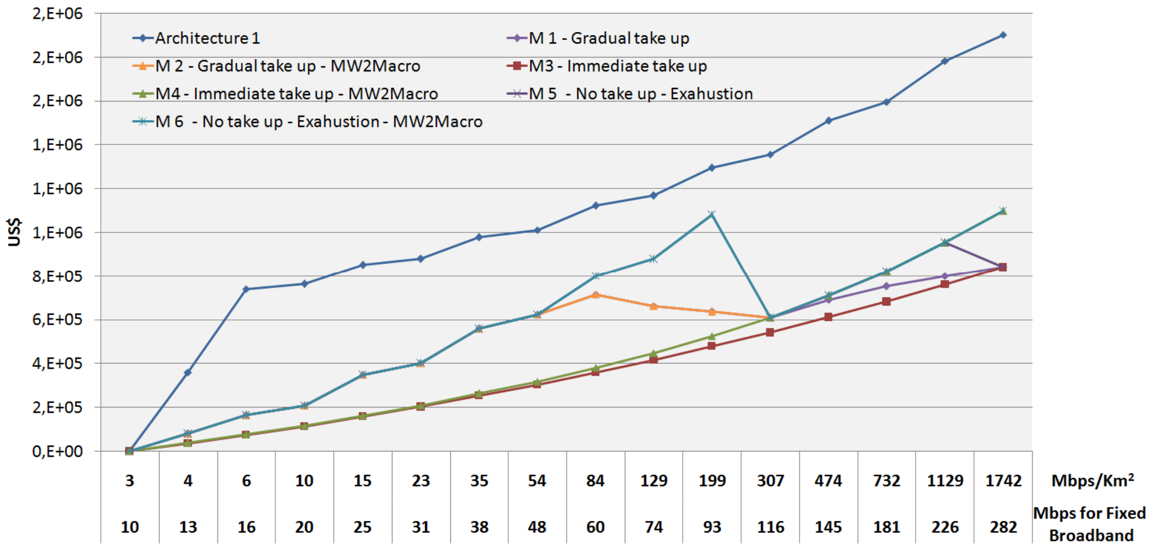
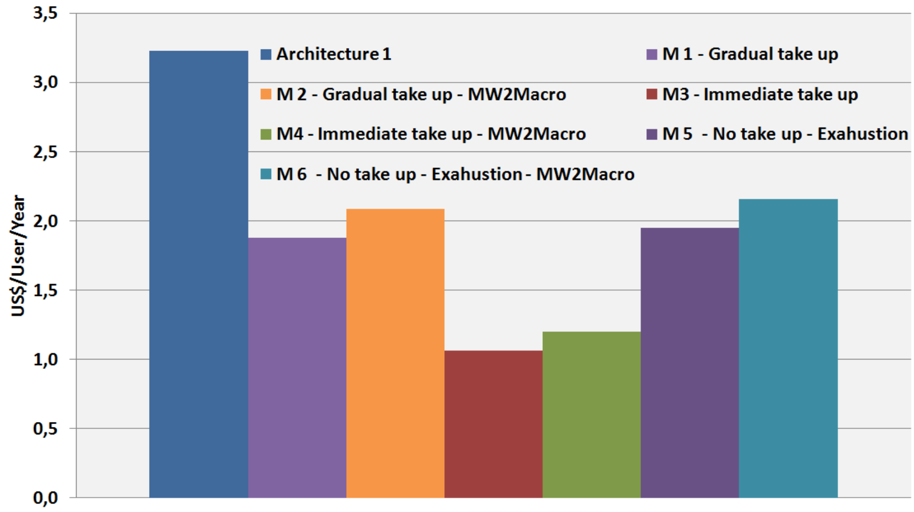
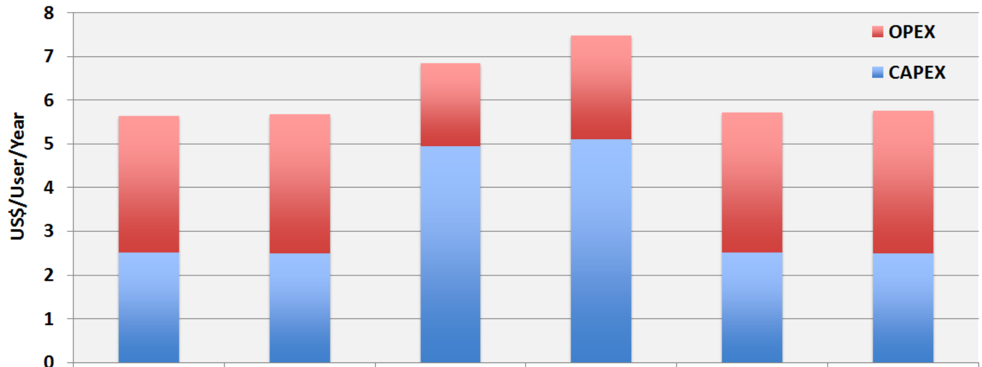


Figure 3.12: Brownfield upgrade - Energy consumption for period *T* is equal to 15.

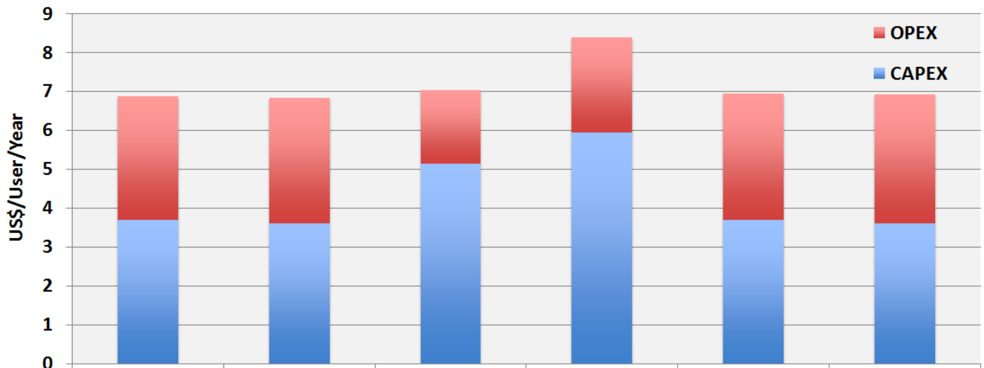


(a)



	M 1 - Gradual take up	M 2 - Gradual take up - MW2Macro	M3 - Immediate take up	M4 - Immediate take up - MW2Macro	M 5 - No take up - Exahustion	M 6 - No take up - Exahustion - MW2Macro
OPEX	3,117898411	3,184892561	1,896472578	2,376666927	3,189842291	3,256836441
CAPEX	2,52285858	2,49004364	4,946133213	5,09451318	2,52285858	2,49004364

(b)



	M 1 - Gradual take up	M 2 - Gradual take up - MW2Macro	M3 - Immediate take up	M4 - Immediate take up - MW2Macro	M 5 - No take up - Exahustion	M 6 - No take up - Exahustion - MW2Macro
OPEX	3,182052435	3,222149455	1,896826294	2,428226044	3,253996315	3,294093335
CAPEX	3,697500661	3,617085001	5,14269036	5,95029766	3,697500661	3,617085001

(c)

Figure 3.13: Brownfield migration. (a) Energy consumption per user per year. (b) TCO assuming an upgrade based on the annual cost of equipment that leads to an increased cost of 5%. (c) TCO assuming that cost of equipment increases by 2.5%.

Fig. 3.13(b) presents the TCO for the proposed Brownfield migration alternatives. It is worth remembering that the results that are obtained take into account a fixed yearly depreciation for the network equipment cost that corresponds to 5%. It can be seen that the migration options based on *immediate take up* (M3 and M4) are the most expensive due to the high initial investment costs (which translates in high CAPEX). However, the migration options based on *gradual take up* (M1 and M2) and those based on *no take up* (M5 and M6) show very similar costs and represent the least expensive alternatives in terms of cost per user per year. This proves that using the legacy copper infrastructure close to (or up to) the capacity exhaustion may bring about significant financial benefits for the operators. However, it should be noted that M5 and M6 have the highest OPEX because of the increased expenditure on *energy, maintenance and fault management.*

Fig. 3.13(c) shows the TCO for the different migration choices which were obtained by employing a yearly depreciation rate for the network equipment of 2.5%. It can be seen that the trends are similar those in Fig. 3.13(b), even if the relative difference between the different solutions is slightly smaller.

It is clear that exploiting the legacy copper infrastructure leads to a reduction in costs for the operators and the M1 and M2 migration models are the most economical.

3.7.3 Sensitivity Analysis

A sensitivity analysis of the TCO involving the five proposed backhaul architectures was conducted to validate the results. In this analysis, the three basic backhaul technologies were divided into three types: copper, fiber and MW. The most significant cost parameter (i.e., the one having the largest impact on the TCO) was determined for each category. This parameter ranges between -30% and +30% with regard to the original market value (as shown in Table 3.1) so that the impact on the TCO can be evaluated.

With regard to the copper based backhaul, the most relevant cost derives from the CAPEX and this is the DSL modem cost (categorized as *Equipment* cost in Fig. 3.3). The cost of the DSL modem ranges from 70% to 130% of its market value (as illustrated in Table 3.1) and no significant change was detected in the total TCO of the backhaul architectures. As a result, it can be concluded that varying the DSL modem cost does not affect the conclusions drawn in the previous sections.

With regard to the backhaul based on fiber, the most relevant cost parameter depends on whether the operator is deploying its own fiber infrastructure or is leasing the dark fiber. In the case of the former, the main cost involves the CAPEX and comes from the fiber trenching cost (i.e., *Infrastructure* cost with reference to Fig. 3.3). Fig. 3.14 shows the results obtained by varying the fiber trenching cost from 70% to 130% of the market value as shown in Table 3.1. It is clear that when the fiber trenching cost for Architecture 3 is reduced, it becomes the most attractive solution in financial terms (Architecture 3 becomes more cost-efficient than Architecture 1 when the fiber trenching cost is reduced to 91% of its original value). However, Architectures 4 and 5 always remain more expensive. Moreover, increasing the fiber trenching cost does not affect the conclusions drawn in the previous section.

If the operator leases the dark fiber, the most relevant cost involves the OPEX and is the fiber leasing cost (i.e., *Spectrum and fiber leasing* cost with reference to Fig. 3.3).

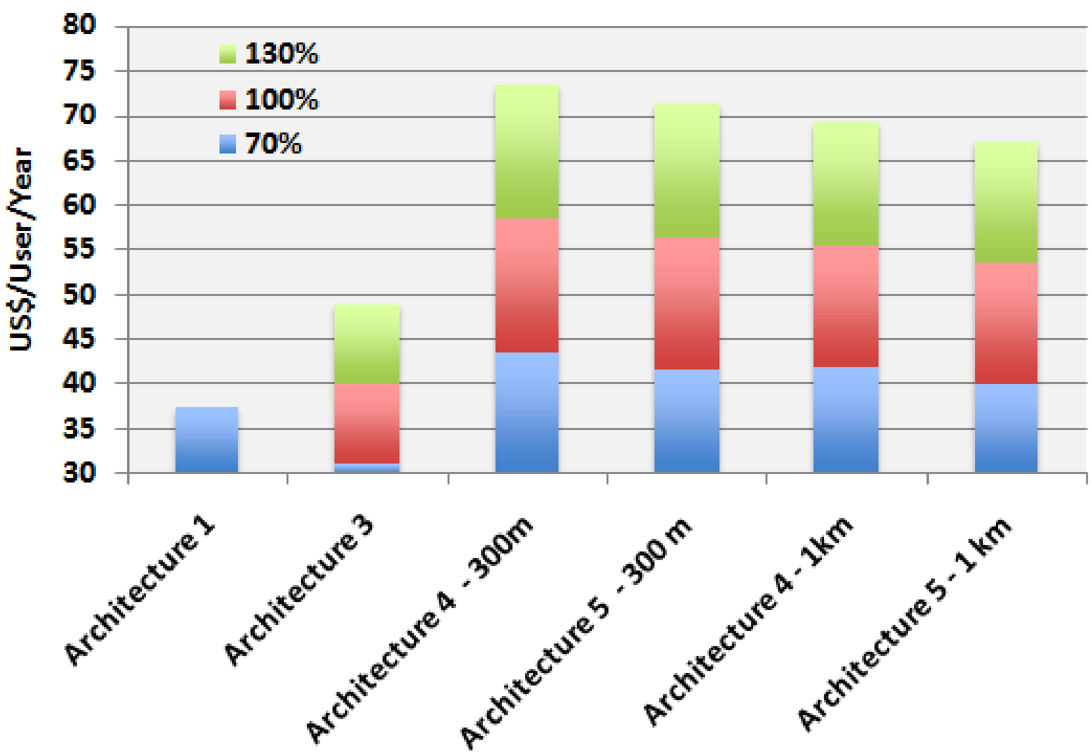


Figure 3.14: Sensitivity analysis of variations in the trenching cost in a range of 70% to 130% of the market price.

Fig. 3.15 shows the results obtained by varying the fiber leasing cost from 70% to 130% of the market value (as shown in Table 3.1). It can also be noted that reducing the fiber leasing cost does not significantly affect the conclusions drawn in the previous section. In fact, Architecture 3 remains the most attractive cost solution. The only observable change is that Architecture 5 is found to be more cost-efficient than Architecture 1 if the cost for fiber leasing is reduced to 72% of its original value (but only in the case where there is a maximum distance of 300m between the femto cells and local exchanges).

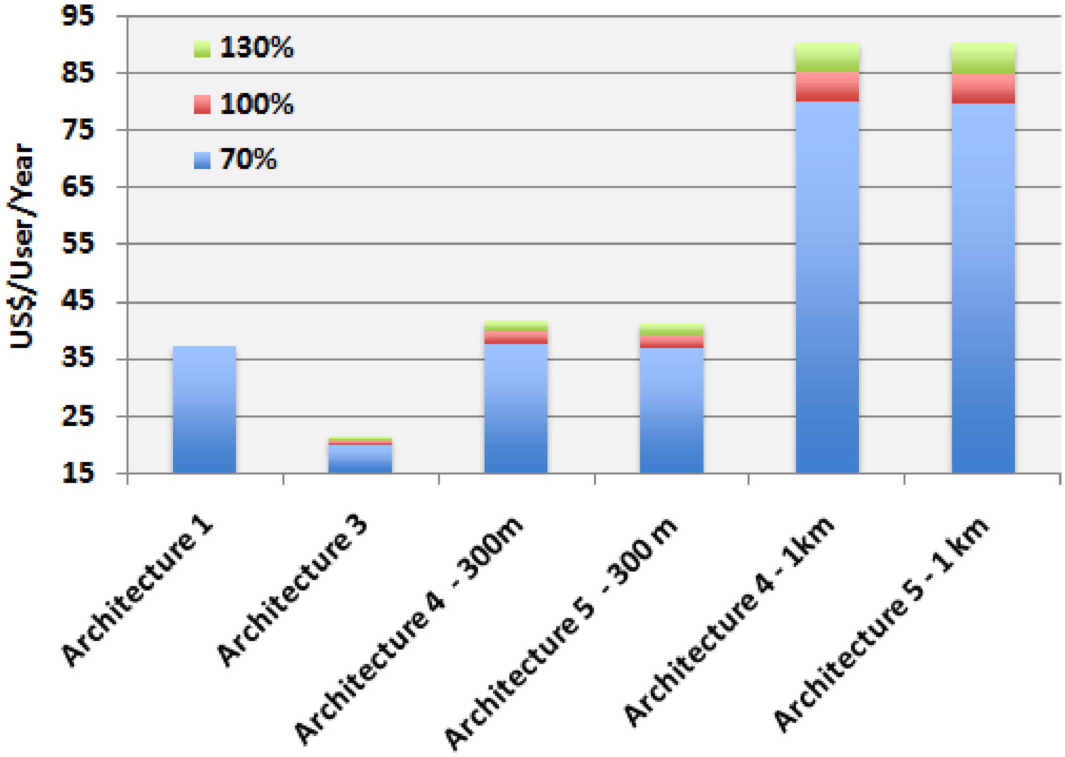
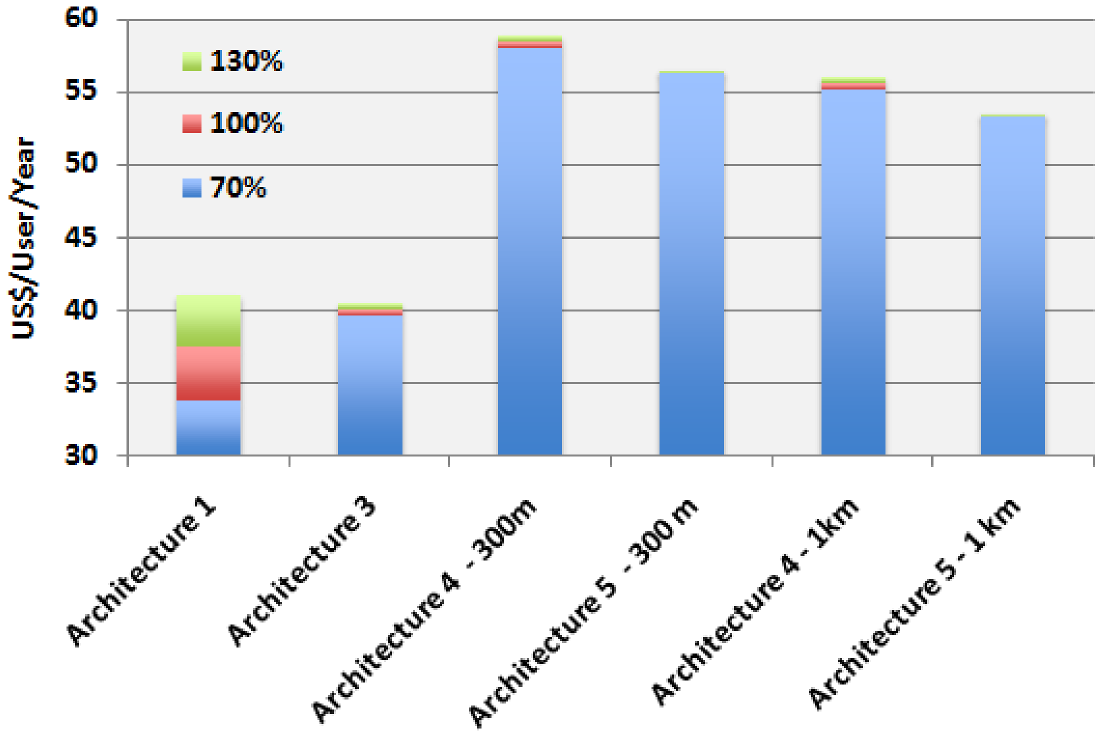


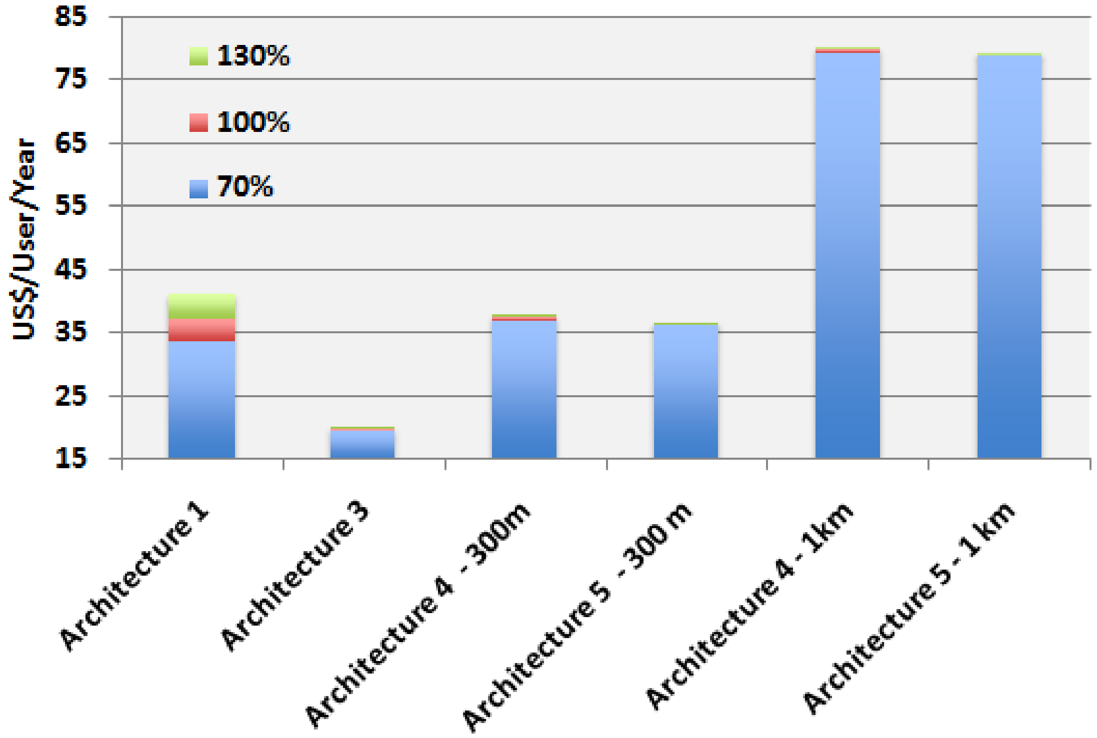
Figure 3.15: Sensitivity analysis of variations in the dark fiber cost within a range of 70% to 130% of the market price.

With regard to the MW based backhaul, there are two main items of expenditure for the TCO. The first is the cost of the antenna and this is related to the CAPEX (and categorized as an *Equipment* cost in Fig. 3.3). Accordingly, the cost of the antenna ranged from 70% to 130% of its market value and the results for the TCO of the backhaul architectures are shown in Fig. 3.16. In specific terms, Fig. 3.16(a) shows the results if the operator trenches the fiber, while Fig. 3.16(b) shows the results if the operator leases the dark fiber. Fig. 3.16(a) shows that decreasing the antenna cost does not change the conclusions that have been drawn and that Architecture 1 remains the most cost-efficient solution. However, increasing the antenna cost to 126% of its original value makes Architecture 3 the most attractive solution from an economic standpoint. Fig. 3.16(b) shows similar trends. In particular, reducing the cost of the antenna does not affect the results and Architecture 3 remains the most cost efficient solution. However, increasing the antenna cost to over 103% of its original value makes Architecture 1 more expensive than Architecture 5 (when there is a distance of 300m from the femto cells to the local exchange). In addition, increasing the antenna cost over 124% of its original value also makes Architecture 4 more cost-efficient than Architecture 1.

The other expenditure which has a considerable impact on the MW based backhaul is the spectrum cost, and this is related to the OPEX (i.e., *Spectrum and fiber leasing* cost with reference to Fig. 3.3). Fig. 3.17 shows the results obtained by varying the spectrum cost from 70% to 130% of its original market value. Only the case with fiber leasing was taken into account because in the case with fiber trenching the conclusions drawn in the previous sections remained unchanged. Fig. 3.17 shows that reducing the spectrum cost does not affect the conclusions, i.e., Architecture 3 remains the most cost-efficient. On the other hand, increasing the spectrum cost by over 28% of its original value makes Architecture 5 more cost-effective than Architecture 1 (a case with a distance of 300m between the femto cells and local exchanges).



(a)



(b)

Figure 3.16: Sensitivity analysis of the antenna cost when it varies from 70% to 130% of the market price. (a) The impact when the operator trenches and owns the fiber infrastructure. (b) The impact when dark fiber is leased.

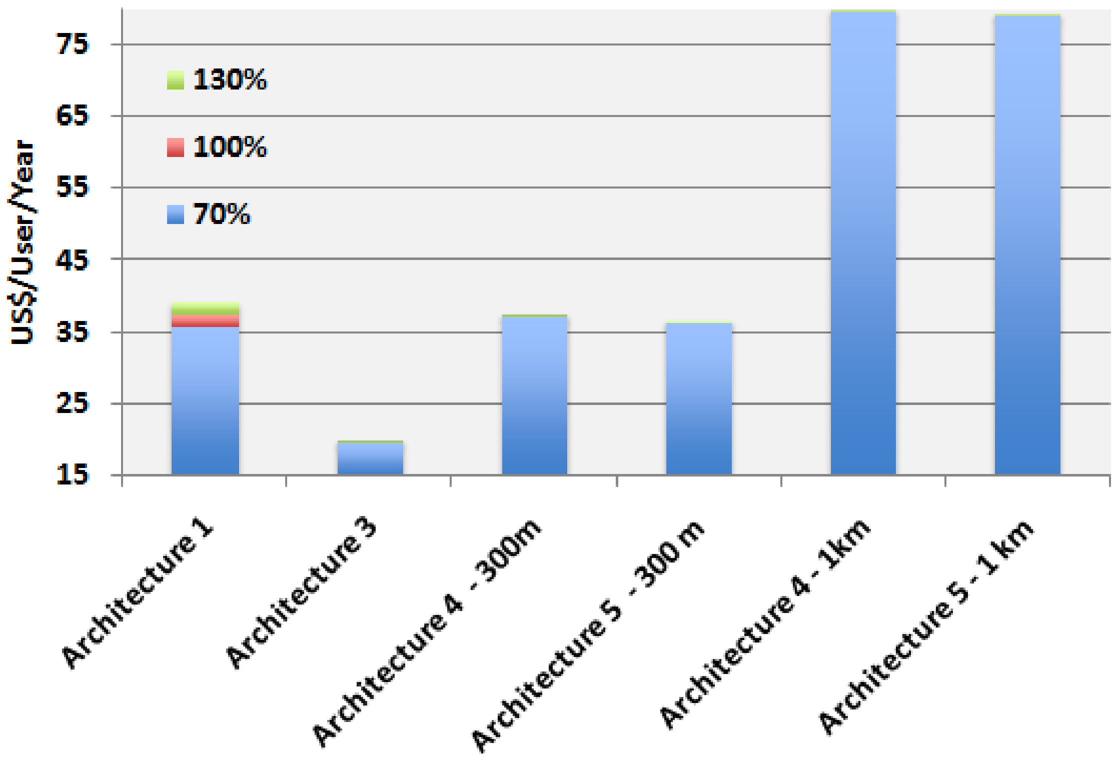


Figure 3.17: Sensitivity analysis of the MW spectrum cost when it varies from 70% to 130% of the market price.

3.8 CONCLUSION

In this chapter, an assessment methodology and a set of math models were employed for evaluating the TCO of backhaul architectures for HetNets. The following models were included: *a)* a traffic model used to forecast the expected data traffic for the next few years, *b)* a wireless deployment model for a European urban scenario, *c)* the backhaul options models for Greenfield and Brownfield deployments and finally *d)* a techno-economic model to assess the backhaul infrastructure.

In the case of HetNets, the methodology involved scenarios comprising outdoor macro base stations and small indoor base stations. Five different backhaul architectures were designed and these were based on different combinations of copper, fiber and microwave technologies where the methodology was employed for both a Greenfield scenario and a Brownfield scenario.

It can be inferred from the results that backhaul constitutes a considerable proportion of the TCO and an investigation between Greenfield and Brownfield deployment strategies must be carried out to encourage operators to find the most cost-efficient and easy-to-upgrade transport network topology. Additionally, exploiting the legacy copper infrastructure can enable operators to reduce their total costs to a considerable extent.

The analysis of the Greenfield scenario proved that backhaul architectures based on PONs are by far the most energy-efficient, even though these solutions are also the very costly in terms of TCO. This is particularly true when the operators decide to build their own fiber infrastructure (i.e., trenching the fiber) and when the maximum distance between the femto base stations and the local exchanges is quite long (i.e., 1km or more). The results have proved that the microwave-based backhaul architecture results in the most attractive approach in terms of costs. One means of reducing the costs of the fiber-based backhaul is by leasing dark fiber instead of building a new infrastructure. The results of this study have provided evidence that when leasing dark fiber the most cost-efficient architecture is based on FTTB+copper for the indoor small base stations and microwave for the outdoor base stations.

With regard to the Brownfield scenario, a number of different options were put forward for the mobile operator when migrating among different backhaul architectures. The results show that from an energy-consumption perspective, as expected, the best alternative is to migrate toward PON as early as possible (i.e., migration options M3 and M4). However, this also represents the most costly solution in terms of TCO. The results have shown that the best solution in terms of TCO is to exploit the existing copper infrastructure for backhauling the indoor small base stations and gradually replace it starting from a few years before the capacity exhaustion (i.e., migration options M1 and M2).

To conclude, it is clear that the variations in the main costs for the copper, fiber and MW backhaul did not significantly affected the conclusions drawn in the previous sections. However, it was noticed that the costs for fiber trenching and for the microwave antenna are the most sensitive since a relatively small change can make some difference in the relative TCO of some backhaul architectures.

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CHAPTER IV

ASSESSMENT OF PROTECTION SCHEMES FOR PASSIVE OPTICAL NETWORKS

4.1 INTRODUCTION

In this chapter, a methodology is set out for the total cost of ownership, which is divided into three phases, i.e., Network Dimensioning Model, Associated Failure Costs and Total Cost of Ownership. In the first the investigated scenario is defined, e.g., are of the city and number of buildings, and its network topology, e.g., type of equipment, number of devices and the distance between the devices and CO. In this stage, the Manhattan street model is employed, which is an analytical model widely used to compute fiber length [69]. It is also assumed that all the streets are connected by means of one street divider, i.e., an orthogonal crossing-point connecting two streets [69], and the topology consists of by the number of subscribers, represented by the number of ONU, and the distance between two adjacent subscribers. More details regarding this stage are provided in Section 4.2. The second stage involves defining the Associated Failure Costs using a finite-state continuous-time Markov Chain Monte-Carlo (MCMC) [35]. Here, a framework is established that is based on MCMC to simulate topologies during an operational time and in an urban scenario with the aid of continuous-time Markov chain to represent the different failed states of the network and a Monte Carlo simulation to solve the Markov chain in a period T [35]. In the Markov chain, each state is defined as a function of the type and amount of failed facilities (e.g., fiber and piece of equipment), their distance to the CO and the number of affected subscribers [6]. Additionally, the state transition rates of the Markov chain are given by the equipment failure, repair rates, energy consumption and excess capacity. To allow the MCMC to be used, the model shown in [35] was adapted to simulate the topology in a period T. More details of this stage are provided in Section 4.3. The final stage is obtaining the Total Cost of Ownership, calculated as the total sum of CAPEX and OPEX. More details regarding this stage are provided in Section 4.4.

As far as we are aware, this is the first attempt to assess the TCO through a simulation that provides the most cost-effective protection scheme for PON topology with regard to network reliability, dependability between failures [36], and the inclusion of hybrid fiber wireless protection [48]. In the hybrid fiber-wireless protection, there are two alternatives: *(a)* the operator owns the mobile transport infrastructure, i.e., the operator owns the physical infrastructure and only signs a contract with the regulator to lease a microwave spectrum that guarantees protection anytime. *(b)* the operator leases capacity from a third mobile provider, i.e., the fixed broadband operator signs a contract with the mobile operator and pays for the practical reserve capacity of traffic in the event of failure. Additionally, if the previously planned traffic is exceeded, the fixed broadband operator is responsible for paying the mobile operator for the exceeded traffic in Gbps/US$.

4.2 NETWORK DIMENSIONING MODEL

The objective of this section is to examine how the number of pieces of equipment in the network is computed and also to describe how the clients involved and the distance from the equipment to the CO are determined. These distances play a key role in determining the simulated operational costs, e.g., the repair cost depends on the location and distance between the place where the failure occurred and the CO.

The set of PON devices consists of three key components: OLT chassis, Splitter/AWG and ONU. During the dimensioning of the equipment, it is only necessary to know the number of ONUs (N_{ONU}) in the scenario, i.e., the number of splitters and OLTs are given by Eq. (4.1) and Eq. (4.2), respectively.

$$N_{Splitter} = \left\lceil \frac{N_{ONU}}{n_{ports}^{Splitter}} \right\rceil \tag{4.1}$$

$$N_{OLT} = \left\lceil \frac{N_{ONU}}{n_{cards}^{OLT} n_{ports}^{Splitter}} \right\rceil \tag{4.2}$$

where $n_{ports}^{Splitter}$, n_{cards}^{OLT} are the number of splitter ports and number of OLT cards respectively. Additionally, the Network Dimensioning Model is based on the Manhattan street model [69], (see Figure 4.1), and assumes a uniform distribution of subscribers over a regular grid and also follows the PON architecture at two levels, i.e., feeder and distribution. The first is the Feeder Fiber Level, which has the CO at the center, *N* is the number of blocks in a row and L is the distance between the adjoining blocks.

Following the same logic, the second level is a Distribution Fiber Level, where a RN is located at the center. One site of the square contains n buildings containing a uniform distributed number of floors (N_{floors}) and apartments per floor ($N_{Ap/floor}$). The number of ONUs in the network is defined as follows $N_{Ap/floor}\, N_{floors}\, n^2$, i.e., it is assumed that each apartment has an installed ONU. The distance between two buildings is indicated by l and the distance between the adjoining buildings, i.e., $L = nl$.

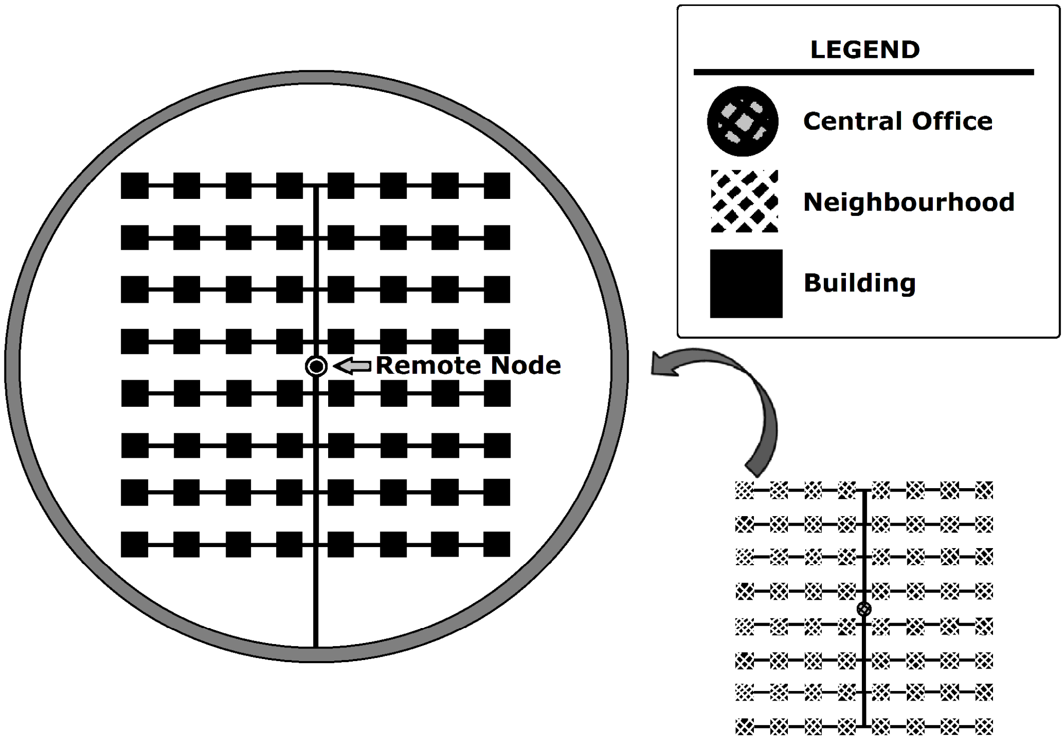


Figure 4.1: Schematic overview of the logical structure of a city with passive optical networks.

Each OLT chassis is associated with a maximum number of OLT ports and each port is connected to a splitter. Thus, the subscribers served by an OLT Chassis are those served by the OLT ports and their related splitter. The number of subscribers served by a feeder fiber trench is determined by the blocks connected to it and in the same way the number of subscribers served by a distribution trench is determined by the associated ONUs. The location of the equipment have two coordinates, i.e., a vertical (P_v) and horizontal (P_h) at the different levels. Those positions vary according to the type of equipment. Moreover, through the coordinates it is possible to find out the distance of any equipment from its position to the Central Office.

The distance from a building to the Remote Node ($D_{Building \to RN}$) is given by Eq. (4.3):

$$D_{Building \to RN} = [n - (a + b) - 1]\, l,$$

$$where: \quad a = \begin{cases} P_h \,, if\ P_h < \dfrac{n}{2} \\ n - P_h - 1 \,, if\ P_h \geq \dfrac{n}{2} \end{cases} \qquad b = \begin{cases} P_v \,, if\ P_v < \dfrac{n}{2} \\ n - P_v - 1 \,, \quad if\ P_v \geq \dfrac{n}{2} \end{cases} \tag{4.3}$$

The distance from a Remote Node to the Center Office ($D_{RN \to CO}$) is defined by Eq. (4.4) using the parameters mentioned before.

$$D_{RN \to CO} = [N - (A + B) - 1]L,$$

$$where: \quad A = \begin{cases} P_h \,, if\ P_h < \dfrac{N}{2} \\ N - P_h - 1 \,, if\ P_h \geq \dfrac{N}{2} \end{cases} \qquad B = \begin{cases} P_v \,, if\ P_v < \dfrac{N}{2} \\ N - P_v - 1 \,, \quad if\ P_v \geq \dfrac{N}{2} \end{cases} \tag{4.4}$$

The distance from a Distribution Fiber Step to the Remote Node ($D_{DFS \to RN}$) is calculated through Eq. (4.5).

$$D_{DFS \to RN} = \begin{cases} \left[n - (a + b) - \dfrac{3}{2}\right] l \,, if\ P_h \neq \dfrac{n}{2} \\ \left(\dfrac{n - 2b - 1}{2}\right) l \,, if\ P_h = \dfrac{n}{2} \end{cases},$$

$$where: \quad a = \begin{cases} P_h \,, if P_h < \dfrac{n}{2} \\ n - P_h \,, if P_h > \dfrac{n}{2} \end{cases} \qquad b = \begin{cases} P_v \,, if\ P_v < \dfrac{n}{2} \\ n - P_v - 1 \,, if P_v \geq \dfrac{n}{2} \end{cases} \tag{4.5}$$

The distance from a Protection Distribution Fiber Step to the Remote Node ($D_{PDFS \to RN}$) is given by Eq. (4.6).

$$D_{PDFS \to CO} = \begin{cases} [n - (a + b) - 1]\, l \,, if\ P_v \neq \left(\dfrac{n}{2} - 1\right) \\ \left(\dfrac{n - 2a - 1}{2}\right) l \,, if\ P_v = \left(\dfrac{n}{2} - 1\right) \end{cases}, \tag{4.6}$$

$$
where: \quad A = \begin{cases} P_h \,, if\ P_h < \dfrac{n}{2} \\ n - \ P_h \ - 1 \,, if\ P_h > \dfrac{n}{2} \end{cases} \qquad B = \begin{cases} P_v \,, if\ P_v < \left(\dfrac{n}{2} - 1\right) \\ n - P_v - 2 \,, if\ P_v \geq \left(\dfrac{n}{2} - 1\right) \end{cases}
$$

The distance from a Feeder Fiber Step to the Center of the Scenario ($D_{FFS \to CO}$) is calculated through Eq. (4.7).

$$
D_{FFS \to CO} = \begin{cases} \left[N - (A + B) - \dfrac{3}{2}\right] L \,, if\ P_h \neq \dfrac{N}{2} \\ \left(\dfrac{N - 2B - 1}{2}\right) L \,, if\ P_h = \dfrac{N}{2} \end{cases},
$$

$$
where: \quad A = \begin{cases} P_h \,, if P_h < \dfrac{N}{2} \\ N - P_h \,, if P_h > \dfrac{N}{2} \end{cases} \qquad B = \begin{cases} P_v \,, if P_v < \dfrac{N}{2} \\ N - P_v - 1 \,, if P_v \geq \dfrac{N}{2} \end{cases} \tag{4.7}
$$

The distance from a Protection Feeder Fiber Step to the Center of the Scenario ($D_{PFFS \to CO}$) is given by Eq. (4.8).

$$
D_{PFFS \to CO} = \begin{cases} [N - (A + B) - 1] L \,, if\ P_v \neq \left(\dfrac{N}{2} - 1\right) \\ \left(\dfrac{N - 2A - 1}{2}\right) L \,, if\ P_v = \left(\dfrac{N}{2} - 1\right) \end{cases},
$$

$$
where: \quad A = \begin{cases} P_h \,, if\ P_h < \dfrac{N}{2} \\ N - P_h - 1 \,, if P_h > \dfrac{N}{2} \end{cases} \qquad B = \begin{cases} P_v \,, if\ P_v < \left(\dfrac{N}{2} - 1\right) \\ N - P_v - 2 \,, if P_v \geq \left(\dfrac{N}{2} - 1\right) \end{cases} \tag{4.8}
$$

4.3 A FAILURE-ASSOCIATED COST MODEL

In this section, there is an examination of the models employed to compute the Failure-Associated costs in a determined period *T*. The cost is obtained by adapting the methodology adopted in [35] of a continuous-time MCMC Simulation.

The definitions of states are given by the number and type of failed equipment, the distance of a equipment from the CO and the number of subscribers affected by the failure. The cost models are included by the Markov reward model, where each state has an associated reward. In this case, the related costs of repairing failed equipment at state i (C_i^{repair}) and penalty costs at state i ($C_i^{penalty}$) are given by the Eqs. (4.9) and (4.10).

$$C_i^{penalty} = \left[NB_{sub}^{fail}(\beta)\right]^{\alpha} \mathrm{Pr_{bus}} + \left[NB_{sub}^{fail}(\beta - 1)\right]^{\alpha} Pr_{res} \tag{4.9}$$

$$C_i^{Repair} = Sal + \sum Pr_k \eta \tag{4.10}$$

where NB_{sub}^{fail} and Pr_{bus} are the number of business subscribers affected by the failure and business penalty rate agreed in the SLA respectively. Furthermore, NR_{sub}^{fail} and Pr_{res} are the number of residential subscribers affected by failures and the residential penalty rates agreed in SLA, respectively. Finally β and α are the parameters that define the number of business clients and the impact factor that measures the loss of reputation suffered by the telecommunication operators, respectively.

In terms of repair costs, the parameter *Sal* is the salary of the repair team, Pr_k is the price of the failed equipment k that is going to be repaired, and finally, η is the parameter that varies the repair cost between [0,1].

The repair rate of the equipment is calculated as the inverse of the sum of the time needed to travel to the equipment location and average time needed to repair it. If more than one piece of equipment fails, the one that saves more penalty costs in less time is repaired first.

With regard to the cost of energy saved when the equipment is in a state of failure, i.e., it is not operating, and the extra capacity that is over the capacity secured in the contract between the fixed broadband operator and mobile operator. Eqs. (4.11) and (4.12) express the power savings during inactivity of the equipment at state i and the extra cost of excess capacity required by the fixed broadband operator at state *i* respectively.

$$P_i^{Energyinacticity} = \sum_k N_k^{failuredEq} \, P_k^{Eq} \tag{4.11}$$

$$C_i^{Exceeded} = \left(N_{sub}^{failed} - N_{avg}^{failureEq}\right) \tau \, Pr_{Gbps} \, \gamma \tag{4.12}$$

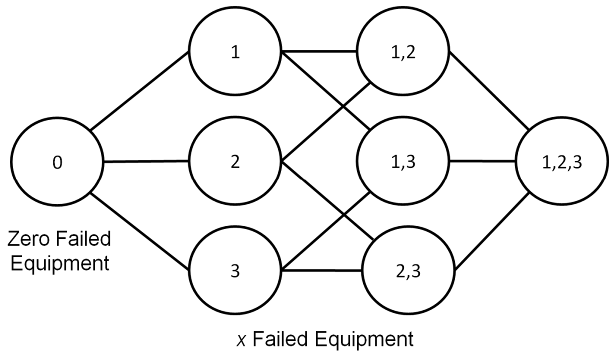
where $N_k^{failuredEq}$, P_k^{Eq}, N_{sub}^{failed}, $N_{avg}^{failureEq}$, τ, Pr_{Gbps} and γ are the amount of failure equipment k, the power consumption of equipment k, the number of failed subscribers in the network, the average amount of failure equipment, the minimum capacity provided to the end-user, price per Gbps agreed with the operator, the price per extra Gbps and the impact factor that controls the price per extra Gbps according to the extra traffic requests, respectively.

For the period under analysis, the model from reference [35] was adapted by carrying out a Monte Carlo trial. This is concluded just when the state transition number gets the expected number of failed ONUs during the time of analysis ($N_{failured}^{ONU}$). The computational effort is reduced by regarding the ONU as stopping criteria. Additionally, ONU is the equipment that has the highest average rate of failure compared to the others, and is also the most common equipment in the network. $N_{failured}^{ONU}$ can be determined through Eq. (4.13).

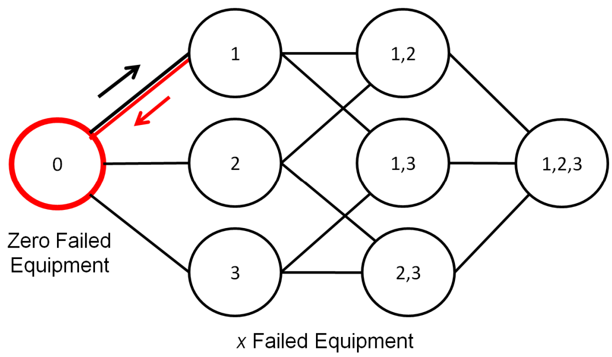
$$N_{failured}^{ONU} = \lceil T_D \, \mu_{ONU} \, N_{ONU} \rceil \tag{4.13}$$

where T_D is the desired time interval in hours and μ_{ONU} is the failure rate of ONU.

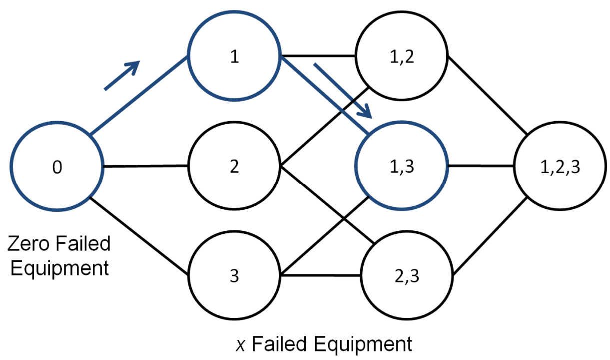
Fig. 4.2 gives an example of how state transitions work. In this example, the network has three pieces of equipment, represented by 1, 2 and 3 (Figure 4.2 (a)). In the first transition illustrated in Fig 4.2 (b), the Monte Carlo simulation is run and the number of faulty equipment changes from state zero to one piece of failed equipment. In this example, equipment 1 is represented in a failed state. Afterwards, the Monte Carlo simulation is executed again and offers two choices: either the other equipment fails or the failed equipment is repaired. Since the probability of repair is higher than that of failure, in this example it is assumed that equipment 1 is repaired and the transition turns to state zero. This is the expected behavior of the network because of its low failure rate for equipment. However, it is expected that it will repair the equipment before the next failure, since before the repairs can be carried out, another piece of equipment may change to failed a state, e.g., if item 1 has failed and either item 2 or 3 has failed as represented in Fig. 4.2 (c). In this case, when two or more items have failed at the same time, the simulation must first fix the item that can reduce the penalty expenses most in the minimum time.



(a)



(b)



(c)

Figure 4.2: Examples of a state diagram including three pieces of equipment (a) a Markov chain with equipment 1, 2 and 3. (b) a Markov chain where equipment 1 fails and is repaired before the next failure (c) a Markov chain where equipment 1 and 3 have failed.

4.4 TOTAL COST OF OWNERSHIP

Operators are designing cost-efficient transport network solutions, by analyzing investments in the *Total Cost of Ownership*, which is a strategy to give network operators a global idea of what is occurring, and what will occur, if a certain topology is deployed. In terms of network designing, a techno-economic study allows the operators to deploy cost effective and profitable topologies to provide the required services to the users. Additionally, a comprehensive cost analysis that covers capital and operational expenditure, can provide a better view for the network operators when deployment or migration are being planned. Thus, the objective of this section is to examine the models needed to compute the CAPEX and the OPEX costs. These models enabled us to obtain the TCO for the broadband transport topologies. It should be highlighted that there is no fixed standard regarding what costs are included in CAPEX and OPEX but it is widely assumed that CAPEX consists of infrastructure costs, e.g., components prices, and installations costs; and OPEX as operational costs, e.g., repair failure, failure penalties, service maintenance, among others [5][6][41].

4.4.1 CAPEX: Equipment Costs

The equipment cost (Tot_{Cost}^{Eq}) is the sum of all the equipment (N_i^{Eq}) times the price (Pr_i^{Eq}) of each item:

$$Tot_{Cost}^{Eq} = \sum_{i=0}^{Eq_{Type}} N_i^{Eq} \times Pr_i^{Eq} \tag{4.14}$$

where i classifies the type of equipment ranging from 0 to Eq_{Type}. N is the quantity of one type of equipment and Pr^{Eq} is its price.

4.4.2 CAPEX: Installation Costs

The installation cost ($Tot_{Cost}^{Install}$) is the sum of all the expenses associated with installing the transport network components in their specific locations:

$$Tot_{Cost}^{Install} = Tot_{InstCost}^{Eq} + Tot_{InstCost}^{Fiber} + Tot_{InstCost}^{FFProtection} + Tot_{InstCost}^{DFProtection} \tag{4.15}$$

where $Tot_{InstCost}^{Eq}$, $Tot_{InstCost}^{Fiber}$, $Tot_{InstCost}^{FFProtection}$, $Tot_{InstCost}^{DFProtection}$ represent respectively the total cost for installing equipment, the total cost of feeding and distributing the fiber over the area, the total cost of installing protection in the feeder fiber and the total cost of installing protection in the distribution fiber.

4.4.2.1 INSTALLATION COST

The installation cost of equipment includes the time to install (T_i^{inst}), the travel time to the equipment ($\frac{dis_i}{vel}$), and the salary of the team of technicians (Sal) as shown in the Eq. (4.16).

$$Tot_{instCost}^{Eq} = \sum_{i=0}^{NumEq-1} \left(\left(T_i^{inst} + \frac{dis_i}{vel}\right) \times Sal\right) \times \ pair_{fiber} \tag{4.16}$$

where, $pair_{fiber}$ is considered to be 0 if *i* is a fiber step, and 1 if it is not.

4.4.2.2 FIBER INSTALLATION COST

Calculating the fiber installation cost ($Tot_{instCost}^{Fiber}$), involves the following Eq. (4.17), which is adapted from [69]:

$$Tot_{instCost}^{Fiber} = \left(\left(\frac{N^3 L}{2}\right)\left\lceil\frac{n^2}{SR}\right\rceil + \left(\frac{n^3 l}{2}\right)N^2\right) \times Pr_{fiber}^{inst} \tag{4.17}$$

where SR, $\left\lceil\frac{n^2}{SR}\right\rceil$, Pr_{fiber}^{inst} is the splitting ratio, the number of splitters in one block and the price to install fiber per Km, respectively.

The following example provides a better understanding of the Eq. (4.17). Consider one block where n = 10, which is divided into four symmetrical quadrants. Figure 4.3 represents one of the symmetrical quadrants.

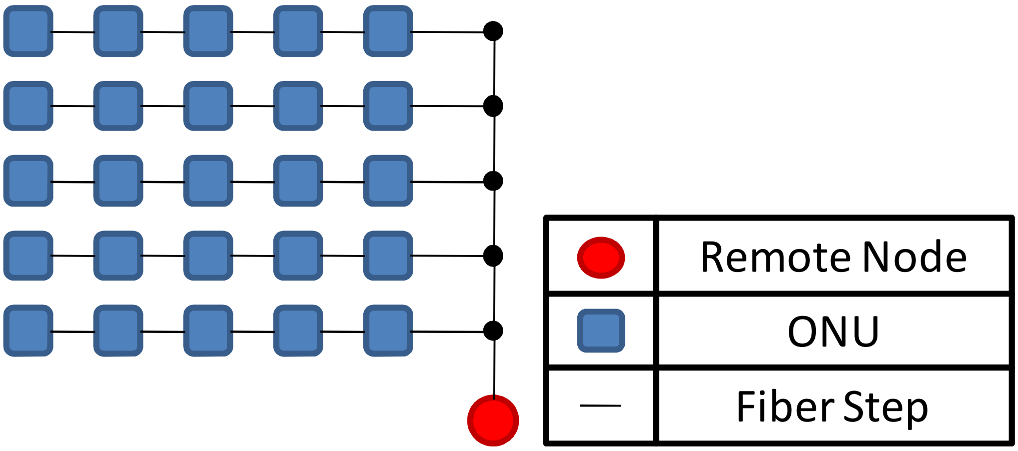


Figure 4.3: Representation of fiber feeding in the quadrant of a certain block.

In Figure 4.3, it can be observed that the number of installed fibers in the distribution level is equal to the number of ONU. Thus, each black dot represented in Figure 4.3 receives $\frac{n}{2}$ fibers, i.e., in this example 5 fiber links, which is the distance between RN and each dot, i.e., from the bottom to the top respectively $\left(\frac{n-1}{2}\right)l$, $\left(\frac{n-3}{2}\right)l$, $\left(\frac{n-5}{2}\right)l$, $\left(\frac{n-7}{2}\right)l$, $\left(\frac{n-9}{2}\right)l$. Thus, the length of the installed fiber to the dots can be given by the following equation: $\frac{n}{2}\left(\frac{(n-1)l+(n-3)l+(n-5)l+(n-7)l+(n-9)l}{2}\right)$, which can be simplified to $\frac{nl}{2}\left(\frac{5n-\sum_{i=0}^{\frac{n}{2}-1}2i+1}{2}\right)$. It is important to be note that for a given block with $n = 10$ the number ONU is 5. Additionally, for a given block with $n = 8$ the number of ONU would be 4. This logic follows for any other n; hence, the equation can be simplified to $\frac{n}{2}$. Finally $\sum_{i=0}^{\frac{n}{2}-1}2i+1$ can also be simplified to $\left(\frac{n}{2}\right)^2$ and yields $\frac{nl}{4}\left(\frac{n}{2}n-\frac{n^2}{4}\right)$.

From the dots to the ONUs, it is known that $\frac{n}{2}$ fibers are necessary, i.e., 5 fibers, to connect to $\frac{n}{2}$ ONUs. Moreover, the distances between the ONUs and dots can be defined as: $\left(\frac{n-1}{2}\right)l$, $\left(\frac{n-3}{2}\right)l$, $\left(\frac{n-5}{2}\right)l$, $\left(\frac{n-7}{2}\right)l$, $\left(\frac{n-9}{2}\right)l$ and the length from the ONU to the dots is given by: $\frac{n}{2}\left(\frac{(n-1)l+(n-3)l+(n-5)l+(n-7)l+(n-9)l}{2}\right)$, which is the same equation defined in the last paragraph. Thus the equation $\frac{nl}{4}\left(\frac{n}{2}n-\frac{n^2}{4}\right)$ is determined and given the symmetrical quadrant one can define the length of the installed fiber in a certain block by $4\times\frac{nl}{4}\left(\frac{n}{2}n-\frac{n^2}{4}\right)=\frac{n^3l}{2}$. Following the same logic in the equations it is possible to obtain the installed fiber in the feeder level and reach the second part of Eq. (4.17).

4.4.2.3 EXTRA INVESTMENT IN FIBER TO INSTALL PROTECTION FOR THE FEEDER AND DISTRIBUTION FIBER

The following equations is employed to calculate the additional investment cost to install protection in the feeder fiber ($Tot_{instCost}^{FFProtection}$):

$$Tot_{instCost}^{FFProtection} = \frac{L}{2}(N^3 + 2N^2)\left\lceil\frac{n^2}{SR}\right\rceil Pr_{fiber}^{inst} \tag{4.18}$$

and finally, to calculate the additional investment cost to install protection in the distribution fiber ($Tot_{instCost}^{DFProtection}$), the following equation is defined:

$$Tot_{instCost}^{DFProtection} = \frac{l}{2}(n^3 + 2n^2)\, N^2\, Pr_{fiber}^{inst} \tag{4.19}$$

and an example is given below for a better understanding of the protection schemes proposed in Eq. (4.18) and Eq. (4.19). Consider one block where *n* equals 10, which is divided into four symmetrical quadrants. Figure 4.4 represents one of the symmetrical quadrants.

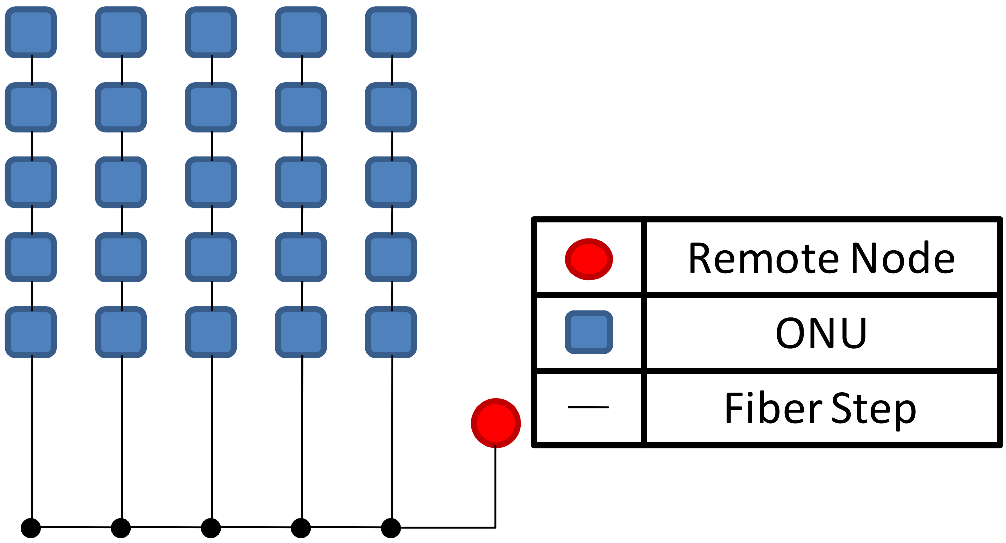


Figure 4.4: Representation of protection in the quadrant of a certain block.

In Figure 4.4, it can be noticed that the number of amount of installed fibers in the distribution level is equal to the number of ONUs. Additionally, each black dot represented in Figure 4.4 receives $\frac{n}{2}$ fibers, i.e., 5 fibers, which is the distance between the RN to each dot, i.e., from the bottom to the top respectively l, $2l$, $3l$, $4l$, $5l$. Thus, the length of the installed fiber to the dots can be given by following equation: $\frac{n}{2}(l + 2l + 3l + 4l + 5l)$, which can be simplified to $\frac{nl}{2}\left(\sum_{i=1}^{i=\frac{n}{2}} i\right)$, where $\sum_{i=1}^{i=\frac{n}{2}} i$ can be simplified to $\frac{n^2+2n}{8}$. Finally, the equation can be shortened to $\frac{nl}{2}\left(\frac{n^2+2n}{8}\right)$.

It is necessary to have $\frac{n}{2}$ fibers from the dots to the ONUs, i.e., 5 fibers, to connect to $\frac{n}{2}$ ONUs. Moreover, the distances between the ONUs and dots can be defined as: l, $2l$, $3l$, $4l$, $5l$, and the length from the ONU to the dots is given by: $\frac{n}{2}(l + 2l + 3l + 4l + 5l)$, which is the same equation defined in the last paragraph. Hence, the equation $nl\left(\frac{n^2+2n}{8}\right)$ was found and, given the symmetrical quadrant, the length of the installed fiber in a certain block can be defined by: $4 \times nl\left(\frac{n^2+2n}{8}\right) = \frac{nl}{2}(n^2 + 2n)$. Following the same logic from the equations, the installed fiber can be obtained in the feeder level and this arrives at Eq. (4.19).

4.4.3 CAPEX: Infrastructure Costs

The installation cost (Tot_{Cost}^{Infra}) is the sum of all the expenses related to installing the transport network components in their specific locations:

$$Tot_{Cost}^{Infra} = Tot_{InfraCost}^{Trench} + Tot_{trenchCost}^{FFProtection} + Tot_{trenchCost}^{DFProtection} \tag{4.20}$$

where $Tot_{InfraCost}^{Trench}$, $Tot_{trenchCost}^{FFProtection}$, $Tot_{trenchCost}^{DFProtection}$ represent respectively the total cost for trenching the path from the central office to the remote node and user-premises, the total cost to trench the protection fiber in the feeder level and the total cost to trench the protection at the distribution level.

4.4.3.1 FIBER TRENCH COST

To compute the infrastructure cost ($Tot_{infraCost}^{Trench}$), it is necessary to calculate the distance of each fiber step and multiply this by the trenching price (Pr_{trench}) as described in Eq. (4.21).

$$Tot_{infraCost}^{Trench} = [(n^2 - 1) \times l \times N^2 + (N^2 - 1) \times L] \times Pr_{trench} \tag{4.21}$$

4.4.3.2 EXTRA INVESTMENT FIBER TO TRENCH PROTECTION FOR THE FEEDER AND DISTRIBUTION FIBER

The following equation can be used to calculate the additional investment cost to trench protection in the feeder fiber ($Tot_{instCost}^{FFProtection}$):

$$Tot_{trenchCost}^{FFProtection} = [(N-1)N\,L]Pr_{trench} \tag{4.22}$$

and finally, the following equation can be used to calculate the additional investment cost to protect the distribution fiber ($Tot_{instCost}^{DFProtection}$):

$$Tot_{trenchCost}^{DFProtection} = [(N-1)\,n\,l\,N^2]Pr_{trench} \tag{4.23}$$

4.4.4 OPEX: Energy Costs

Calculating electricity bills is the responsibility of OPEX. The (Tot_{Cost}^{Energy}) is obtained by adding up the energy costs of all active appliances in the various backhaul locations (i.e., CO, cabinets, microwave sites).

$$Tot_{Cost}^{Energy} = Pr_{kWh} \sum_{i=1}^{m} Tot_i^{kWh/y} - \ Tot_{Inactivity}^{Energy} \tag{4.24}$$

where $Tot_i^{kWh/y}$ and Pr_{kWh} are the yearly kWh consumed by the equipment and the kWh price respectively. i represents the type of equipment, e.g., Switch, DSLAM, modem. Finally, the energy inactivity is the total of kWh when the equipment was not working during the Markov chain, i.e., total energy saving due to network failures, is given by $Tot_{Inactivity}^{Energy} = \sum_i P_i^{Energyinactivity} t_i$, where t_i is the time that the system remains in state *i*.

4.4.5 OPEX: Failure Costs

The OPEX analysis includes a failure cost equation ($Tot_{cost}^{failure}$), illustrated in Eq. (4.25), which is the product of the sum of the penalty and repair costs with the expected time at state *i* (t_i), derived from Monte Carlo method described earlier.

$$Tot_{cost}^{failure} = \sum_i \left(C_i^{penalty} + C_i^{repair}\right) t_i \tag{4.25}$$

where t_i is the time when the system remains in state *i*.

4.4.6 OPEX: Leasing Costs

The leasing cost ($Tot_{cost}^{Leasing}$) refers to the leased capacity in Gbps, total cost of exceeded traffic and microwave spectrum leasing, as defined in Eq. (4.26):

$$Tot_{cost}^{Leasing} = Tot_{Cost}^{TrafficRent} + Tot_{Cost}^{TrafficExceeded} + Tot_{Cost}^{SpectrumRent} \tag{4.26}$$

where $Tot_{Cost}^{TrafficRent}$, $Tot_{Cost}^{TrafficExceeded}$ and $Tot_{Cost}^{SpectrumRent}$ are the total cost of traffic rented, total cost of excess traffic required for the mobile operator and total cost of microwave spectrum leasing, respectively.

4.4.6.1 TRAFFIC RENTAL COST

The traffic rental cost ($Tot_{cost}^{TrafficRent}$) denotes the contract agreed to guarantee protection capacity in Gbps. The providers must sign it to guarantee backup protection through a microwave infrastructure. The model is defined in Eq. (4.27):

$$Tot_{Cost}^{TrafficRent} = N_{avg}^{failuredEq}\ \tau\ Pr_{Gbps}\ t \tag{4.27}$$

where $N_{avg}^{failuredEq}$, τ, Pr_{Gbps}, t and $Tot_{rent}^{TrafficExceeded}$ are the average number of subscribers with failed equipment in the network, minimum capacity provided to the end-user, price per Gbps agreed with the operator, time of analysis in hours, and the total cost associated with failures that are above the expected average of failures in the network, respectively.

4.4.6.2 EXCESS CAPACITY

The traffic excess cost ($Tot_{Cost}^{TrafficExceeded}$) refers to the extra capacity in Gbps that the provider must contract to cover extra traffic generated by end-users, e.g., when the demand is bigger than the capacity contracted. The model is defined in Eq. (4.28):

$$Tot_{Cost}^{TrafficExceeded} = \sum_{i} C_{i}^{Exceeded}\ Z_i \tag{4.28}$$

where Z_i is the total time that it remained in state *i* during the simulation.

4.4.6.3 SPECTRUM LEASING

The spectrum leasing cost ($Tot_{Cost}^{SpectrumRent}$) refers to the leased links that provide point-to-point communication between base stations and the aggregation traffic point, i.e., two antennas transmitting information in downlink and uplink directions. The model is defined in Eq. (4.29):

$$Tot_{rent}^{SpectrumRent} = N_{Bs}\, N_{Direction}\, Pr_{link}\, t \tag{4.29}$$

where N_{BS} , $N_{Direction}$, Pr_{link} and t are the number of base stations in the area, number of antenna directions (always equal to 2), the price of one link to interconnect the base station to the aggregation node, and the operational time in years, respectively.

4.7 CASE STUDY

This section outlines a case study where the proposed methodology is applied. It compares the following six PON topologies: No protection, protection in the Feeder Fiber (FF), protection in the FF and Distribution Fiber (DF), protection on Optical Line Terminal (OLT) and FF, protection only based on the microwave infrastructure and protection through OLT and based on the microwave infrastructure. All the protection schemes are illustrated in Fig. 4.5 (a), (b), (c), (d), (e), (f). Additionally, there is a calculation of the number of pieces of equipment in the scenario, link failures, energy savings and excess capacity over a period of T = 20 years using the MCMC. Finally, there is a discussion of the overall cost to deploy and operate different PON topologies.

A city is imagined with 10000 buildings/residences with one floor and a distance of 1/24km between each of the residences.

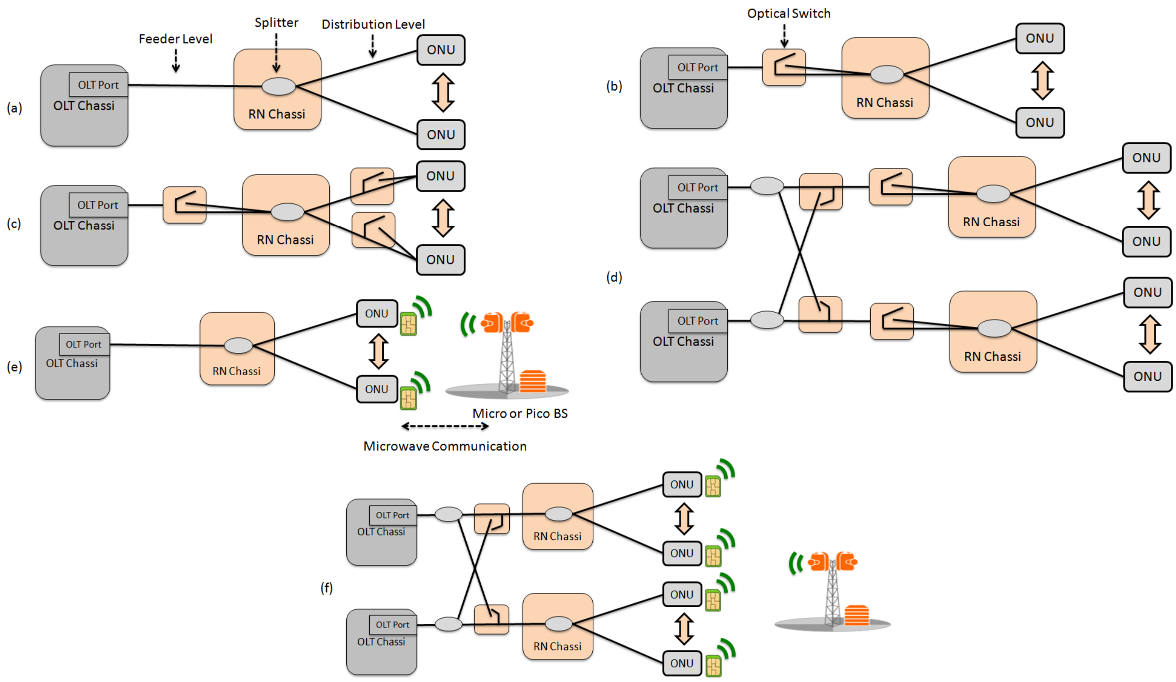


Figure 4.5: Topologies for schemes under investigation. (a) PON with no protection scheme. (b) PON with protection in the feeder fiber. (c) PON with protection in the feeder and distribution fiber. (d) PON with protection in the OLT and feeder fiber. (e) PON with protection using microwave. (f) PON with protection in the OLT and using microwave.

The parameters used in the equations were extracted from [42][6][70][75] and are shown in Table 4.1. The costs used to calculate CAPEX and OPEX are given in Table 4.2. Additionally, a scenario is imagined where 80% of the properties are commercial and 20% are residential. The equipment failure rates have been extracted from [6][35][36][41][42][70][74][75].

Table 4.1 - Scenario Parameters.

Parameters	**Value**
N	10
n	10
l (km)	1/24
SR	01:32
$N_{OLT/C}$	72
Business Users Penalty(US$/h)	100
Residential Users Penalty(US$/h)	10
Staff Salary(US$/h)	190
τ (Gbps)	0.1
η	0.1
α	1.1
β	0.8
Small cell radius	100 meters

4.8 RESULTS

The results of the simulations carried out in the case study are analyzed in this section. The results for CAPEX and OPEX required investments to operate a PON. In the case of CAPEX, the investment costs of infrastructure, installation and equipment acquisition are shown, while those for OPEX the investment costs of repairs, penalties, energy consumption, spectrum leasing and capacity acquisition. Moreover, a sensitivity analysis is conducted of the variations in the cost of the most expensive elements in the topology, i.e., trenching, business penalty and spectrum leasing.

Table 4.2 – Parameters Used to Calculate CAPEX and OPEX.

Equipment and Trench	Cost (US$)	Installation Time (min)	Failure Rate (FIT)	Mean Time to Repair (h)	Energy Consumption (W)
ONU	350	60	256	1	5
Splitter	50	10	120	1	0
RN Chassi	700	10	666	1	0
OLT port	7600	10	256	1	1197
OLT Chassi	4500	30	500	1	0
Optical Switch	50	10	200	2	0
Small Cell	1600	60	1612.9	2	45
Antenna	2000	10	540	1	20
Macro Cell	22000	1440	32258.06	7	22000
Trench	130000/ Km	-	570/Km	7	0

Figure 4.6, (represented in a scale from 290 to 370 US$/User/Year), shows the CAPEX for the PON and includes the investment for the network operation during 20 years of the network lifetime. It is evident that all the PON topologies are cheaper than a fully protected topology, i.e., Protection in the FF and DF accounts for about 640 US$/User/Year, which represents about twice the amount of any other proposed architecture. The main reason for these CAPEX savings is that the fully protected topology requires extra trenching, which is the predominant expense in terms of capital investments, i.e., FF has to cover long distances just to connect the CO and RN, while DF connects the splitter with *N* ONUs and thus represents a higher proportion in terms of investment. Moreover, it was found that the topologies based on Protection in the FF and Protection in the OLT and FF are about 8% more expensive than PON with No

Protection, PON with Protection using Microwave and PON with Protection in the OLT and using Microwave. Additionally, the results show that protection in the OLT adds only 1 US$/User/Year and guarantees redundancy in the most critical component in the network, i.e., the OLT because when this fails, it means that several users are without service.

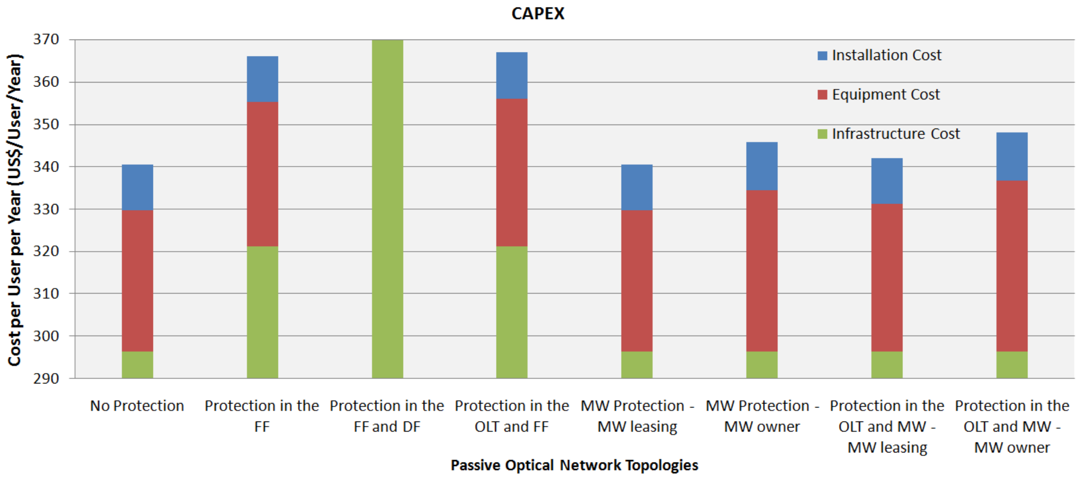


Figure 4.6: Comparison of investment in capital expenditures in different PON topologies.

With regard to microwave-based protection, it was found that when the fixed broadband operator signs a contract with the mobile operator, i.e., a amount of capacity in Gbps are reserved to be used in case of failure, there is no need for extra CAPEX investment. In contrast, when a fixed broadband operator also owns the mobile transport infrastructure the extra investment in equipment increases by about 5 US$/User/Year. This increase in CAPEX is due to the deployment of base stations and transport infrastructure.

The CAPEX investment in the protection has OLT and MW and the leasing and ownership of the infrastructure are 1 US$/User/Year and 7 US$/User/Year, respectively. The OLT protection guarantees that the mobile transport will only handle failures from splitters and ONUs, thus reducing network complexity by avoiding traffic overload in the mobile network. With regard to CAPEX, the results show that protection schemes based on microwave transport solutions are the most economical topologies.

Figure 4.7 shows the financial investment in OPEX. It should be noted that the Protection in the FF, the Protection in the FF and DF and the Protection in the OLT and FF save almost the same amount in OPEX, i.e., about 54 US$/User/Year, which is higher than No Protection scheme. However, the amount invested in CAPEX to deploy the Protection schemes does not pay off, i.e., as illustrated in Figure 4.6. On the other hand, microwave-based protection schemes strike a better balance between CAPEX and

OPEX, e.g., when protection in the OLT and FF is compared with the MW protection that leases capacity. The extra OPEX paid in the MW protection is 7 US$/User/Year, while the CAPEX savings for this transport topology may reach up to 26 US$/User/Year.

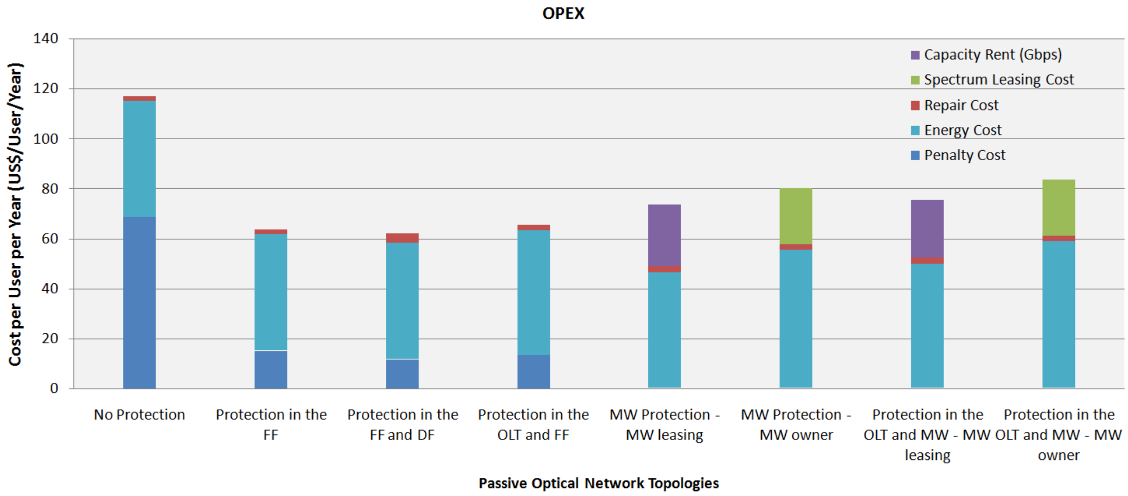


Figure 4.7: A comparison of expenditure in operational undertakings within different PON topologies.

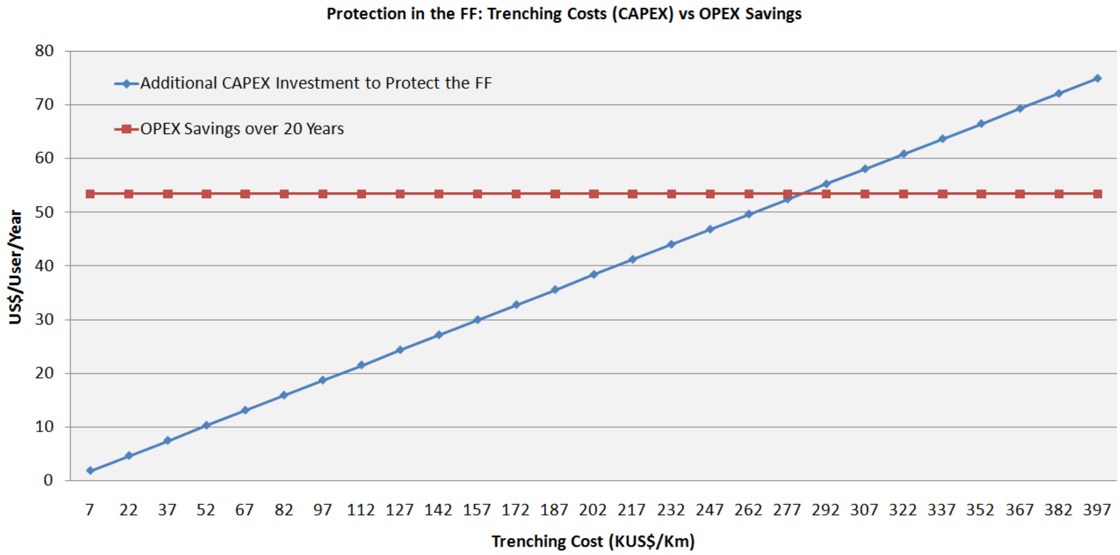
With regard to all the OPEX metrics for protected transport solutions, energy consumption emerges as the most expensive item when compared with the repair, penalty, and capacity leasing/spectrum costs. Energy consumption represents on average $49.75 User/Year per topology.

In terms of economy, the topologies based on Protection in the OLT and MW stand out as the most reasonable alternative to guarantee reliability for the users and to reduce extra expenses.

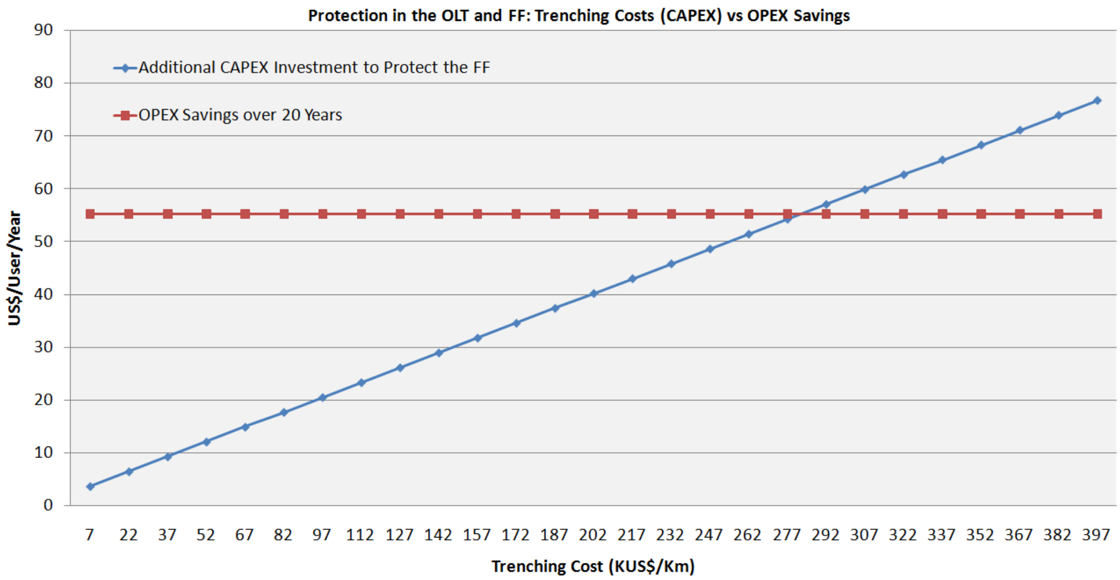
4.8.1 Sensitivity Analysis

This section examines the effects caused by the cost variations of the most expensive elements. In the case of CAPEX the trenching cost used was in a range of 7000US$/Km [75] to 400000US$/Km [51], while for OPEX the Business Penalty fee was in the range of 100US$ [6] to 1200US$ [42]. Finally, there was a variation in the network densification of the base station and in the effect of the measurements in OPEX.

Figure 4.8 (a) and (b) show the additional investment in trenching to upgrade a No Protection topology towards Protection in the FF topology and No Protection topology in the OLT and FF topology respectively. The results are expressed by comparing the extra CAPEX invested to deploy a protection transport scheme with the OPEX savings achieved by the protection deployment scheme. In both cases, it was found that the extra investment in protection is offset by the reduction in OPEX over a period of years. Moreover, it is clear that the extra trenching investment is 100% recovered over a period of 20 years when the trench cost is in the range of 7000US$/Km to 292 KUS$/Km, for the case represented in Fig 4.8 (a), and in the range of 7000US$/Km to 277000US$/Km to the case of Fig 4.8 (b).



(a)



(b)

Figure 4.8: Sensitivity analysis for trenching ranging from 7000US$/Km to 400.000US$/Km. (a) Protection in the feeder fiber. (b) Protection in the feeder fiber and optical line terminal.

Figure 4.9 illustrates the Protection in the FF and DF. In this case, the savings in OPEX do not offset the CAPEX investments, e.g., given the fact that trenching equals 37000US$/Km the additional CAPEX investment is about 78.48US$/User/Year and the OPEX savings is about 56.85US$/User/Year.

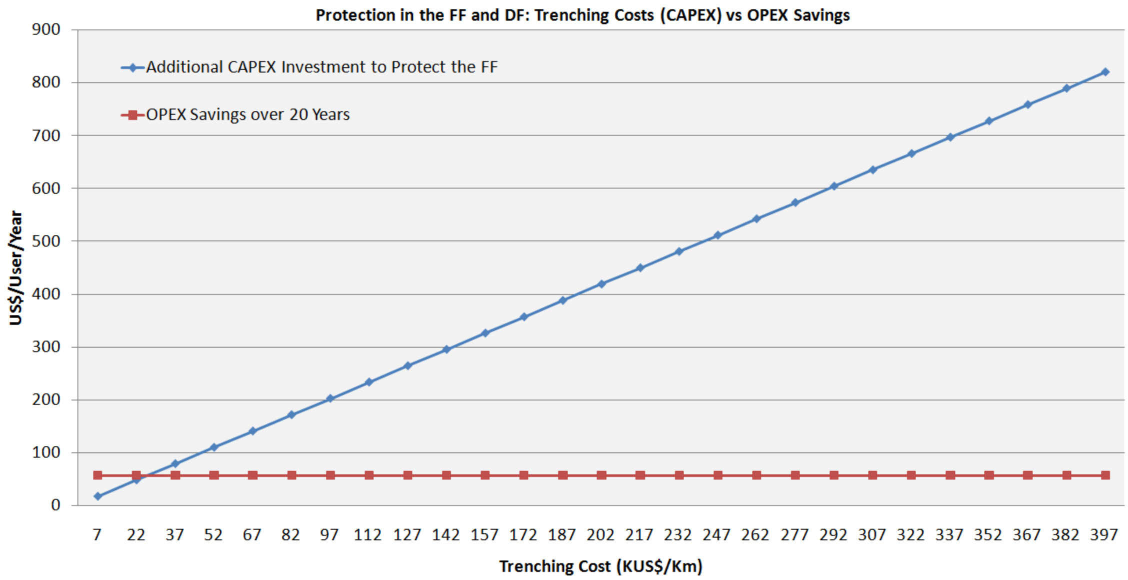


Figure 4.9: Sensitivity analysis showing the protection in the feeder and distribution fiber with trench costs ranging from 7000US$/Km to 67.000US$/Km.

Figure 4.10 shows the variation in the business penalty cost versus the following: OPEX for No Protection, Protection in the FF, Protection in the FF and DF, Protection in the OLT and FF, Protection using MW, and Protection in the OLT and MW topologies. The business penalty cost varies in a range between 100US$/hour up to 1200US$/hour. In Figure 4.10, it is evident that the No Protection topology is unreliable, since it results in significant profit losses, e.g., a business penalty fee of 1200US$User/Year and increases operational costs about 7 times more than the topology with protection in the FF. Moreover, it was found that “Protection” reduces OPEX revenues far more than the No Protection topology.

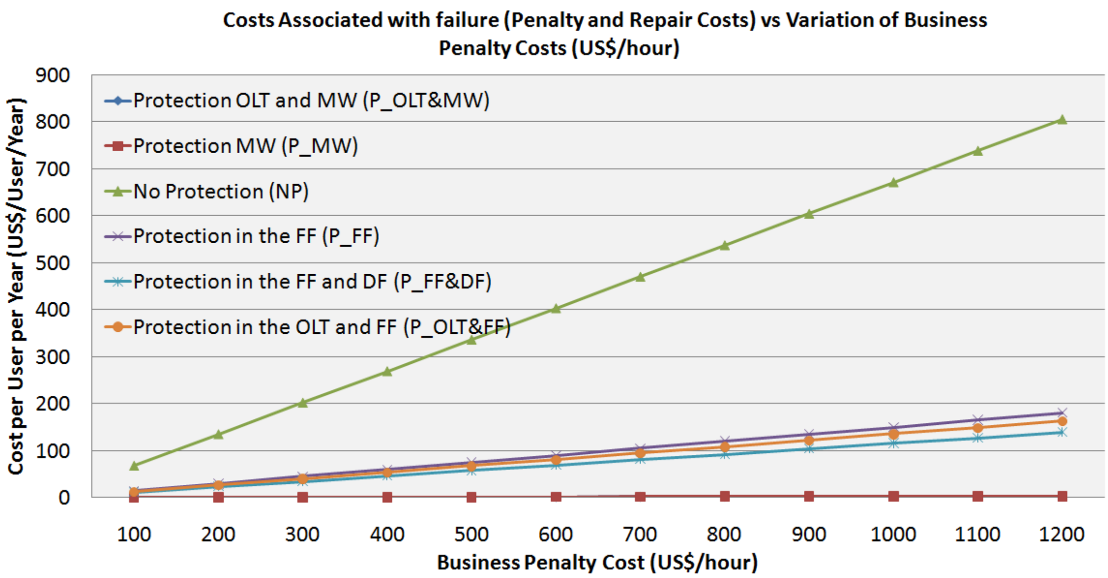


Figure 4.10: Sensitivity analysis of the business penalty cost ranging from 200US$/hour to 1200US$/hour.

Figure 4.11 shows the impact on the operational cost caused by the variation of the base station radius. The results show that the capacity rent is not affected by the network densification at the base station. On the other hand, if the operator owns the mobile backhaul infrastructure, the densification leads to a sharp rise in the operational expenses due to the spectrum leasing. Additionally, Figure 4.11 illustrates that the deployment of small cells increases the OPEX, e.g., *Micro* or *Pico* base stations with a radius lower than 50 meters consumes more energy and spectrum.

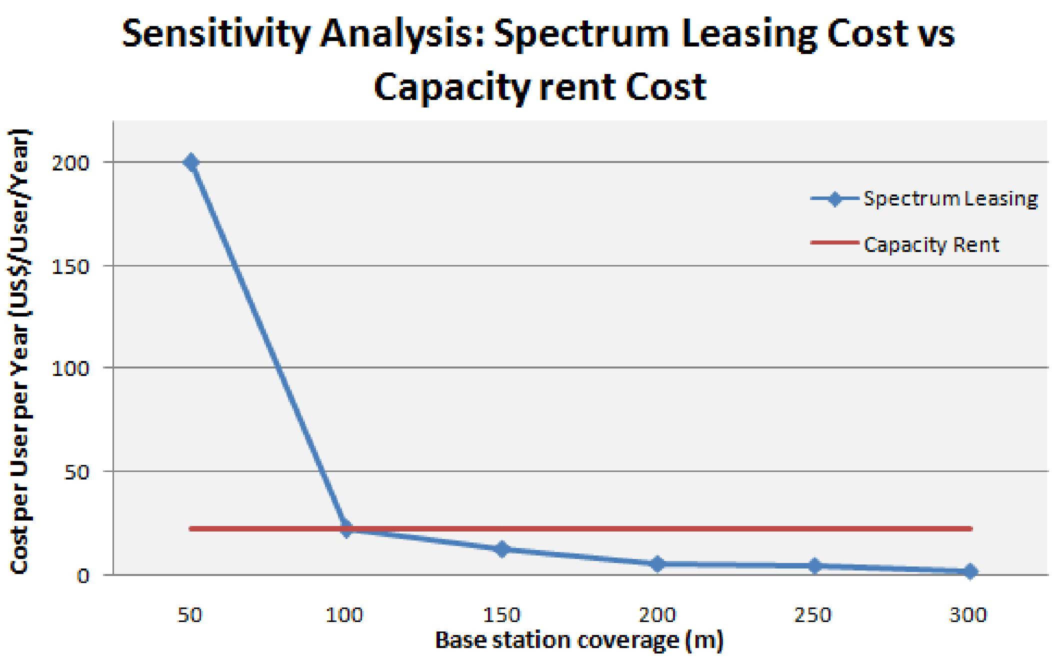


Figure 4.11: Sensitivity analysis comparing spectrum leasing x rental capacity as a result of the base station providing coverage.

4.9 CONCLUSION

In this chapter, a comprehensive methodology has been outlined that is based on a set of mathematics models divided into three stages, i.e., Network Dimensioning, Failure-Associated Costs and Assessment of Total Cost of Ownership. The main objectives were to simulate and compute CAPEX and OPEX protection transport schemes for PON as well as to investigate the commercial viability of investing in reliable PON topologies through the use of hybrid fiber- and MW-based topologies.

The study made a comparison between six different transport topologies: No Protection, Protection in the Feeder Fiber, Protection in the Feeder Fiber and Distribution Fiber, Protection in the Optical Line Terminal and Feeder Fiber, and Protection based on Microwave and Protection in the Optical Line Terminal and Microwave. The assessment models were used to determine the most attractive choices for protection with regard to cost-efficiency and reliability over a period of 20 years. The results demonstrate that trenching and energy consumption are the most significant expense for CAPEX and OPEX, respectively.

With regard to CAPEX, it was concluded that all the PON topologies are about twice as cheaper as a fully protected PON topology, i.e., Protection in the FF and DF. Moreover, it was found that the topologies based on Protection in the FF and Protection in the OLT and FF are about 8% more expensive than PON with No Protection, PON with Protection using Microwave and PON with Protection in the OLT and using Microwave, which makes microwave an attractive option. Additionally, it was noted that protection in the OLT adds only 1 US$/User/Year and guarantees redundancy in the most critical devices in the network, i.e., the OLT. With regard to microwave-based protection, it was discovered that extra CAPEX financial investment to install protection (based on OLT with either leased MW or owned MW infrastructure) are 1 US$/User/Year and 7 US$/User/Year, respectively.

In terms of OPEX, it was concluded that the installation of fiber-based protection considerably reduces the operational costs. On the other hand, it was estimated that the CAPEX investment in these Protections schemes was profitable, i.e., it does not pay off. In this way, it can be claimed that microwave-based protection schemes strike a better balance between CAPEX and OPEX. Finally, it was also concluded that protection schemes based on microwave transport solutions are the most economical topologies, i.e., among all the topologies, the Protection in the OLT and

MW topology feature as the best alternative to guarantee reliability for the end-users and to reduce extra expenses.

On the basis of sensitivity analysis, it was found that depending on the trenching cost for protection, (i.e., whether it is lower than or equal to 292000US$/Km, the investment in feeder fiber protection can be fully recovered through OPEX over a period of 20 years. Additionally, it can be concluded that the business penalty cost makes No Protection topology uneconomical for cities which have strict regulation and high penalty costs. As well as this, it was noted that protection might sharply reduce OPEX revenues since they require the addition of extra facilities. Finally, the results demonstrated that in cities with high network densification of base stations, i.e., a base station radius shorter than 100 meters, it is better to sign a contract and pay for a third operator for the traffic used, instead of building the infrastructure and having to pay for spectrum leasing.

CHAPTER V

CONCLUSION

This thesis focuses on the techno-economic evaluation of transport solutions for mobile and fixed broadband access. In the first part, i.e., for future mobile access networks, an assessment methodology was set out for a total cost of ownership. This was based on wireless deployment, different backhaul architectures and an economic analysis of use fiber and microwave applied to a Greenfield deployment and copper-legacy backhaul infrastructure based on Brownfield migration, i.e., using legacy infrastructure to its full capacity.

In Chapter III, the following models were investigated: a traffic model used to forecast the expected data traffic for the next few years, a wireless deployment model for a European urban scenario, the backhaul options model for Greenfield and Brownfield deployments and finally a techno economic model to assess the backhaul infrastructure.

In the case of the wireless scenarios, there were assumed scenarios consisting of outdoor macro base stations and small indoor base stations. Additionally, five different backhaul architectures were put forward, based on different combinations of copper, fiber and microwave technologies that applied the proposed methodology to both Greenfield and Brownfield options.

The analysis of the Greenfield scenario proved that backhaul architectures based on Passive Optical Networks (PON) is by far the most energy-efficient system. However this does not necessarily mean that all current and future backhaul solutions should be based on a massive fiber deployment. There are in fact also other factors that play an equally important role. If they are neglected, it may lead to backhaul solutions that are energy-efficient, but suboptimal (or worse) with regard to their performance in other areas. This is particularly true when the operator decides to build its own fiber infrastructure (i.e., trenching the fiber) and when the maximum distance between the small base stations and the local exchanges is vast (i.e., 1km or higher). In this case, microwave-based backhaul architecture emerges as the most attractive approach in terms of costs. Another solution for reducing the costs of the fiber-based backhaul is to lease dark fiber instead of building a new infrastructure. The results of our study have provided evidence that by leasing dark fiber the most cost efficient architecture is based on Fiber-to-the-Building+copper for the indoor small base stations and microwave for outdoor base stations.

With regard to the Brownfield scenario a number of different options were suggested on how the mobile operator could migrate between different backhaul architectures. The results show that from an energy-consumption perspective, as expected, the best option is to migrate toward PON as early as possible (i.e., options based on immediate migration take-up, where the operator invests a large amount of money to replace both the copper and the Microwave (MW) infrastructure with PONs immediately). However, this also represents the most expensive solution in terms of Total Cost of Ownership (TCO). The results have shown that the best solution in terms of TCO, is to exploit the existing copper infrastructure for backhauling the indoor small base stations and gradually replace it, starting a few years before the capacity exhaustion (i.e., options based on Gradual migration take-up, where the operator decides to exploit the copper infrastructure to backhaul the indoor small cells).

On the bases of the results, it can be inferred that backhaul constitutes a considerable proportion of the TCO, and the investigation between Greenfield and Brownfield deployment strategies must be taken into account so that operators can be encouraged to find the most cost-efficient and easy way to upgrade the transport network topology. Moreover, exploiting the legacy copper infrastructure can encourage operators to reduce their total costs to a considerable extent. The results also show that copper-based transport can still play a key role, especially in regions where it is not economically feasible to invest in new kinds of transport technology. Additionally, it was observed that microwave and fiber transport are the technologies that are able to handle the next generation of data traffic. To conclude, it is apparent that the main cost variations for the copper, fiber and MW backhaul did not significantly affect the conclusions drawn in previous sections. However, it was noticed that the costs for fiber trenching and for the microwave antenna are the most sensitive since a relatively small change can make some difference in the relative TCO of some backhaul architectures. Finally, the results make it clear that it is not possible to find a "one size fits all" backhaul solution. Even if there are no doubts that both microwave and fiber will be predominant features in future backhaul networks, the possible migration paths leading to these scenarios might vary. This can be attributed to a number of factors, such as the presence of an existing infrastructure; spectrum and license costs; the availability of equipment; the degree of willingness to invest in a completely new infrastructure; time for the technological deployment; and the Quality of Service (QoS) levels to be provided to the end user.

In the second part of the thesis, there was a comprehensive assessment methodology for total cost of ownership divided into three stages, i.e., Network Dimensioning, Failure-Associated Costs and Total Cost of Ownership Assessment. The main objectives were to simulate and compute the Capital Expenditures (CAPEX) and Operational Expenditures (OPEX) of protection transport schemes for PON as well as to investigate the commercial viability of investing in reliable PON topologies through the usase of hybrid fiber- and MW-based topologies.

The case study outlined in Chapter IV included a comparison between six different transport topologies: No Protection, Protection in the Feeder Fiber, Protection in the Feeder Fiber and Distribution Fiber, Protection in the Optical Line Terminal and Feeder Fiber, Protection based on Microwave and Protection in the Optical Line Terminal and Microwave. The assessment models were used to simulate the most attractive protection option regarding cost-efficiency and reliability over a period of 20 years. The results demonstrate that trenching and energy consumption are the most significant expense for CAPEX and OPEX, respectively.

With regard to CAPEX, it was concluded that all the PON topologies are about twice as cheap as a fully protected PON topology, i.e., Protection in the Feeder Fiber (FF) and Distribution Fiber (DF). Moreover, it was observed that the topologies based on Protection in the FF and Protection in the Optical Line Terminal (OLT) and FF are about 8% more expensive than PON with No Protection, PON with Protection using Microwave and PON with Protection in the OLT and using Microwave, which makes microwave an attractive option. Additionally, it was observed that protection in the OLT adds only 1 US$/User/Year and guarantees redundancy in the most critical equipment in the network, i.e., the OLT. With regard to microwave-based protection, it was found that the extra amount of CAPEX financial investment to install protection based on OLT and with either leased MW or owned MW infrastructure are 1 US$/User/Year and 7 US$/User/Year, respectively.

In terms of OPEX, it was concluded that the installation of fiber-based protection considerably reduces the operational costs. However, the CAPEX investment to deploy these Protections schemes is not profitable, i.e., it does not pay off. In this way, it is clear that microwave-based protection schemes strike a better balance between CAPEX and OPEX. Finally, it was also concluded that protection schemes based on microwave transport solutions are the most economical topologies, i.e., among all topologies, the Protection in the OLT and MW topology stands out as the most promising alternative to guarantee reliability for the end-users and to reduce extra expenses.

On the bases of the sensitivity analysis, it is apparent that depending on the trenching cost for protection, i.e., lower than or equal to 292 thousand US$/Km, the investment in feeder fiber protection can be fully recovered through OPEX over a period of 20 years. Additionally, it can be concluded that the business penalty cost makes No Protection topology uneconomical for cities where there are strict regulations and high penalty costs. As well as this, it was found that protection might sharply reduce the OPEX revenues due to the addition of extra active equipment, e.g., OLTs, ONUs, etc. Finally, the results demonstrated that cities with high densification of base stations, i.e., with base station radius shorter than 100 meters, it is better to sign a contract and pay for a third operator for the traffic used instead of building the infrastructure and having to pay for spectrum leasing.

There are a number of points that need to be more fully explored in future works, such as the following:

- Employing the methodologies for different scenarios, e.g., rural and suburban, etc, to determine the impact of different transport technologies on different scenarios, i.e., scenarios with variations in population density, area, etc.
- Testing the framework established for protection of mobile backhaul scenarios to enable economical protection schemes to be recommended for mobile operators.
- Simulating the protection schemes based on fiber and microwave to determine the impact on the mobile user service caused by traffic from the protected architectures, e.g., jitter and service failures.
- Adding copper technologies in the last mile to the protection models with the aim of determining the impact of CAPEX and OPEX on hybrid protected schemes based on fiber, copper and microwave. This more complex scenario might better represent developing countries such as Brazil.

- Adding new transport architectures that are being developed for 5G. In this case, it is aimed at making a comparison between new and legacy technologies.
- Expanding the framework models by adding new architectures in order to explore other transport options.
- Applying the models in scenarios that have different PON technologies such as Wavelength Division Multiplexing (WDM) and Next Generation PON (NGPON).

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