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Masters' Thesis

Converged Network Migration Planning

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Begin:	01. April 2018
End:	30. September 2018

With my signature below, I assert that the work in this thesis has been composed by myself independently and no source materials or aids other than those mentioned in the thesis have been used.

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Abstract

With the advent of the Information and Communication age, every day new services with better quality and higher bandwidth demands are being developed for a plethora of subscribers. To keep up with this, operators are moving away from copper based access network technologies and towards more future proof optical access network technologies. Depending on the area of deployment and demands of subscribers, there is a need to conduct a quick analysis to find the best time and technology for migrations, in order to maximize the benefits to both the subscribers and operator.

This thesis proposes: (i) A techno-economic analysis of different kinds of optical access network architectures, modelling costs in each case, (ii) a classification of different kinds of subscribers present in the network along with their behaviour of joining and leaving the network, (iii) a migration model based on a modified adversarial search technique, which takes as input the techno-economic costs and subscriber behaviours and finds the best technology to migrate to, resulting in the maximum accumulated Net Present Value (NPV) of the project along with the migration path in time and (iv) a sensitivity analysis to show the effect of various input parameters on the output results.

Contents

Chapter 1

Introduction

From high definition video streaming to gaming on demand, the need to have households connected with fast internet is now more than ever. As far as Internet Of Things (IOT) applications are concerned, residential users have many appliances and devices constantly connected to the internet, sending and receiving volumes of data. With more employees choosing to work from home and many businesses employing cloud computing and storage solutions to help increase their revenue and profits, a high speed internet connection has become an inseparable part of our daily lives. Hence, as innovation in technological comfort moves ahead in leaps and bounds, it is imperative that operators upgrade their infrastructure to provide households and businesses with sufficient capabilities to cater for this growth.

According to a report by Strategy Analytics, the current market penetration of 10% for 4K television users in the U.S. is predicted to jump up to 50% by the end of financial year 2020 [Str15]. These high levels of data consumption can no longer be satisfied by full copper deployments like Asymmetric Digital Subscriber Line 2+ (ADSL). The onus is on operators to upgrade their infrastructure to quickly migrate to newer technologies. This migration is a multi-dimensional, multi-period planning problem and its solution involves forecasting, dimensioning of network infrastructure and processes, as well as evaluation of their economic costs [RRM14].

The research question we seek to answer is how can a physical infrastructure provider achieve migration of all the different types of subscribers (Residential, Business and Intelligent Transportation Systems (ITS) back-haul) to a required data-rate, while maintaining profitability over the given network lifetime. In this thesis, an in-depth techno-economic analysis of Passive Optical Networks (PON) technologies is done, which involves finding the Total Cost of Ownership (TCO) of every technology, followed by a migration decision process which is modelled upon an Artificial Intelligence (AI) adversarial search algorithm known as *Expectimax Search* [Kle10]. Expectimax Search is a brute force depth-first search tree which uses an underlying Markov Decision Process (MDP) and evaluation functions to find the most profitable scenario in a given function.

Combining these two processes over various scenarios and factoring for the uncertainties of a project, a migration model is developed, which returns the technologies with the highest Net Present Value (NPV) (defined in Chapter 2), from a set of candidate technologies and the years in which the migrations should occur. This model serves as an analysis tool to help network planners, researchers and industry managers to make decisions while undertaking a migration study. The model parameters are also examined through a sensitivity analysis.

The thesis is divided as follows: *Chapter 2* introduces relevant background required to understand this work. This includes the motivation and need for fiber technologies in access networks, convergence, definitions from both techno-economics as well as network migration and important related work in the field of passive optical access network migration. *Chapter 3* then discusses the implemented business scenario and how the deployment area is modelled for generating exact subscriber demands. *Chapter 4* discusses the analysis of various passive optical network architectures used in this thesis, followed by a detailed description of the network dimension. *Chapter 5* deals with the techno-economic analysis used in this migration study, followed by the cost and demand modelling. *Chapter 6* deals with the migration model based on search techniques. In *Chapter 7* we discuss all the results of different scenarios along with a sensitivity analysis done on input parameters before concluding with *Chapter 8* where the outlook and future work are discussed and the thesis is concluded.

Chapter 2

Background

In this chapter, all background necessary to understand the research problem is dealt with. First, the need of using fiber in access networks is discussed. Then, all the important concepts related to techno-economics of networks and migrations are defined and briefly discussed. Finally, the related work is presented and the contributions of this thesis in overcoming the shortcomings found in the state-of-art is discussed.

2.1 Need of Fiber in Access Networks

As established in Chapter 1, the demands of residential and business users are ever increasing. According to [FTT16], the demands of residential users, small and medium enterprises are the major drivers for investment into better access network technologies.

Optical Access Network technologies provide, among other benefits, longer reach and higher sustainable data-rates, which makes them a candidate for deploying into cities and towns [SM17]. However, these optical access networks come in various configurations, each with their own type of equipment and dimensioning. A simple modelling of costs cannot suffice in finding the best technology to be deployed.

Since deployment of optical access networks lasts over a long period of time (between five and ten years), an analysis involving time value of money is required to find out a cost-effective solution. Hence, Total Cost of Ownership (TCO) and Net Present Value (NPV), both defined in Section 2.2, are widely used metrics to analyze the overall benefits to the operator over a period of time.

With different types of subscribers co-existing in the network, the operator needs to minimize costs of deployment. This is done by two methods, described as follows.

- **Network Convergence** [SM17], which involves planning a network such that multiple networks for multiple subscriber types, benefit from being deployed in the same

Optical Distribution Network (ODN) which allows them to share the costs of both deployment and operations.

- Careful **Strategic Planning** incorporated by network planners, which is defined by [MS99] as a complete planning involving the assessment of needs in a region, identifying goals, constraints and finally crafting a future-proof plan which is beneficial for all stakeholders.

As observed in real-life fiber deployments like [Pri16], a technology upgrade can take up to ten years and can cost upwards of 350 Million Euros. Operators know that within these years, the demand will increase further. Hence physical deployment done in the present day should be able to support demands of future, with little or no additional capital investment.

2.2 Techno-economics of Optical Access Networks

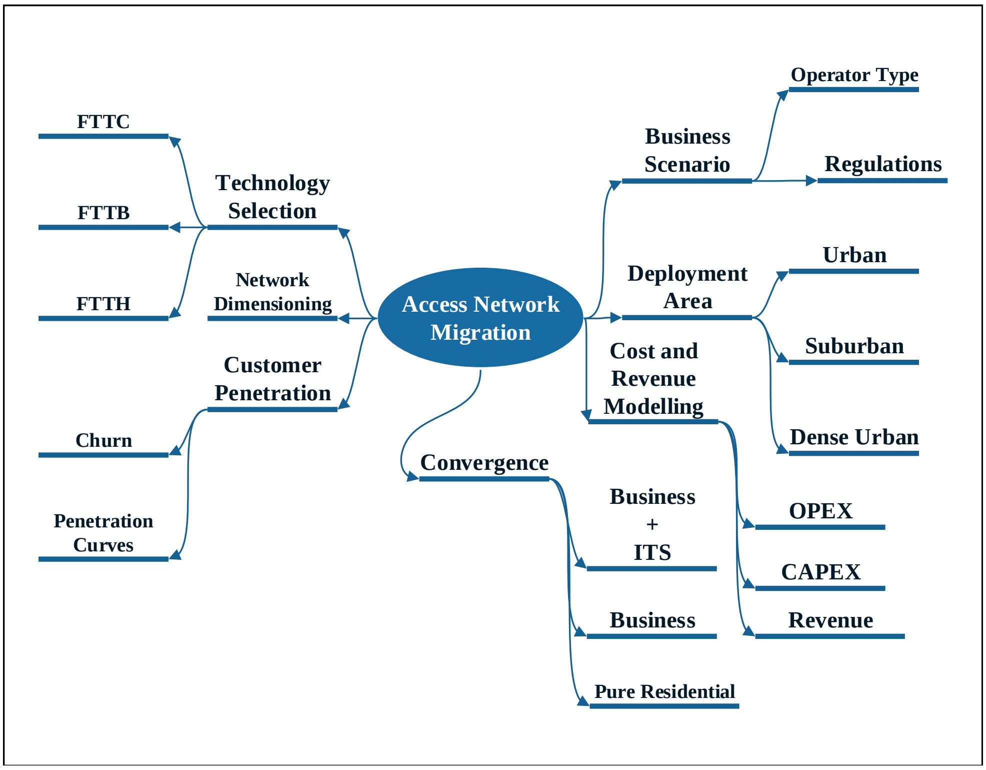


Figure 2.1: Techno-economic Framework for access network migrations [Cas09]

As has been already established in Section 2.1, optical access networks can be deployed in cities and towns in order to satisfy subscriber demands. Optical networks can be broadly classified into two different types, namely **Active Optical Networks (AON)**, which uses energy consuming equipment at Remote Nodes (RNs) and **Passive Optical Networks (PON)**, which uses passive equipment at RNs and have lower operating costs. In this thesis, we look into PON based technologies since the technology is now mature and affordable to deploy [Opt11, VVT+14]. We look into different types of PON technologies and deployments in Chapter 3.

A techno-economic framework is used to analyze information based on the technical as well as economic aspects of an access network deployment [CLV+09]. Figure 2.1 shows the framework used in this thesis, which closely follows the framework defined by [Cas09]. Broadly, we analyze the business scenarios, deployment areas, technology selections, network dimensioning, subscriber behaviours, costs and revenues associated to finally get an output metric using which comparisons can be made. This techno-economic analysis in this thesis not only derives its model from existing methods in literature [Cas09, vdMGGK09, Ana08, CWMJ10, KWL+10, Opt11], but also extends it to fit the defined business scenario.

2.2.1 Fiber Technologies

To understand the PON technologies used in this thesis, the different classifications of fiber technologies have to be understood. These classifications can be modelled in many permutations and combinations to provide a subscriber the required data-rate.

Deployment Stages and Types of Fibers

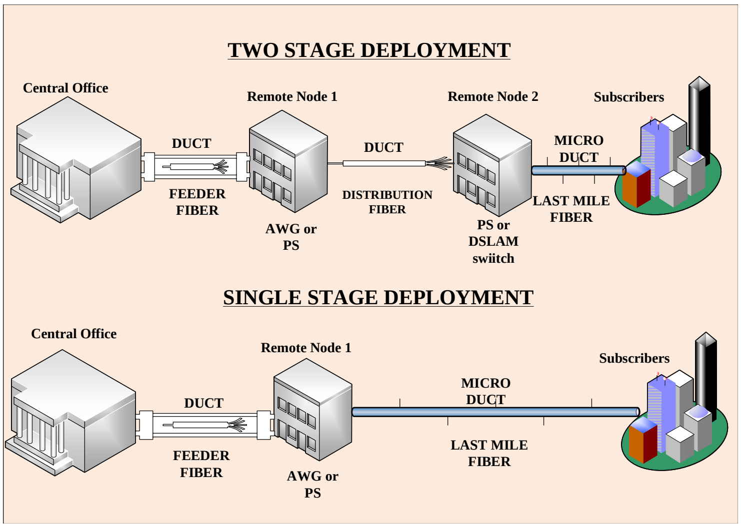


Figure 2.2: Single stage and two stage access network deployment [Hay09]

A PON network differs in the way of deployment, based on how near the fiber is from the subscriber. As illustrated in Figure 2.2, PON deployment can be broken into either a single-stage or a two-stage deployment. A two-stage deployment consists of two remote nodes, Remote Node 1 (RN1) and Remote Node 2 (RN2), between the Central Office (CO) and fiber drop points at subscriber locations. Similarly, a single-stage deployment consists of only RN1. As mentioned in [Hay09], we can define the types of fibers as follows.

- **Feeder Fiber (FF)**: Extends from Optical Line Termination (OLT) in the CO to a distribution point in the city which may house the PON based Power Splitter (PS).
- **Distribution Fiber (DF)**: Present in two-stage deployments, DF connects the two distinct distribution points or remote nodes.
- **Last Mile Fiber (LMF)**: The fiber connecting the RNs to the Optical Networking Unit (ONU) placed at the subscriber locations.

Based on the end-point of the fiber in the network we can define three different types of deployments, namely, **Fiber to the Cabinet (FTTC)**, **Fiber to the Building (FTTB)**, **Fiber to the Home (FTTH)** [vdMGGK09, MM17, Pri16]. In FTTC, fiber terminates with an ONU at RNs and the buildings are further connected with RNs using copper. In FTTB, the the ONU extends to the buildings. In case multiple dwellers exist in the building, they are connected to the network using copper cables. Finally FTTH involves in installing a dedicated ONU for every single subscriber and additional in-building cabling. In combination, these deployment methods are also known as **FTTx**, where 'x' stands for *Cabinet*, *Building* or *Home*.

PON Technology

PONs can also be defined using the type of equipment and components being used. The following definitions closely from the work done in [Opt11].

- **Gigabit-ethernet Passive Optical Network (GPON)**:- One of the earliest time domain optical network technology, each GPON OLT card can provide up to 2.5 Gbps of asymmetrical data-rate [OAS13], making it a cost-effective solution for low bandwidth demands. This data-rate can be split among subscribers using a Power Splitter (PS).
- **10-Gigabit-ethernet Passive Optical Network (XGPON)**:- An extension of the GPON technology, XGPON provides symmetrical 10 Gbps data-rate per OLT card [Opt11].
- **Wavelength Division Multiplexing Passive Optical Network (WDM-PON)**:- A newer technology as compared to GPON and XGPON, WDM-PON makes it possible to send up to 500 Mbps of data-rate on up to 80 separate wavelengths, per OLT card. These wavelengths are split at RNs using an Arrayed Waveguide Grating (AWG) which can have a splitting ratio of up to 1:80. Due to individual wavelengths provided to each ONU, WDM-PON has a higher level of security [Opt11].

- **Hybrid Passive Optical Networks (HybridPON)**:- As a combination of both time division and wavelength division multiplexing, HybridPON provides the security of WDM-PON and the high bandwidth of an XGPON technology. It uses both AWGs and PSs at RNs [Opt11].

2.2.2 Business Scenario and Deployment Area

As discussed in Section 2.1, strategic planning needs to start with assessment of the region where technology has to be deployed. This assessment can be further split into two parts, namely Business Scenario and Deployment Area.

Business Scenario

Converged Network Migration Planning is a more specific application of Strategic Planning (defined in Section 2.1) and like any project, the first step is to define the business scenario which describes the type of operators and subscribers, along with their demands and objectives. After the scenario has been defined, .

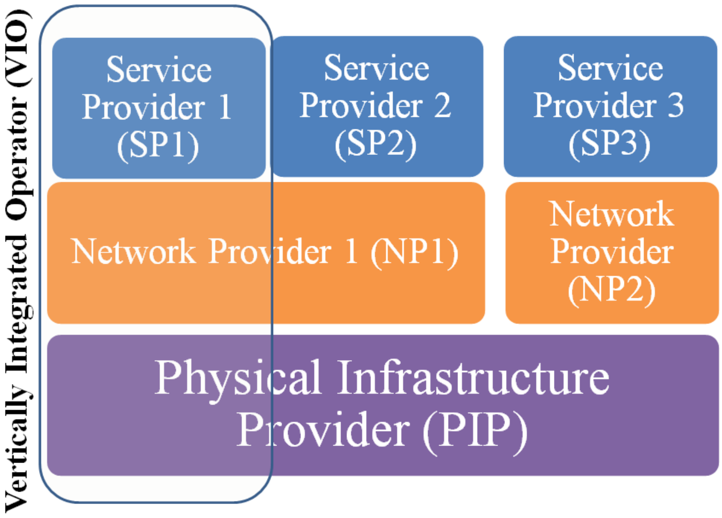


Figure 2.3: Hierarchy of telecommunication providers based on levels of access [MM17]

As defined in [MM17], the three major types of access network providers are:

- **Physical Infrastructure Provider (PIP)** :- PIP are responsible for construction and maintenance of physical elements of the network, such as cables ducts, fibers, rights of way, base stations, etc.

- **Network Provider (NP)** :- NP operate one level higher to PIPs and own the active and passive equipment at RNs and use the PIP infrastructure to provide internet access to their customers.
- **Service Provider (SP)** :- SP use the network deployed by NPs to provide the end customers various services like 'triple-play' services, streaming services, on-demand services, edge-of-cloud computation, etc.

The hierarchy is shown in Figure 2.3. Since our focus is mainly on migrations, we chose a simple model, which is Vertically Integrated Operator (VIO) [MM17]. This model is mainly applicable in countries where there is a single PIP and less number of NP. This ensures that the VIO enjoys an almost monopolistic market with less competitors.

Deployment Area and Network Dimensioning

After deciding the technologies involved in the migration study, the network is deployed and the lengths of the ducts and fibers in the FF, DF and LMF are calculated. Broadly, there exist two main classes of network dimensioning tool, namely *Geometric Models* and *Geographic Models*.

Geometric Models, for example, Triangle Model or Simplified Street Model [MKC$^+$10], are used to deploy access networks based on an abstract level by modelling the required parameters for the deployment using a mathematical approach. Generally, a lot of assumptions for the number of demands, the distribution of demands, population density, type of road network etc. have to be made. Since a lot of assumptions are involved, network planners use average values in most cases, which result in inaccurate lengths of fiber [Cas09]. As shown in the work done by [MKC$^+$10], The Simplified Street Model offers a 20-30% underestimation in costs as compared to real-life maps, however where reliability of cost calculation is of higher importance, it is preferable to use *Geographic Models*.

Geographic Models [MKC$^+$10] use real and detailed geospatial information of a region in order to get accurate results. Instead of assuming the distribution of demands, real building locations are used. However, this method requires more calculations as compared to Geometric Model. An example is the network dimensioning tool developed at the Chair of Communication Networks, Technical University of Munich, which is also introduced in [SM17]. Data of the required area is taken from OpenStreetMaps (OSM) [Ope17]. The resulting shapefile is then loaded into ArcGIS 10.3.1 ®[Ins11] and cleared of unnecessary pathways and buildings, before creating a network data-set. This network data-set contains the information of streets and intersections in the form of a network graph which is used to calculate the lengths of fibers.

2.2.3 Costs, Revenue and Churn

Once all the data from the PON technologies and the network dimensioning is done, a Bill of Materials (BoM) can be created. a BoM gives the quantity of equipment and materials required to deploy a particular technology. The two major costs in a techno-economical analysis originate from **Capital Expenditures (CAPEX)** and **Operational Expenditures (OPEX)**, which are defined as follows in [MM17].

CAPEX are the costs which occur during deployment of a new access network. This is a non-recurring, one time cost which quantifies the investment required to deploy a current technology. Broadly, CAPEX itself is divided into civil works and equipment costs, themselves comprising of multiple sub-components as explained in the list below.

- **Civil Works Cost** : The cost related to trenching and laying of ducts and fibers come in the purview of civil costs. These costs are taken from [Opt11] to evaluate the various cases.
- **Equipment Costs** : This cost refers to the hardware and software installed in CO, RNs, buildings and subscriber premise. The hardware at central office include but are not limited to OLT port card, Optical Distribution Frame (ODF), racks, tunable lasers (in case of WDM-PON). For RNs, the equipment can be PSs, Digital Subscriber Line Access Multiplexer (DSLAM) switches, AWG or ONUs, depending on the type of deployment. At buildings and subscriber premises, ONUs or DSLAM switches can be deployed. Apart from equipment, we also include additional costs for purchasing back-up power units and Heating Ventilation Air Conditioning (HVAC). All these values are available in [Opt11].

OPEX are the recurring costs, which need to be paid by the VIO every month [CWMJ10, MM17]. However, for simpler calculations, we compute the OPEX cost yearly. These costs include energy, rent, failure maintenance and service provisioning, defined as follows:

- **Energy Costs** : Spending on energy contributes for a major factor in OPEX calculations. Energy costs refer to the yearly expenditure required due to energy consumption by various electronic hardware and support elements (like power backup and switching) in the network. To calculate this, we take the energy consumption values in Watts given in [Opt11]. The average cost per unit of electricity is taken from [JS18, Cit18].
- **Rent Costs** : Many VIOs, instead of purchasing and constructing cabinets, prefer to lease. The area required to lease depends on factors such as, the footprint of various network elements, the number of network elements required and the rental costs. The average cost of rent per square meter per year is found in [Cit18, JLL16].
- **Failure Management Costs** : In a real life scenario, network electronics cannot be considered as ‘deploy and forget’. They are prone to failures and need to be replaced or repaired by technicians. To cater for such failures, we need to model failure

reparation into the OPEX calculations. The two most important parameters required for failure reparation are Failures in Time (FIT) [CWMJ10], which is the amount of failures of a network element in 10^9 hours and Mean Time To Repair (MTTR) [CWMJ10], which is the time required to repair a network element.

- **Network Operations and Marketing Costs** : These are costs related to marketing and the daily running of operations, like billing and charging cycles, customer service, etc. We assume a yearly static overhead of 7% for network operations and 5% for marketing costs, which follows closely the values in both [Opt11] and [CWMJ10].

Revenues are the amount of money recovered from the subscribers in a network for the services provided to them by the VIO. In a techno-economic analysis, revenues for various services are set after modelling costs and finding the minimum revenue that needs to be charged in order to generate profits [Cas09].

Penetration Curves are a result of mathematical equations or models which define how many subscribers join the network every year [vdMGGK09]. In this work, we use the results of [Opt11], where forecasting is done over a network lifetime of 20 years and has three variations, namely, *Conservative, Likely and Aggressive.* As seen from Figure 2.4, the maximum percentage of subscribers who join the network over a 20 year period varies between 65-80% depending on the type of curve. As mentioned previously in Section 2.2.2, we assume that the lack of subscribers reaching full penetration may be due to the remaining number of subscribers joining competition.

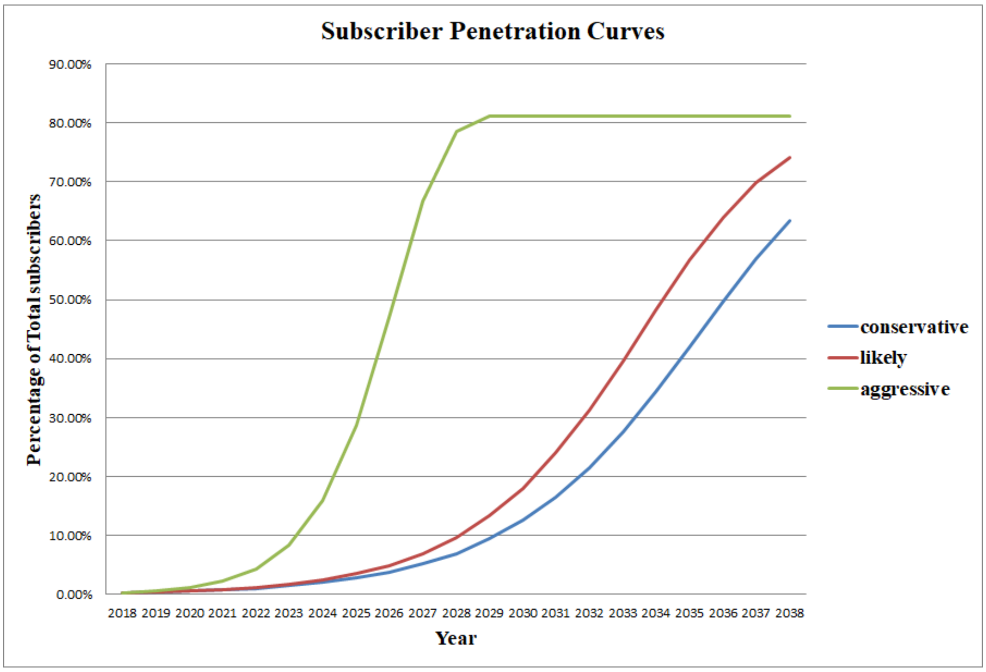


Figure 2.4: Subscriber penetration curves defined for 20 years [Opt11]

Churn [MSCn99] can be defined as the percentage of total connected subscribers who disconnect from the network, for various reasons. Although the churn rate and the probability that a churn may occur involve complex model calculations, for the sake of simplicity, we assume a 10% subscriber churn at a uniform probability distribution of 0.1 [Opt11]. This probability defines the likelihood that a churn of 10% may occur in any given year. In general, fixed access networks have lower churn probabilities than mobile networks because subscribers are more likely to stay in the network [MSCn99]. In this work, we model the churn as lost revenue, which is explained further in Chapter 4.1.

2.2.4 Modelling Demands

The total revenue depends on the total number of potential subscribers in an area, as well as the rate at which they join the network. The number of subscribers can be calculated from OSM data of the number of buildings in a given area, as well as the average number of inhabitants per residential or business buildings in [JLL16, Cit18].

Subscribers

In this thesis, we define the following three different types of subscribers in our network:

- **Residential Subscribers** : The inhabitants of residential buildings are known as residential subscribers. Following the definition in [TVC$^+$12], they are the largest subscriber base. These subscribers are charged a lesser tariff since any drastic increase would lead to subscribers leaving the network. At the same time, they are not offered any guarantee of service by the VIO.
- **Business Subscribers** : The small and medium businesses demanding high speed data-rates are known as business subscribers. These subscribers need high reliability and availability of connection and hence are willing to pay for more. In a city, about 7-10% of the total subscribers can be assumed to be business subscribers [TVC$^+$12, Rok15]. There are also Service Level Agreement (SLA) which incur penalties on the VIO for a downtime exceeding a pre-determined time [Opt11, CWMJ10].
- **Public ITS backhaul** : The VIO has enough dark fiber present in order to provide its network as a backhaul for public Intelligent Transportation Systems (ITS) providers. Here we use the public ITS case which is defined by [GMK16], we assume the demand of a single ITS Mobile Base Station (MBS) to be anywhere between 50-100 Mbps, depending on the service. Public ITS providers need this backhaul to interconnect the base stations with a Service Server (SS), which helps in routing and forwarding of low demand messages like timing schedules, emergency co-ordination etc. As shown in [GMK16], for a city, Long Term Evolution (LTE) is a more reliable and future-proof option, as compared to Dedicated Short Range Communications (DSRC), since they allow higher bandwidth and are easier to operate and

maintain. Therefore, we consider that the VIO earns extra revenue by providing connections to every MBS in the public ITS network. The number of public ITS MBS are calculated using the values provided in [GMK16, BER17].

Convergence

The definition of *Network Convergence* has already been provided in 2.1. To delve deeper, we define two scenarios and consider the results for each of them in Chapter 6. The salient features of these scenarios, namely Pure Residential and Converged are:

- **Pure Residential** : In a pure residential scenario, all the demands (buildings) in the network dimensioning are considered to be residential buildings. Residential users pay less tariff for the same amount of services [Pri16], hence it takes longer to achieve profits in this scenario.
- **Converged** : This is a more realistic scenario where we assume a percentage of the total buildings to be business buildings, which accommodate approximately six small and medium businesses. Business users are willing to pay far greater than residential subscribers [FTT15]. In case there is a violation in SLA, the VIO is charged a penalty. A seperate modelling for business subscribers and ITS MBSs does not reveal a significant difference in results, due to the low quantity of acITS MBSs deployed. Hence the converged scenario considers residential subscribers, business subscribers as well as ITS MBSs.

2.2.5 Net Present Value

Net Present Value (NPV) [MM17] is an investment metric which utilizes the time value of money to valuate long-term projects. It is the difference between the present value of cash inflows and the present values of cash outflows [MM17]. To find profitability of a project, network planners use either the NPV or the Total Cost of Ownership (TCO) method. In this thesis, we use the NPV as it gives us an estimate of how profitable migrations are over a long period of time. The equation for the NPV is given as follows.

$$NPV = \sum_{t=1}^{T} \frac{R_t}{(1+i)^t} - R_0 \, , \tag{2.1}$$

where t is the current time period, T is the maximum time, R_t is the net cash flow at time t and R_0 is the the initial investment at the start of the project. i is the discount rate[TVW$^+$14] of the project. Like many telecommunication projects, we assume the discount rate to be fixed to 10% [TVC$^+$12, Cas09].

Since the NPV is the sum of many "discounted cashflows" at different periods in times, each of these cashflows are known as **Present Value (PV)**. The PV can be defined by the following equation:

$$PV = \frac{R_t}{(1+i)^t} \ , \tag{2.2}$$

where t is the current time period, R_t is the net cash flow at time t and i is the discount rate which stays the same as defined for Equation 2.1.

We use this definition of PV to model the value function of migrations, which is first introduced in Section 2.3 and discussed in greater detail in Chapter 5.

2.2.6 Migration in Access Networks

Migration in access networks, as defined by [TLRL13] is the "technical process of upgrading the existing equipment and infrastructure to a more future-proof technology, which can generate cost savings for the operator". VIOs prefer a migration when the already deployed technology is either expensive to operate or is unsuitable to meet the requirements of different kinds of subscribers [FTT15].

Since migration studies are always time bound, we define two important times to be used in this thesis, whose definitions follow closely from [RZM14].

Migration Window (T_{mig}) is the time period in which the migrations are allowed to occur. In this thesis, we define a migration period of ten years as $T_{mig} = \{0, 1, 2..., 9\}$. The search technique discussed in Chapter 5 exists during this time period.

Network Lifetime (T_{NW}) is the time period for which the economic analysis exists. We define a network lifetime of twenty years as $T_{NW} = \{0, 1, 2..., 19\}$, so that operators have time to recover the costs of migrations from the subscribers.

The value of the entire migration is found out using a NPV method. Since there are many PON technologies to choose from, we define different possible **migration paths** [RZM14], which are the PON technologies which the VIO can migrate to in the given migration window T_{mig}.

There can be multiple migration paths, based the migration rules or constraints and the number of available PON technologies. Every migration path is a list of the same size as T_{mig} and each item of the list tells the technology deployed in the area at that year.

2.3 Migrations and Adversarial Search

Once the required costs from techno-economic framework have been generated, the migration study can be started. To model the migration study, we employ a search technique based on an early Artificial Intelligence (AI) algorithm. We first define AI search related terminologies and then explain this search technique which serves as a basis for the methodology used in this work.

2.3.1 Agents and Environments

Although many definitions of AI exist in literature, we use the definition provided by [Bel78], who states that AI is the "automation of activities using a commercially available digital computer, that we associate with human thinking, activities such as decision-making, problem solving, learning, creating, game playing and so on."[Bel78]. Decisions such as when to migrate and to which technology to migrate to can be automated using computer programs, however, these decisions have to seem rational to a human being. The three main components of an AI model are *agents, environments and search techniques*, all of which are discussed below.

Environment

The first object to be designed in any AI model is the environment. An environment consists of the initial state, a set of rules and regulations in which certain actions done, result in specific outputs [BM09].

We define the environment to be the business scenario (Pure Residential or Converged) with different type of subscribers (residential, business, ITS). The migration from the current deployed technology to the next one can only occur according to the migration matrix, as explained in the Chapter 5. Every migration has its associated CAPEX, OPEX and increase in revenue. The uncertainty of the environment is then the probability distribution of subscriber churn (refer Chapter 4.1). We also define a time period for which the migration lasts, given as $T_{mig} = \{0, 1, 2, ..., 9\}$ which means that the environment is valid for a period of 10 years.

Agent

An agent creates rational and legal actions, after judging the current state of the environment. This agent can be either a robot, a machine or a utility function [RN10]. Agents can work with either maximizing or minimizing the benefits. There can also be a scenario where there is only one agent playing against the environment. Here the agent can either maximize its benefits or minimze the opponent's benefit. A simplified action-reaction relationship between the agent and the environment is shown in Figure 2.5.

We assume that the agent is the VIO, which has to make a decision every year in order to maximize its benefits. In the same year, the environment updates its values according to the decision of the agent, as well as the probability of subscriber churn (which, in this thesis, is defined as a Bernoulli Distribution). An optimal agent [Hay07], is an agent which takes the best available decision, given an expected value of the probabilities of different choices. The combination of this expectation and choosing the maximum value, leads to the Expectimax algorithm [Kle10].

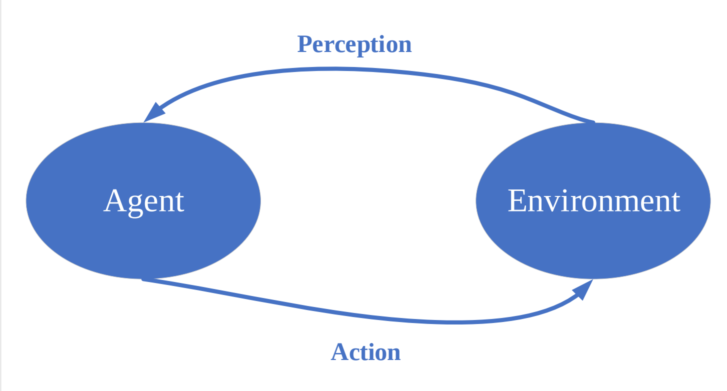


Figure 2.5: Agent Environment interaction [RN10]

2.3.2 Search Techniques

Once the rules of the environment and the agents have been defined, the search starts. The lifetime of the game exists till the current time T_{curr} reaches the end of T_{year} and every year the agent takes a decision, due to which there are changes in the current environment [RN10]. The objective here is to find a list of moves, or a migration path, with the maximum benefit. An end is reached either when the problem is solved completely, or when T_{curr} becomes equal to the largest value of T_{year}. Various techniques to search exist in literature. Some of them are briefly discussed here.

- **Uninformed Search** : In this search, the agents have no extra information of the environment, other than the initial state, rules and the final goal to achieve. After every action, the agent checks if it has reached its goal. Strategies like breadth first search, uniform cost search, depth first search and depth-limited search fall in this category [RN10, Kle10].
- **Heuristic Search** : In this search, the agent uses problem-specific knowledge [RN10] to add to the information which is already provided by the environment. These

searches involve an evaluation function based on a cost estimate and a heuristic function based on the information currently available in the environment.

The algorithm used in this thesis is an extension of an **uninformed adversarial search** [Kle10], where instead of two agents playing against each other, we have only one agent playing against a non-deterministic environment.

2.3.3 Expectimax Search

As established in Chapter 1 and further in Section 2.2.2, we need to find a way to incorporate uncertainty in migration study. This uncertainty also needs to be modelled in the search tree, by introducing a random element.

The **Expectimax Search** [Kle10] is a simplified uninformed adversarial search technique used in artificial intelligence to model sequential games. This algorithm is a simplified version of *Expectiminmax Algorithm* [RN10].

Like any search tree, the Expectimax Search is made up of different types of nodes, each of which is associated to a different function. The definition of the nodes, according to [Kle10] is as follows:

- **Max Node**: This node models the behaviour of the agent and maximizes the output of its child nodes. In our thesis, the decisions taken by the VIO every year happen at this node, represented by a triangle in Figure 2.6
- **Chance Node**: This node models the behaviour of the environment and finds the ‘expectation’ [Kle10] of all scenarios possible in the environment. In our thesis, this node signifies the lost revenue when churn has occurred or not and is represented by a circle in Figure 2.6.
- **Terminal Node**: At this node, the migration path terminates. In our thesis, this can happen in two cases, either when the search reaches the maximum depth or when it satisfies the final demands of the subscribers (i.e. 100 Mbps data-rate). This is represented by a rectangle in Figure 2.6.

To explain Expectimax Search, we use a toy example of depth two and having only two choices at the chance node in Figure 2.6. The general format of each of the node name is given as $Node\_TypeNode\_Number_{depth}$. The double-headed arrows indicated that the tree is first built from top to bottom and the values are then propagated up from bottom to top in a depth-first search fashion. Considering that the time step $T_{mig} \in \{0, 1, 2\}$ is modelled into a tree of depth 2, the terminal state value at depth t, for a state s, contains a value from an evaluation function $V(s, n, t)$ [Kle10].

$$U(s, n, t) = V(s, n, t) \tag{2.3}$$

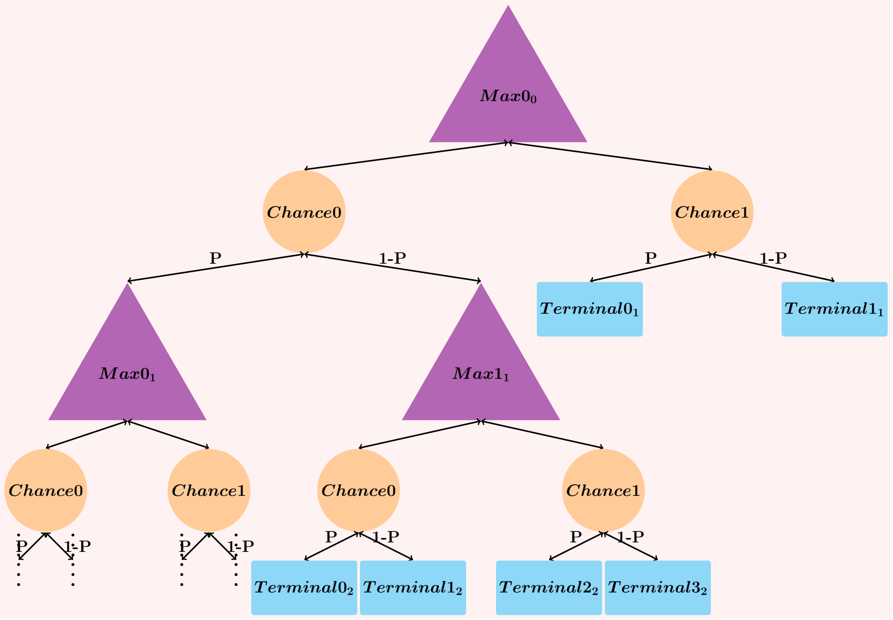


Figure 2.6: A generalized Expectimax tree running for a time period of two years

Here $U(s,n,t)$ is the value of the n^{th} terminal node which represents state s at depth t. In the example, this can be the value stored at $Terminal0_2, Terminal1_2, Terminal2_2$ and $Terminal2_2$. Since each of the different terminal states can be reached from a chance node $(Chance0, Chance1)$, depending on the probability distribution, the value at chance nodes is the weighted average of the value of its children:

$$H(n,t) = \sum_{i \in \, C_{n,t}} Pr(s_i) U(s,n,t), \tag{2.4}$$

where $H(n,t)$ is the value of the n^{th} chance node at depth t, $C_{n,t}$ is the set of all children of the n^{th} chance node at depth t and $Pr(s_i)$ is the probability that a state of a child s_i may be reached given a depth t. This probability is represented by **P** and **1-P** in Figure 2.6.

Finally, the value of the maximizer node $(Max0_0, Max0_1$, etc.), which is the parent of chance nodes can be given as:

$$U(s,t-1) = \max_i H(i,t) \tag{2.5}$$

where $U(s,t-1)$ is the value of the parent maximizer node, which is one depth above the children chance nodes, $H(i,t)$ is the value of the i^{th} child chance node at depth t.

The values of Equations 2.3, 2.4 and 2.5 are propagated upwards towards their respective parent nodes till $t = 0$ is reached. Then the expected value at the top most node is the maximum expected value of the likely path. There is a possibility of reaching the terminal nodes before the complete depth is accomplished. Figure 2.6 shows two terminal nodes at depth 1, where the search stops. With every calculation of the value, the state s and depth t of the visited nodes are also stored, which makes it easier to access the entire path traversed in the path which results in the highest utility function value. In Chapter 5, we modify the utility and value functions for Expectimax Search using present value in the given situation for every different PON technology.

2.4 Related Work

Much of the research in Access Network migrations up until now either focuses on only one migration path or only one technology and mostly is done for specific use-cases. This is because the data required for accurate results changes according to use case, business scenario and demand. However, the methodologies discussed in this section are helpful in defining the problem statement.

2.4.1 Techno-economic Comparison Model for Optical Access Technologies

One of the earliest works done to choose the best available optical access technology, given a variety of different technologies was done by [vdMGGK09]. Different types of optical access technology deployments are compared using a well-defined cost model. The basic building blocks of the cost model are the market input, Capital Expenditures (CAPEX), OPEX and scenario analysis.

The advantages of this work are a well defined general methodology on how to approach comparison of various technologies. In the OPEX calculations, the authors don't consider failure management and service provisioning, which according to the work done by [CWMJ10] is one of the major factors in the increase of OPEX costs. Apart from this, the authors of [vdMGGK09] also conclude that the technologies considered are quick but not accurate since geometric models instead of real street maps have been used to generate fiber lengths and number of central offices, cabinets and drop locations.

2.4.2 Dynamic Migration to FTTH

The work done by [ZZM10] and the additions to it by [RZM14], contribute to planning migrations in case multiple technologies and scenarios are present. In both these works, the authors define a 'Generalized Migration Model' [ZZM10, RRM14] which takes into account CAPEX, OPEX, revenue and a time a schedule limit [ZZM10] which is the maximum time allowed to reach FTTH. [RRM14], in addition to the GPON deployment considered in [ZZM10], also considers AON as well as both protected and unprotected scenario.

As suggested in [ZZM10], prior work only considered one-step migration, that is, direct migration to a final technology, however, when there exist more intermediate steps or technologies to migrate to, finding the most beneficial migration path becomes a complex optimization problem. As seen in Figure 2.7, [ZZM10] defines a simple yet dynamic migration model with S states with 1 being the lowest or the starting technology and S being the final technology which needs to be reached in the scheduled time.

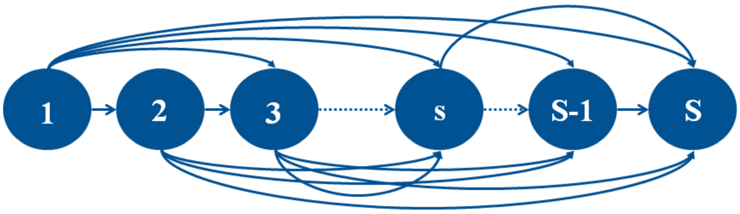


Figure 2.7: Dynamic Migration Model with S states and all potential forward paths [ZZM10]

The advantages of this solution are:

- Multi-step, multi-period migration strategy is defined.
- Optimal migration path considers migration window as well as holding time in every intermediate technology. AON and protection scenario considered by [RRM14]

At the same time, there are some disadvantages of using this algorithm:

- Only one final state (FTTH) is available. Different deployments like FTTC, FTTB or even Very-high-bit-rate Digital Subscriber Line (VDSL) could provide the same data-rate as FTTH to its subscribers and shall be evaluated.
- The choice of technologies is limited and does not include WDM-PON.

2.4.3 A Real Option Approach to Access Network Migration

Another approach for flexible network migration was undertaken by [TVC$^+$12] using a real options approach. Real Options Analysis (ROA), as defined by [Mun06] is a strategic analysis of long-term projects which takes into account underlying uncertainties and allows for flexibility in managerial choices and decisions. Given the probability distribution for these uncertainties, ROA finds the valuation at the end of the time period and provides the analysts with a migration path having the lowest TCO [Mun06].

In the studied business case of an FTTx migration from a full copper deployment, this translates to options like the size of cabinets to deploy, the services to be provided to customers, etc. It is important that there exists a time window inside which all migrations should start and finish, so that the upgrades can be performed in more than two stages (hence, making it a multi-stage planning project). Figure 2.8 explains this decision making process in the form of a decision tree.

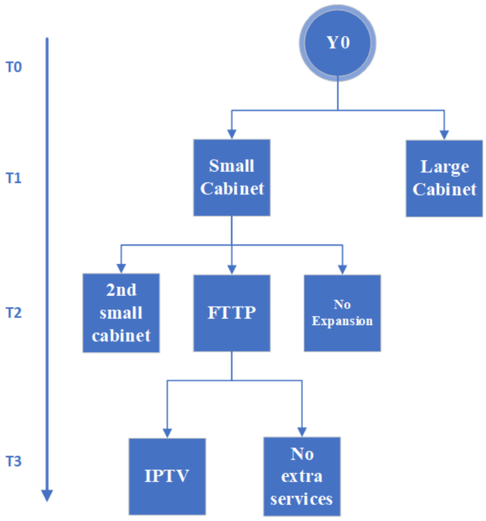


Figure 2.8: Decision tree in a real options approach for VDSL/FTTP Deployment [TVC+12]

In this decision tree, there are two kinds of options available to the network operator after year $T0$. The first option is to deploy a VDSL network with small cabinets and provision services according to customer uptake. The second option is to deploy a VDSL network with large cabinets which will have capabilities for future connections as and when the customers join the network.

The advantages of this approach are:

- Uncertainty in terms of customer take up rate is taken into account.
- Use of decision tree which makes it easier to add different technologies and options.

The disadvantages of using this solution are discussed below:

- The authors of [TVC+12] focus on a very particular migration scenario and model the probability based on assumptions made about the per-cabinet take up rate and then adding it together to form a joint distribution. Hence the model only works for this particular scenario and is not general.
- As suggested in [Mun06], if the uncertainty is removed, the real options analysis reverts back to the values of static analysis. ROA also requires investment in terms of analysts experienced in real option theory, in-house experts and advanced tools for model building. Finally, the use of complex mathematics makes it difficult to interpret and present results to senior management.

2.4.4 Access Network Migration using Heuristic Optimization

Recent research has also explored heuristic options to find the best time to migrate in a planning horizon. Heuristic Optimization Algorithms as defined in [RU01], "seek good feasible solutions to optimization problems in circumstances where the complexity of the problem or limited time available for its solution do not allow exact solution". These algorithms are broadly classified into *design problems* and *planning problems*. Algorithms like *Local Search, Tabu Search, Simulated Annealing*, etc. are examples of heuristic optimization algorithms.

The use of heuristic optimization in access network migration planning is studied in the work done by [TLRL13] and [TNRL14]. In [TNRL14], the researchers implement four different algorithms, namely, *Tabu Search (Random)*, *Pre-Calc*, *Genetic Algorithm* and a *Deterministic* approach. The problem statement defined in this work is to optimize the migration process from VDSL to FTTC GPON in an urban access network, undertaken in a pre-defined migration period. The goal is to find the exact time period in which to migrate various clusters of a network in order to maximize profit and minimize the TCO.

This approach gives the best possible time for migration of each cluster in the network, thereby maximizing the profits. The results achieved show that migration window should be as early into the planning horizon as possible, since sooner the customers migrate to a newer technology, higher is the possibility of the network operator to earn more profit.

The advantages of this method are as follows:

- Well defined workflow for network migration which leads to easily interpreted results in the form of profits and TCO.
- Provides a flexible migration window with consideration of time taken to migrate from VDSL to FTTC GPON.

The disadvantages are as follows:

- Only one scenario of migration from VDSL to FTTC GPON is covered in this approach. There is no evidence as to these algorithms are sufficient to calculate multi-stage migration, for example, VDSL to FTTC GPON to FTTB XGPON.
- Since the clustering and migration are optimized independent of each other, there is a risk that the solutions may return a local minimum instead of the global minimum.

2.5 Methodology Overview

As described in Section 2.4.1, a techno-economic model of fine granularity is required for accurate calculation of CAPEX and OPEX. As discussed in Section 2.4.1, real-street maps are required to calculate the lengths of all ducts and fiber accurately, which constitute for a majority of the costs. For this, we use ArcMap 10.3.1® [Ins11] and using a network dimensioning toolbox, we find the duct and fiber lengths of feeder, distribution and last mile fibers, according to a configured splitting ratio. Then, we model the equations for CAPEX and OPEX based on the available information. After the CAPEX, OPEX and tariffs for each of the technologies are ready, we propose a migration approach which finds the migration path with the maximum accumulated NPV, from a permutation of different PON technologies, across different deployment areas and in a converged fashion.

This migration algorithm is introduced in Chapter 5, based on Expectimax Search with an underlying Markov Decision Process (MDP) [Kle10]. It provides a multi-period, multi-step migration with the option to choose from various PON deployments, each of which are discussed in Chapter 3. To complete a converged scenario we also combine three different types of subscribers, namely residential, business and Public ITS providers in our planning scenario, to create a Pure Residential and a Converged scenario. We then apply this modified Expectimax Search method across various types of areas (Urban, Dense Urban and Rural, as discussed in Section 2.2) to find the migration path with the highest NPV in each of the case, for every type of subscriber penetration (Conservative, Likely and Aggressive), which leads to fulfillment of the demands of the subscribers (at least 100 Mbps by the year 2025) [FTT16].

Chapter 3

Input Modelling and PON Architectures

In this chapter we discuss the business scenario based on a VIO and various deployment areas considered in this thesis. Since any network migration planning model is only as good as the business case it is made for, we define multiple scenarios and network deployments in order to cover all major cases.

3.1 Business Scenario

We further extend the business scenario of a VIO in Section 2.2, to include constraints in order to create more realistic results. The EU Broadband Regulation Policy on Digital Single Market directs network providers to upgrade all connected households to at least 100 Mbps data-rate of internet connection by 2025 [Eur14]. Using this constraint we create four different scenarios, mentioned as follows.

1. **Unforced FTTC/FTTB/FTTH** :- Migrations are not forced to achieve 100 Mbps by 2025 and all types of technologies like FTTC, FTTB and FTTH can provide the subscribers with 100 Mbps.
2. **Unforced only FTTH** - Migrations are not forced to achieve 100 Mbps by 2025, however, only FTTH technologies can provide 100 Mbps.
3. **Forced FTTC/FTTB/FTTH** - Migrations are forced to achieve 100 Mbps by 2025, with all different types of technology available to them.
4. **Forced only FTTH** - Migrations are forced to achieve 100 Mbps by 2025, with only FTTH technologies available to provide the end user with 100 Mbps.

3.2 Deployment Area

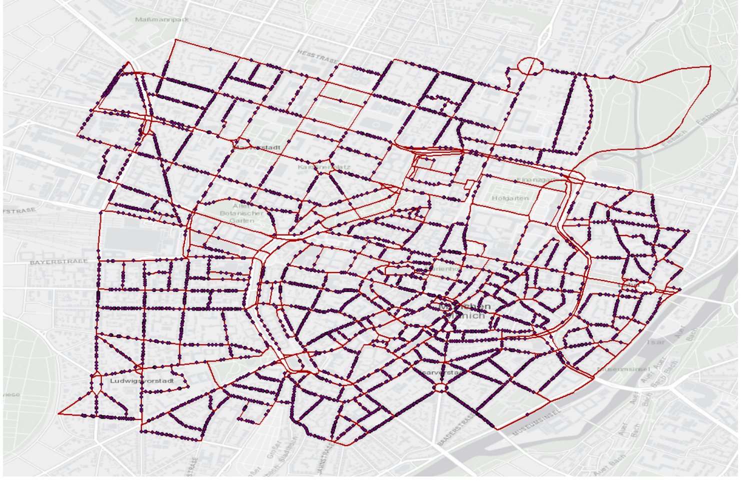


Figure 3.1: Munich 7 sq.km. streets with 4877 building points

Figure 3.2: New York 7 sq. km. streets with 7895 building points

As seen in Figure 3.1, 3.2 and 3.3, we represent buildings (demands) as points on the street because that gives us an accurate estimate of the fiber drop points for each building. We also consider that each of these buildings are Multiple Dwelling Units (MDUs), each of which houses on an average six potential residential or business subscribers [JLL16]. These approximately 30000 subscribers can be divided into residential and business subscribers using the percentage of business subscribers in a city (7% for Munich) mentioned in [Rok15, vdMGGK09].

Figure 3.3: Ottobrunn 7 sq. km. streets with 8813 building points

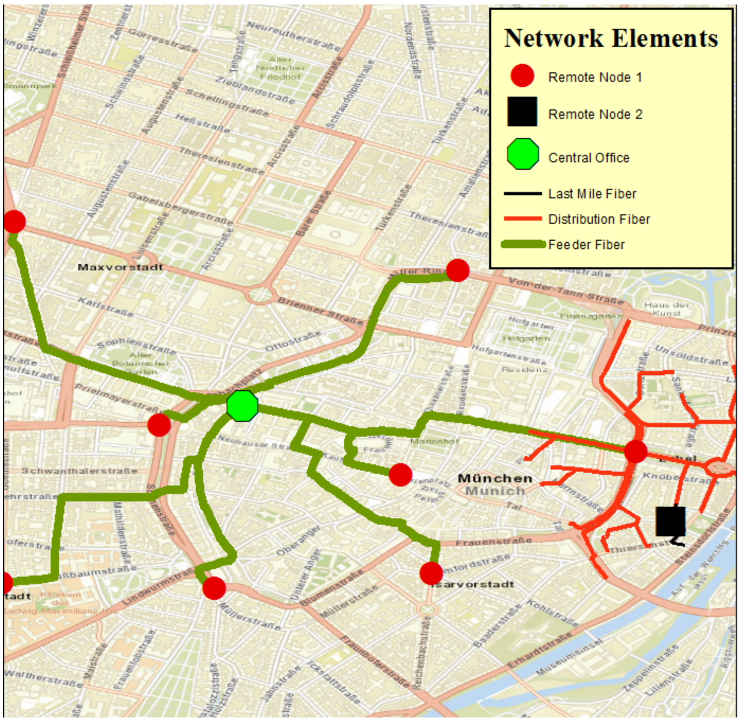


Figure 3.4: Shortest Path Routing output in ArcGIS ArcMap 10.3.1®

Once the shortest path routing algorithm mentioned in [SM17] is run, we get the lengths of fibers and ducts for each of the deployments in ArcGIS ArcMap 10.3.1 ®[Ins11]. This is illustrated in Figure 3.4.

For a dense urban deployment, we choose an area of Manhattan, New York, U.S.A., which is a densely populated area. We follow the same deployment technique as described for the urban deployment. For Manhattan, majority of the buildings are multiple dwelling units and each of these are, on an average, taller, hence have more dwellers per building. As we confirm from the data given in [Cit18], an assumption of eight residence or business subscribers per building in New York City holds true.

Finally, for a sub-urban employment, we choose Ottobrunn, Germany. Since we assume mostly Single Dwelling units (SDUs) in this area, we can assume that there is no need for FTTB technologies here, because if fiber reaches a building, it is already in FTTH configuration.

A summary of the salient features of these areas is given in Table 3.1. The classification of Urban, dense urban and sub-urban closely follows

Name	Deployment Area (in sq. km.)	Number of Intersections	Number of Demands	Number of Subscribers
Munich, Germany	7	583	4877	29262
Manhattan, New York City, USA	7	586	7895	63160
Ottobrunn, Germany	7	364	8813	8813

Table 3.1: Deployment Area Features

3.3 PON Architectures

As current technology stands, there are several permutations and combinations which can be used to generate Passive Optical Network (PON) deployments.

Broadly we classify three degrees of freedom, namely *deployment type*, *technology type* and *data-rate offered*. To elaborate, the classification is as follows:

- **Deployment Type** - A PON network differs in the way of deployment, based on how near the fiber is from the residential, business or ITS subscriber. The different possibilities, in the increasing order of optical fiber deployments are FTTC, FTTB and FTTH, already defined in Chapter 2.
- **Technology Type** - Different deployment technologies based on type of equipment, like GPON, XGPON, WDM-PON and HybridPON, can be deployed in an area. These have been defined in Section 2.2.
- **Data-Rate Offered** - Different deployment methods have the capabilities of offering different data-rates. This is possible by adding more active infrastructure at the central office and remote nodes, and also by blowing additional fiber through a duct,

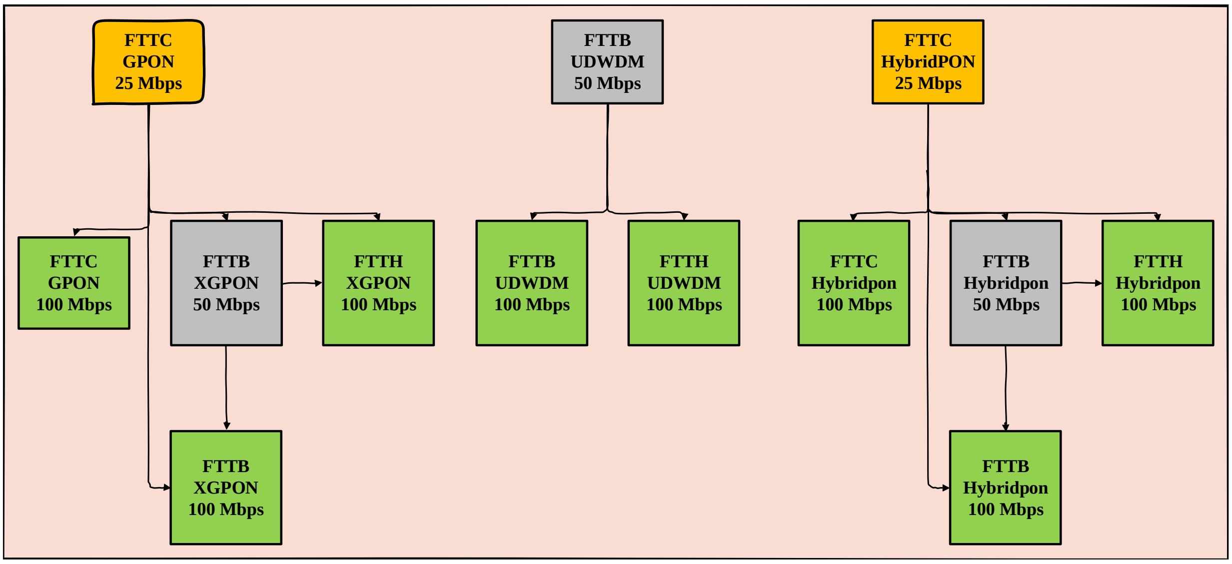


Figure 3.5: Possible migrations between various PON architectures

which is less expensive as compared to digging and closing the ducts again. The different data rate offered are 25 Mbps, 50 Mbps and 100 Mbps.

As seen in Figure 3.5, there are multiple paths of migrations a VIO can use to achieve 100 Mbps deployment for its subscribers. However, some transfers, like migrating from FTTC_GPON_25 to FTTH_UDWDM_100 are not allowed, because of the difference in technologies.

We define and analyze 13 different PON architectures, each one of which has been described in detail in the coming subsections. All the features of these architectures like data-rate provided, components required, etc. are given in detail in [Opt11]. This project serves as the major source of data throughout this thesis. The legend of the figures and different types of fibers is provided in Appendix A.1, for reference.

FTTC_GPON_25

The first PON architecture we look into uses the simplest technology with the maximum re-use of existing copper technology. This is a Fiber to the Cabinet Gigabit-Ethernet Passive Optical Network architecture which guarantees the end user an average of 25 Mbps asymmetrical data-rate (average downlink of 25 Mbps and average uplink of 12.5 Mbps). This deployment is a two stage deployment, which means that there is an additional distribution fiber in the network, along with two different types of remote nodes.

Each Optical Line Termination (OLT)) port at the Central Office (CO) provides 2.5 Gbps which can be shared among almost 80 subscribers. The first stage connection between the CO and the first Remote Node 1 (RN1) is point-to-point and is done using FF. At each

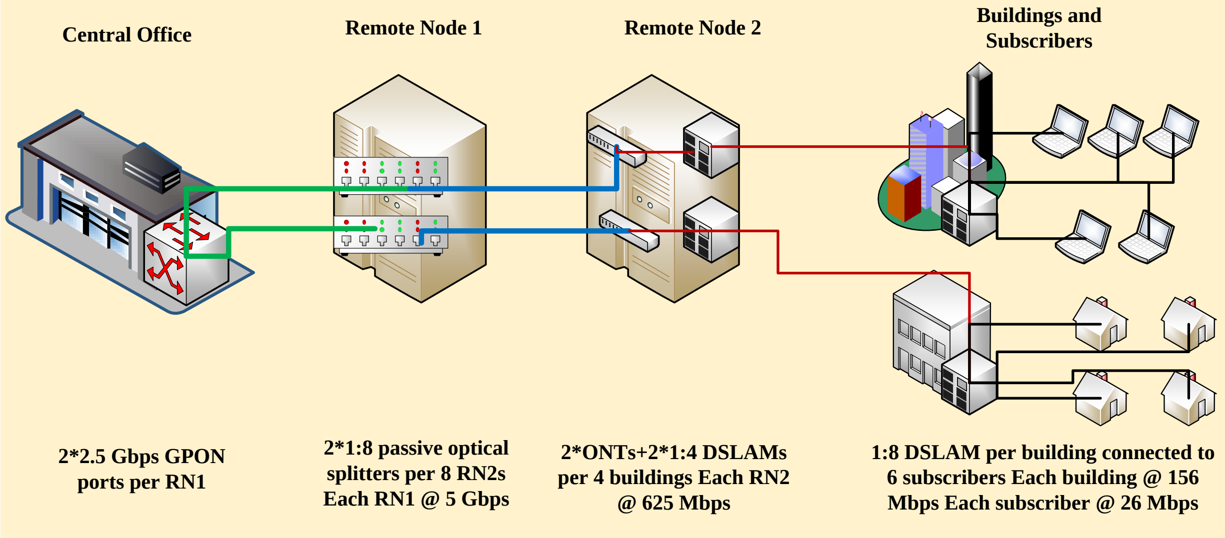


Figure 3.6: FTTC GPON 25 Mbps architecture

RN1, a passive 1:8 optical splitter is placed. This optical splitter, divides the data-rate equally for the second Remote Node 2 (RN2) connected to it via Distribution Fiber (DF). The Optical Networking Unit (ONU), is placed at each RN2 and serves as the termination point for the optical part of this deployment. Each RN2 is connected to 4 buildings using the existing copper and Digital Subscriber Line Access Multiplexer (DSLAM) switches. There is a point to point copper wire connection for every subscriber from the RN2. A visual representation of this architecture is shown in Figure 3.6 for better understanding.

FTTB_XGPON_50

Fiber to the Building 10-Gigabit-Ethernet Passive Optical Network providing 50 Mbps to thesubscriber can either be deployed directly over the existing copper deployment (Greenfield) or can be reachable from FTTC_GPON_25 (Figure 3.6). To migrate from FTTC_GPON_25, the VIO has to upgrade the ports at OLT from GPON ports to XGPON ports. The difference is that each GPON port can support 2.5 Gbps downlink traffic whereas each XGPON port allows upto 10 Gbps downlink traffic. This increase in data-rate makes it possible to provide the subscribers data-rates upto 50 Mbps. Here the ONUs are placed in each of the MDUs and receive 312 Mbps. This is further connected to a 1:6 mini-DSLAM switch which then provides each of the 6 households with approx. 50 Mbps data-rate.

Being a two-stage architecture, both the remote nodes contain passive components (optical splitters), which has a potential to reduce long term operational costs. Also, the energy costs of the ONU and DSLAM in each building can be assumed to be paid half by the VIO and half by the residents as a part of their “utility costs”. This can potentially be paid

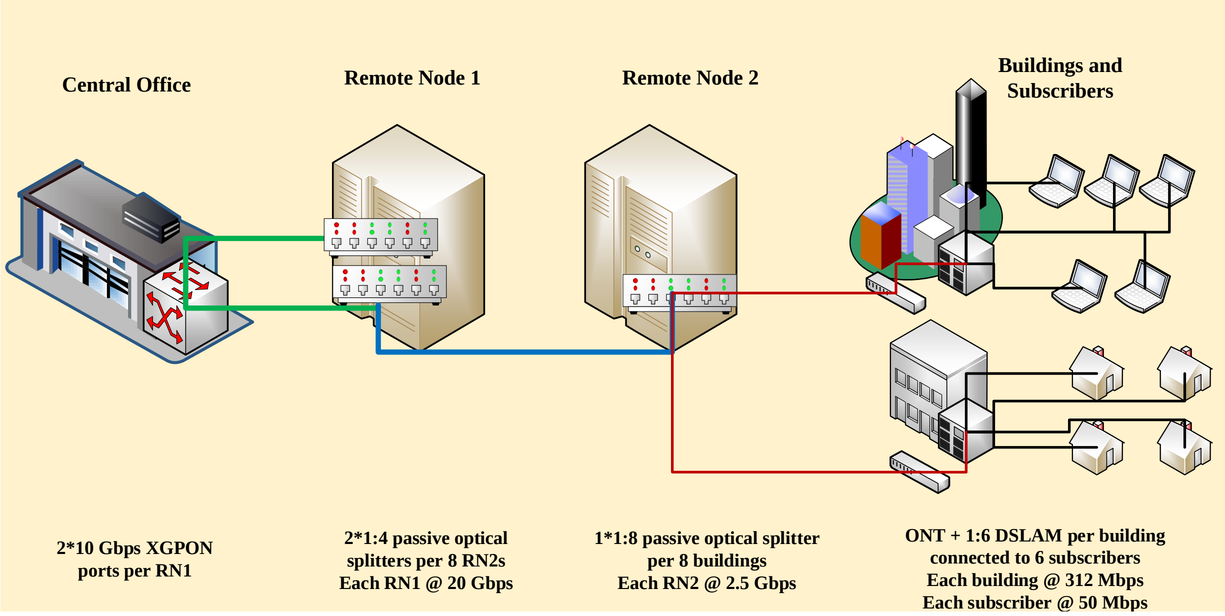


Figure 3.7: FTTB XGPON 50 Mbps architecture

fully by the users in order to reduce OPEX costs further. This architecture can also be an intermediate architecture for migrations to an FTTH XGPON architecture.

FTTH_XGPON_100

One of the final technologies in the migration is Fiber to the Home 10-Gigabit-Ethernet Passive Optical Network which provides subscribers with 100 Mbps of data-rate. As seen later, this technology has extremely high capital expenditure, since the VIO has to purchase ONUs for each of the subscribers, do in-house cabling. provision the services and also increase the capacity at the OLT side. However, in the long run, the operational costs in this technology are significantly lower since the only active components that the VIO has to pay energy costs for, are the OLT ports and supporting hardware in the Central Office. Both the remote nodes contain passive equipment and do not add to any operational costs in terms of energy or rent.

FTTB_UDWDM_50

Moving away from the previously discussed two-stage architectures, we look into single stage architectures in the form of Fiber to the Building Ultra Dense Wave Division Multiplexing Passive Optical Network which provides the end users 50 Mbps of symmetrical data-rate. The primary reason for choosing this technology is its long reach capability, due to the use of filters, rather than power splitters [Opt11]. Another important advan-

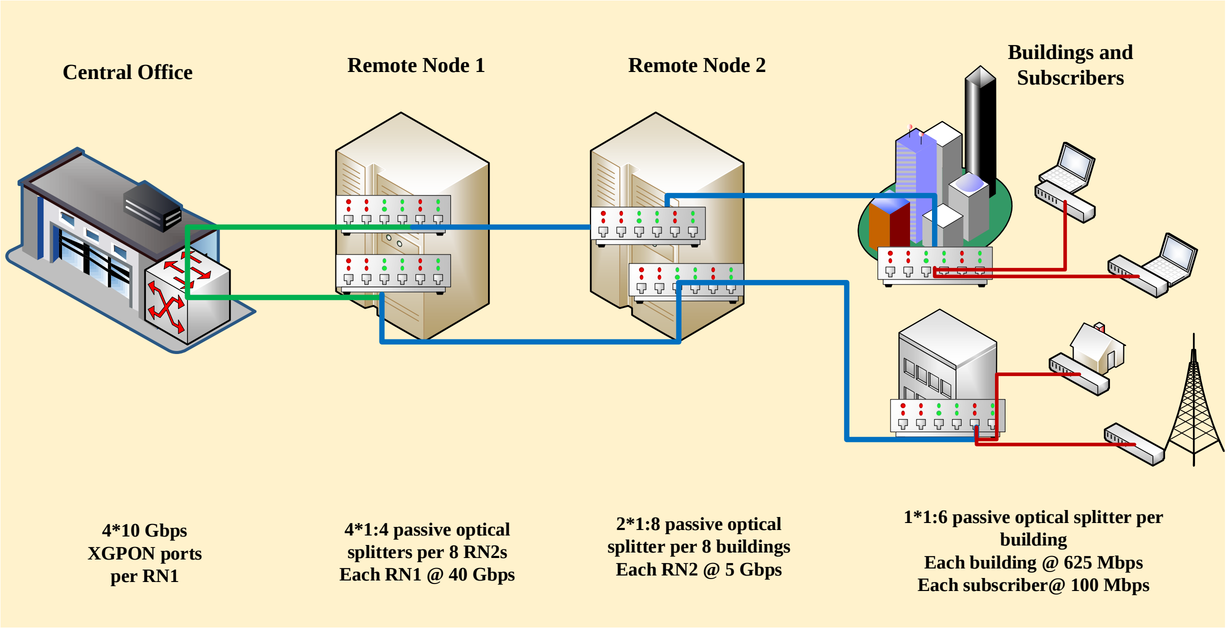


Figure 3.8: FTTH XGPON 100 Mbps architecture

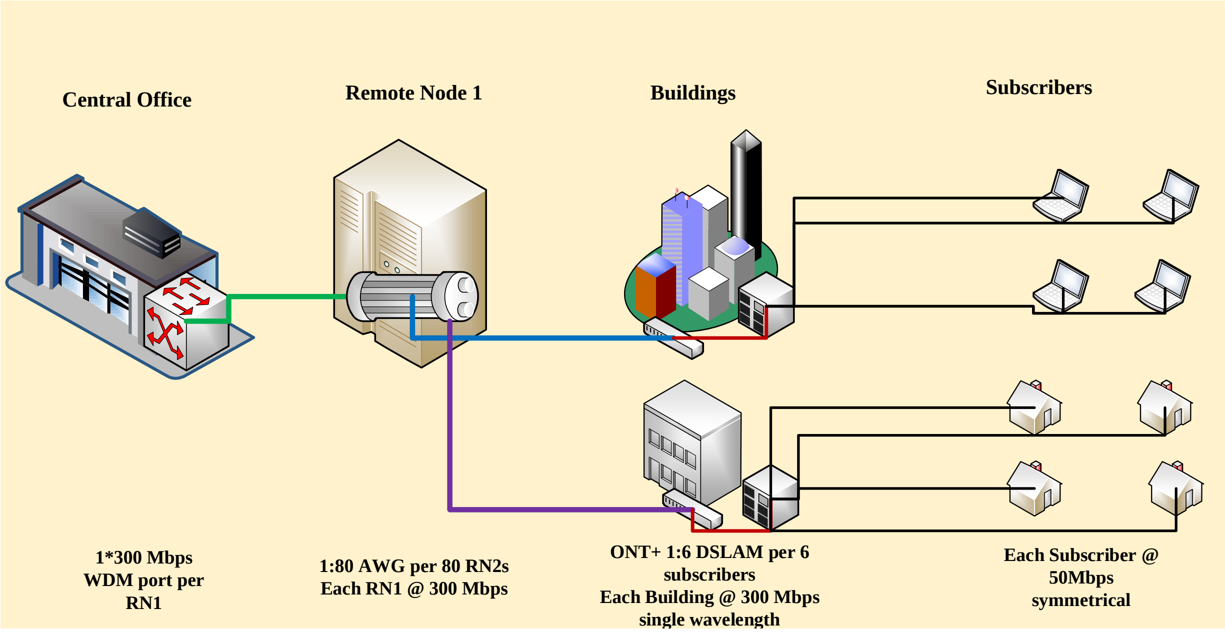


Figure 3.9: FTTB UDWDM 50 Mbps architecture

tage this technology holds that every remote node can support a higher number of ONUs (up to 96 ONUs at times) as compared to the GPON and XGPON technology. However, the equipment related to this technology is still not widely available. Assuming that the 80-port Arrayed Waveguide Grating (AWG) and tunable lasers are available by the time migration starts, UDWDM-PON could support up to 80 users with the same symmetrical data-rate.

It is important to note that this technology should be deployed in only a greenfield scenario since in single stage architecture, only one remote node between the OLT and ONUs exist. This results in reduction of civil works costs making it an interesting candidate for migration. As in the FTTB_XGPON_50, we assume that the energy costs for the ONU and DSLAM at the buildings are paid on a share basis between the VIO and subscribers.

FTTH_UDWDM_100

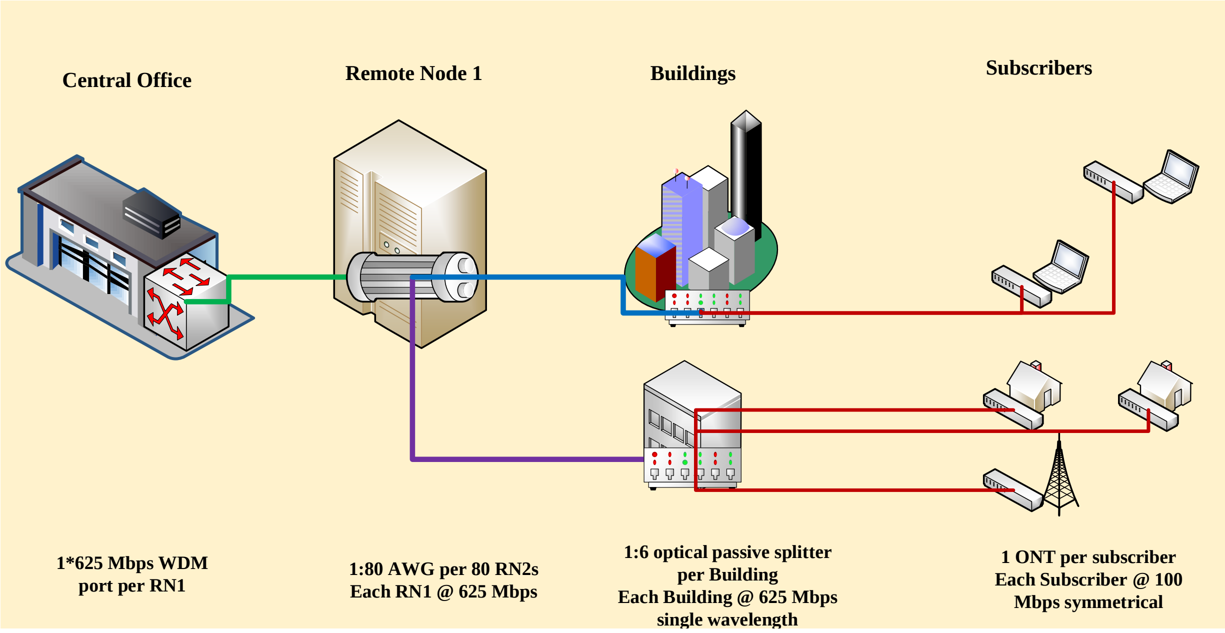


Figure 3.10: FTTH UDWDM 100 Mbps architecture

For another final technology, we chose the natural successor to the previous FTTB single stage solution. Which leads us to Fiber to the Home Coherent Ultra Dense Wave Division Multiplexing Passive Optical Network. This technology can be either deployed directly as greenfield or can be migrated to from FTTB_UDWDM_50. The main reason for shifting of technology from UDWDMPON to Co-UDWDMPON is because the number of ONUs in the network increase six-fold and it becomes difficult to assign those many separate wavelengths to each of the ONUs. Hence, as discussed in [Opt11], a pre-filtering at WDM OLT ports and a power split at the buildings is required, to ensure higher data-rates on each of the wavelengths.

FTTC_GPON_100

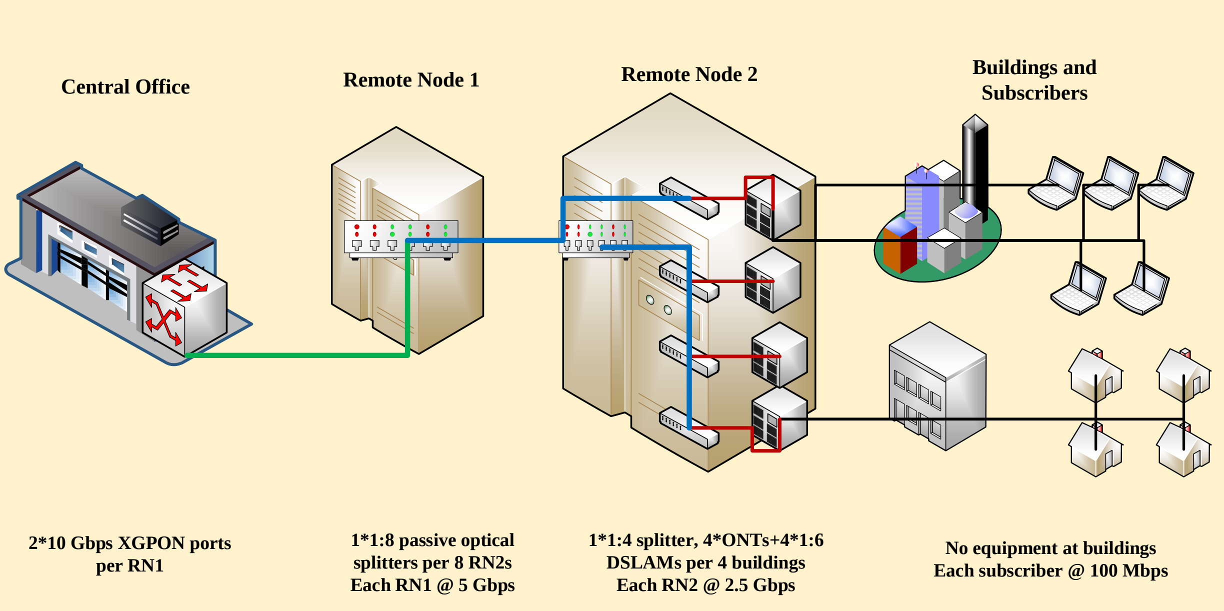


Figure 3.11: FTTC GPON 100 Mbps architecture

Since we assume that there is enough dark fiber present due to about 10% over-provisioning [Mü17], we can upgrade any given technology to 100 Mbps by introducing more hardware without adding civil works cost. Here, to provide the end-users with 100 Mbps, extra hardware needs to be added, especially in the RN2 cabinets as seen in Figure 3.11. This is due to the fact that to provide each subscriber with 100 Mbps of data-rate, the number of parallel fibers and ports at OLT and the remote nodes must be increased. This technology can be deployed either greenfield or can be migrated to from FTTC_GPON_25. Upgrading to XGPON at the OLT side is needed in order to reduce the number of active equipment in remote nodes.

FTTB_XGPON_100

Another non-FTTH architecture which could be upgraded to provide 100 Mbps to end users is the FTTH_XGPON_100. This is an important architecture because compared to FTTC_XGPON_100, the operational costs are considerably lower, since it does not require large equipment upgrade. Since the deployment as well as operational costs are low, one can consider this to be a strong candidate technology for migrations. This technology can either be deployed as greenfield, or can be migrated to from FTTB_XGPON_50, FTTC_GPON_25 or FTTC_XGPON_100, as seen in Figure 3.5. However, migration from FTTC_XGPON_100 is not preferable because FTTC_XGPON_100 has a larger equipment CAPEX and migrating to this architeture would mean that civil works cost increases, while

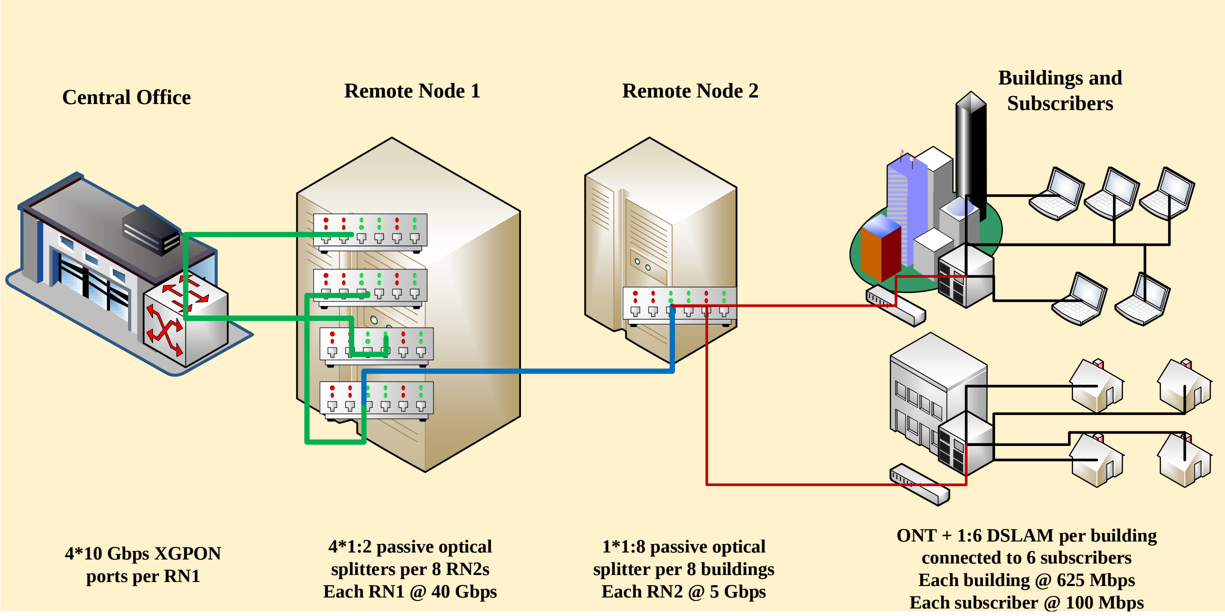


Figure 3.12: FTTB XGPON 100 Mbps architecture

the benefits stay the same. However, as seen later on in the results, the algorithm does not consider FTTC_XGPON_100 as a good option for migrations.

FTTB_UDWDM_100

As discussed earlier, UDWDM technology provides longer reach couples with a possibility to connect more number of ONUs with each OLT port but the technology is expensive to deploy. however, upgrading from 50 Mbps to 100 Mbps, could provide the opportunity for VIOs to recover the costs of deployment. The solution of FTTB_UDWDM_100 is probably one of the most easiest to deploy, since it has no civil costs when being deployed in a brown-field scenario and the equipment costs only involve upgrade of hardware at OLT side. This leads to increase in the overall Net Present Value, making this a prime candidate for deployments. The operational costs are slightly more than FTTB_UDWDM_50, since only the energy costs of OLT increases, but the benefits exceed the risks because every subscriber can be charged extra monthly for provision of better data-rates.

FTTC_Hybridpon_25

As established earlier, GPON and XGPON technologies have cheap components, but can only achieve low splitting ratios of upto 1:16. WDM-PON technologies can support more subscribers per remote node, however, the technology is very expensive to deploy. Fiber to the Cabinet Hybrid Passive Optical Network offering the end users about 25 to 30 Mbps

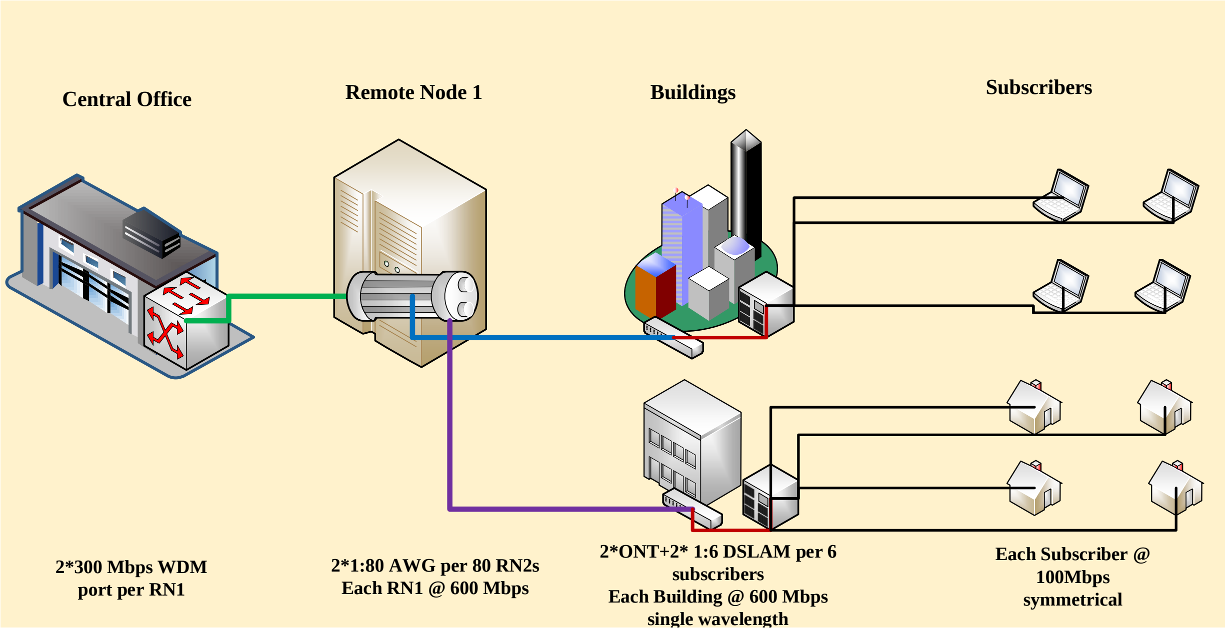


Figure 3.13: FTTB UDWDM 100 Mbps architecture

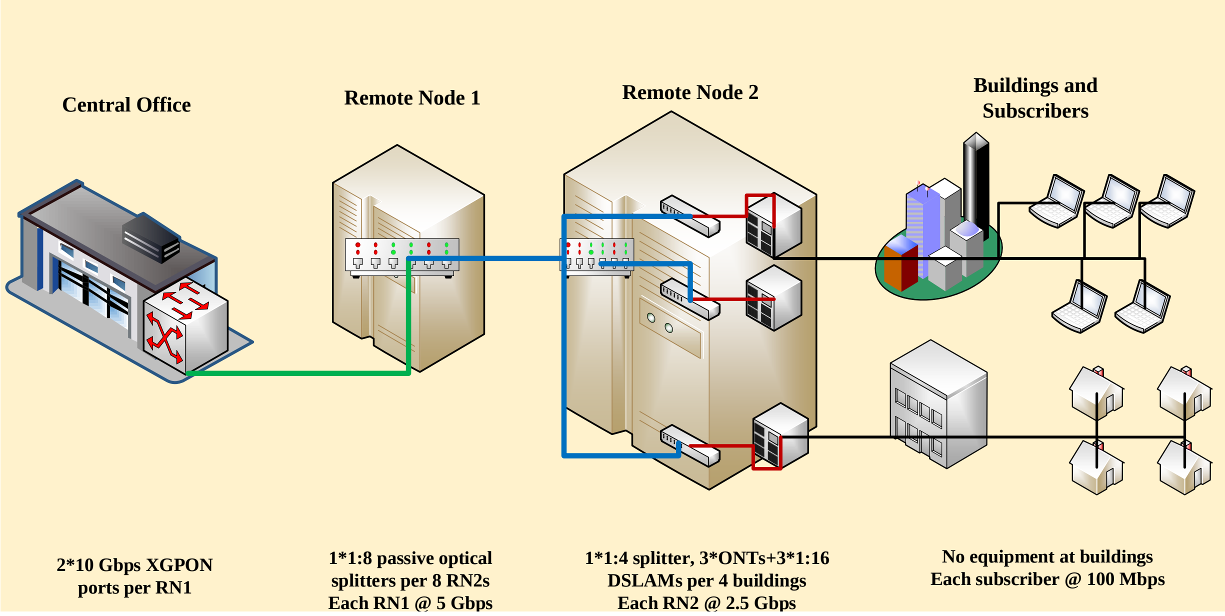


Figure 3.14: FTTC Hybridpon 30 Mbps architecture

of symmetric data-rate, combines features from GPON as well as WDM-PON. This is a two-stage architecture and the first stage consists of GPON OLT cards connected to a 1:80 AWG. This architecture can be seen as several GPONs embedded into a WDM-PON system [Opt11].

The RN2s contain the GPON part of the system with a 1:4 power splitter, 3 ONUs and 3 1:16 DSLAM switches for a total of 48 subscribers in a cluster of 8 buildings. Finally, each subscriber ends up with 35 Mbps of symmetrical data-rate. With less equipment at the cabinet, this technology can be an alternative to the traditional GPON or WDM-PON approaches. This technology can only be deployed in a greenfield scenario.

FTTB_Hybridpon_50

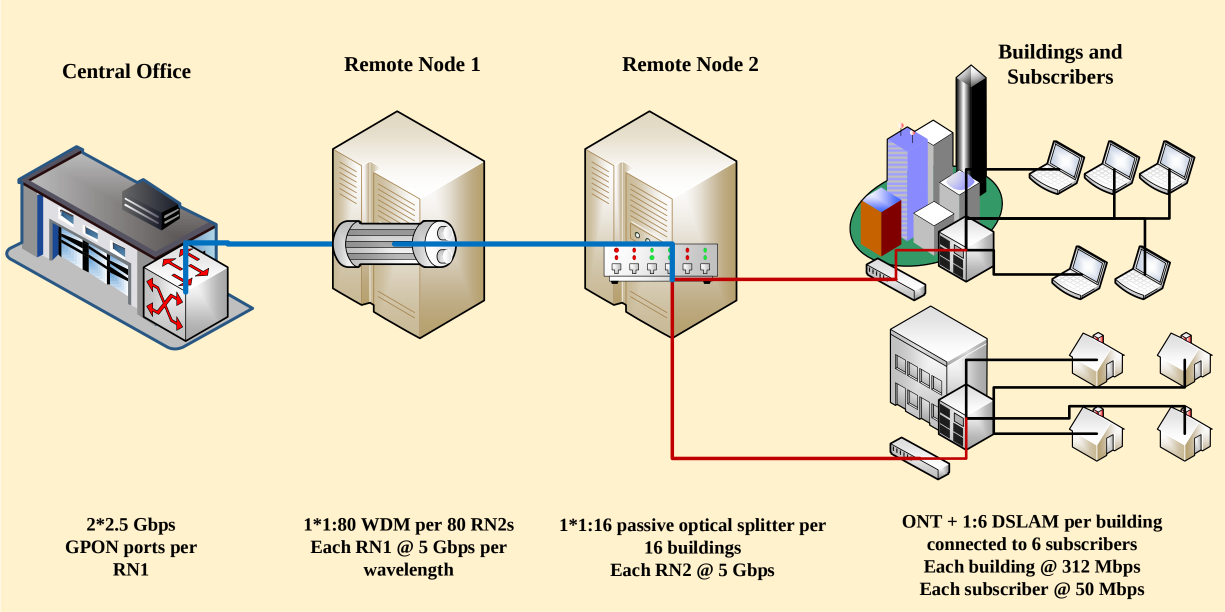


Figure 3.15: FTTB Hybridpon 50 Mbps architecture

Compared to the FTTC implementation of HybridPON, FTTB is less complicated since the data-rates offered to the end user (i.e. 50 Mbps) can easily be provisioned using a GPON card, 1:80 AWG and a single 1:16 power splitter. However in this scenario, the number of ONUs increase more than double, since every building is provided with an ONU. The increase in ONUs and DSLAMs also increases the operational costs, however, since the active equipment are placed in a building, rent and energy costs can be shared. This technology can be deployed either greenfield or can be reached from FTTC_Hybridpon_30.

FTTH_Hybridpon_100

As one of the final solutions in the Hybrid PON technologies, Fiber to the Home Hybrid Passive Optical Network offers end users data-rates upto 100 Mbps while maintaining the hybrid nature of combining both WDM and GPON deployment. The architecture of the remote nodes stays the same as the FTTB_Hybridpon_50 solution, however, there are changes at the buildings. The active equipment of ONU and DSLAM switch are replaced with a passive optical splitter and the ONUs are pushed to the end users. The difference from previous HybridPON solutions is that instead of using one GPON port per remote node, one XGPON port per remote node needs to be used.

As seen from earlier FTTH solutions, although it is expensive to deploy, this offers benefits in the long run in terms of lower operational costs. It is possible to deploy this architecture greenfield as well as migrate to this from FTTC_Hybridpon_30 or FTTB_Hybridpon_50. This architecture is considered as future proof because it is possible to provide end users upto 500 Mbps of speeds by just upgrading the number of OLT ports per AWG in RN1s [Opt11].

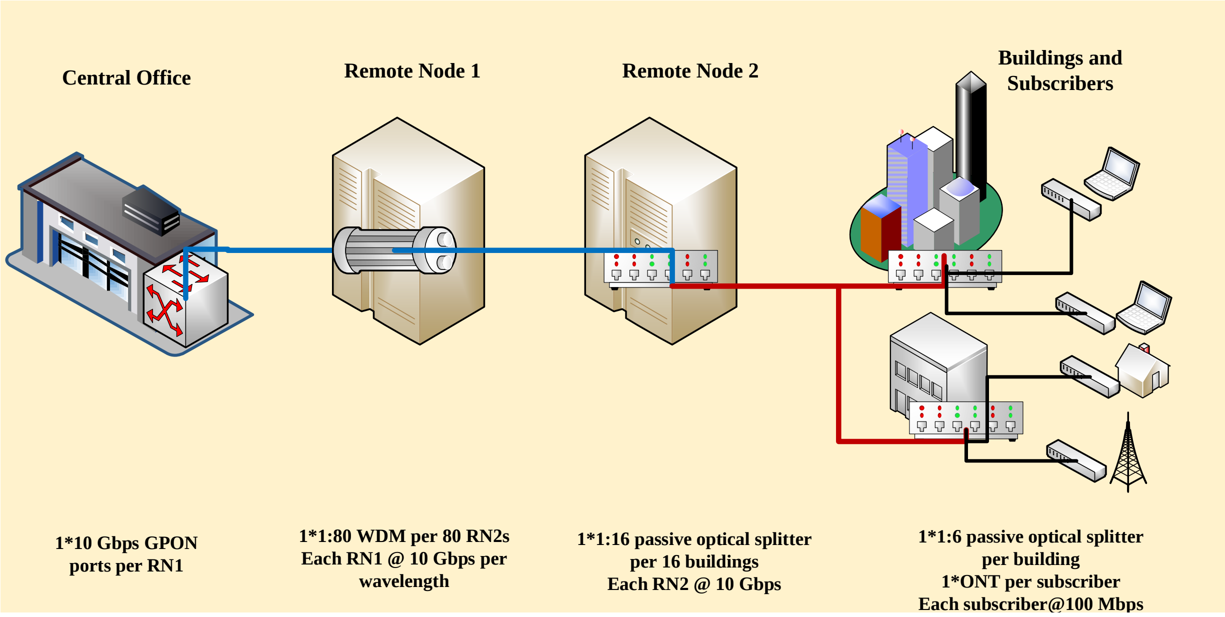


Figure 3.16: FTTH Hybridpon 100 Mbps architecture

FTTC_Hybridpon_100

Instead of migrating to FTTH_Hybridpon_100 by investing in additional civil works and purchasing new equipment, it is possible to provide the end users with 100 Mbps using FTTC in a Hybrid PON configuration. We need to double the equipment at almost every

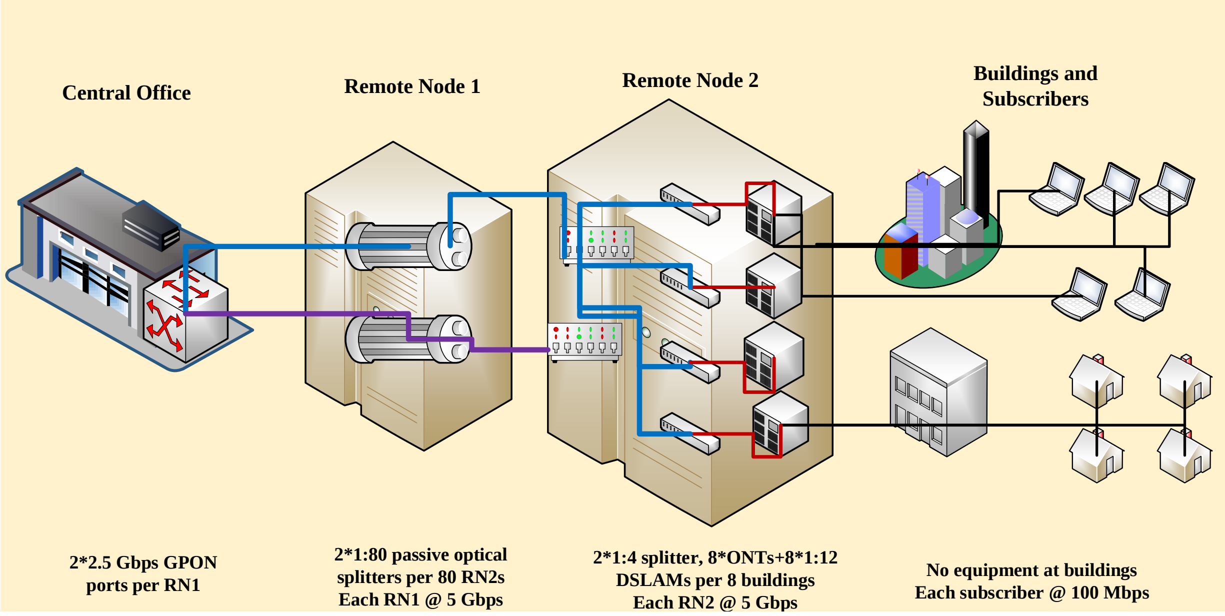


Figure 3.17: FTTC Hybridpon 100 Mbps architecture

location. Instead of one 2.5 Gbps port, we would need two operating in parallel. At every RN1, there would be two AWGs. At RN2s, we would need 2 1:4 splitters, 8 ONUS, connected to every output of the splitter and 1:6 DSLAM for each building. The advantage of this technology over any FTTH deployment is minimal civil works investment for the same user tariffs and data-rate. However, the bottleneck is with RN2, which are big and contain more equipment, which add up significantly to energy and rent costs.

FTTB_Hybridpon_100

Finally, a Fiber to the Building Hybrid PON connection makes sure that end users are provided 100 Mbps. The only difference from FTTB_Hybridpon_50 is the upgrade of OLT from 2.5 Gbps GPON ports to 10 Gbps XGPON ports. This technology can be migrated from FTTB_Hybridpon_50 or from FTTC_Hybridpon_30.

Once all these technologies have been decided, network dimensioning (as shown in Section 2.2.2) is undertaken for each of the technologies, which result in various lengths of the ducts and fibers. Using the costs given, cost modelling for each of these technologies is done.

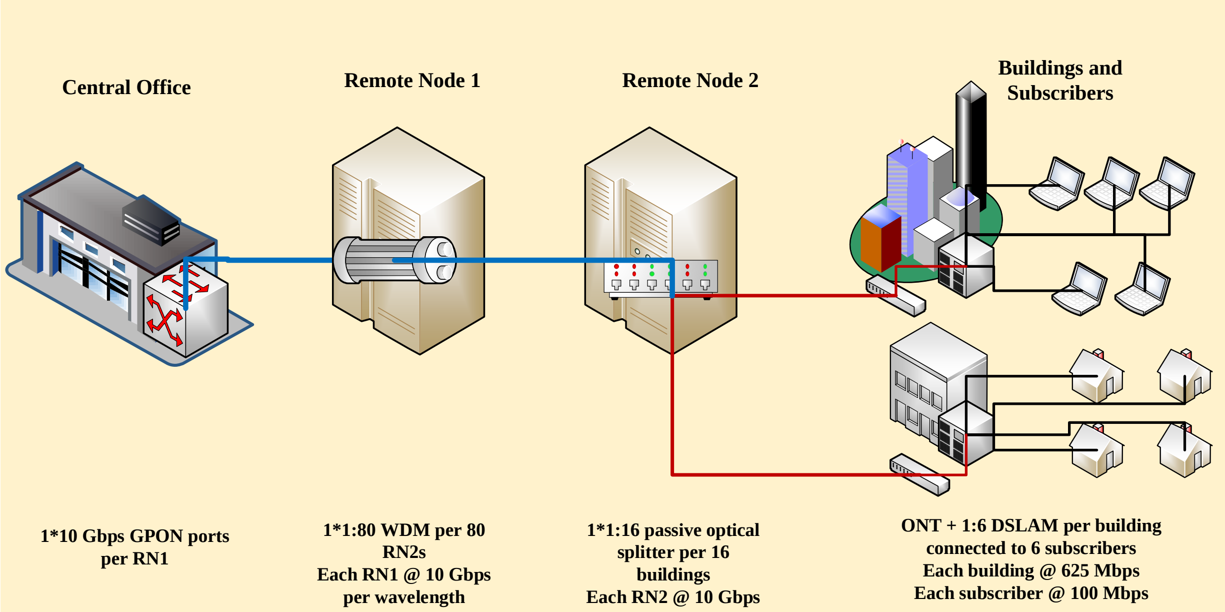


Figure 3.18: FTTB Hybridpon 100 Mbps architecture

3.4 Fiber and Duct Lengths

As discussed in Section 3.2, we first need to choose the area where the prospective access networks need to be deployed. We use the above mentioned network dimensioning tool to find the lengths of ducts and fibers for the feeder fibers, distribution fibers and last mile fibers. This output of the tool, shown in Figure 3.4, converts the streets and intersections into a network of nodes and edges where the nodes correspond to junctions and the edges correspond to the streets between the junctions. With the length of each of these streets already known and the network elements like COs and RNs placed on the intersections, a shortest path routing function using ArcMap 10.3.1® [Ins11] generates the required results. Following inputs are needed for running the tool.

Required Input	**Input Description**	**Options**
Network Dataset	ArcGIS Network Dataset file	-
FTTx	Type of network to be deployed	FTTC, FTTB
Demands	Building locations in the network	-
Intersections	Intersections to place prospective RNs	-
Streets	Streets between intersections with lengths in m	-
CO	Central Office location in the network	-
FTTB Splitting Ratio	Single stage splitting ratio	8,16,32,40,80
FTTC Initial SR Buildings	Second stage SR for connecting RNs with buildings in FTTC	4,8,16,32
FTTC SR Migration Buildings	Second stage SR for connecting RNs with buildings in FTTB	8,16,32,64
FTTC SR RNs	First stage SR to connect RN1 to RN2 in 2 stage FTTC/FTTB	8,16,32,40,80
Last Mile	Last Mile connectivity type	DSL, Fiber
DSL Reach	Maximum distance between RN2 and Nodes in m	1000,1500,2000,4000

Table 3.2: Input Parameters for Shortest Path Routing Tool

Using clustering and shortest path routing, the tool generates all the required lengths needed to calculate the costs for digging ducts and laying of fibers or coppers. It needs to be clarified that for the same Fiber to the Premise (FTTP) in an area footprint, if the splitting ratios are the same, the tool generates similar fiber lengths. An example of the output generated for a Fiber to the Cabinet GPON architecture (two stage with first splitting ratio as 8 and second splitting ratio as 4) is shown in the table below:

Output Type	**Total Length (meters)**
Feeder Fiber Duct	31505.12
Distribution Fiber Duct	54442.32
Last mile Copper Duct	68598.26
Feeder Fiber	171056.49
Distribution Fiber	85582.63
Last Mile Copper	685372.28

Table 3.3: Lengths for Munich 7 sq.km. FTTC_GPON_25 deployment

Chapter 4

Cost and Demand Modelling

The techno-economic framework results in CAPEX, OPEX and revenues. Along with these, inputs like subscriber churn and probability of churn are also needed to model demands. Each of these methods are discussed in detail in the following sections.

4.1 Cost Modelling

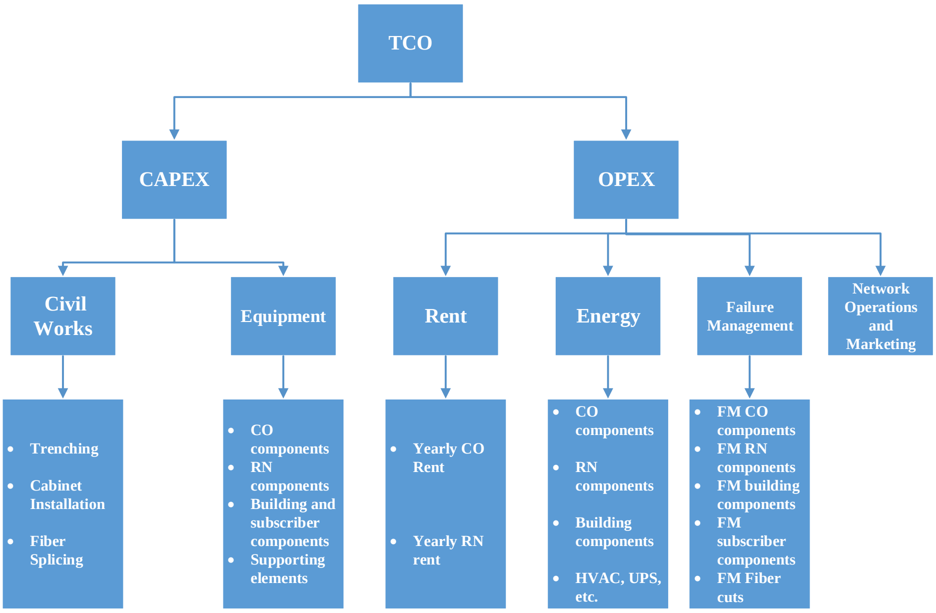


Figure 4.1: Components of cost modelling
[CWMJ10, Cas09, vdMGGK09]

Although the modelling is similar to that mentioned in 2.4.1, it involves greater detail in terms of cost components. It is important to mention here that many projects involving a techno-economic study, including this thesis, mention costs in terms of *Cost Units (C.U.)* which is the **cost of one GPON ONU**. It can be assumed to be approximately around **50 euros**.

4.1.1 CAPEX

Following closely the equations in [vdMGGK09, MM17, Cas09], the equation for CAPEX The equation for CAPEX can be split into two parts, namely civil works and equipment. The CAPEX for civil work is given as

$$CAPEX_{CW} = \sum_{d \in \ Ducts, f \in \ Fibers} (L_d \cdot C_d + L_f \cdot C_f) \ , \tag{4.1}$$

where $Ducts \in \{FeederDuct, DistDuct, LastMileDuct\}$ is a set of the different types of ducts, $Fibers \in \{FF, DF, LMF\}$ is a set of different type of fibers, L is length in meters, C is cost in cost units per meter of ducts and fibers. The CAPEX for equipment can be given as

$$CAPEX_E = \sum_{i \in \ N_{COComp}} C_{comp_i} . q_{comp_i} + N_{RN} \sum_{j \in \ N_{RNComp}} C_{comp_j} . q_{comp_j} + N_{Build} \sum_{k \in \ N_{BuildComp}} C_{comp_k} . q_{comp_k} \ , \tag{4.2}$$

where N_{COComp} is the number of different types of components in a CO, q is the quantity of each component, N_{RN} is the number of remote nodes in the network, N_{RNComp} is the number of components in each remote nodes in the network, N_{Build} is the number of buildings in the network, $N_{RNBuild}$ is the number of components in each building and premise in the network.

Finally, the complete CAPEX of a technology a can be provided as

$$CAPEX_{Total,a} = CAPEX_{CW,a} + CAPEX_{E,a} \ \ , \tag{4.3}$$

where $CAPEX_{CW,a}$ and $CAPEX_{E,a}$ are the civil and electronic costs of candidate technology a, given by Equations 4.1 and 4.2 respectively. use the per-meter costs of digging ducts and laying fibers provided in OASE project[Opt11]. For the electronic components, most of the costs have been provided in the OASE project, however, we still need to make assumptions for the unavailable components. The table below discusses thennt and the number of components known from the requirements of each subscribers, the CAPEX is then generated for each of the 13 different PON architectures. The table below gives an example of the CAPEX calculation for the technology FTTC_GPON_25 to provide at least 25 Mbps to about 30000 subscribers. Here as we can see, the costs of RN2 are extremely high, since every cabinet requires an additional 100 C.U. to buy additional equipment like cabinet infrastructure and HVAC. Although the component costs do not change in this thesis, we increase the number of components, when business users and ITS users are present. This is because business users cannot share the same network electronics with residential users.

Position of Component	**Component Name**	**Cost per Unit (C.U.)**	**Quantity**	**Component Cost(C.U.)**
Central Office	GPON OLT Card(8*2.5Gbps)	40	40	1600
Central Office	Pluggable B+	4	312	1248
Central Office	Switching Cost	0.011	800	8.888
Central Office	Additional	200	1	200
RN1	Power Splitter 1:8	1.8	312	561.6
RN1	Pluggable B+	4	312	1248
RN2	GPON ONT	1	2488	2488
RN2	1:32 DSLAM+Cabinet	124	1244	154256

Table 4.1: Component Cost for FTTC_GPON_30 deployed in Munich 7 sq.km.

4.1.2 OPEX

The OPEX costs can be split into energy, failure management and rent costs. The equations defined here closely follow the definitions given in [CWMJ10, MM17].

The energy OPEX costs per subscriber passed are defined as:

$$OPEX_{Energy} = C_{Energy} \sum_{comp \in \, Components} E_{comp} \cdot 1000 \cdot 24 \cdot 365 \cdot q_{comp} \ , \tag{4.4}$$

where C_{Energy} is the yearly energy cost in $\frac{C.U.}{kWh}$, E_{comp} is the energy consumed by a single network element or component in $Watts$, q_{comp} is the quantity of each component present in that network.

The rent costs per subscriber passed can be modelled as follows:

$$OPEX_{Rent} = C_{Rent} \sum_{comp \in \, Components} A_{comp} \cdot q_{comp} \ , \tag{4.5}$$

where C_{Rent} is the yearly rental costs in $\frac{C.U.}{m^2}$, A_{comp} is the footprint of a single component in m^2 and q_{comp} is the quantity of each component in the network.

The failure management cost per subscriber passed are derived as follows:

$$OPEX_{FM} = \frac{C_{tech} . 24 . 365}{10^9} \sum_{comp \in \, Components} (N_{tech_{comp}} \cdot FIT_{comp} \cdot (MTTR_{comp} + 2 \cdot \tau_{comp})) \ , \tag{4.6}$$

where C_{tech} is the hourly cost of a technician in cost units, $N_{tech_{comp}}$ is the number of technicians required to repair a single component, FIT_{comp} is the failure in time of the component, $MTTR_{comp}$ is the mean time to repair a component in hours and τ_{comp} is the travel time in hours from the central office (where technicians are located) to the components.

Finally, the final yearly OPEX can be given as:

$$OPEX_i = 1.12 \cdot (\frac{OPEX_{Energy} + OPEX_{Rent} + OPEX_{FM}}{Sub_{total}}) \cdot (1 + r^i_{inf}) \cdot Sub_{NW} \ , \tag{4.7}$$

where r_{inf} is the inflation rate, i is the year index since the start of the migration window and the factor 1.12 occurs due to the fact that we also have to consider static costs of 7% and 5% for networking and marketing OPEX. Sub_{total} are the total number of subscribers present in the area footprint and Sub_{NW} are the total subscribers who are already connected to the network.

The OPEX equation given in 4.7 demands the OPEX values for failure maintenance, rent and energy costs. We take these values mostly from the work done by Chen et. al. in [CWMJ10]. However, as with CAPEX, there are still a few assumptions which need to be made. The rent costs for each city is taken from the values provided in online resources like [JLL16], [Cit18] and [JS18]. Similarly the energy costs are taken from utility companies in all the cities used in this thesis [Mü18, CMP18].

These values increase according to a fixed cost inflation of about 2% every year, which is the average yearly inflation in developed economies, as mentioned in [Cit18, JS18]. An example calculation is shown in the Table 4.2.

Position of component	**Component Name**	**Quantity**	**Rent cost (CU)**	**Energy Cost (CU)**	**FM Cost (CU)**
Central Office	GPON OLT Card(8*2.5Gbps)	40	2120.00	3.20	0.89
Central Office	Pluggable B+	312	0.00	9.84	0.00
Central Office	Switching Cost	800	0.00	2.10	0.00
RN1	Power Splitter 1:8	312	212.00	0.00	10.16
RN2	GPON ONT	2488	0.00	261.54	178.54
RN2	Cabinet+1:32 DSLAM	1244	6593.20	1634.36	680.69
Fiber	FF	171.05 km	0.00	0.00	78.22
Fiber	DF	85.58 km	0.00	0.00	39.30
Fiber	LMF	685.37 km	0.00	0.00	317.31

Table 4.2: Example of OPEX calculation for FTTC_GPON_30

4.1.3 Revenue

We calculate the values of revenue generated per customer per year from the actual tariffs listed in the case studies of [FTT15]. For business and ITS subscribers, the yearly generated revenues are higher since business users need separate hardware at remote nodes and central offices for better security and faster fault reparation. [FTT15].

In real life scenario, after migration window starts, the technology is not accepted by all subscribers in the same year. For this reason, we need to define a penetration curve [VVT^{+}14]. This penetration curve has been already introduced in Section 2.2 and is taken from [Opt11].

Data-rate (Mbps)	Residential (C.U./year)	Business (C.U./year)	ITS (C.U./year)
20 Mbps	3.6	3.6	-
30 Mbps	7.2	36	-
50 Mbps	10.8	84	84
100 Mbps	13.2	110	110

Table 4.3: Revenue charged per year for different subscriber types [FTT16]

To model realistic revenues, we take the values from the tariffs listed in the case studies of [FTT15], as shown in Table 4.3. We assume a single ITS MBS to generate the same revenue as one business subscriber, however, as mentioned in [GMK16], the VIO charges a one-time installation fee of 125 C.U. per MBS, to provide back-haul access to the Public ITS provider.

4.2 Demand Modelling

The rate of subscribers joining the network is given by the subscriber penetration curves as shown in Figure 2.4. When business users are present, for urban scenario, we consider that 7% of the total buildings present in the network are business buildings[TVC+12]. Similarly, for dense urban scenario (New York) the percentage of businesses are increased 10% and in the suburban scenario (Ottobrunn), they are reduced to 5%. The number of ITS subscribers depends upon the area of the network, the backhaul demand planning and the reach of the ITS LTE base station, as given in [BER17]. The table below gives the total number of subscribers of each type in an area.

Area	Area Type	Residential Subscribers	Business Subscribers	ITS Subscribers
Munich, Germany	Urban	27213	2049	5
New York, USA	Dense Urban	62974	6316	8
Ottobrunn, Germany	Suburban	7932	881	3

Table 4.4: Different types of customer in different network deployments

Every year, apart from the number of subscribers who join the network, a certain number of the total connected subscribers also leave. This variation in the total number of connected subscribers every year helps us model customer behaviour and prepare for the worst case scenario. Since the total number of subscribers connected to the network, at the end of the network lifetime does not exceed 60-85%, it is not possible to make profit out of the entire potential subscriber base. Adding to that, there is a probability that a churn of 10% as mentioned in [OAS13], which means 10% of the connected subscribers leave the network. This leads to lower revenue for the same operational expenditures, since the services or the connection to the subscriber exists, but there is no monetary benefit out of it. Overall, the equation for revenue calculation in a single year t can be given as follows.

$$R_t(\gamma_t) = \sum_{s\in\ Sub} (1-c)^{\gamma_t} n_{s,t}.R_{s,p}\ , \tag{4.8}$$

where $Sub \in \{Residential, Business\}$ and takes values from Table 4.3, $n_{s,t}$ is the number of subscribers of type s who are connected to the network at year t, $R_{s,p}$ is the per subscriber yearly revenue of type s when a technology offering data-rate $p \in \{20, 30, 50, 100\}$ Mbps is deployed, $0 \leq c \leq 1$ is the yearly churn rate of the subscribers and γ_t is a binary variable which can be defined as follows.

$$\gamma_t = \begin{cases} 1 & \text{if churn occurs} \\ 0 & \text{otherwise} \end{cases} \tag{4.9}$$

Chapter 5

Migration Model

As discussed in Sections 2.4.2, 2.4.3 and 2.4.4, there exist various forms of decision processes for access network migration in literature. However, this work tries to overcome the disadvantages of these approaches using a modified *Expectimax Algorithm* [Kle10].

5.1 Migration Model based on Expectimax Search

There are many search methods which can be used for making migration decision. However, we take the Expectimax Search explained in detail in Section 2.3.3 and modify it to suit our needs. We use a variation of Expectimax Search, since this algorithm allows for modelling of uncertainty in the environment and choosing the maximum value when many options are available. In this section, we discuss the necessary equations while defining a migration matrix, the modified search algorithm, explained with an example and finally a pruning strategy to help make faster decisions.

5.1.1 Migration Matrix and Evaluation Function

After the techno-economic and demand modelling is finished, we have the necessary CAPEX, OPEX and Revenue for each of the available candidate technologies. We also have the subscriber penetration curves, which we use to calculate the yearly revenue of each of the technology using Equation 4.9. As seen from the Expectimax Search defined by Equations 2.3 to 2.5, we require a an evaluation function which needs to be evaluated at every step and use this value to traverse the decision tree. As seen from Equation 2.1, one of the widely used output metrics in techno-economic analysis is the NPV analysis, which involves taking into account the present value at each of the nodes of the tree and then finding the outcome which results in the highest NPV. We use the NPV for evaluation since we require the maximum possible value of the migration project over the entire network life-cycle. We also need to cater for the time value of money, which the NPV method allows [MM17].

Technology	**Allowed Migration to**	**Pseudonym**
ADSL	All technologies	ADSL
FTTC_GPON_25	FTTB_XGPON_50, FTTH_XGPON_100, FTTC_GPON_100, FTTB_XGPON_100	PON1
FTTB_XGPON_50	FTTH_XGPON_100, FTTB_XGPON_100	PON2
FTTB_UDWDM_50	FTTH_UDWDM_100, FTTB_UDWDM_100	PON3
FTTH_UDWDM_100	NA	PON4
FTTH_XGPON_100	NA	PON5
FTTC_GPON_100	FTTB_XGPON_100, FTTH_XGPON_100	PON6
FTTB_XGPON_100	FTTH_XGPON_100	PON7
FTTB_UDWDM_100	FTTH_UDWDM_100	PON8
FTTC_Hybridpon_25	FTTB_Hybridpon_50, FTTH_Hybridpon_100, FTTC_Hybridpon_100, FTTB_Hybridpon_100	PON9
FTTB_Hybridpon_50	FTTH_Hybridpon_100, FTTB_Hybridpon_100	PON10
FTTH_Hybridpon_100	NA	PON11
FTTC_Hybridpon_100	FTTB_Hybridpon_100, FTTH_Hybridpon_100	PON12
FTTB_Hybridpon_100	FTTH_Hybridpon_100	PON13

Table 5.1: Migration possibilities for each candidate technology

Out of the 13 technologies defined in Section 3.3, migration is restricted between technologies only to certain variations, due to technological or deployment constraints. We define Table 5.1 which first explains all the technologies which are available to migrate to, given the VIO has already deployed a particular technology. We keep in mind that in all the different scenario, the migration window T is of 10 years [Pri16, RZM14].

Since different scenarios (Residential, Business, ITS) to be deployed in the same area have different CAPEX, there is a different migration matrix for each of the different business scenario. This migration CAPEX can be defined by the following equation, which shows the additional cost incurred when migrating from technology s to technology s'

$$M_{s,s'} = \kappa_{i,j}\Delta_{CW_{s,s'}} + \upsilon_{p,q}\Delta_{Equip_{s,s'}} \ \forall\ s, s' \in \{\text{Possible\_Technologies}\}, s \neq s' \ , \tag{5.1}$$

where $\Delta_{CW_{s,s'}}$ is the difference in civil works cost and $\Delta_{Equip_{s,s'}}$ is the difference in equipment costs. The two binary variables $\kappa_{i,j}$ and $\upsilon_{p,q}$ can be given as:

$$\kappa_{i,j} = \begin{cases} 1 & \text{if } i \neq j \ \forall\ i,j \in \{\text{FTTC, FTTB, FTTH}\} \\ 0 & \text{otherwise} \end{cases} \tag{5.2}$$

and

$$\upsilon_{p,q} = \begin{cases} 1 & \text{if } p \neq q \ \forall\ p,q \in \{20,\ 25,\ 50,\ 100\}\ Mbps \\ 0 & \text{otherwise} \end{cases} \tag{5.3}$$

These binary variables are important to distinguish between various types of upgrades required while migration, since moving to a newer technology can result in the VIO needing to make upgrades in either civil works, in electronics work or in both.

Using the values from a migration matrix, based on difference of deployment costs between allowed migrations as mentioned in Table 5.1 and the PV and NPV given in Equation

2.1, we can create new evaluation function for different types of nodes. We define a new evaluation function $U'(s, t, \gamma_t)$ for terminal nodes and maximizer nodes, as follows:

$$U'(s,t,\gamma_t) = \begin{cases} \displaystyle\sum_{i=t}^{T_{NW}} \frac{R_i(\gamma_i) - OPEX_i}{(1+r)^{T_{start}-i}} & \text{if terminal node} \\ \max\limits_{s'} \left[H(s', t+1) + \frac{R_t(\gamma_t)-OPEX_t}{(1+r)^{T_{start}-t}} - \mu_t \cdot M_{s,s'}\right] & \text{if maximizer node ,} \end{cases} \tag{5.4}$$

where $R_i(\gamma_i)$, $OPEX_i$ and $M_{s,s'}$ is defined in Equations 4.8, 4.7 and 5.1 respectively. T_{NW} is the network life-cycle. s is the current state of the chance node and s' is th T_{start} is the starting year of the network life-cycle, r is the internal rate of return of the project, μ_t is a binary variable which is 1 when migration takes place in year t, otherwise, is 0. The network life-cycle is $T_{NW} = [2018, 2019, ..., 2037]$. T_{NW} have been defined previously in Section 2.3. $H(s', t+1)$ is the value generated by chance node at depth $t+1$ for child technology s'.

At the maximizer nodes, the subtraction of $\mu_t \cdot M_{s,s'}$ implicitly refers to the capital expenditures required for migration. These are similar to the value of R_0 given in Equation 2.1, which defines the NPV of a project.

5.1.2 Search Tree

As discussed in Section 2.3, the Expectimax search tree has three different kind of nodes, namely, terminal, chance and maximizer nodes. Each of these nodes holds the value of the evaluation function, along with the best path to that node. Every year for every possibility, there is both a maximizer node as well as a chance node, which represents the decision by the VIO and the uncertainty offered by the environment due to customers leaving, respectively. Using recursive functions, the tree is first built to the defined depth, which is equal to T_{mig}. Once the tree is built, the algorithm starts at the bottom-most terminal node, calculating the evaluation function and propagating the value to the top, in a “depth-first” fashion. It is important to note that the terminal nodes present at the bottom of the tree will hold the sum of the present value from that year till the end of T_{NW}.

To explain the building and evaluation of the search tree, we use a toy example. Suppose our migrations last only till the year 2020, which means that $T_{mig} = \{2018, 2019, 2020\}$ and there are only two technologies to choose from, namely FTTC_GPON_25 and FTTB_XGPON_100.

Building the search tree

Before the evaluation starts, a search tree needs to be built following the rules of Expectimax Search, as mentioned in 2.3.3. The tree is illustrated in Figure 5.1. At depth $t = 2018$,

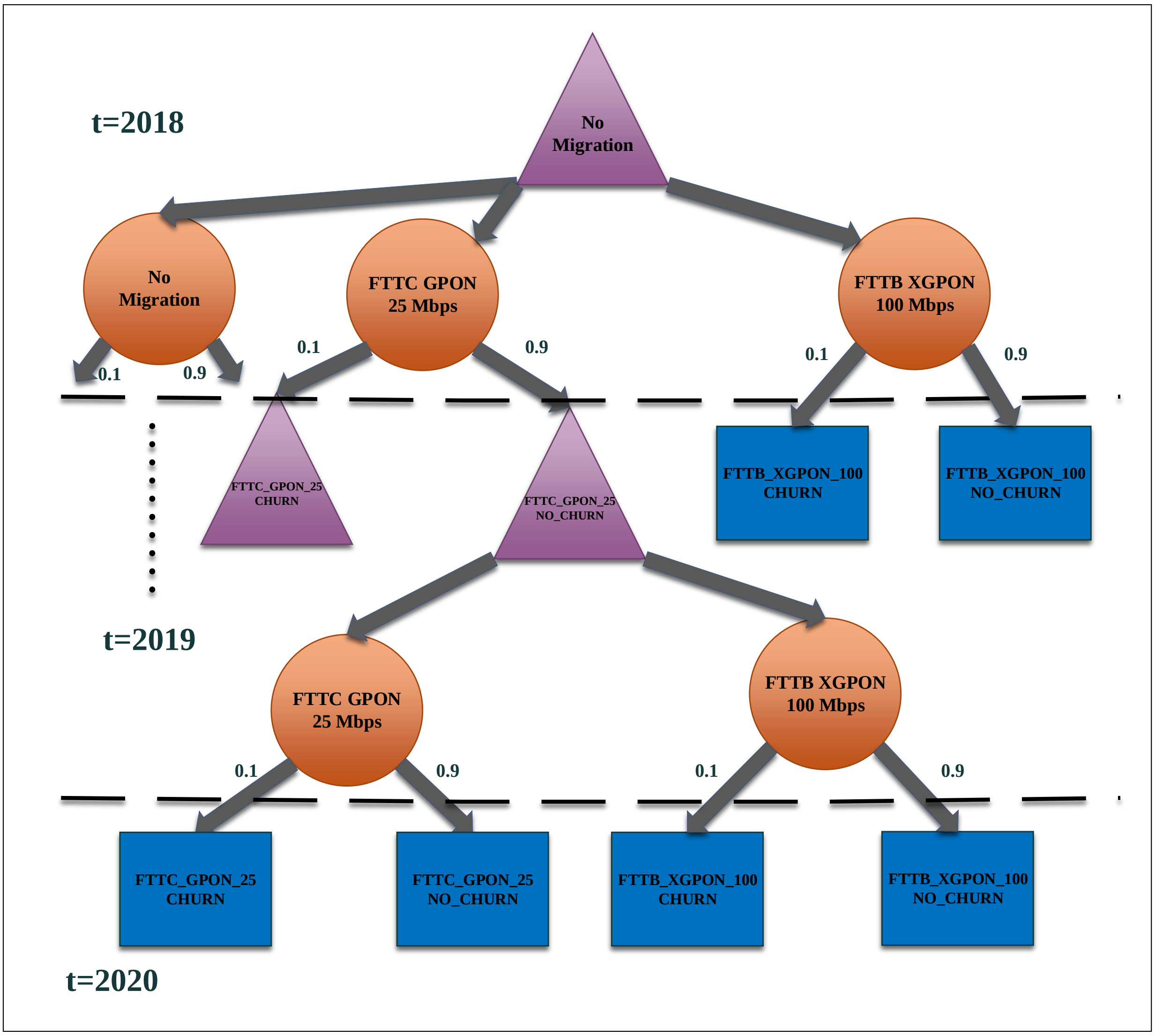


Figure 5.1: Expectimax tree with all possible migrations built for a depth of 10 years

there is a maximizer node (**No Migration**). Each of its child node, which is a chance node is assigned a new technology to which migration is possible (**FTTC_GPON_25** and **FTTB_XGPON_100**). For each chance node in the starting year, there are two possibilities, namely *Churn* and *No_Churn*. *Churn* signifies that 10% of the total connected subscribers leave the network and the probability of this occurence is fixed at 0.1 [OAS13]. *No_Churn* signifies that no customers leave the network in that year and the value of the chance node is calculated using Equation 2.4. Moving over to depth $t = 2019$, the children of these chance nodes are either maximizer nodes or terminal nodes, depending on whether a final technology has been reached before the tree reaches the depth of $t = 2020$. At the final depth of $t = 2020$, we only create terminal nodes which calculate the present value of staying in the same technology from $t = 2020$ to the end of the network lifecycle, defined in Section 2.3.

If we recall the agent-environment interaction from Figure 2.5, we see that in our Expectimax search tree, the agent is the VIO choosing the maximum NPV from the available technologies to migrate to. Every year, the choice between *Churn* and *No_Churn* can be defined by a two state Markov chain having steady-state probability as 0.1 and 0.9 respectively. This is shown in Figure 5.2 below. The steady-state probability matrix can be given as follows:

$$\begin{array}{cl} \begin{array}{cc} \text{Churn} & \text{No\_Churn} \end{array} & \\ \left[\begin{array}{cc} 0.1 & 0.9 \\ 0.1 & 0.9 \end{array}\right] & \begin{array}{c} \text{Churn} \\ \text{No\_Churn} \end{array} \end{array}$$

Figure 5.2: Steady-state probability matrix for customer churn

Evaluating the search tree

Once the tree is built, we need to start evaluating it, to find the migration path with the highest evaluation function described in Equation 5.4. For explaining this evaluation, we refer to Figure 5.3. The new evaluation function first traverses to the bottom-most depth ($t = 2020$) and evaluates the values of all the terminal nodes in it. For the shown toy example, let us assume arbitrary values of the evaluation function as 450 C.U., 500 C.U., 900 C.U. and 1000 C.U. for the different nodes, as shown in Figure 5.3.

These values are then propagated upwards to the chance nodes at $t = 2019$, the chance node uses Equation 2.4 to find the expectation of each of its child nodes. This expectation models the behaviour of the environment. In the same year, the maximizer node of FTTC CHURN and FTTC No CHURN calculate the maximum of their children using the evaluation function in Equation 5.4. Here the migration costs are also added, in case the technology changes the chance node to the maximizer node in the same year. This is repeated till the control reaches to the top-most maximizer node at year $t = 2018$.

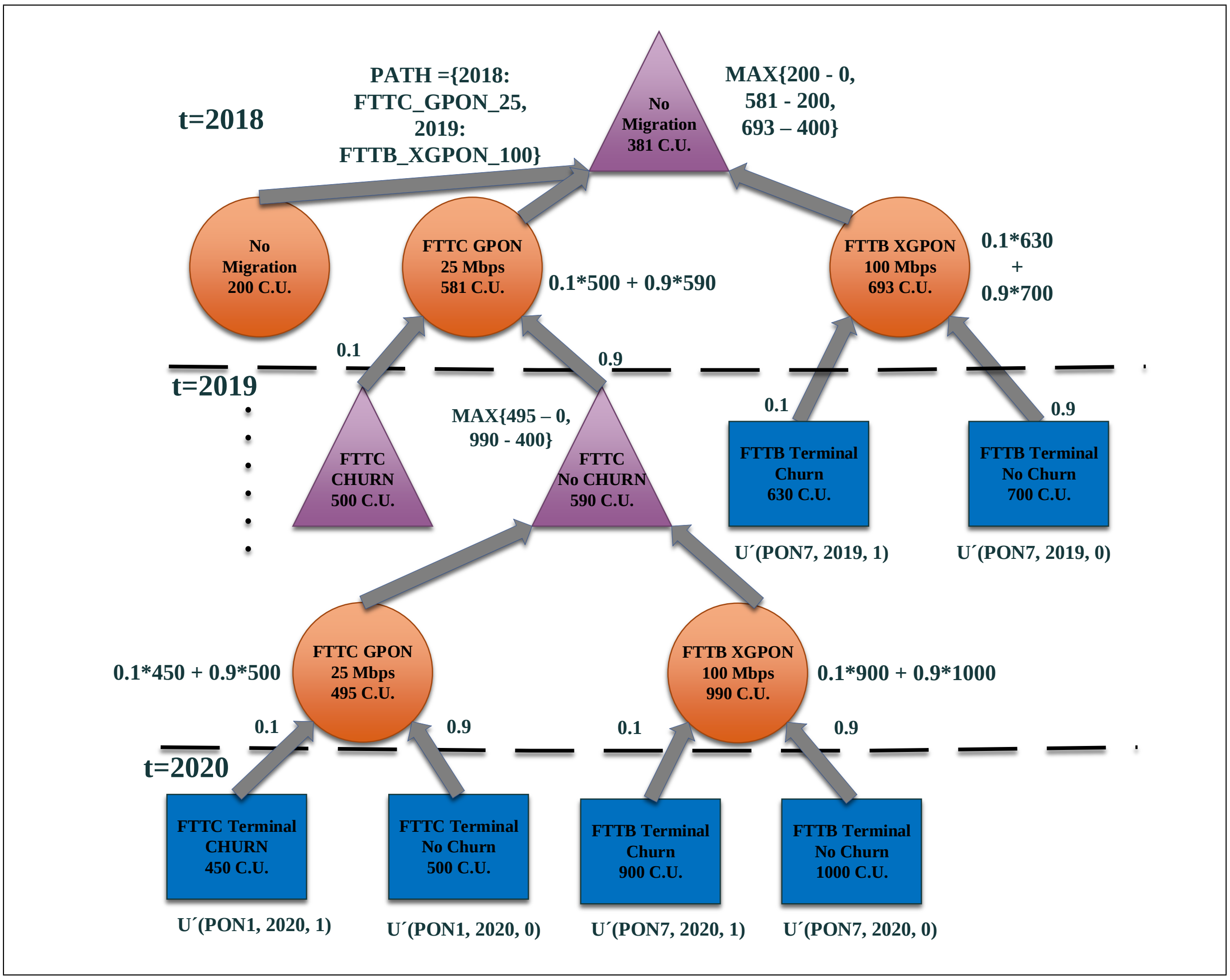


Figure 5.3: Expectimax tree evaluation to choose migration path

At every maximizer node, we also store the path traversed by the maximum evaluation function from that depth, to the bottom most depth ($t = 2020$ in this case). This means that the path stored at the top-most maximizer node would be the migration path which results in the maximum NPV. In the illustrated example in Figure 5.3, the path with the highest NPV of 381 C.U. is {2019: FTTC_GPON_25, 2020:FTTB_XGPON_100}.

5.1.3 Pruning Strategy

For a general Expectimax tree, the computational complexity is given by $\mathcal{O}(b^m)$[RN10, Kle10], where b is the maximum number of branches in the tree and m is the depth of the search tree. In our work, the maximum fan-out is 14 (ADSL, PON1....,PON13) and the maximum depth is 10 years ($t = 2018$ to $t = 2027$), which means that there are a maximum of 14^{10} possible paths which can be calculated. This calls for pruning of the tree to get rid of illegal or illogical tree nodes, thereby reducing the time and computational complexity of the search tree. Unlike other search trees, there are no clear pruning strategies in an Expectimax search, because of the randomness introduced by the chance node. Here we define two pruning methods, namely *rule-based pruning* and *look-ahead pruning*, which are explained in detail.

Rule-based pruning [Kle10] refers to the rules set out by the environment. In our case, there are two rules which are set while building the search tree, which does not allow excessive maximizer, chance and terminal modes to be created.

- Migration technology rule - For any given PON technology, migration is only allowed to certain technologies. These possible migrations have been already explained in Table 5.1. This means that at every level, instead of having 14 child nodes for every maximizer node, we would only have the quantity allowed. For example, for a max-node of PON2, there are three child nodes, namely PON2, PON5 and PON7. This reduces the number of nodes to be traversed in the search tree.
- Migration year rule - As discussed in earlier sections, the European Commission Digital Single Market's Broadband Policy [Eur14] has set guidelines to provide at least 100 Mbps of symmetric data-rate to all types of internet subscribers by 2025. Hence in our work, we set year $t = 2025$ at depth 7 as a cut-off, after which there are no technologies in the child nodes which can offer less than 100 Mbps. If this rule is applied, after year 2025 we prune away all the nodes which are related to technologies which offer 20, 25, or 50 Mbps to the customer.

If a search tree of depth greater than 10 years is required, say, for 15 years, the algorithm takes a longer time to operate because, as the depth increases linearly, the computations increase exponentially. To avoid unnecessary evaluation of nodes, we add a small penalty calculation and decide which node has the highest evaluation function. Equation 5.5 models this heuristic behaviour.

$$\{Child\_Tech\} = \Big\{ \min_i \big(\frac{Cost_{H_i}}{R_{H_i}} + \max(0, Pen_i^2)\big) \Big\}_4 \;\; \forall\, i \in \{Possible\_Children\} \tag{5.5}$$

where $\{Child\_Tech\}$ is the set of four minimum child technologies for every maximizer node, $Cost_{H_i}$ is the cost per household of a possible migration technology i. R_{H_i} is the revenue per household of a possible migration technology i, P_i is a penalty variable of technology i defined in the equation below.

$$Pen_i = \rho . \frac{C_i - C_{parent}}{OPEX_i - OPEX_{parent}} \tag{5.6}$$

where C_i and $OPEX_i$ are the CAPEX and OPEX of possible child technology i. Similarly, C_{parent} and $OPEX_{parent}$ are the CAPEX and OPEX of the current technology. The scaling factor ρ is used to adjust the penalty in such a way that it becomes comparable with the other terms in Equation 5.5. This reduces the number of technologies to be evaluated to a maximum of 4, reducing the total runtime of the algorithm, while not compromising on the authencity of results. As a small test, all the different pruning strategies were tested with the Expectimax Algorithm, written in Python 3.6.1 [Fou16] and running on a desktop computer with an Intel® Core$^{\text{TM}}$ i7-4770 CPU @ 3.40 GHz and a 16 GB RAM produced the results shown in Table 5.2. We see that if all the pruning methods are applied, the execution time of one tree reduces from 10.5 minutes to 3.9 minutes. However, care must be taken as to not prune out potential nodes which might be beneficial.

Pruning Strategy	**Depth**	**Execution Time for one complete tree (mins)**
Technology Pruning	15	10.5
Technology and Year Pruning	15	4.2
Technology, Year and Heuristic Pruning	15	3.9
Only Heuristic	15	8.9

Table 5.2: Pruning strategies in Expectimax search and related computation times

Chapter 6

Results

In this chapter, we present the result of our migration study for different business scenario and deployment area. We investigate three types of deployment areas, namely, Urban, Dense Urban and Suburban. For each of these deployment areas, we look into two different kind of demands, that is Pure Residential and a complete converged scenario. For each of the demands, there are four different possibilities, which have been introduced in Section 2.2.2. These results are analyzed and compared with each other. We then undertake a sensitivity analysis by changing the various assumed parameters and noting their impact on the final NPV and migration path. For all the three deployment areas, the parameters of the migration model like area, migration window, network lifecycle and subscriber churn are kept fixed. These values are shown in Table 6.1 as follows:

Parameter	**Value**
Total area	7 sq.km.
Start year	2018
Migration Start	2018
Migration End	2027
NW Lifecycle end	2038
Migrations to 100 Mbps	2025
Churn Rate	10%
Churn Probability	0.1

Table 6.1: Migration Study Parameters for all scenarios

6.1 Scenario Analysis: Urban

The first deployment area we look into is a 7 *sq.km.* area of Munich, Germany. This is classified as an urban deployment scenario because the population density is high [TVC+12]. The results of the techno-economic analysis, followed by the results given by our migration model for various scenarios are discussed below.

6.1.1 Residential Results

In a pure residential scenario, we assume that all the demands in the network are residential subscribers, whose tariffs are given in Table 4.3. The CAPEX, as generated by the methods described in Chapter 4.1 is shown in the figure below.

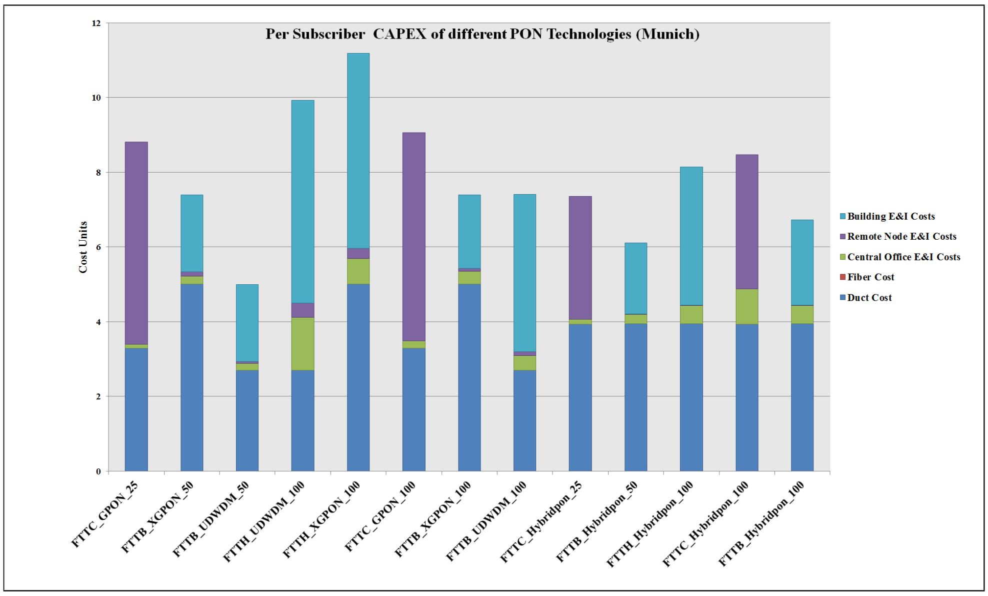


Figure 6.1: Per Subscriber CAPEX of Munich 7 sq km

Figure 6.1 shows the per subscriber CAPEX costs of each of the 13 different PON technolgoies in cost units. We observe that FTTH technologies are more expensive by non-FTTH ones, with the most expensive technology to deploy being FTTH_XGPON_100 at 11.18 C.U per subscriber. The least expensive technology which can offer 100 Mbps to customers is FTTB_XGPON_100 at about 7.38 C.U per subscriber. Due to a single stage deployment, UDWDM technologies have lower civil works cost. However their deployment for a non FTTH 100 Mbps configuration is about 0.02 C.U. per subscriber more expensive because the equipment costs of UDWDM technologies are higher than GPON and XGPON technologies. FTTC based GPON technologies are not preferable because of high remote node costs of up to 9 C.U. per subscriber. To supplement the migration model, we fix the equipment replacement cost in ADSL (greenfield) to 3.76 C.U. per subscriber.

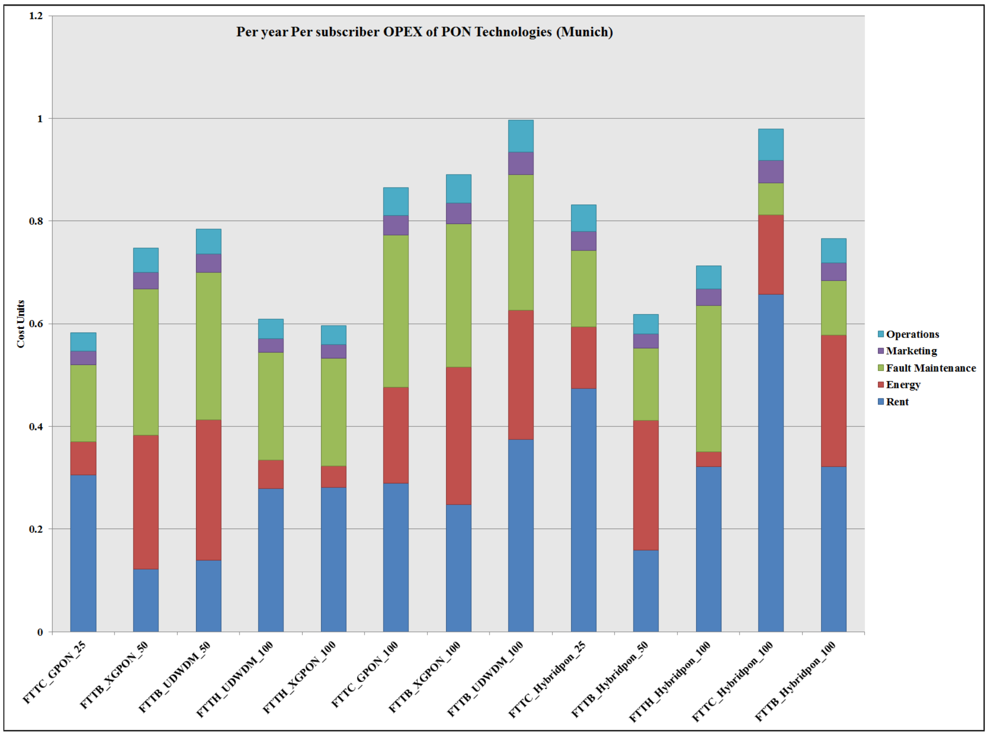


Figure 6.2: Per Subscriber OPEX of Munich 7 sq km

The CAPEX costs of a FTTB deployment are also compared to the investment values for an FTTB deployment in Munich, Germany in [Pri16]. Table 6.2 compares the values obtained from our cost modelling, which is based on the costs given by [Opt11]. We see that the per sq.km. CAPEX values in the case of a single stage deployment (FTTB_UDWDM_50) are comparable to the per sq.km. CAPEX mentioned by [Pri16].

Deployment	City	Area (sq. km.)	CAPEX (C.U.)	CAPEX per sq. km.
SWM FTTB Deployment [Mü17]	Munich, Germany	~160	~3200000	~20000
FTTB_UDWDM_50 Deployment	Munich, Germany	7	146245.86	20892.26
FTTB_Hybridpon_50 Deployment	Munich, Germany	7	178789.18	25541.31
FTTB_XGPON_50 Deployment	Munich, Germany	7	216506.82	30929.54

Table 6.2: Comparison of FTTB 50 Mbps technologies with deployment costs given in [Pri16]

The OPEX is calculated as explained in Section 4.1.2. The per subscriber per year base OPEX value in Cost Units for all of the different PON technology deployments is shown in Figure 6.2. The value of OPEX keeps increasing every year depending on the number of subscribers connected to the network. Here, we see that FTTH technologies have the least OPEX, around 0.6 C.U. per subscriber. This is because the subscribers pay for the rent and energy costs of the ONU. The highest OPEX of about 1 C.U per subscriber per year is from FTTB_UDWDM_100. To supplement the migration model, we fix the per subscriber OPEX in ADSL (greenfield) to 0.25 C.U. The OPEX results obtained are 1-3 C.U. lower to the per subscriber OPEX values shown in [CWMJ10], since we do not consider the service provisioning costs in this thesis.

The results of the expected NPV and the migration path followed by each of the different subscriber penetration curve is shown in Figure 6.3.

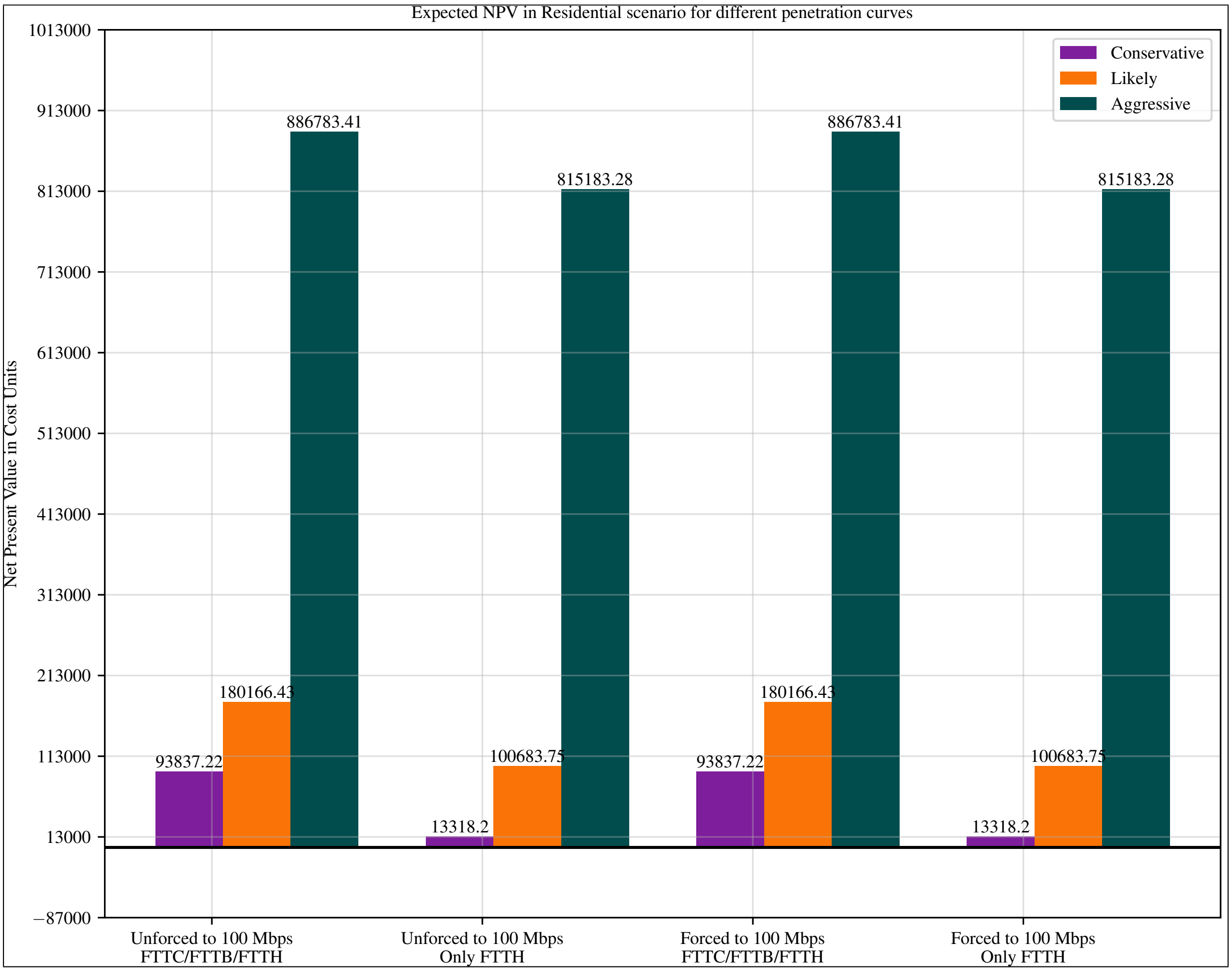


Figure 6.3: Expected NPV for different scenario of Munich pure residential

As we can see from the four scenarios, earlier introduced in Section 2.2.2, the NPV over a network lifecycle of 20 years is low both in the case of conservative and likely subscriber penetration rates, with the optimistic scenario of Unforced FTTC/FTTB/FTTH providing a maximum of 93837.22 C.U. in conservative curves and 180166.43 C.U. for the likely curves. Due to the low take-up rate and various constraints, the VIO cannot make much profit in a purely residential deployment. We see that when only FTTH technologies provide 100 Mbps, the NPV is lower by about 80000 C.U. because non-FTTH technologies with 100 Mbps (like FTTB_UDWDM_100) have a higher return on investment. We also observe that in case of migrations are forced, the migration model prefers to migrate in

Scenario	Conservative	Likely	Aggressive
Unforced FTTC/FTTB/FTTH	2019: FTTB_UDWDM_50 2020: FTTB_UDWDM_100 NPV: 93837.22 CU	2019: FTTB_UDWDM_50 2020: FTTB_UDWDM_100 NPV: 180166.43 CU	2019: FTTH_UDWDM_100 NPV: 886783.41 CU
Forced FTTC/FTTB/FTTH	2019: FTTB_UDWDM_50 2020: FTTB_UDWDM_100 NPV: 93837.22 CU	2019: FTTB_UDWDM_50 2020: FTTB_UDWDM_100 NPV: 180166.43 CU	2019: FTTH_UDWDM_100 NPV: 886783.41 CU
Unforced only FTTH	2019: FTTH_Hybridpon_100 NPV: 13318.2 CU	2019: FTTH_Hybridpon_100 NPV: 100683.75 CU	2022: FTTH_Hybridpon_100 NPV: 815183.28 CU
Forced only FTTH	FTTH_Hybridpon_100 NPV: 13318.2 CU	FTTH_Hybridpon_100 NPV: 100683.75 CU	2022: FTTH_Hybridpon_100 NPV: 815183.28 CU

Table 6.3: Technologies deployed in each scenario for Munich pure residential

the beginning of the migration window, in order to get more revenue from the subscribers. This behaviour is also recorded by the heuristic optimization models of [TLRL13], which has been discussed in Section 2.4.

Overall, a VIO would not prefer migrations in the worst case scenario if the deployment area is completely residential. To acheive a positive NPV in all cases, the tariffs charged per subscriber have to be increased. However, a revenue variation study is not part of this thesis.

6.1.2 Converged Results

We now look into a converged scenario where we plan deployments for residential, business as well as ITS back-haul users together. Since we assume that public ITS providers deploy MBSs, we calculate that these MBSs require at least 50 Mbps of data-rate [BER17]. So, they are not deployed if the entire network in the area is not upgraded to at least 50 Mbps offered by FTTB technologies. Since the range of an LTE MBS is between 0.5-1 km [GMK16, BER17], the number of ITS MBSs present in a 7 sq.km. area are only 5. Hence, the requirement for a 7 sq. km. area for Public ITS back-haul is 3 GPON/XGPON/UDWDM ONTs. The services provided to and the revenue gained from a single ITS MBS subscriber is the same as those of business users.

Compared to the pure residential scenario, both the CAPEX and OPEX are between 5-10% higher in the converged scenario. While deploying the network, it is made sure that the business subscribers and residential subscriber do not share equipment, hence, even if there is capacity in the remote nodes to add business subscribers to splitters or DSLAM switches, new equipment is purchased and the whole network on an average is overprovisioned.

Similarly, the OPEX costs are higher by 0.1-0.3 C.U. per technology per subscriber due to the added SLA violations for business subscribers. The amount for SLA violations is taken from [CWMJ10] as well as [TVC$^+$12]. The remaining migration study parameters are kept the same, as described in 6.1. We see that due to the above factors, there are significant changes in the migration model, as compared to a pure residential scenario. The results from the migration model are shown in the Figures 6.4, along with the technologies used shown in Table 6.4.

From the results, it is clear that if we classify 7% of the total subscribers as business subscribers [TVC+12], we get NPVs which are about 45-49% higher than the pure residential scenario. In case migrations to FTTC/FTTB/FTTH technologies are allowed, FTTB_Hybridpon_100 is preferred and this gives higher NPV as compared to deploying FTTH_UDWDM_100. Compared to the pure residential scenario, the search tree here prefers HybridPON for slower penetration curves, since they are more cost effective as compared to GPON and WDM-PON technologies. Among FTTH technologies, for all the four scenarios, migration is preferred to FTTH_UDWDM_100 because the high operational costs are offset by charging a higher tariff from business and ITS subscribers.

As discussed in Section 2.1, Stadtwerke München has deployed an FTTB connection across Munich [Mü17, Pri16, FTT15] starting from the year 2012. From Table 6.4, it is clear that in the most likely scenario, our migration model shows that FTTB_Hybridpon_100 is the technology which would be the option with the highest NPV of 272726.55 C.U.

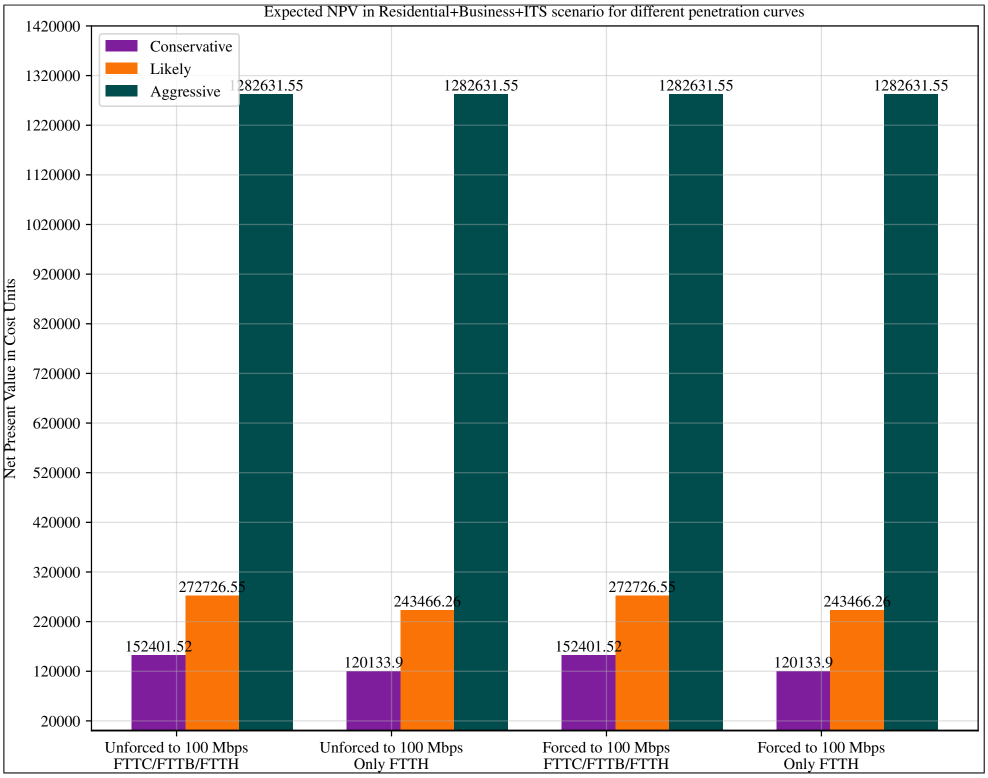


Figure 6.4: Expected NPV for different cases of Munich converged scenario

Scenario	Conservative	Likely	Aggressive
Unforced FTTC/FTTB/FTTH	2019: FTTB_Hybridpon_50 2020: FTTB_Hybridpon_100 NPV: 152401.51 CU	2019: FTTB_Hybridpon_50 2020: FTTB_Hybridpon_100 NPV: 272726.55 CU	2019: FTTH_UDWDM_100 NPV: 1282631.54 CU
Forced FTTC/FTTB/FTTH	2019: FTTB_Hybridpon_50 2020: FTTB_Hybridpon_100 NPV: 152401.51 CU	2019: FTTB_Hybridpon_50 2020: FTTB_Hybridpon_100 NPV: 272726.55 CU	2019: FTTH_UDWDM_100 NPV: 1282631.54 CU
Unforced only FTTH	2019: FTTH_UDWDM_100 NPV: 120133.89 CU	2019: FTTH_UDWDM_100 NPV: 243466.25 CU	2019: FTTH_UDWDM_100 NPV: 1282631.54 CU
Forced only FTTH	2019: FTTH_UDWDM_100 NPV: 120133.89 CU	2019: FTTH_UDWDM_100 NPV: 243466.25 CU	2019: FTTH_UDWDM_100 NPV: 1282631.54 CU

Table 6.4: Technologies deployed in each migration scenario for Munich converged scenario

6.2 Scenario Analysis: Dense Urban

For the dense urban area, we choose a 7 sq km area of Manhattan, New York, which is a densely populated place, with the number of subscribers given by Table 3.1. In our analysis, there are a total of 7895 buildings, out of which 10% are business buildings. In every building, an average of 8 subscribers are accommodated [Cit18].

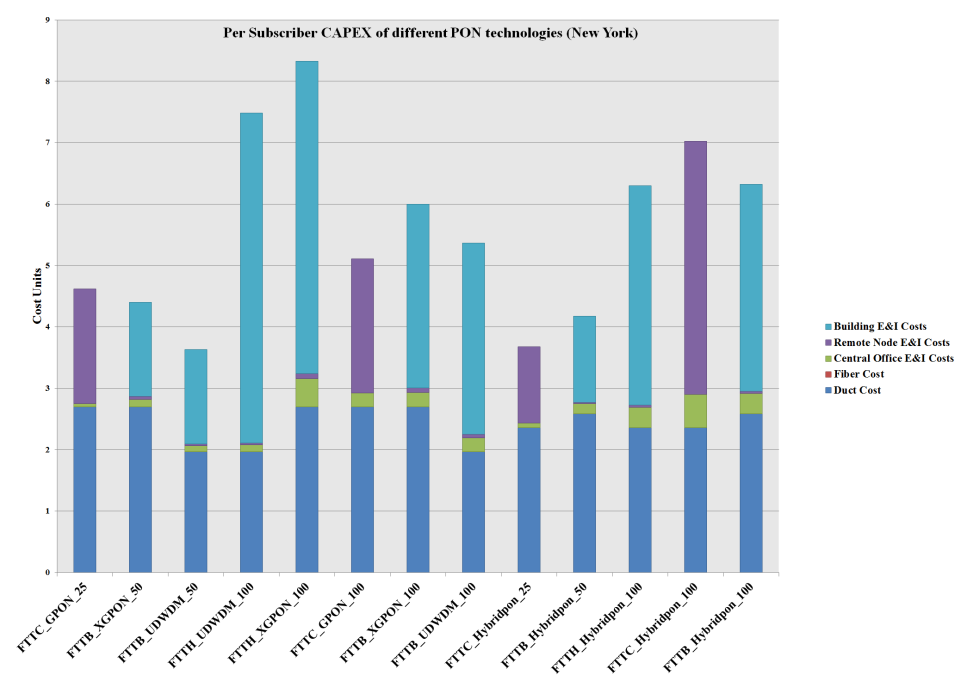


Figure 6.5: CAPEX of New York 7 sq km

Post techno-economic modelling, the CAPEX and OPEX are generated. The costs are linear with the number of demands in the area and follow the same behaviour as in the urban scenario. From the per subscriber CAPEX illustrated in Figure 6.5, it is evident that every PON technology is between 1-4 C.U. cheaper than for the deployment in dense areas. This is because increased number of subscriber lead to better sharing of costs as also observed in [SM17]. The OPEX is higher for FTTC/FTTB technologies as compared to FTTH technologies by only 0.1 C.U. per subscriber per year (as seen in Figure 6.6), since the VIO needs to pay for the rent and energy costs of ONUs and DSLAM switches.

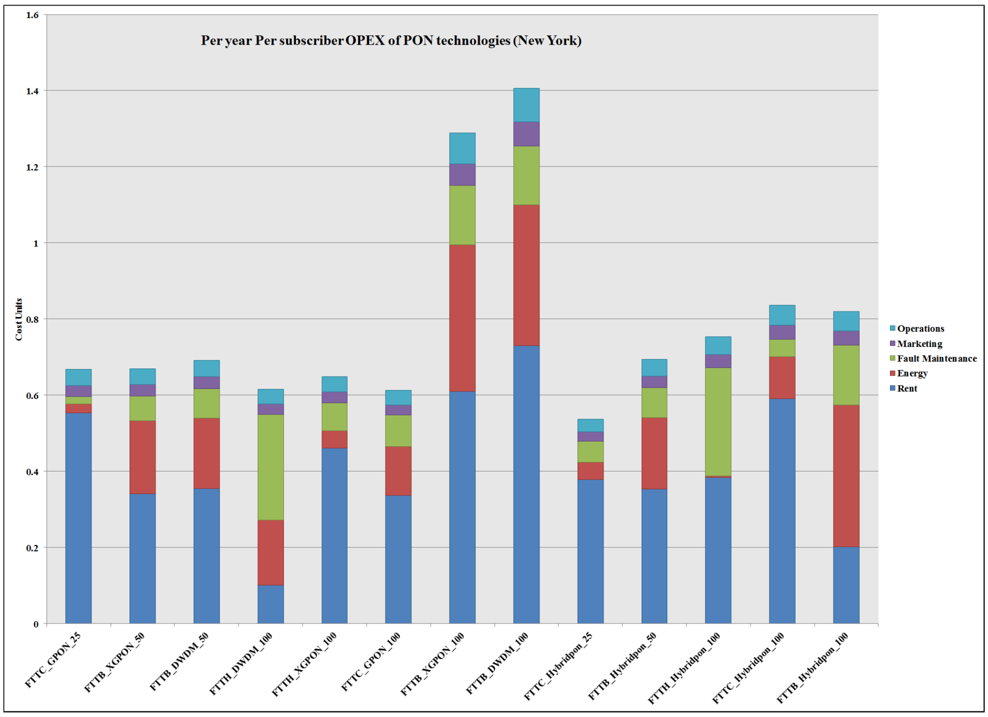


Figure 6.6: OPEX of New York 7 sq km

6.2.1 Residential Results

Upon running the migration model, we see that a 111% increase in the NPV, as compared to the urban residential scenario, majorly because more subscribers are joining the network every year. In this deployment, the two final technologies are FTTC_GPON_100, and FTTH_Hybridpon_100. This is due to the lower OPEX for both these technologies.

As seen in Table 6.6, in case migrations are not forced, there is a possibility of getting an NPV of 416483.53 CU in the likely scenario by deploying FTTC_GPON_100. This is because the number of subscribers per building is increased to 8 in this deployment and over-provisioned technologies in the urban scenario now become affordable to deploy.

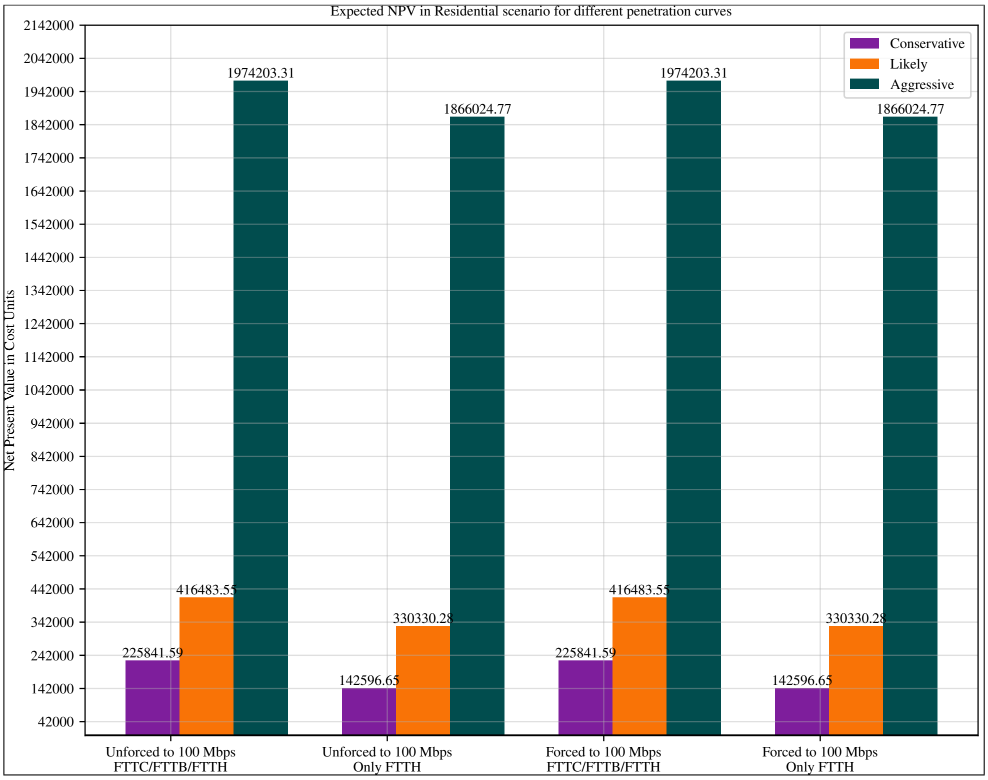


Figure 6.7: Expected NPV for different cases of New York residential scenario

Scenario	Conservative	Likely	Aggressive
Unforced FTTC/FTTB/FTTH	2019: FTTC_GPON_100 NPV: 225841.71 CU	2019: FTTC_GPON_100 NPV: 416483.53 CU	2019: FTTH_UDWDM_100 NPV: 1974203 CU
Forced FTTC/FTTB/FTTH	2019: FTTC_GPON_100 NPV: 225841.71 CU	2019: FTTC_GPON_100 NPV: 416483.53 CU	2019: FTTH_UDWDM_100 NPV: 1974203 CU
Unforced only FTTH	2019: FTTH_Hybridpon_100 NPV: 142596.65 CU	2019: FTTH_Hybridpon_100 NPV: 330330.23 CU	2021: 2019: FTTH_UDWDM_100 NPV: 1866024.77 CU
Forced only FTTH	2019: FTTH_Hybridpon_100 NPV: 142596.65 CU	2019: FTTH_Hybridpon_100 NPV: 330330.23 CU	2021: 2019: FTTH_UDWDM_100 NPV: 1866024.77 CU

Table 6.5: Technologies deployed in each migration scenario for New York residential scenario

6.2.2 Converged Results

In the converged scenario, we consider that 10% of the total subscribers are business subscribers, who pay a higher revenue, as shown in Table 4.3. The number of ITS subscribers are increased to 8, because the vehicular density is higher and more base stations are required for efficient coverage. Due to this, an overall increase in the NPV can be expected.

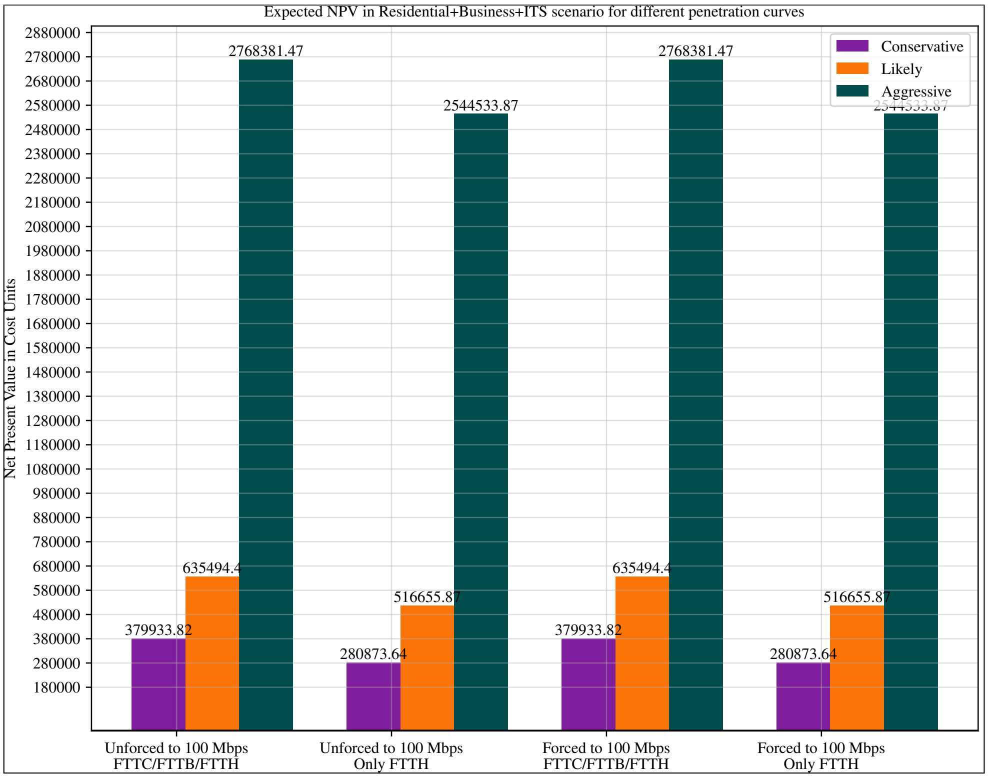


Figure 6.8: Expected NPV for different cases of New York converged scenario

Scenario	Conservative	Likely	Aggressive
Unforced FTTC/FTTB/FTTH	2019: FTTC_GPON_25 2020: FTTC_GPON_100 NPV: 379933.82 CU	2019: FTTC_GPON_25 2020: FTTC_GPON_100 NPV: 635494.39 CU	2019: FTTC_GPON_25 2020: FTTC_GPON_100 NPV: 2768381.46 CU
Forced FTTC/FTTB/FTTH	2019: FTTC_GPON_25 2020: FTTC_GPON_100 NPV: 379933.82 CU	2019: FTTC_GPON_25 2020: FTTC_GPON_100 NPV: 635494.39 CU	2019: FTTC_GPON_25 2020: FTTC_GPON_100 NPV: 2768381.46 CU
Unforced only FTTH	2019: FTTH_Hybridpon_100 NPV: 280873.64 CU	2019: FTTH_Hybridpon_100 NPV: 516655.86 CU	2019: FTTH_XGPON_100 NPV: 2544533.86 CU
Forced only FTTH	2019: FTTH_Hybridpon_100 NPV: 280873.64 CU	2019: FTTH_Hybridpon_100 NPV: 516655.86 CU	2019: FTTH_XGPON_100 NPV: 2544533.86 CU

Table 6.6: Technologies deployed for New York converged scenario

After running the migration model, we see from Table 6.6, that the final technologies preferred in the different scenarios are FTTC_GPON_100 and FTTH_Hybridpon_100. Compared to the residential deployment, in the converged deployment, we see an increase of about 35-40% C.U. This improvement in the NPV is attributed to the presence of business customers, who are the major source of revenue generation.

6.3 Scenario Analysis: Suburban

For simulating suburban deployments, we choose a 7 sq. km. area of Ottobrunn, Germany, which is a sparsely populated space. Although the number of subscribers are quite less in this scenario, we see that the number of buildings are more. This is quite common in suburban areas since both the residential and business buildings are single dwelling units (SDUs). Hence, we make an assumption that for every building in the suburban scenario there is only one subscriber present. From the techno-economic analysis, it is seen that a majority of the costs in CAPEX (Figure 6.9) arise from the civil works, as compared to urban and dense urban deployments where the remote node costs were comparable with the civil work costs. The per subscriber CAPEX is also twice as high for a suburban subscriber, as compared to an urban subscriber.

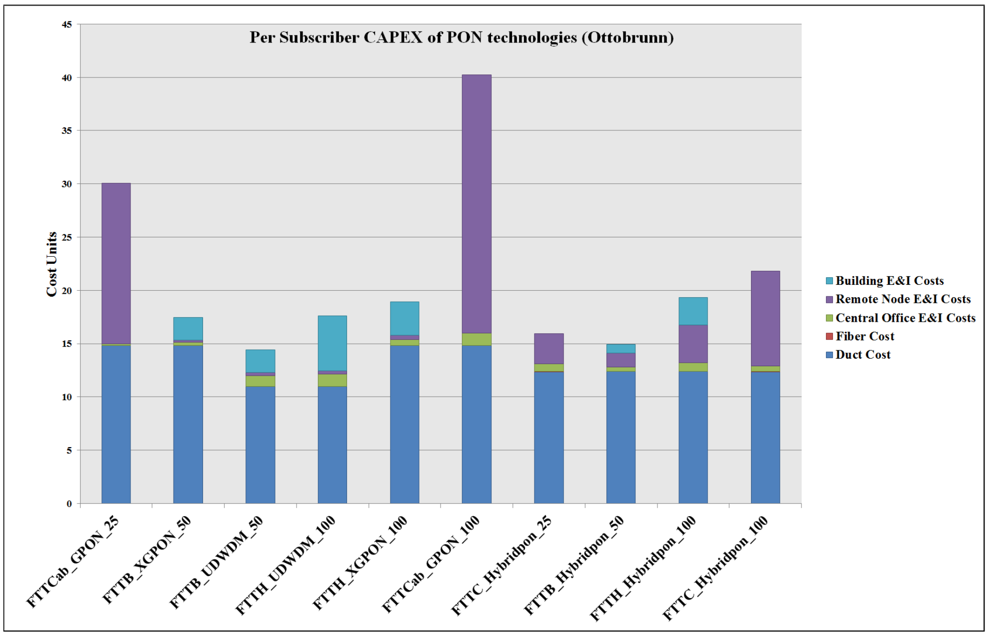


Figure 6.9: CAPEX of Ottobrunn 7 sq km pure residential scenario

As seen in Figures 6.9 and 6.10, the number of technologies used in this deployment are lesser as compared to the previous two area footprints. This is due to the fact that we consider the buildings to be SDUs, which means that there is only one subscriber in every building. Hence, technologies like FTTB_XGPON_100 and FTTB_UDWDM_100 will have the same architecture and configuration as FTTH_XGPON_100 and FTTH_UDWDM_100 respectively. This helps in reducing the size of the Expectimax search tree. The per subscriber per year CAPEX is more than 10-14 C.U. higher than an urban residential deployment. This is because of most of the buildings house only individual subscribers, hence the costs cannot be shared.This behaviour has also been observed in works like [TVW$^+$14, Cas09, CWMJ10].

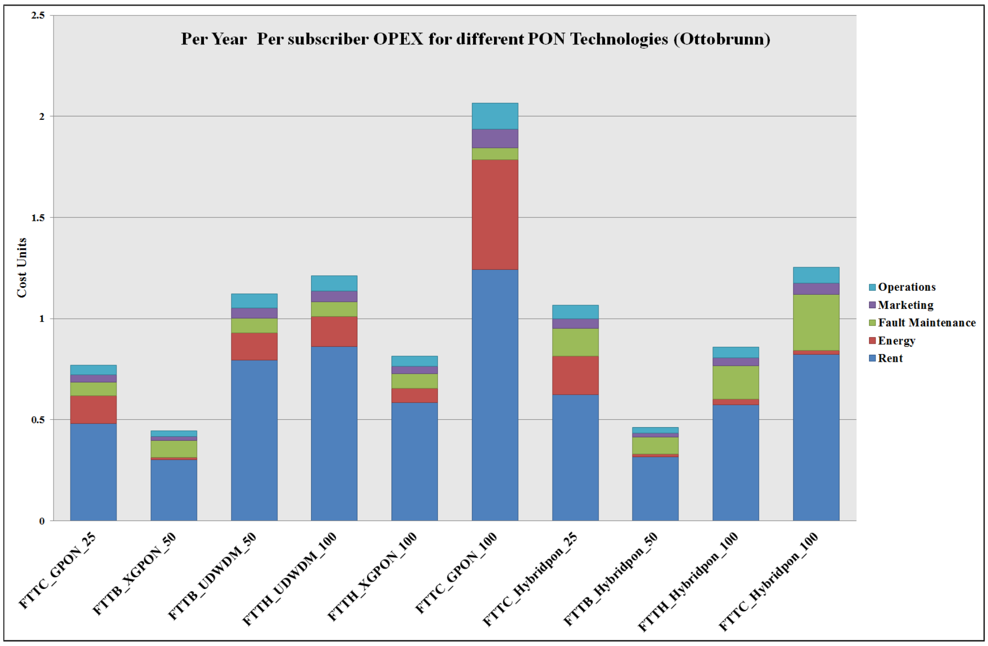


Figure 6.10: OPEX of Ottobrunn 7 sq km

From the cost modelling, we see that FTTH_UDWDM_100 has one of the lowest per subscriber CAPEX of about 17 C.U., however it has a higher operational expenditure of 3.2 C.U. per subscriber per year, compared to other technologies. Hence, just by looking at the costs, it is not possible to decide on a migration strategy. We now run the migration model for the residential as well as the converged scenario and discuss the results obtained.

6.3.1 Residential Results

When the migration model is run with the parameters mentioned in Table 6.1, we see that all scenarios lead to the same results. Since there are not enough subscribers joining within the 10 year migration period to reap the benefits of migrations. We also see that when migrations are forced, conservative and likely curves migrate to FTTH_UDWDM_100 whereas the aggressive curve migrates to FTTH_XGPON_100. The technology of choice in this scenario is FTTH_UDWDM_100 since it offers a lower CAPEX of around 16 C.U. per year per subscriber, as compared to its other 100 Mbps counterparts.

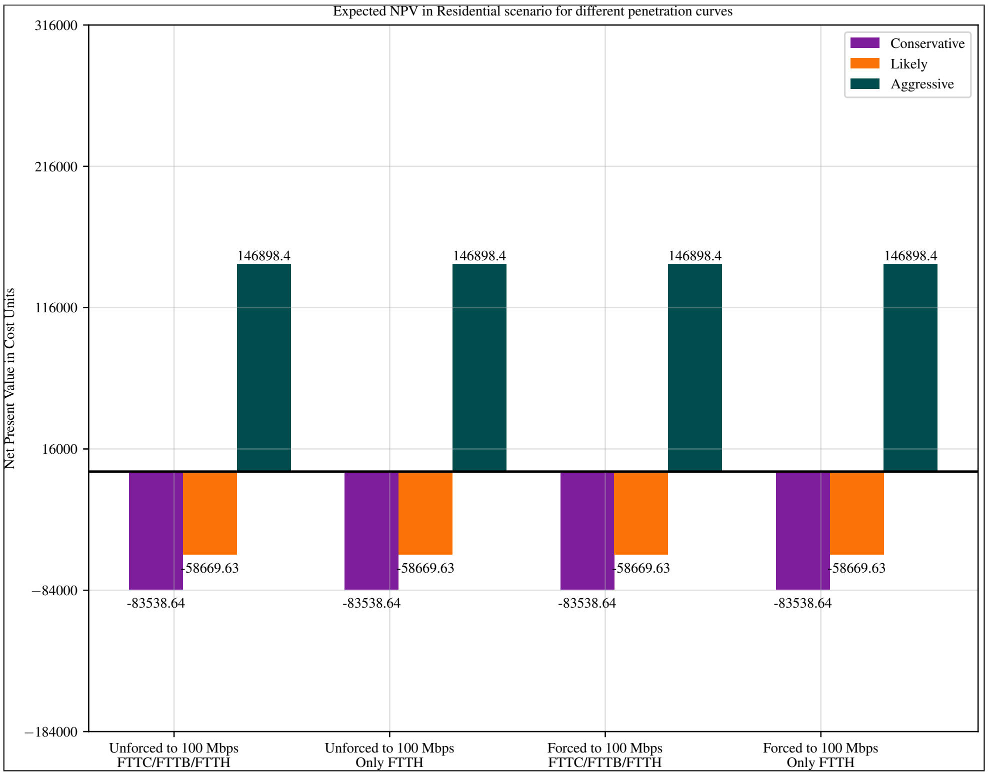


Figure 6.11: Expected NPV for different cases of Ottobrunn residential scenario

Scenario	Conservative	Likely	Aggressive
Unforced FTTC/FTTB/FTTH	2019:FTTH_UDWDM_100 NPV: -83538.64 CU	2019:FTTH_UDWDM_100 NPV: -58669.63 CU	2019: FTTH_XGPON_100 NPV: 146898.40 CU
Forced FTTC/FTTB/FTTH	2019:FTTH_UDWDM_100 NPV: -83538.64 CU	2019:FTTH_UDWDM_100 NPV: -58669.63 CU	2019: FTTH_XGPON_100 NPV: 146898.40 CU
Unforced only FTTH	2019:FTTH_UDWDM_100 NPV: -83538.64 CU	2019:FTTH_UDWDM_100 NPV: -58669.63 CU	2019: FTTH_XGPON_100 NPV: 146898.40 CU
Forced only FTTH	2019:FTTH_UDWDM_100 NPV: -83538.64 CU	2019:FTTH_UDWDM_100 NPV: -58669.63 CU	2019: FTTH_XGPON_100 NPV: 146898.40 CU

Table 6.7: Technologies deployed for Ottobrunn residential scenario

6.3.2 Converged Results

For a converged scenario, we assume that 5% of the total subscribers are business subscribers generating a higher revenue. After the migration model is run, we see that the NPVs for conservative and likely penetration curves are -40522.60 C.U. and -1176.66 C.U. respectively. The migration behaviour is similar to that of residential scenario because the small percentage of business subscribers does not make a major impact on revenue generation. The migration model suggests a migration to 100 Mbps as soon as possible in order to generate as much revenue as possible.

Scenario	**Conservative**	**Likely**	**Aggressive**
Unforced FTTC/FTTB/FTTH	2019:FTTH_UDWDM_100 NPV: -40522.60 CU	No Migrations NPV: -1176.66	2019: FTTB_XGPON_100 NPV: 322960.57 CU
Forced FTTC/FTTB/FTTH	2019:FTTH_UDWDM_100 NPV: -40522.60 CU	No Migrations NPV: -1176.66	2019: FTTB_XGPON_100 NPV: 322960.57 CU
Unforced only FTTH	2019:FTTH_UDWDM_100 NPV: -40522.60 CU	No Migrations NPV: -1176.66	2019: FTTB_XGPON_100 NPV: 322960.57 CU
Forced only FTTH	2019:FTTH_UDWDM_100 NPV: -40522.60 CU	No Migrations NPV: -1176.66	2019: FTTB_XGPON_100 NPV: 322960.57 CU

Table 6.8: Technologies deployed for Ottobrunn converged scenario

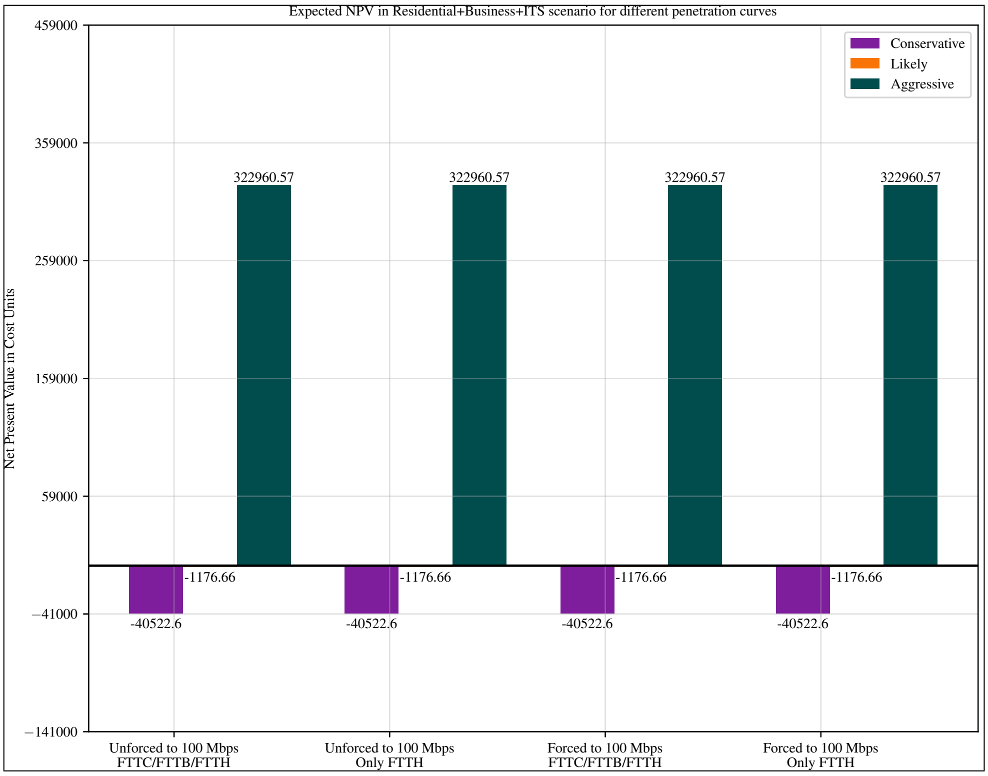


Figure 6.12: Expected NPV for different cases of Ottobrunn converged scenario

6.4 Sensitivity Analysis

As seen from the Section 2.2 and Sections 6.1, 6.2 and 6.3, there are many input parameters and assumptions in the migration model . Due to the complexities involving in the methods and process, it is difficult to find the exact relationship between the inputs and outputs. Hence, in this thesis we employ a sensitivity analysis [MM17], to study the effects on the outputs (Net Present Value and migration years), when some input parameters are varied.

For a sensitivity analysis, we will fix on the type of deployment scenario, to show the exact effect of the input parameters. The remaining scenarios have been implemented and tested and found to be behaving in the same way as the one presented here. Table 6.9 shows the fixed parameters used in the sensitivity analysis. Here we choose a positive scenario where all migrations are possible and there are no constraints on when to migrate.

Parameter	**Value**
Deployment Type	Urban Munich Converged
Scenario	Unforced FTTC/FTTB/FTTH
Total population	29262
Residential Subscribers	27213
Business Subscribers	2049
ITS Subscribers	3
Migration Start	2018
Migration End	2027
NW Lifecycle end	2038
Migrations to 100 Mbps	Not Forced
Churn Probability	0.1

Table 6.9: Fixed parameters used in the Sensitivity Analysis

6.4.1 Churn Rate

As discussed in Section 2.2, churn rate is defined by the percentage of connected subscribers who leave the network every year for a variety of reasons. In this thesis, we model churn as lost revenue. Hence we take the different values of churn rates mentioned in [OAS13]. For the fixed scenario mentioned in Table 6.9, we vary use three different churn rates, namely 5%, 10% and 20%. It is expected that with increase in churn rate, the overall NPV should reduce. The CAPEX and OPEX for all the technologies are kept the same as mentioned in Figures 6.1 and 6.2 respectively. As we see from Figure 6.13 and Table 6.10, small changes in churn rate lead to small changes in overall cost borne by the VIO. As seen in the NPV, the difference is between 10000 to 30000 C.U. if we compare a churn rate of 5% and 10%

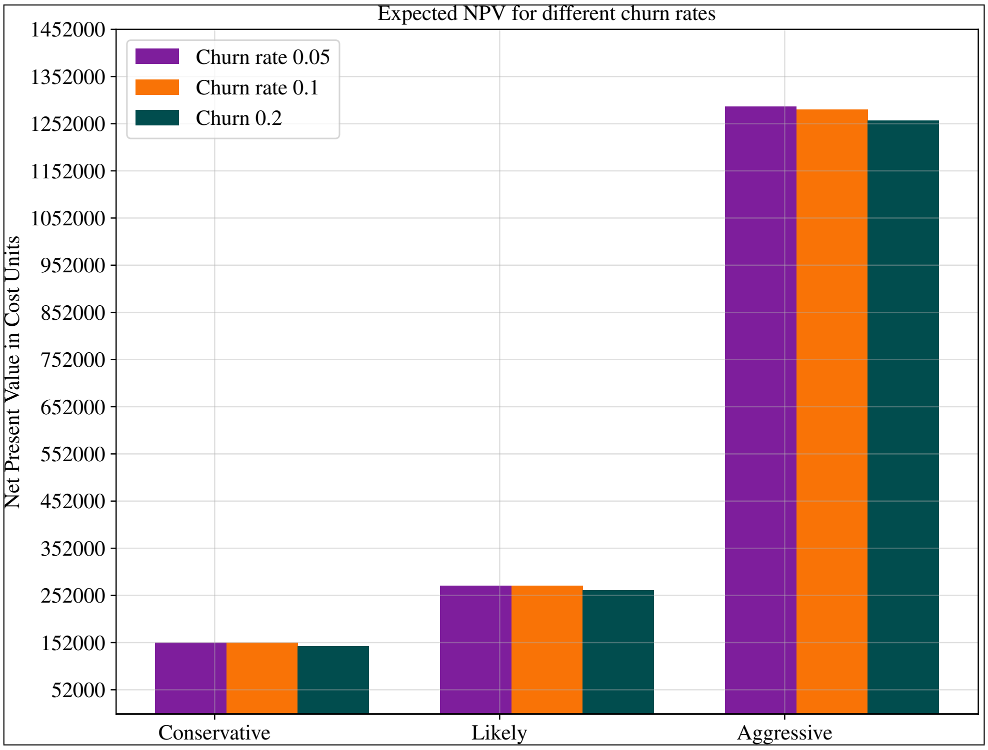


Figure 6.13: Expected NPV for different churn rates

respectively. This shows that for a rough analysis, the churn rate does not vary the output result to a great extent, which has also been shown in [OAS13].

Churn Rate (%)	**Conservative NPV (C.U.)**	**Likely NPV (C.U.)**	**Aggressive NPV (C.U.)**
5% churn rate	152401.51	273265.39	1289079.80
10% churn rate	152137.36	272726.55	1282631.54
20% churn rate	145045.34	263694.36	1259358.38

Table 6.10: Expected NPV value for different churn rates in Munich Converged Scenario

6.4.2 Component Costs

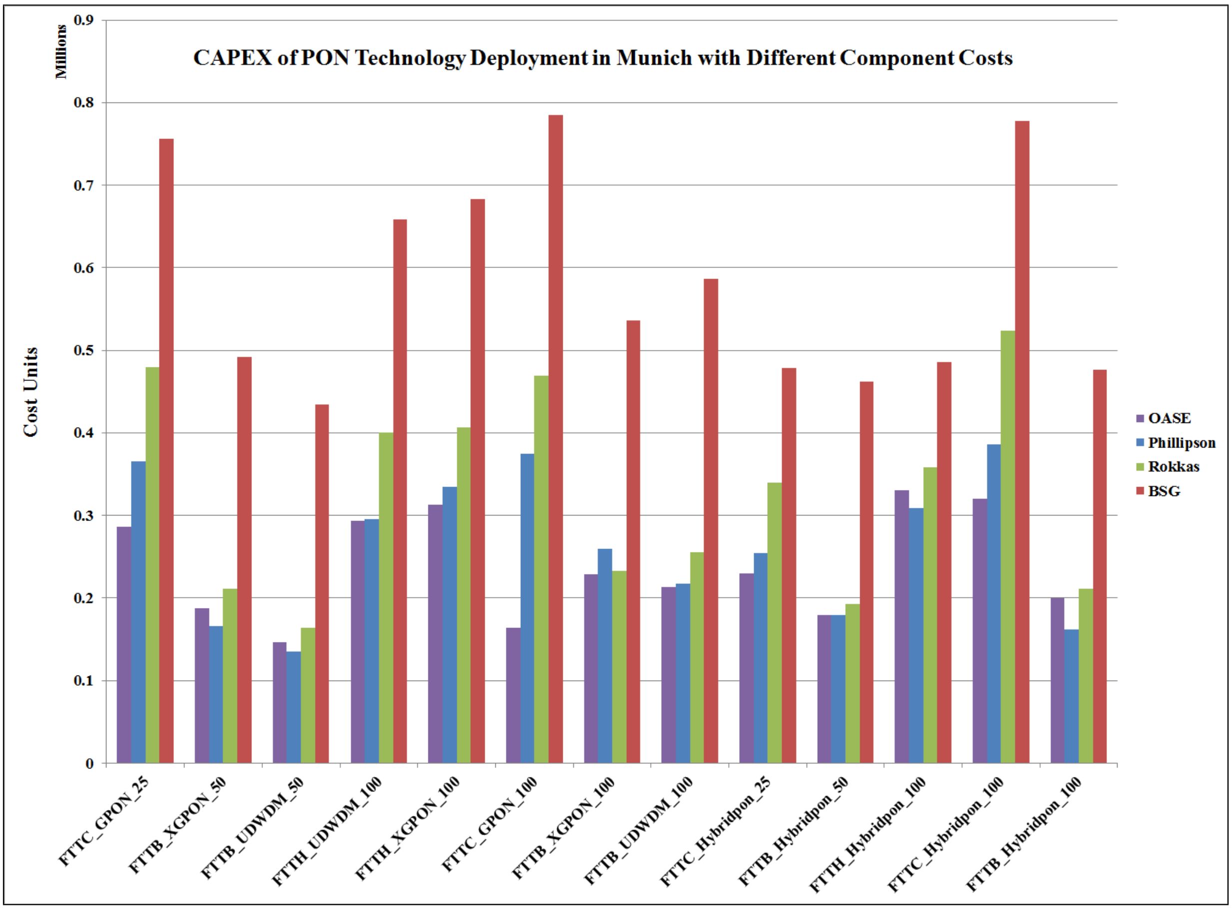


Figure 6.14: CAPEX per technology for different component costs: Munich Converged Scenario

Since techno-economic studies are specific to the costs involved in an area, different cost models have different expected NPVs. In this study, we take the costs mentioned in three different studies, namely [Rok15] (deploying GPON based technology in an unnamed city), [PSRV13] (Deploying Hybridpon based technology in a Dutch city) and [Ana08](deploying FTTC based technology in London). As a contribution to this thesis, we first collect the data and undertake the cost modelling for CAPEX and OPEX for all the different deployment technologies, while also varying both the assumed parameters mentioned in Table 4.1. We then compare all the technologies with each other and with also the base case, which is the values taken from [OAS13]. Since different studies have different units of currency, like Pounds, Euros and Cost Units, we convert all the currencies into cost units using the current currency conversion. Here 1 Cost Unit is approximately 50 Euros and 44.97 GBP. Figure 6.14 shows the CAPEX of all the different technologies.

For each of the four studies, we run the migration model and find the expected NPV and

Component	Cost per Unit OASE (C.U.)	Cost per Unit Phillipson (C.U.)	Cost per Unit Rokkas (C.U.)	Cost per Unit BSG (C.U.)
Fiber Duct	1.12 /m	0.54 /m	0.7 /m	1.42 /m
Fiber	0.00002 /m	0.006 /m	0.006 /m	0.192 /m
GPON OLT Card	40	50	70	288
XGPON OLT Card	80	55*	200	300*
WDM OLT Port Card	8.8	60*	200	350*
Power Splitter	1.8	2*	10	1.4*
AWG	2.2	2*	12*	2*
DSLAM+Cabinet	124	220	300	294
GPON ONU	1	5	2	1.6
XGPON ONU	1.8	5*	4	1.8*
WDMPON ONU	2.3	5*	5*	2.3*
HybridPON ONU	3.1	5.5*	5	3.1*

* Assumed according to model trend.

Table 6.11: Component Costs from [OAS13], [Rok15], [Ana08], [PSRV13]

the migration steps. Both [Rok15] and [PSRV13] are comparable in terms of cost to the OASE base model [OAS13]. Hence the results can vary according to the costs. Table 6.11 gives a list of major component costs from each of the studies. Since all components used in our thesis are not mentioned in every study, we assume these components to follow model trends.

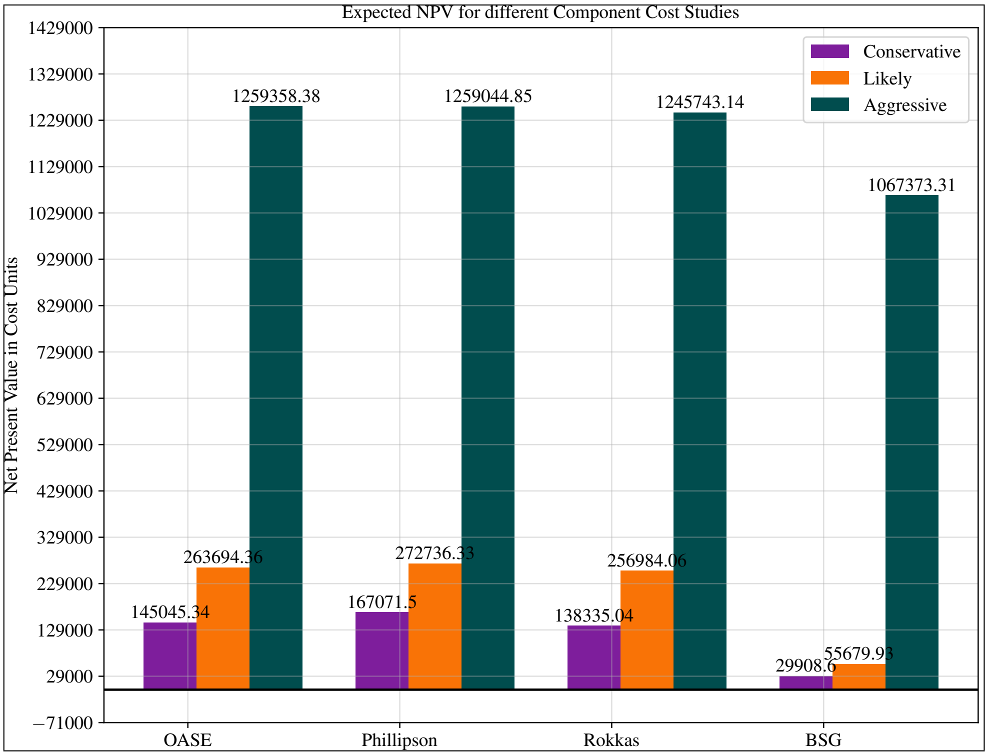


Figure 6.15: Expected NPV for different component costs

We see that as the component costs increases, the NPV decreases, which is the expected behaviour. As seen in Table 6.12, Except the OASE base case, the other components choose FTTH_Hybridpon_100 as the final technology and prefer early migrations to reap maximum benefits. The only exception to this is the BSG costs in a conservative scenario, which suggests not undertaking any migrations. This is because of the high costs involved and no change in the revenue. Since the BSG study was done for an expensive and densely populated city like London, it is possible that the revenue per subscriber would be higher than what is used in our analysis.

Component Cost Model	Conservative	Likely	Aggressive
OASE	2019: FTTB_Hybridpon_50 2020: FTTB_Hybridpon_100 NPV: 145045.34 CU	2019: FTTB_Hybridpon_50 2020: FTTB_Hybridpon_100 NPV: 263694.36 CU	2019: FTTH_UDWDM_100 NPV: 1259358.38 CU
Phillipson	2019: FTTB_UDWDM_50 2020: FTTB_UDWDM_100 NPV: 167071.49 CU	2019: FTTB_UDWDM_50 2020: FTTB_UDWDM_100 NPV: 272736.33 CU	2019: FTTB_UDWDM_50 2020: FTTB_UDWDM_100 NPV: 167071.49 CU
Rokkas	2019: FTTB_Hybridpon_50 2020: FTTB_Hybridpon_100 NPV: 138335.04 CU	2019: FTTB_Hybridpon_50 2020: FTTB_Hybridpon_100 NPV: 256984.06 CU	2019: FTTB_Hybridpon_50 2020: FTTB_Hybridpon_100 NPV: 1245743.13 CU
BSG	2019: No Migrations NPV: 29908.60 CU	2019: FTTH_Hybridpon_100 NPV: 55679.92 CU	2019: FTTH_Hybridpon_100 NPV: 1067373.30 CU

Table 6.12: Migration results of different component costs

6.4.3 OPEX

The final part of the sensitivity analysis includes looking at how choosing a more accurate OPEX results in avoidance of misleading results. In many techno-economic works including [TVC$^+$12] and [vdMGGK09], OPEX is considered to be a function of CAPEX. This is because techno-economic researchers generally don't have access to component specific data like MTTRs, energy consumption, component footprint and technician salaries. While it is known that in long-term projects, OPEX becomes more expensive as compared to CAPEX [MM17], we need to verify the same with our implemented migration model.

Here we choose two different OPEX models. The base model is defined using Equations 4.5 to 4.7, using the values provided in [CWMJ10] and [OAS13]. The percentage based OPEX model is taken from [TVC$^+$12], where we define the OPEX of a technology t as follows.

$$OPEX_t = 0.1 * C_{Elect_t} + 0.01 * C_{CW_t} \tag{6.1}$$

where C_{Elect_t} and C_{CW_t} are the electronic and the civil works CAPEX of a technology t, respectively.

As seen in Figure 6.16, the OPEX based on Equation 6.1 is directly proportional to the CAPEX values shown in Figure 6.1. For most technologies, the percentage based OPEX is cheaper per subscriber connected. However, in the case of FTTH based technologies, the

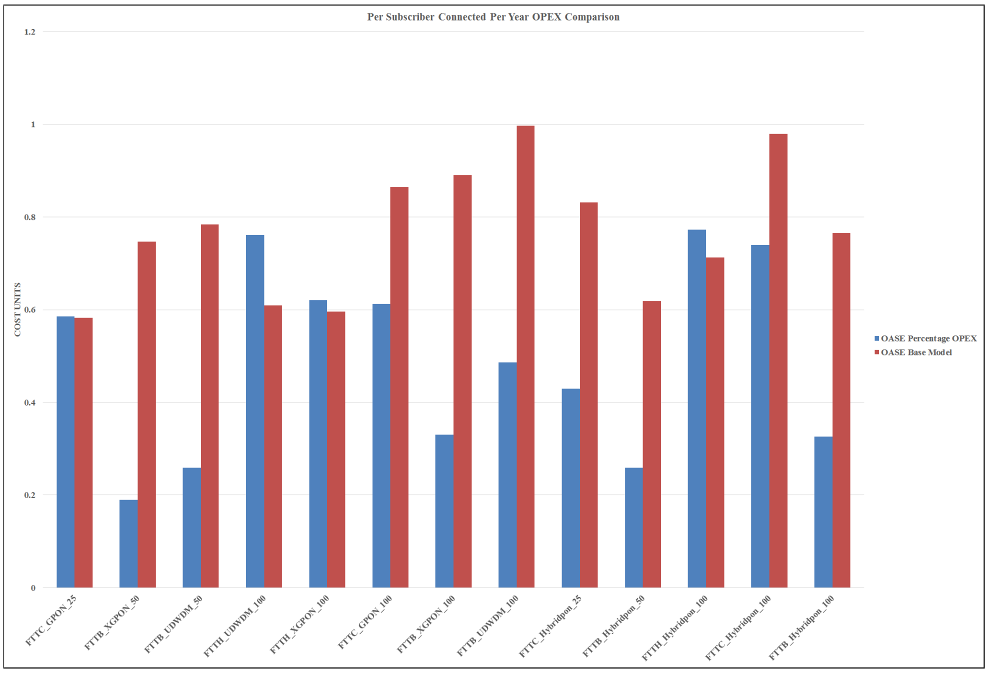
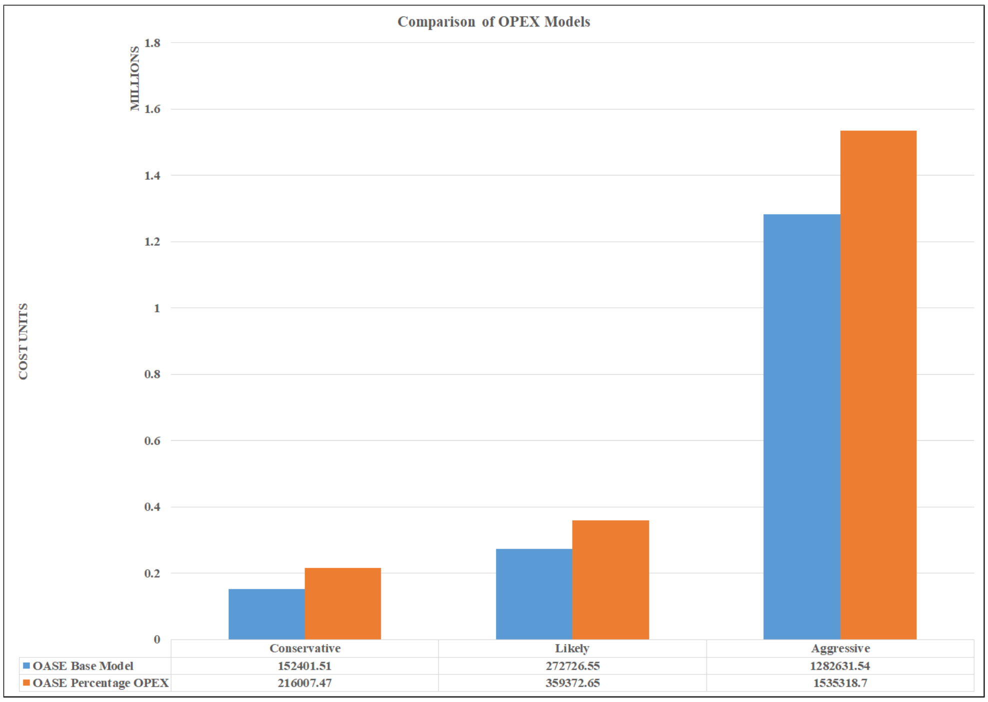


Figure 6.16: OPEX comparison for different technologies



	Conservative	Likely	Aggressive
■ OASE Base Model	152401.51	272726.55	1282631.54
■ OASE Percentage OPEX	216007.47	359372.65	1535318.7

Figure 6.17: Expected NPV for different OPEX models

newer OPEX model is between 0.25-1 CU higher, for every subscriber connected. Hence, the benefits of OPEX savings due to lower energy costs in FTTH architectures is not considered in this model.

The migration model is then run for both the base case as well as the new OPEX case, resulting in NPVs and migration paths in time which can be compared. As we see from Figure 6.17, the NPV in case of the OPEX model defined in Equation 6.1 is 20-40% higher for different subscriber penetration curves. This arises due to the fact that the OPEX calculated using this are lower as compared to the base model.

As seen from Table 6.13, for the aggressive penetration curve, the base model generates an NPV of about 1.28 Million CU by migrating to FTTH_UDWDM_100 and the new OPEX model generates 19% more higher revenue by migrating to FTTB_Hybridpon_100. This is because in the base model, the per year OPEX for the FTTH technology is lesser and the VIO can deploy it as an option. Hence, we can infer that for a rough analysis, a percentage based OPEX could be considered, keeping in mind the risk of underestimating cost factors.

OPEX Model	**Conservative**	**Likely**	**Aggressive**
OASE Base Model	2019: FTTB_Hybridpon_50 2020: FTTB_Hybridpon_100 NPV: 152401.51 CU	2019: FTTB_Hybridpon_50 2020: FTTB_Hybridpon_100 NPV: 272726.55 CU	2019: FTTH_UDWDM_100 NPV: 1282631.54 CU
OASE New OPEX	2019: FTTB_Hybridpon_50 2020: FTTB_Hybridpon_100 NPV: 216007.47 CU	2019: FTTB_Hybridpon_50 2020: FTTB_Hybridpon_100 NPV: 359372.65 CU	2019: FTTB_Hybridpon_50 2020: FTTB_Hybridpon_100 NPV: 1535318.7 CU

Table 6.13: Technologies deployed based on different OPEX Models

Chapter 7

Conclusions and Outlook

Given the current and future demands of different kinds of subscribers, it is important that network operators quickly upgrade their access network infrastructure in order to provide better and new services. The solution lies in moving away from copper based access networks to optical access networks, which are more flexible, easy to maintain and future proof. However, there exist various configurations of optical access networks in the market and operators need to quickly decide on the best options for migrations so that they can provide high speed symmetrical data-rate to their subscribers, while also trying to achieve an overall profitability from the investment. These migrations, apart from the known costs of deployment and operations also depend on many uncertainties like subscriber penetration, customer churn and various socio-economic or political constraints.

This thesis takes into account all these moving parts and offers a quick solution using a modified Expectimax based tree search algorithm to find the feasibility and the exact year in which to deploy a particular network scenario. We look into various constraints in different types of network area deployments, namely, urban, dense urban and suburban. Using this we can decipher that in urban scenarios, it is profitable to deploy an FTTB architecture which is capable of providing 100 Mbps to subscribers. In dense urban situations, the same can be achieved by deploying FTTC architectures. Finally, for suburban topologies, an FTTH solution is the only feasible option due to higher cost per subscriber passed. The low NPVs in this scenario can be recovered by charging the subscribers a higher tariff.

Using various policy constraints, it is also shown that operators can expect an increase of more than 30000 C.U. in the NPVs if they are allowed to provide 100 Mbps to their customers using a non-FTTH technology. Finally a sensitivity analysis is done on various assumptions and input parameters and their results are obtained. This sensitivity analysis highlights the benefits of using a detailed OPEX model over a simple one and also highlights the fact that the migration study is quite dependent on the costs of the components being deployed. It is seen that different churn rates induce only a 2-5% change in the NPV, however, the migration remains the same. With this, we can conclude that VIOs should look at non-FTTH based technologies like FTTC or FTTB in order to obtain maximum benefits.

The migration model in this thesis is flexible and can be used for a migration study with a migration window of up to 15 years. For a future upgrade, the churn probability can be modelled using a more realistic model. Real world data can can be used to get more accurate estimates. Also, a revenue study can be done which gives revenues to charge the subscribers, in order to recover migration costs. If migration data is indeed present, with known outputs for certain inputs, this model will be able to work like a learning-based artificial intelligence model, which can provide estimations for future migrations.

Appendix A

Appendix

A.1 Legend for PON architecture

PON Architectures described in 3.3 are complex and involve a lot of small figures. For ease of understanding the following legend can be used.

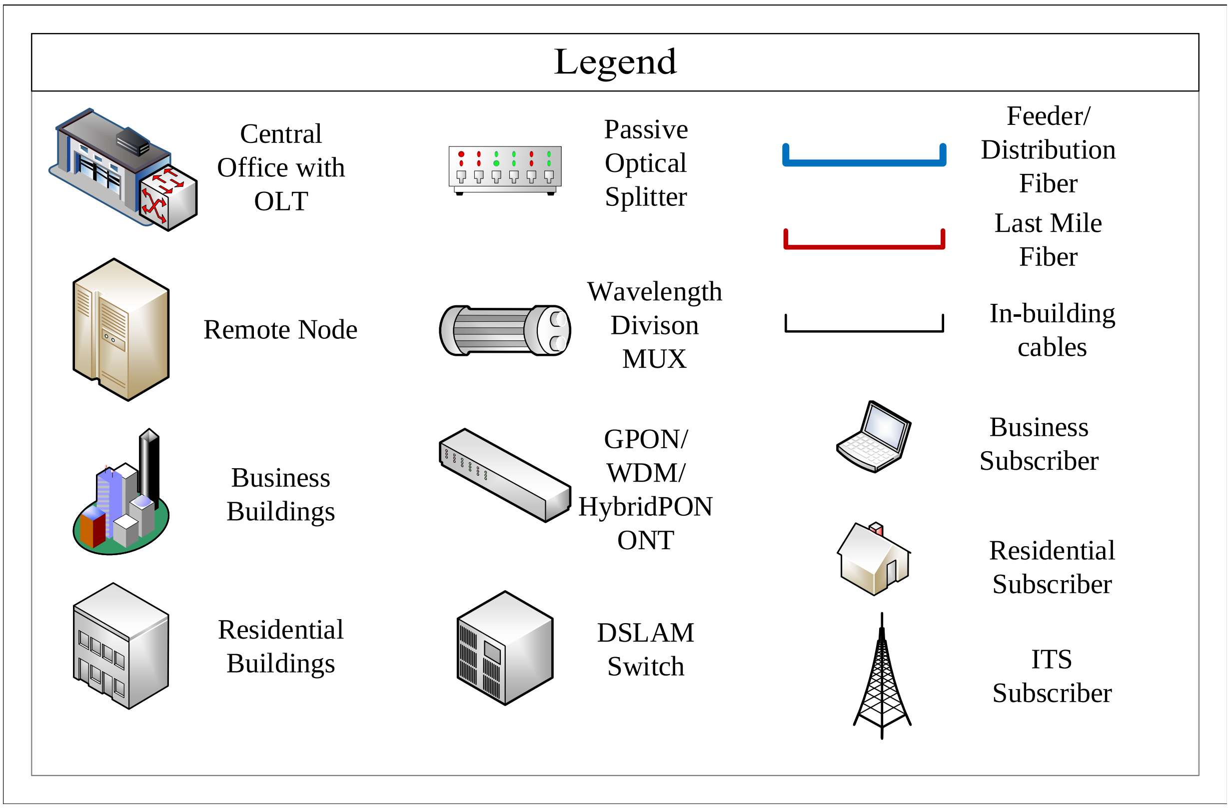


Figure A.1: Legend for Passive Optical Network Architecture

Appendix B

Abbreviations

This chapter contains tables where all abbreviations and other notations like mathematical placeholders used in the thesis are listed.

ADSL	Asymmetric Digital Subscriber Line 2+
AI	Artificial Intelligence
AON	Active Optical Networks
AWG	Arrayed Waveguide Grating
BoM	Bill of Materials
BSG	Broadband Stakeholders Group
CAPEX	Capital Expenditures
CO	Central Office
Co-UDWDMPON	Coherent Ultra Dense Wavelength Division Multiplexing Passive Optical Network
DF	Distribution Fiber
DSLAM	Digital Subscriber Line Access Multiplexer
DSRC	Dedicated Short Range Communications
FF	Feeder Fiber
FIT	Failures in Time
FTTB	Fiber to the Building
FTTC	Fiber to the Cabinet
FTTH	Fiber to the Home

FTTP	Fiber to the Premise
GPON	Gigabit-ethernet Passive Optical Network
HKT	Hong Kong Telecom
HVAC	Heating Ventilation Air Conditioning
HybridPON	Hybrid Passive Optical Networks
ITS	Intelligent Transportation Systems
IOT	Internet Of Things
LMF	Last Mile Fiber
LTE	Long Term Evolution
MBS	Mobile Base Station
MDP	Markov Decision Process
MDUs	Multiple Dwelling Units
MTTR	Mean Time To Repair
NPV	Net Present Value
NP	Network Provider
ODF	Optical Distribution Frame
ODN	Optical Distribution Network
OLT	Optical Line Termination
ONT	Optical Network Termination
ONU	Optical Networking Unit
OPEX	Operational Expenditures
OSM	OpenStreetMaps
OSP	Outside Plants
P2P	Point-to-Point
PIP	Physical Infrastructure Provider
PON	Passive Optical Networks
PS	Power Splitter
PV	Present Value
RNs	Remote Nodes

RN1	Remote Node 1
RN2	Remote Node 2
ROA	Real Options Analysis
RSUs	Road Side Units
RSU	Road Side Unit
SDUs	Single Dwelling units
SLA	Service Level Agreement
SP	Service Provider
SS	Service Server
TCO	Total Cost of Ownership
UDWDM-PON	Ultra Dense Wavelength Division Multiplexing Passive Optical Network
UHD	Ultra High Definition
VDSL	Very-high-bit-rate Digital Subscriber Line
VIO	Vertically Integrated Operator
WDM-PON	Wavelength Division Multiplexing Passive Optical Network
XGPON	10-Gigabit-ethernet Passive Optical Network

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