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Master's Thesis

Enhanced Dimensioning and Comparative Analysis of Different Protection Schemes for Hybrid PON Converged Access Networks (HPCAN)

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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

Optical access networks are continuously evolving, in order to increase the bandwidth offered to the end users. However, as the delivered bandwidth grows, the data losses due to failures also rise. Moreover, the importance of uninterrupted network access is also growing, which makes network reliability a crucial problem to address.

Today's access network telecommunication arena has become very competitive and challenging, which forces network operators to reduce costs in order to gain/ keep benefits. Cost reduction in access networks has been shown to be possible by "Nodes Consolidation" and "Fixed Mobile Convergence", due to the use of a single access network for different types of users and longer reach.

In order to cope with the new requirements (higher bandwidth, longer reach, larger client count, heterogeneous end points) optical access networks are evolving towards Next Generation Optical Access (NGOA) Networks such as NG-PON2 or Hybrid PON.

This thesis proposes: (i) an enhanced dimensioning tool of two stage NGOA networks and different protection schemes to provide highly reliable connection when required. The comparison of the schemes is done in three different types of areas (i.e., Dense Urban, Urban and Rural) with respect to various comparative and analysis aspects: component cost, power consumption, connection availability, indirect improvement in connection availability of residential users, Failure Impact Factor (FIF), protection fiber length/Macro Base Stations (MBS) and the additional fiber required for working paths from reference scenario. Comparative and consolidated performance analysis of each protection scheme has also been carried out with even and uneven weights distribution to select the best protection scheme in a particular scenario/ area.

Contents

Chapter 1

Introduction

The purposes of this chapter is to give a general overview about the latest information and communication technology evolution in telecommunication access networks and the details of previous work performed in the field of dimensioning and protection of **Hybrid PON Converged Access Networks** (HPCANs). Furthermore, to highlight the main motivation, scope and goals of the thesis. Finally, the structure of the thesis report will also be presented in the end of this chapter.

1.1 Information and Communication Technology Revolution

Over the past 15 years the Information and Communication Technology (ICT) revolution has driven global development in an unprecedented way. Technological progress, infrastructure deployment, and rapid falling prices have brought bewildering growth in ICT access and connectivity to billions of people around the world. The objective number 8 of Millennium Development Goals [UN2], which were defined in 2000 by UN, is about global partnership for development. The ultimate objective of **"Connect Everyone and to Create a Truly Inclusive Information Society"** have been rightly dilated upon and pondered in detail in last 15 years to achieve desired results. Latest ICT facts and figures statistics[ITU15a] highlighted the same and acknowledge the worldwide efforts both at academic and industry level. It is highlighted that total internet users has increased to 3.2 billion which were just 400 million in year 2000, reference: Fig. 1.1, it also shows the remaining gaps to achieve the desired results/ goals. Besides this, what has been achieved till 2015 in different telecommunication fields have also been reflected in Fig. 1.2. Salient are as under:-

- Mobile cellular subscriptions increased to **more than 7 billion** by end 2015, which were mere 738 million in 2000, results in penetration rate of almost 97%.

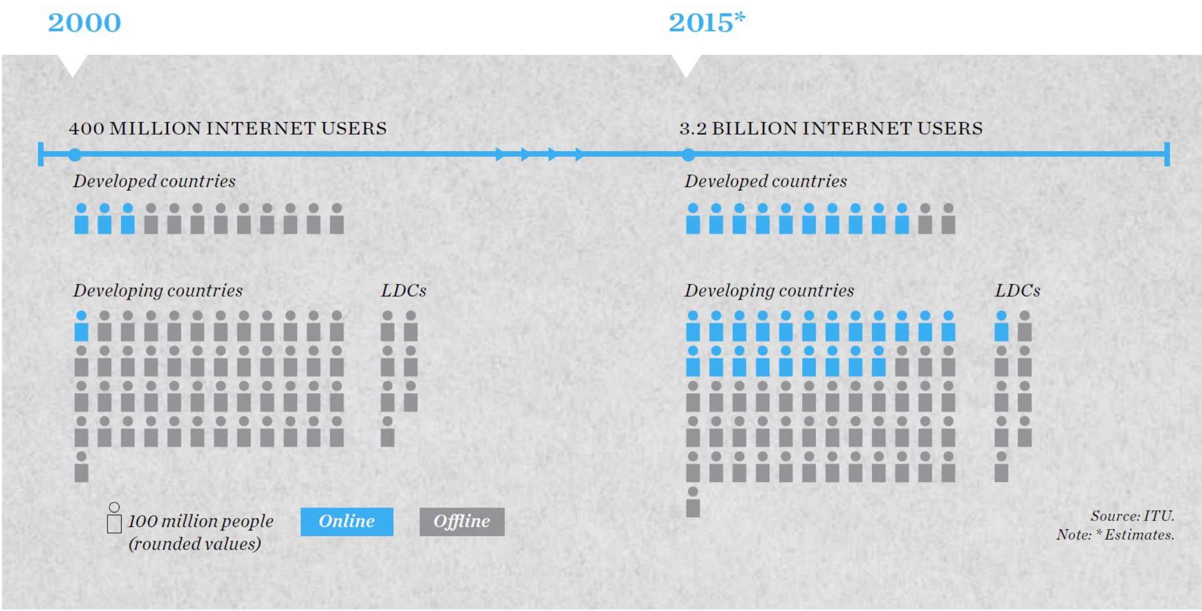


Figure 1.1: ICT progress in last 15 years, huge increase in internet users, LDCs stands for Least Developed Countries, Source[ITU15]

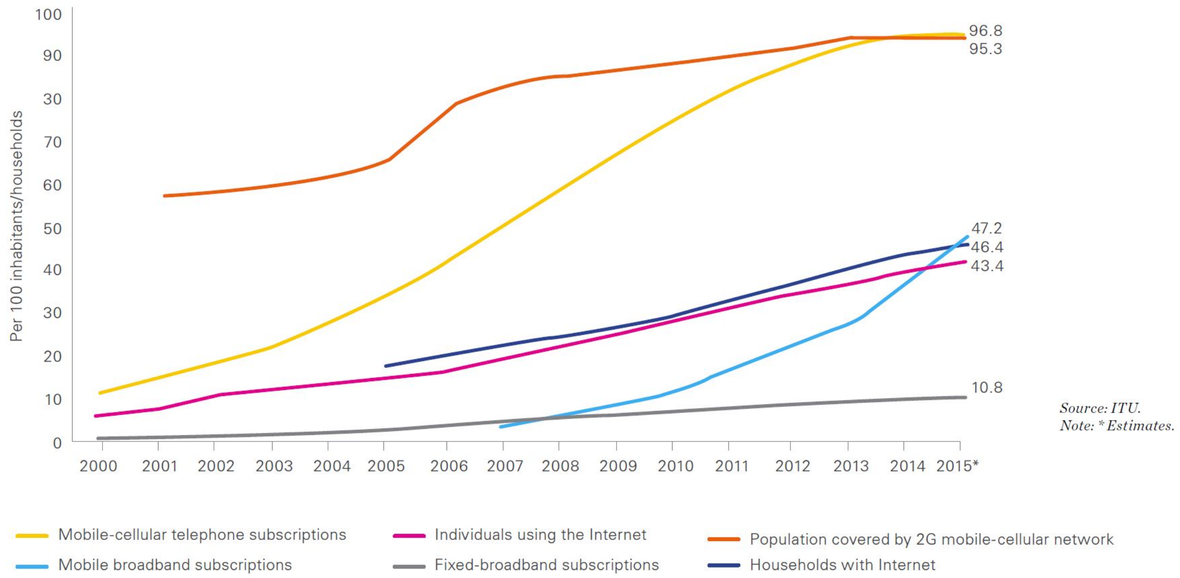


Figure 1.2: Progress made world wide from year 2000 till 2015 in telecommunication arena,Source[ITU15]

- Internet access/connections at home increased from 18% in 2005 to **46%** in 2015.
- 2G mobile-cellular network coverage germinated from 58% in 2001 to **95%** in 2015.

- **7%** annual increase over the past three years in fixed-broadband and achieved **11%** penetration by end 2015

3G mobile world wide broadband coverage has also been increased to **69 %** in 2015 which was 45% in year 2011. In 2015 the 3G rural population coverage is 29% against the population of 3.4 billion, but on other side it is 89% against the population of 4 billion in urban areas, which has been duly highlighted in Fig. 1.3

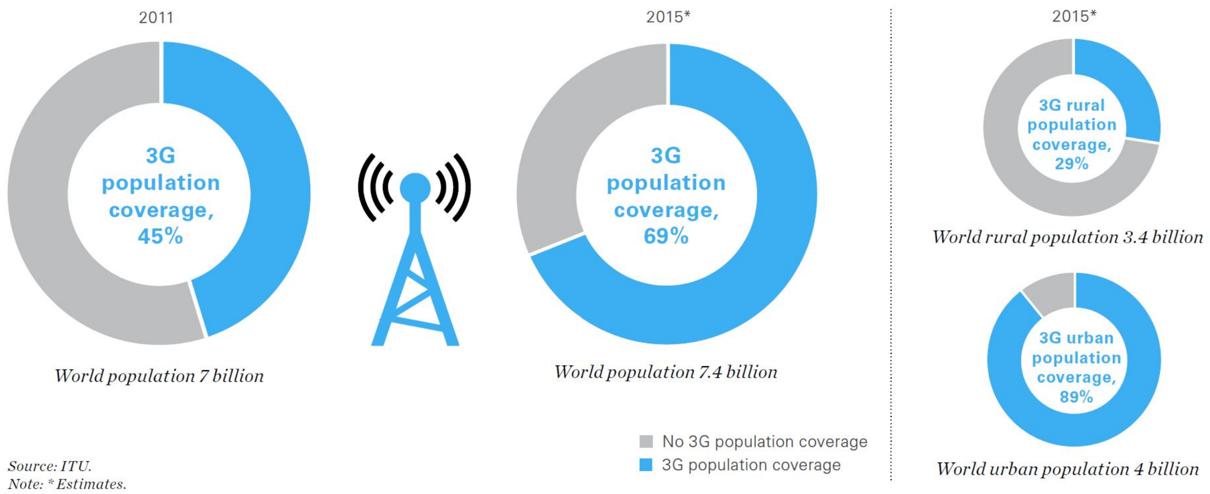


Figure 1.3: 3G mobile-broadband coverage is extending rapidly and into the rural areas,Source[ITU15]

1.2 Challenges, Goals and Future Requirements

1.2.1 Cost Efficient Fulfillment of Customers' Ever-increasing Bandwidths

Due to ICT revolution in last decade, which has been amply highlighted in Section 1.1 and also explained in [MCW$^+$14] that recent huge increase of internet users and frequent launching of more and more bandwidth focused applications all over the world has postured many demands/ challenges for operators and service providers to migrate towards new architectures/ schemes. Future access networks must able to full fill the per user ever-increasing high bandwidths requirements, while keeping Total Cost of Ownership - **TCO**, which includes the Capital Expenditure - **CAPEX**, Implementation Expenditure - **IMPEX** and Operational Expenditure - **OPEX** as minimum as possible to retain benefits. Access networks are generally more cost sensitive than aggregation and core networks, since it scales with the number of areas required to be served, moreover its cost is shared among less number of users and its expenses should be affordable for majority of the customers to make it a strong business case.

1.2.2 LIGHT is the Solution

The options available for access networks are copper, wireless and fiber optics. The most viable solution available to meet the challenges/ goals and to full fill the future requirements lies in **LIGHT!!**. Fiber optical networks are able to meet high bandwidth requirements i.e 1x optical cable can support more than **50 Tbps** as shown in Fig. 1.4, (Original source: [Mac14]). Furthermore it is energy efficient, offers low signal attenuation, immune to electromagnetic interference and has low space requirements.

Operators and service providers aim to maximize the number of services to gain more and more market share, thus more profit. More services require more bandwidth and to meet this operators have to think and take necessary proactive steps. One of the most viable solution is the deployment of optical fiber deeper to curb to offer high BW to end users/customers, which enables network future proofing, provides network reliability, reduces operational expenses and enhances revenues opportunities and thus makes it a strong business case.

1.2.3 Targets to be Achieved

As bandwidth requirements of today's end user will increase to almost 300-500 Mbps per residential user by 2020 [FBC+15] this is forcing operators to upgrade their already deployed legacy optical access networks, e.g., by reducing the splitting ratio of their deployed Gigabit-enabled Passive Optical Network (GPON), or to migrate to new solutions, e.g., next generation PON2 (NGPON2) as highlighted in this ITU-T Study Group 15, Question 2, [ITU15c]. It is also pertinent to highlight that optical access networks are the only viable solution to be deployed in the last mile segment, due to its potential to offer very high capacities and long reach, as dilated upon and very well explained in [Koo06] and [J.P08]. Different access network structures have been proposed and implemented to full fill the specific needs of access networks/ service providers, like Fiber to the Cabinet -FTTC, Fiber to the Building - FTTB, Fiber to the Home - FTTH etc, usually it refers as FTTX. As we already know that comparing Active Optical Network with Passive Optical Network (PON), PON reduces the amount of fiber, transceivers and line terminals. Different technologies are being used as N customers are sharing the same fiber. The most common in use are TWDM and WDM, the most promising solution is TDM+WDM called Hybrid PON or HPON (more details will be covered in subsequent sections). The emerging and still developing technologies includes OFDMA, OFDMA+TDM+WDM etc.

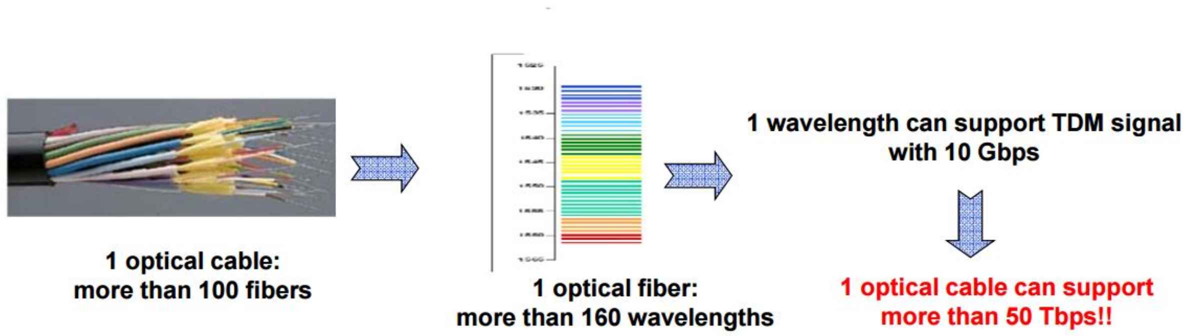


Figure 1.4: Which is the capacity of an optical fiber/cable? Source: [Opt]

1.3 State of the Art

1.3.1 Next Generation Optical Access (NGOA) Networks

As highlighted in Section 1.2, the solution to our ever increasing bandwidth requirements lies in **Optical Access Networks (OAN)** and several promising, cost effective and energy efficient solutions are available e.g., NGPON2 [FBC+15], WDMPON [GRA+11], HPON [MCW+14]. All these multistage architectures fulfills the NGOA networks requirements i.e., higher bandwidth, longer reach, larger client count and heterogeneous end points. However in this thesis we will focus on Hybrid Passive Optical Networks (HPON), which uses WDM to increase the capacity using an additional wavelength layer, while TDM to improves the scalability and leads to flexible resource utilization as highlighted and shown in Fig. 1.5.

1.3.2 Fulfillment of NGOA Requirements

As discussed NGOA demands longer reach and larger client count which is made possible by Nodes Consolidation (NC). The demand of heterogeneous endpoints have been realized through Fixed Mobile Convergence (FMC). Details of both of these very important concepts are as under:-

Nodes Consolidation (NC)

One of the most promising solution to reduce cost is **Large Coverage** means long reach from originating node till the farthest terminating node or in other words from stem to the farthest leaf called optical reach and besides this maximize the total number of users/

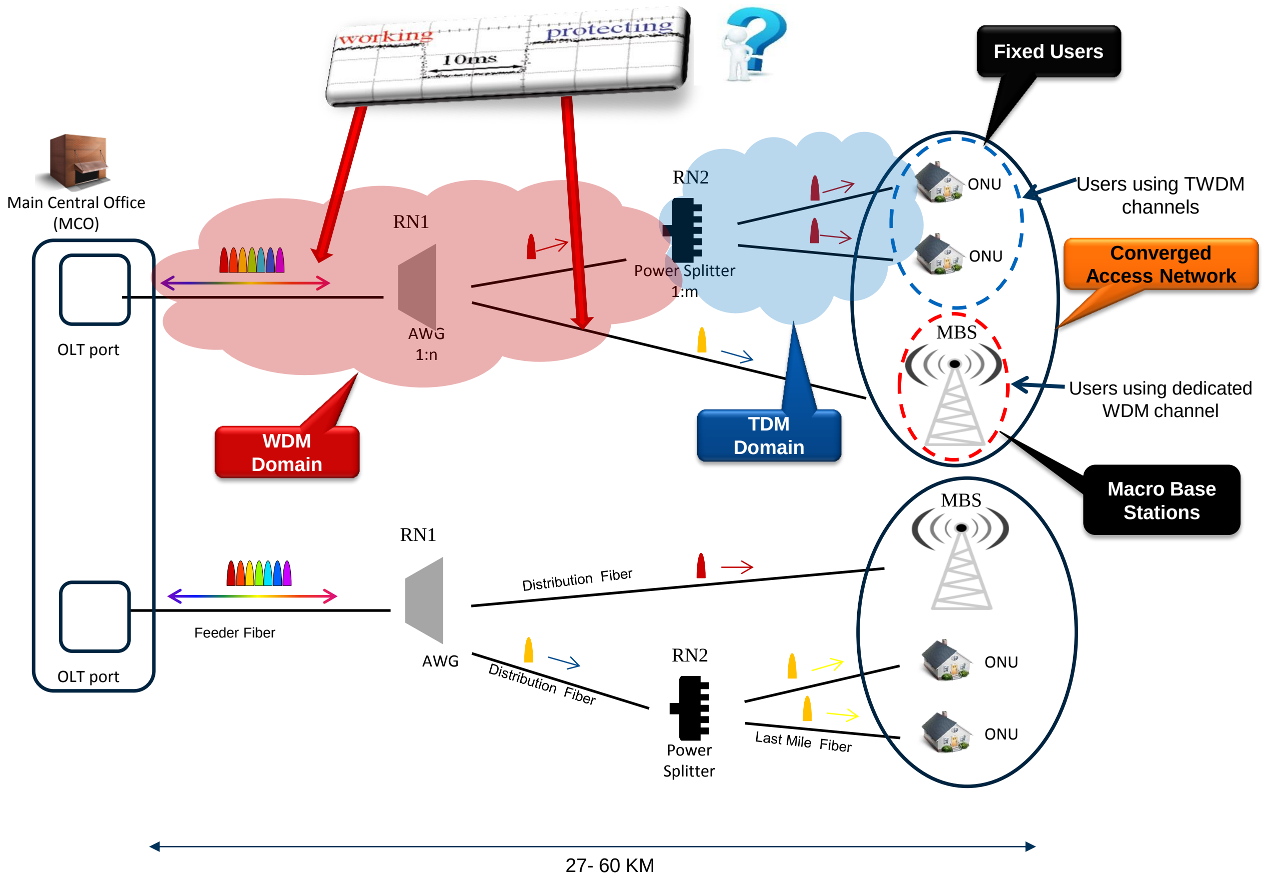


Figure 1.5: HPON architecture and requirement of highly reliable and cost-efficient protection scheme. Converged access network is connecting fixed users as well as macro base stations. **Acronyms:** OLT, Optical Line Terminal: RN1, Remote Node 1: AWG, Arrayed waveguide Grating: WDM, Wavelength Division Multiplexing: RN2, Remote Node 2: TDM, Time Division Multiplexing: ONU, Optical Network Unit.

number of leafs per service area. Large coverage makes it possible to reduce the total cost of the network by merging several central offices (COs)/ originating nodes into a single CO or lesser number of COs, this is often referred as node consolidation in the literature as highlighted in Fig. 1.6. Nodes consolidation merge metro and access networks into one network serving thousand of users/ customers due to it's larger coverage, this has substantially reduced the operational expenditure per user as explained in [BGH+11] and [Fin09]. Resultantly passive reach has increased from a few kilometers up to several tens of kilometers and large coverage with tens of thousands of users in one service area.

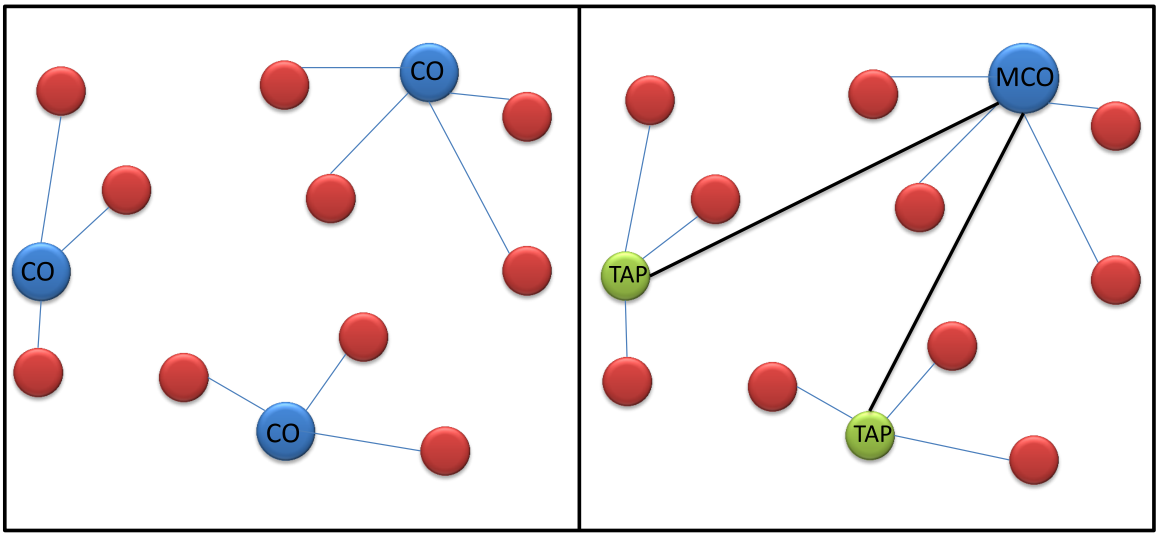


Figure 1.6: Optical access network (a) without node consolidation - 3x Central Offices,(b) with node consolidation - 1x Main Central Office or MCO and 2x TAPs (Traffic Aggregation Points), Red dots are the terminating/ end points

Fixed Mobile Convergence (FMC)

Based on a study presented by Ericsson [Eri14] has forecasted that data traffic from mobile devices is expected to increase 8 times from 2014 till 2020. This means that a large part of broadband access will be served by the wireless networks. High performance fixed and mobile networks are expected to co-exist and most importantly **should support each other to minimize TCO and optimize performance**. Hence, the **Fixed and Mobile Convergence** (FMC) has emerged as an important and interesting research topic in the recent years. Because of the intended advantages service providers around the world has now purchasing and getting the license of provisioning of both fixed and mobile services in a particular area/ country e.g., vodafone Germany [Vod]. Considering its importance several large scale projects funded by European Union are trying to address FMC e.g., **COMBO** [EUF13], **iCirrus** [ici], **CHARISMA**[cha] and **Xhaul** [Xha]. The brief summary of each is as under:-

- **COMBO**. COnvergence of fixed and Mobile BrOadband access/aggregation networks (COMBO) proposes new integrated approaches for FMC broadband access / aggregation networks for different scenarios (dense urban, urban, rural). COMBO architectures are based on joint optimization of fixed and mobile access / aggregation networks around the innovative concept of Next Generation Point of Presence (NG-POP).
- **iCirrus**. intelligent Converged network consolidating Radio and optical access aRound USer equipment (iCirrus) aims to examine the advantages and challenges

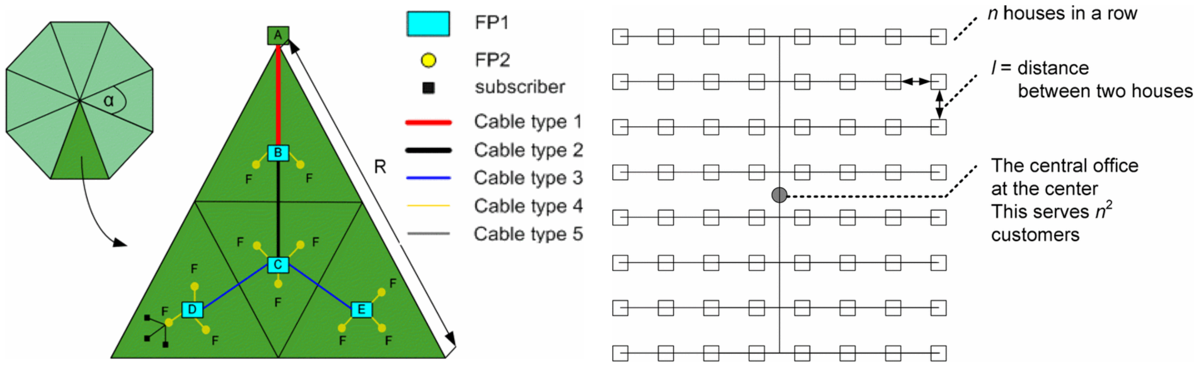
of bringing an Ethernet-based optical fibre fronthaul to fifth-generation (5G) mobile networks, considering the benefits of such an architecture and its effects on performance on key 5G service aims such as device-to-device (D2D) communications and mobile cloud networking

- **CHARISMA**. Converged Heterogeneous Advanced 5G Cloud-RAN Architecture for Intelligent and Secure Media Access (CHARISMA) proposes an intelligent hierarchical routing and paravirtualised architecture that unites two important concepts: devolved offload with shortest path nearest to end-users and an end-to-end security service chain via virtualized open access physical layer security (PLS). The CHARISMA architecture meets the goals of low-latency ($<$ 1ms) and security required for future converged wireless/wireline advanced 5G networking. This provides a cloud infrastructure platform with increased spectral and energy efficiency and enhanced performance targeting the identified needs for 1000-fold increased mobile data volume, 10-100 times higher data rates, 10-100 times more connected devices and 5x reduced latency.
- **Xhaul**. The 5G Integrated fronthaul/backhaul transport network (Xhaul) aims at developing a 5G integrated backhaul and fronthaul transport network enabling a flexible and software-defined reconfiguration of all networking elements in a multi-tenant and service-oriented unified management environment.

1.3.3 FTTX Modeling and Dimensioning Tool

Planning and dimensioning of access networks should be as accurate and realistic as possible. Primarily two approaches are available, one is geometric and other is geographic. **Geometric models** like Triangle model [MKC$^+$13], Simplified Street Length Model [MKC$^+$13], Gabriel graphs [MV15] and TITAN [OZG$^+$93] are easy to use but may lead to inaccurate results/ estimations especially for uneven distributed data, which is the case in most practical cases [MKC$^+$13]. Geometric models are using only the area-wide average parameters, and not their local characteristics. In practice, the areas where FTTH networks are deployed are not evenly populated and the fiber trenching is constrained by various local conditions, e.g. parks, railways or highways. This is a reason why the geometric models can not contribute to the accurate estimation of the deployment cost, as truly highlighted and explained in [MKC$^+$13].

Hybrid solutions like [MV12] which uses GIS information and prepare very complex graphs, these are more accurate/ realistic than geometric model but are specific only to selected area of study and can not be implemented as a general solution. **Geographic models** are the most preferred by operators, because of its highly accurate and realistic results which are most desired by any network operator for selection of right technology and weighing vital expenditures like Capital Expenditures (CAPEX), Implementation Expenditures (IMPEX) and Operational Expenditures (OPEX). This methodology directly operates on



(a) Triangle Model (TM) (b) Simplified Street Length (SSL) model

Figure 1.7: Geometric Models [MKC+10]

geospatial representation of the service area, provides valid access network topologies, and provides most reliable and accurate base for trenching and fiber length and for count of Remote nodes. Geographical models also allows seamless management of the entire integrated infrastructure which results in speedy layout of network infrastructure and significantly reduce IMPEX. Some work has been presented on access planning using geographic models ([MKC+10], [MGM] and [KMAG12]). However all of them miss most of the following aspects such as (i) comprehensive step by step dimensioning process description, (ii) completeness of information (e.g. trenching diameter/ depth, conduits/ tubes sizes), (iii) methodology to remove any inconsistent data from geographic database (e.g., like free standing features, dangles, cul-de-sacs), (iv) coping with two or more stage splitting of NGOA networks, (v) application to Fixed Mobile Convergence (FMC), (vi) details of the clustering methodology incorporating real network distance instead of euclidean, and considering RNs splitting ratio and usage.

1.3.4 Resilience and Different Protection Schemes

In this era of smart cities, smart roads, smart cars etc. customers are more and more dependent on uninterrupted access to the Internet services. In the future they will not accept and tolerate long service unavailability and they will easily switch to other more reliable service providers. **Customers' satisfaction** has become a most dominating factor in today's marketing policy, as a result, it has become vital for every operator to offer an acceptable level of reliability performance in their access networks in addition to their already protected aggregation and core networks.

Several protection schemes have been proposed and analyzed in the literature for protection of critical components like MCO or FF or DF etc or combination of these based upon fiber or microwave solution. Any protection scheme which provides protection from originating node (OLT) till final terminating node (ONU) is considered as E2E solution. A fiber based solution has been proposed [SHLC05] basing on two self-protecting architectures for the bidirectional WDM PON. It utilizes different optical bands for adjacent Optical Network Unit (ONU) groups, the disrupted signals can be restored through the neighboring fiber links without duplicating the entire fiber links. This architecture requires wavelength assignment plan in which available wavelengths have been equally divided into two bands thus only half of the wavelengths can be used in any of the ODN. A hybrid protection scheme [YSWC14] based upon fiber for protecting FF and microwave links for protecting DF, it was shown that it provides relatively high flexibility and reliability performance while maintaining low complexity, this scheme neither put light on how radio planning and clear LOS analysis will be done for installation of microwave antennas nor its suitability to particular area/ scenario like Dense Urban (DU), Urban (U) or Rural (R) areas.

1.4 Scope, goals and approach

A Technical University Munich (TUM) student in year 2014-15 put in an excellent effort to introduce one of the dimensioning tool for this purpose as explained in [MD15]. This tool was completely developed in Matlab and was using Open Street Maps (OSM) as database source. This thesis is based on this tool and the objective was to use ArcGIS [Arc15b] in order to further enhance the dimensioning tool that should take the input of any area where we have to deploy the network and the output should be the number of required stores for the ODN and their exact placement/ dimension including duct, fibers and conduits with the aim to reduce the overall cost per user. Tool should also explain the detailed step by step implementation methodology of dimensioning and planning process. Besides this, efforts must be made to improve the clustering methodology which should use actual network distance rather than euclidean and should also allow to control the cluster capacity and quality i.e., compactness. The dimensioning tool should also allow to implement and analyze following different fiber and microwave protection schemes as shown in Chapter 3, to find most appropriate and cost effective solution for DU, U and R areas

- Disjoint Fiber Protection (DFP)
- Ring Feeder Fiber Protection (RFFP)
- Inter MBS DF Protection (IMBSP)
- Ring Inter MBS Protection (RIMBSP)
- Microwave MBS Protection (μWP)

The approach to solve these problems and to develop state of the art dimensioning tool which should be flexible enough to plan the HPCAN for different areas is the combination of numerical methods and Geographical Information Systems (GIS). We used the best of both the worlds which are Matlab and ArcGIS. The best thing is that both are compatible and anytime results can be shared and analyzed in both the domains. GIS based solutions provide more accurate planning for HPCANs and allows seamless management of the entire integrated infrastructure thus ensures and guarantees fast and up to date network rollout, which is the most desired thing for any investor/ businessman. Salient and intended advantages of this GIS approach has been explained in detail in reference paper [MGM], moreover more details will also be unfolded as we go along in the thesis report.

1.5 Structure of Thesis

The structure of thesis and subsequent work has been organized as follows; **Chapter 2** In this chapter, we will discuss about HPCAN architectures and before diving into protection schemes in next chapter we will focus on how these HPCANs are actually dimensioned. We will highlight different enhancements which has been made to improve the overall dimensioning quality. In **Chapter 3** we have proposed different end to end (E2E) protection schemes for converged access network architecture based on fiber and microwave based solutions. Protection schemes and their reliability models has been illustrated by Reliability Block Diagrams (RBD). In **Chapter 4** we have implemented the proposed protection schemes in Dense Urban (DU), Urban (U) and Rural (R) areas . Before proceeding to results and comparisons in next chapter we have defined the parameters for logical and fair conclusions about different case studies. In **Chapter 5** we have compared and analyzed all the proposed protection solutions and their suitability to different areas based on various parameters including Component cost, Power consumption, Connection availability, Indirect improvement in connection availability of residential users, Failure Impact Factor (FIF), Protection fiber length/Macro Base Stations (MBS) and the Additional fiber required for working paths from reference scenario. Comparative and consolidated performance analysis of each protection scheme has also been carried out with even and uneven weights distribution to select the best protection scheme in a particular scenario/ area. In **Chapter 6** Conclusions have been drawn and future outlook has also been proposed.

Chapter 2

Hybrid PON Converged Access Networks

In this chapter, we will discuss about Hybrid PON Converged Access Networks (HPCANs) architecture, its intended advantages and how these networks are actually dimensioned. We will also highlight how our GIS based dimensioning tool works, with special focus on its different enhancements, which has been made to improve the overall dimensioning quality.

2.1 Architecture and Scenario

The HPCAN architecture is presented in Fig. 2.1. The Optical Line Terminal (OLT) is placed at the Main Central Office (MCO), which is one of the central office kept after nodes consolidation. As explained in *Chapter 1*, Nodes consolidation is the process in which several conventional/ old central offices (CO's) have been merged in one MCO, resultantly deployment and operational cost has been decreased to large extent. This all has been made possible due to increase in maximum reach of HPON from OLT till ONU and number of subscribers per FF line. This is how MCO is able to serve the much larger service area and more number of customers as mentioned in [MAH15] ,but this decreased the network resilience and reliability due to larger distances and dependability of more number of users on single component/ installation. The scenario as depicted in Fig. 2.1 has M number of connected Arrayed Waveguide Grating (AWGs), N number of Power Splitters (PS) and O number of Macro Base stations (MBS). This architecture has two stages of remote nodes: The first stage uses WDM filters (e.g., AWGs) for de-/multiplexing the downstream and upstream wavelengths. Compared to PS, AWG has lower insertion loss, avoids the necessity of Optical Network Units (ONUs) with tunable filters to select the assigned wavelength and adds system integrity through wavelength separation. The second stages of remote nodes are MBS and PSs. Each MBS has dedicated wavelength from its respective AWG, whereas at PS per-wavelength Time Division Multiple Access (TDMA) scheme is used to provide access to a number of subscribers depending on the PS splitting ratio. System will guarantee provisioning of higher data rate of almost 10 Gbps to each MBS or business user and lower data rate of 300-500 Mbps to each residential user. To summarize the

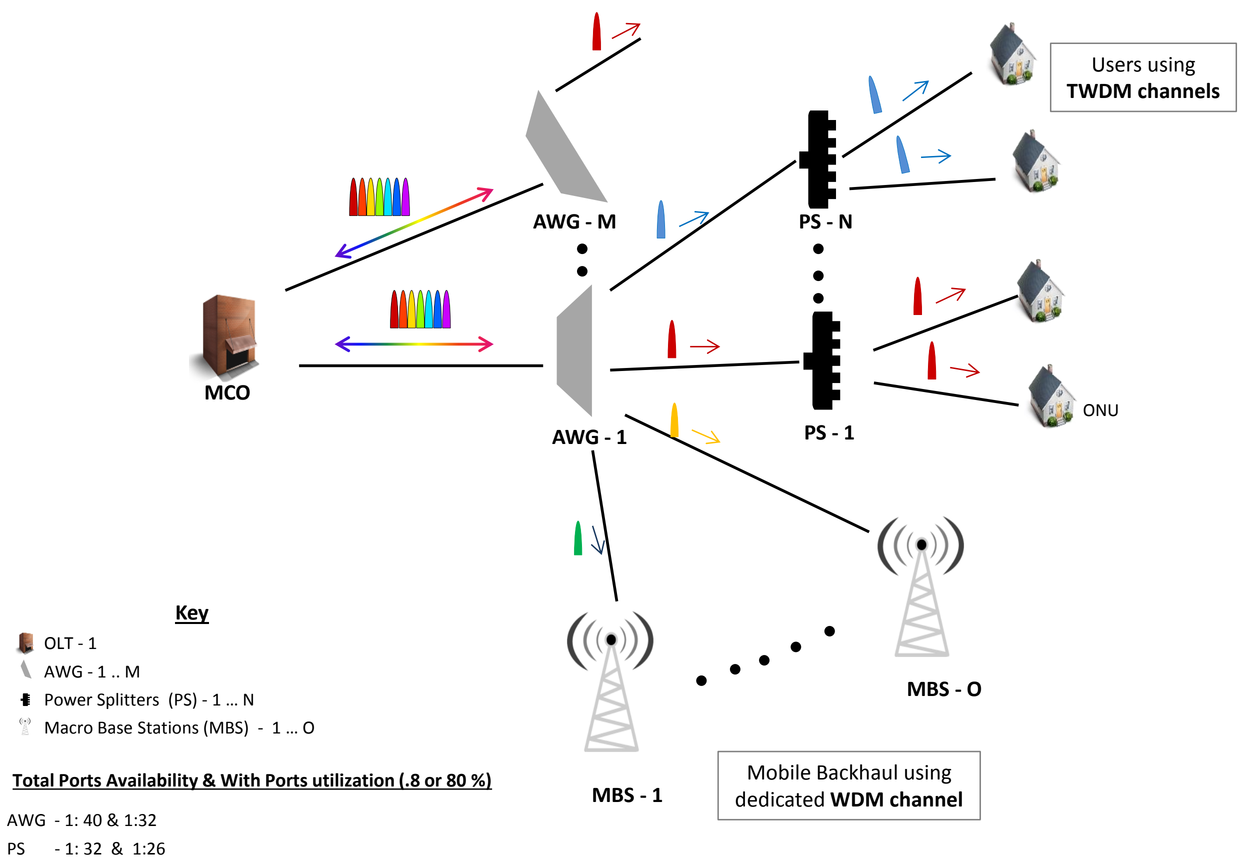


Figure 2.1: HPCAN Scenario - Details of different components and their positioning

advantage of having WDM is the increase of spectrum utilization, while the advantage of TDM is the high scalability and flexibility on bandwidth allocation. This architecture has a tree topology where the OLT is at the root and is connected to AWGs, which are further connected to MBSs and PSs. Multiple type of users with different BW requirements can be connected to the same MCO e.g., Mobile xhauling (front and backhaul), business and residential users. Three fiber sections are considered and depicted in Fig. 2.2:

- Feeder Fiber (FF) is the fiber from the MCO to AWG.
- Distribution Fiber (DF) is the fiber from AWG to PS or MBS.
- Last Mile Fiber (LMF) is the fiber from PS to the residential users ONU.

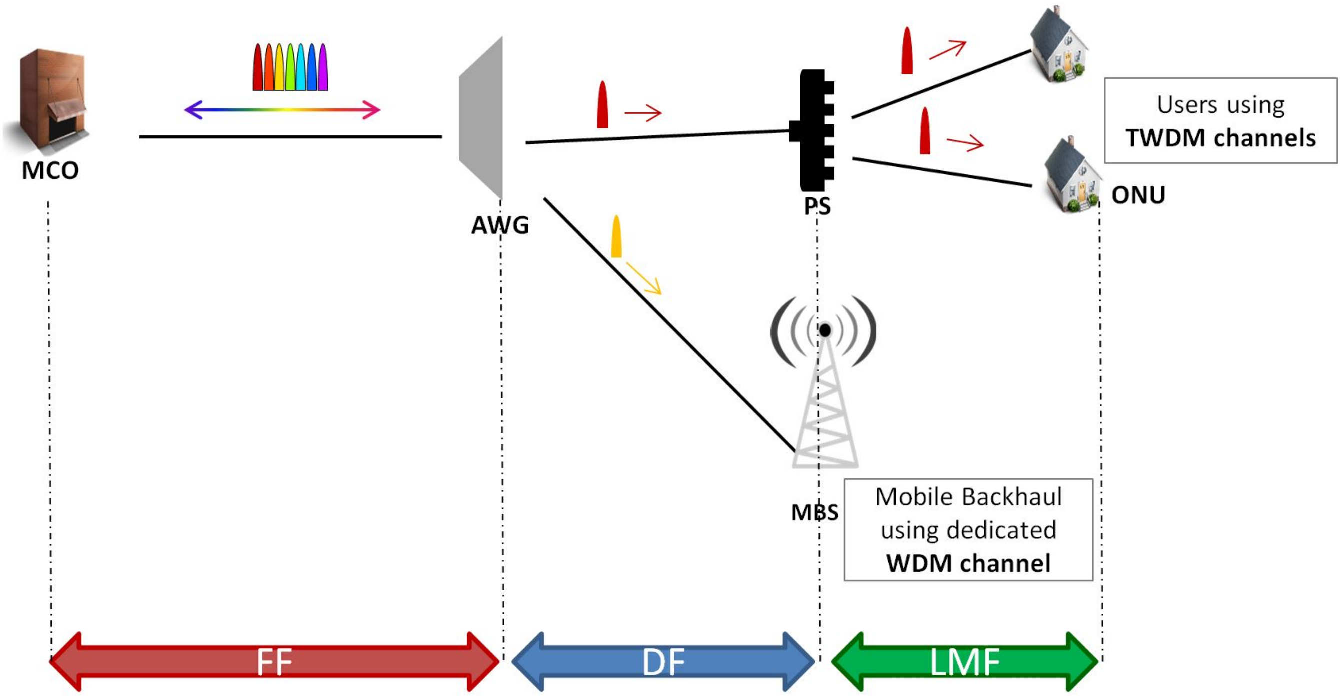


Figure 2.2: HPCAN - Fiber layout

2.2 Benefits and Intended Advantages

As already discussed, in this thesis, next generation Hybrid PON using combined Wavelength Division Multiplexing (WDM) and Time Division Multiplexing (TDM) is considered as the most viable transport solution for Converged Access Networks, which is referred to as Hybrid PON Converged Access Networks (HPCANs). The main advantages of such architecture are as under:-

- It can reuse existing Optical Distribution Networks (ODN) of e.g., GPON.
- It can offer two different bit rates (high bitrate for dedicated wavelength, and lower bitrate for end users sharing a wavelength by TDM).
- It supports smooth migration from legacy GPON.
- Its longer transmission reach allows node consolidation (i.e., reduction of central offices).

2.3 Planning Methodology and Enhanced Dimensioning

In short, the dimensioning starts from area selection followed by its' parsing, after this we will have details of buildings and roads infrastructure of our area of study. After this Macro Base Stations distribution will be done.Two stage clustering is performed for placement of Power Splitters (PS) and Arrayed Wavelength Grating (AWG). The final step is fiber layout to connect all the components from OLT till ONU in a tree topology, which is the most compact and cost efficient topology and allows long reach.The detailed dimensioning is explained in subsequent subsections.

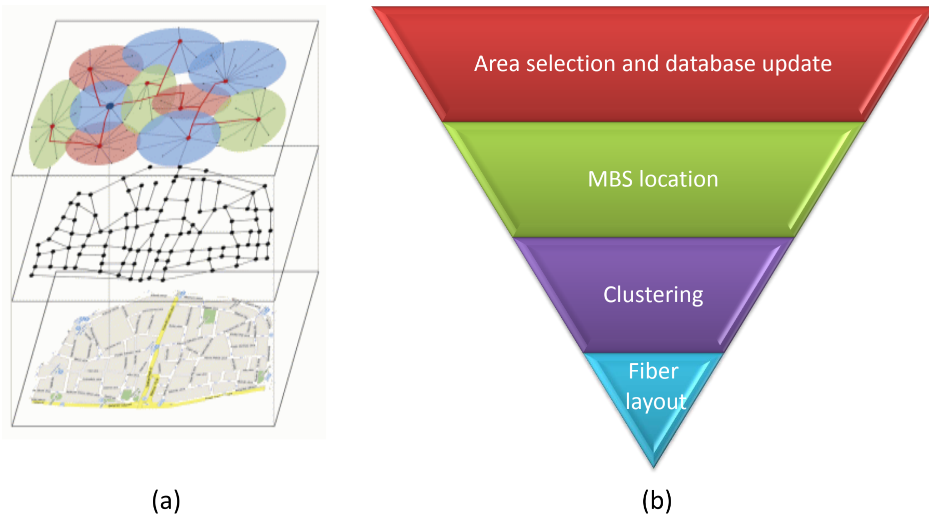


Figure 2.3: General overview of planning methodology(a) GIS results,Original source: [MKBP11](b) Major Steps

2.3.1 Area Selection and Database Update

In order to have a realistic building distribution, Open Street Map, which is a project that allows the creation and provision of free geographic data anywhere in the world, is used. The data of the selected area can be downloaded and the database which contains information such as buildings, streets, crossroads can be parsed as shown in Fig. 2.4. Inconsistent data such as dangles,free standing line features and cul-de-sacs are then removed/ filtered. Reference Fig. 2.5.

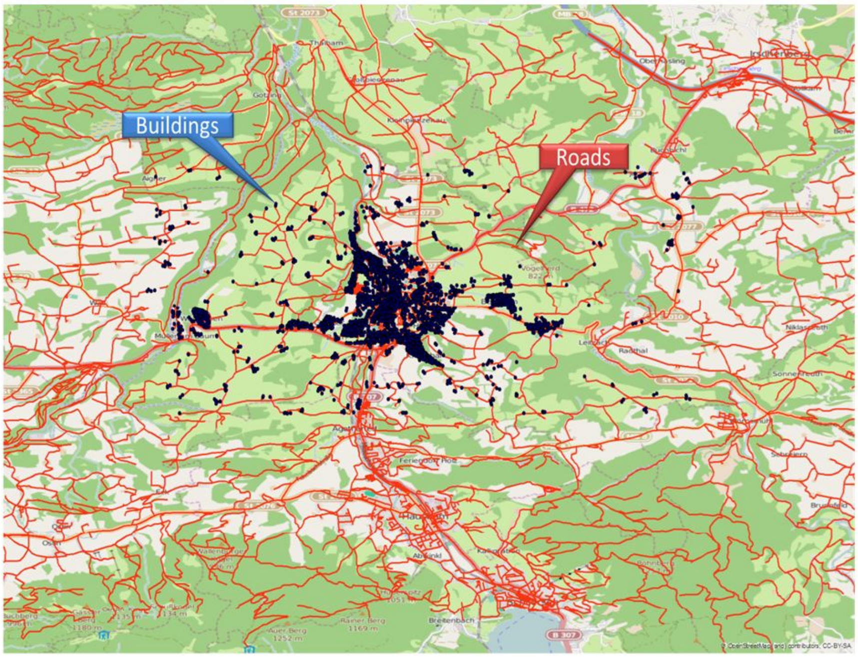


Figure 2.4: Parsed rural area with highlighted buildings (3103 buildings in black) and roads (in red)

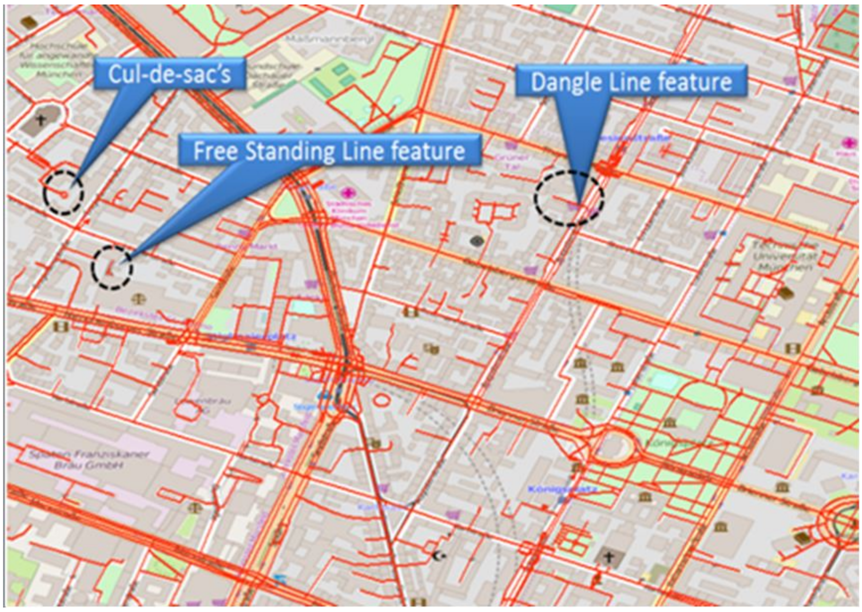


Figure 2.5: Filtration/ removal of inconsistent data

2.3.2 MBS Distribution and Placement

The location of the MBS can be either based on real MBS coordinates or on a solution provided by a planning tool. In our case, the number of MBS is determined by the area size and type (dense urban, urban or rural) and distributed in a grid with a given inter MBS distance. The exact MBS locations are adjusted to the closest street points based on the realistic assumption that operators place MBS close to roads as highlighted in Fig. 2.6. It is pertinent to mention here that fishnet polygons mesh size can be adjusted to meet the operators specific requirements considering technology used and the range of its microwave equipment.Furthermore specific individual segments of fishnet polygons can also be selected to deny MBS placement as there is no need to deploy MBS in jungles or rivers with the same density as buildup areas. The dimensioning tool is flexible enough to meet all type of these scenarios for deployment of MBS.

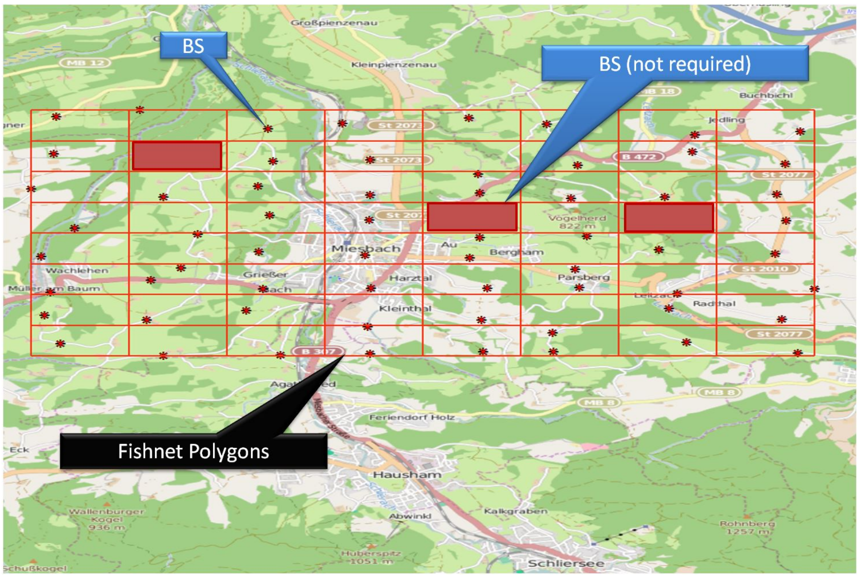


Figure 2.6: MBS distribution by fishnet polygons

2.3.3 Clustering

Once the buildings and MBS are identified and placed, a two-stage clustering is performed. The first-stage clustering groups residential users (i.e. buildings since Fiber To The Building (FTTB) implementation is considered) in clusters of size limited by the power splitter ratio and the port utilization. The centroid of each cluster is associated to a power splitter and re-located to the closest intersection node (where two or more street intersects). The second clustering groups the power splitters and the MBS in clusters of size limited by the AWG's number of wavelengths and the port utilization. The centroid of each cluster is associated to an AWG and afterwards, it is also re-located to the closest intersection node.

The clustering algorithm used by dimensioning tool mentioned in [MD15] is using KMEANS. The K-Means algorithm used to partition features into groups when No spatial constraint is selected for the spatial constraints parameter and find seed locations or use random seeds is selected for the initialization method, it incorporates heuristics and may return a different result each time you run the tool (even using the same data and the same tool parameters). This is because there is a random component to finding the initial seed features used to grow the groups. Because of KMEANS the clusters results into unequal sizes and even larger than the splitting ratio of PS or AWG due to which we have to deploy additional PS or AWG at the same remote location, furthermore it also costs another DF or FF for additional component i.e., PS or AWG. It has also been found that the additional number of PSs required due to such clustering method ranges from an increase of almost 30-40%, which forces us to explore new strategies.

To counter these problems Clustering algorithm has been designed to generate clusters of fixed size with the possibility to dynamically adjust individual cluster size and/or total number of clusters to maintain cluster quality and to reduce the required infrastructure. New clustering method has been developed in Matlab because of its superior performance to solve numerical problems (*attached as Appendix 1*). Clustering method is named as **Cost Matrix Penalty Matrix and Threshold (CMPMT)** which are actually the three steps, which it follows. Details are as under:-

- **Cost Matrix (CM)** It is the matrix which stores the distance from one cluster Element (CE), which can be building or MBS or PS to rest of the cluster elements. It can use the euclidean space or network space for finding this. Euclidean space is more fast but less accurate/ optimum, but for initial estimation and rough guess can be used as fast track approach Reference Fig. 2.7. Network space is more accurate and yields very good quality compact clusters but requires some additional steps like selection, parsing and building of larger network data set etc, as compared to first approach i.e. CMPMT Euclidean. Reference Fig. 2.8.
- **Penalty Matrix (PM)** The most important thing for any clustering algorithm is to decide from which starting node or seed master to start for building up of clusters often known as initialization method. Algorithm has been designed and made flexible enough to decide this, covering different scenarios/ area types i.e. considering distance from seed master to the farthest seed member or the aggregate distance from seed master to all its members, Ascending or Descending sorting order. We have found that for build up areas like DU, U or R areas with reasonable roads infrastructure, selecting aggregate distance with ascending order yields the best results.
- **Threshold (T)** By defining appropriate Threshold value clustering total cost can be reduced significantly i.e. the clustering algorithm will also consider the threshold value which is a user defined cost before putting the cluster element in a cluster group. This ensures that whenever the cluster quality which is its compactness goes low, clustering algorithm will not include more cluster elements, rather it will include one or more additional clusters to cover the leftover cluster elements.

The step wise implementation of clustering algorithm is shown in Fig. 2.9. To check the efficacy and comparing KMEANS, CMPMT Euclidean (CMPMT-E) and CMPMT

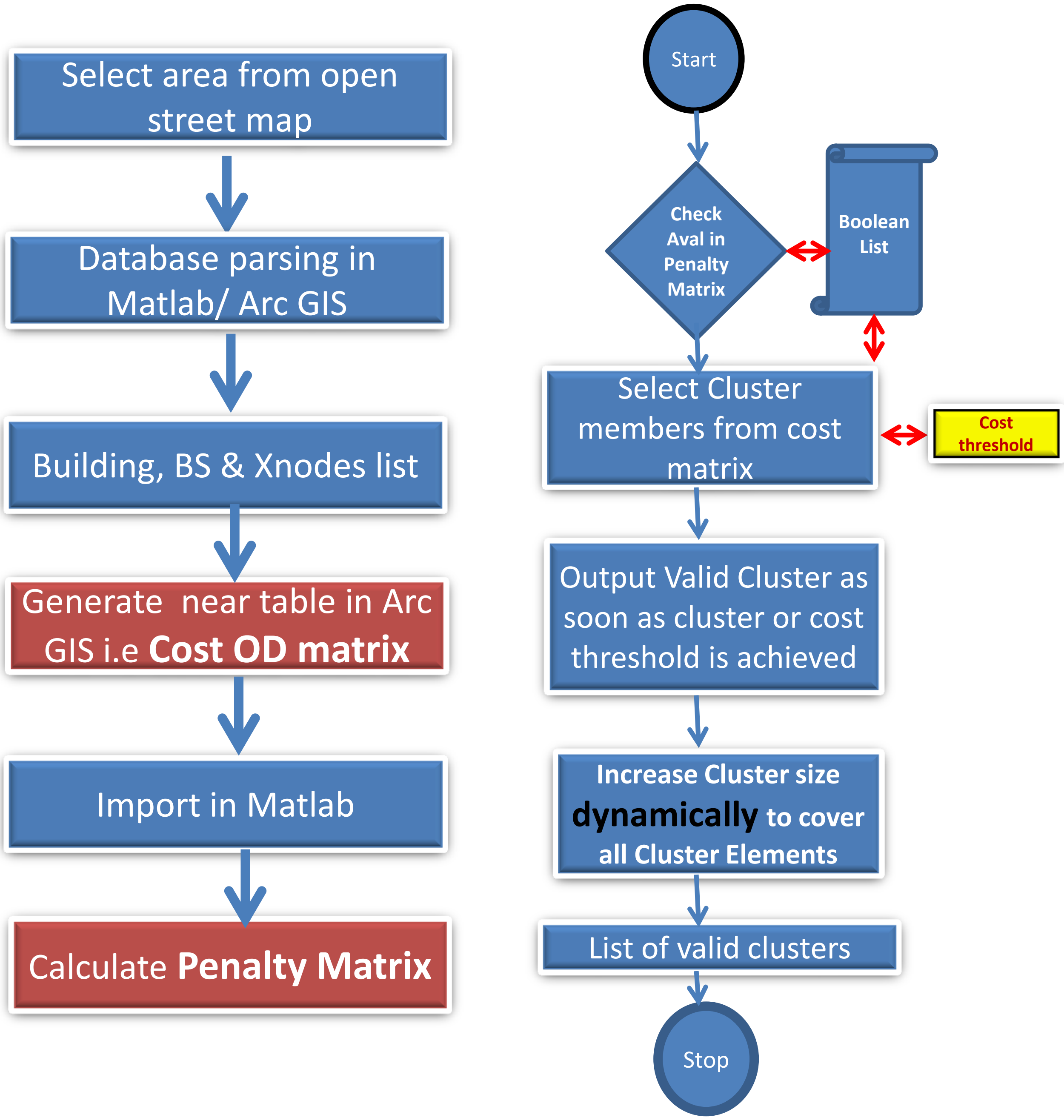


Figure 2.7: CMPMT Clustering - Euclidean space

Network (CMPMT-NW). A test case of 72 MBS has been dimensioned in Berlin area of 3 KM^2 with inter MBS distance of 200 meters. Details are shown in Fig. 2.10 it is highlighted that KMEANS and CMPMT-E requires almost the same amount of Duct but KMEANS require more number of AWGs and more length of fiber due to exceeding the cluster size more than the splitting ratio. CMPMT-NW gave best results which is 5.87% improved

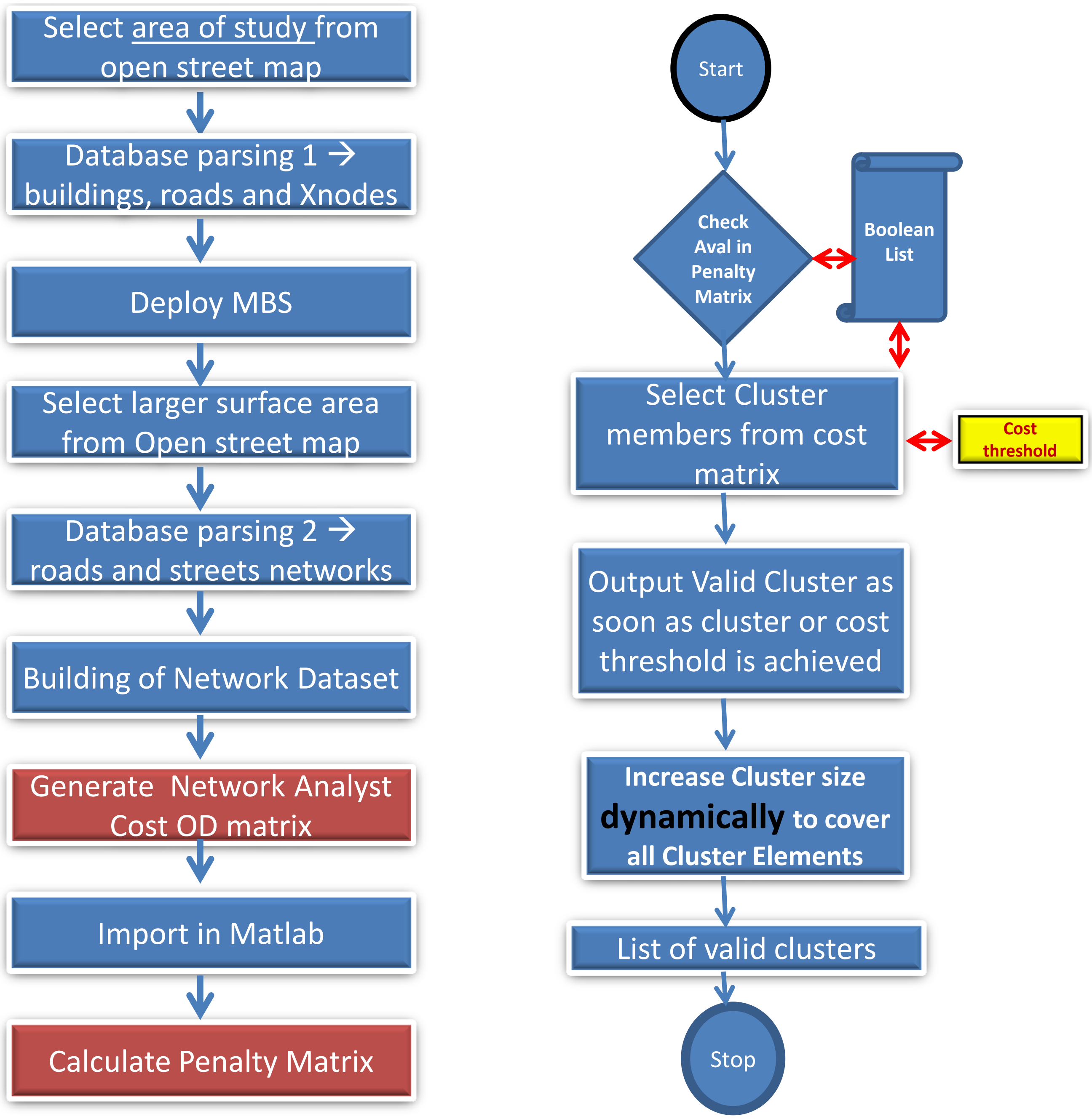


Figure 2.8: CMPMT Clustering - Network space

version of KMEANS and 4.71 % improvement has been seen compared to CMPMT-E. Last but not the least results were consistent and user has all the control to tailor the clustering, which suites best to a particular scenario. It has also been observed that all clustering methodologies yield different results thus requiring different length of Duct and fiber.

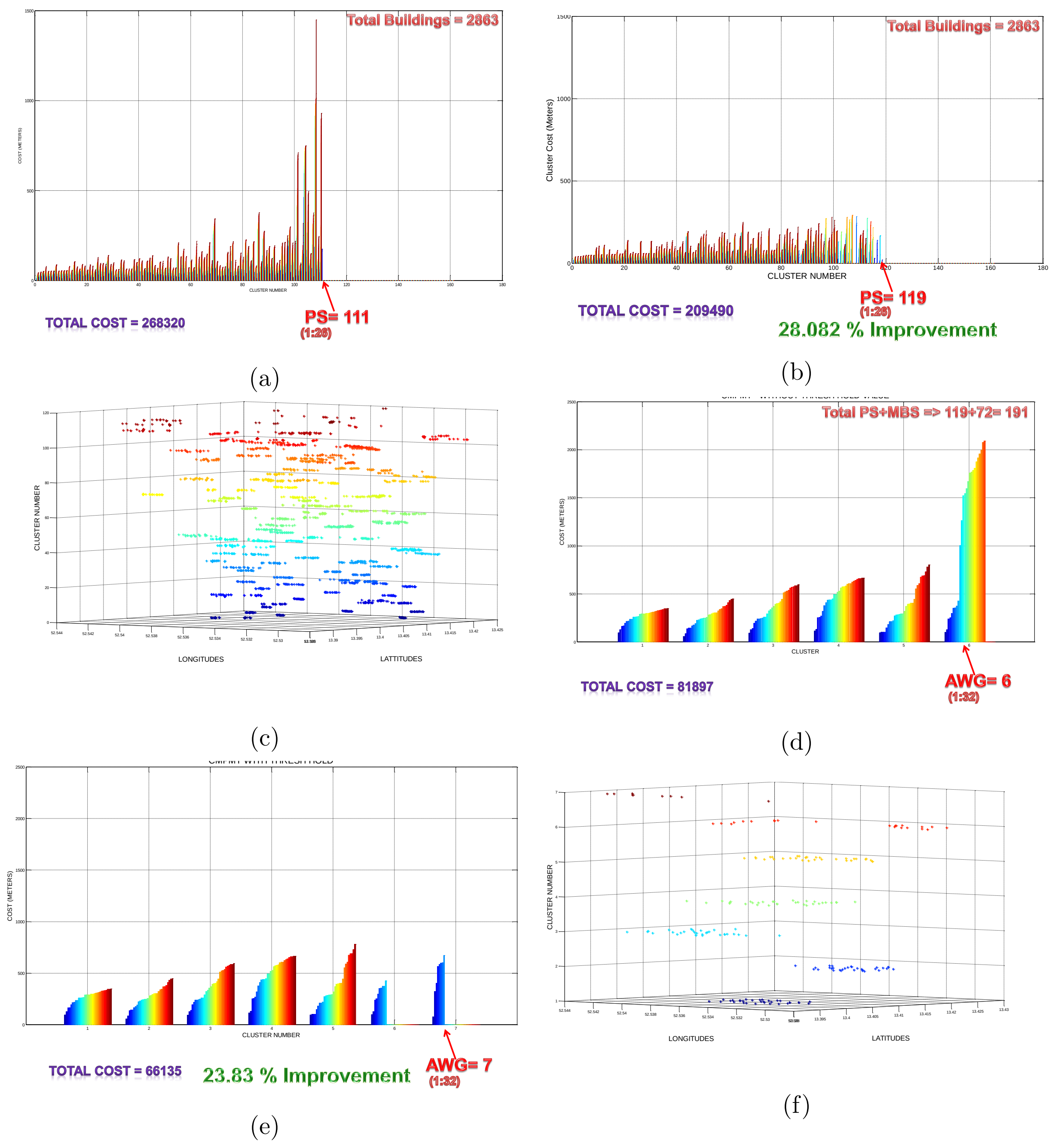
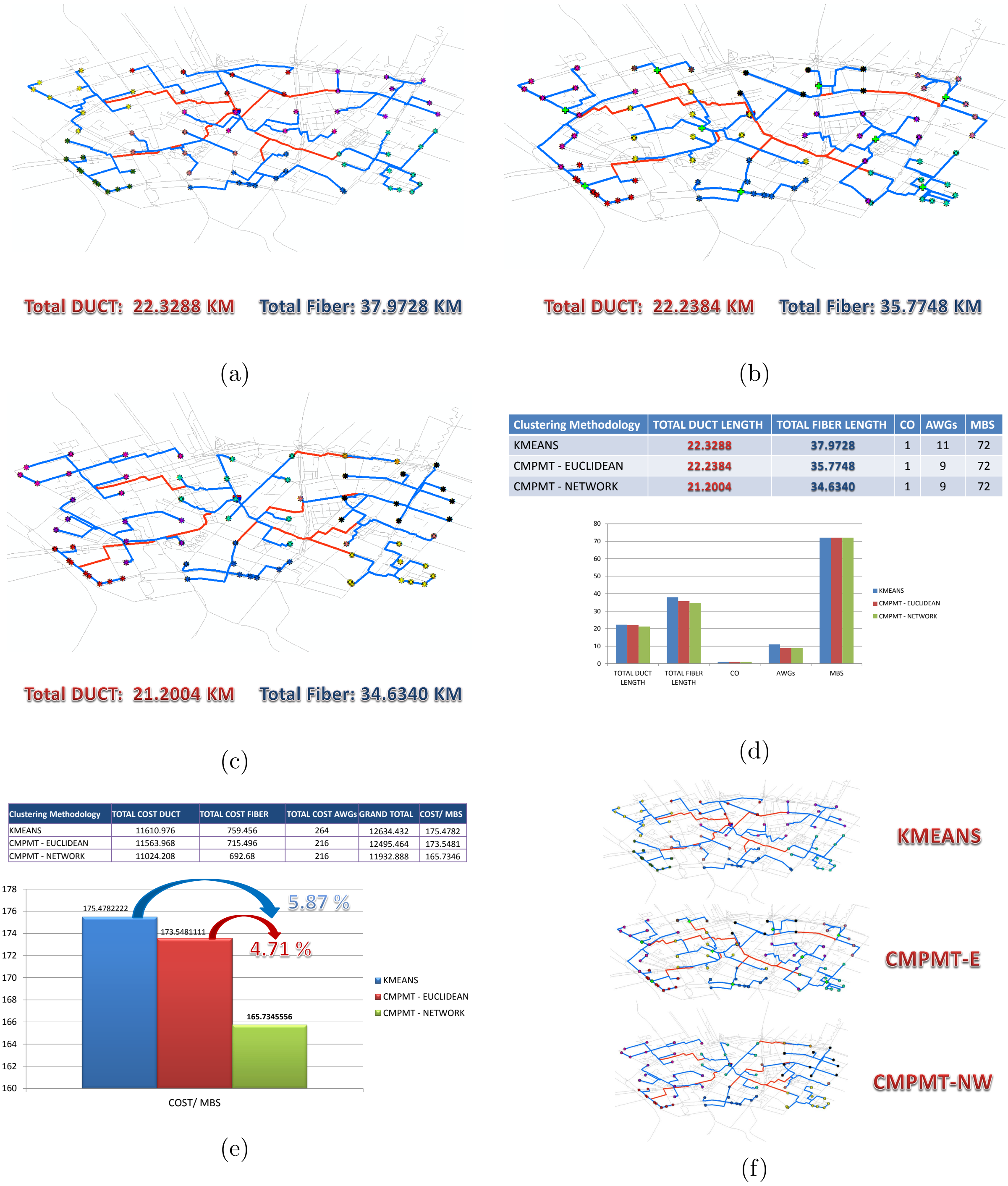


Figure 2.9: **(a)** 1^{st} stage clustering without setting threshold value **(b)**1^{st} stage clustering after setting the threshold value **(c)** 1^{st} stage clustering results **(d)** 2^{nd} stage clustering without setting threshold value **(e)** 2^{nd} stage clustering after setting threshold value **(f)** 2^{nd}stage clustering results

Clustering efficacy has also been gauged against optimal solution. Same 72 MBS have also been grouped and connected by optimization engine which solves the location allocation

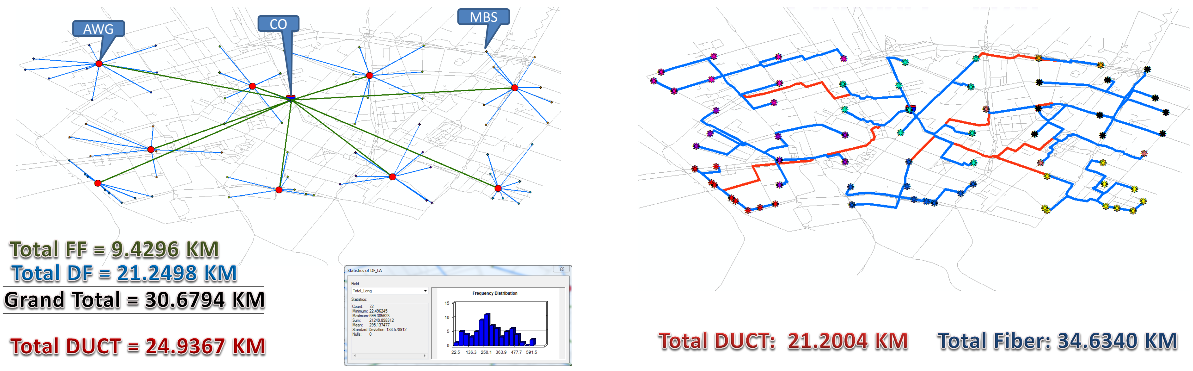


Clustering Methodology	TOTAL DUCT LENGTH	TOTAL FIBER LENGTH	CO	AWGs	MBS
KMEANS	22.3288	37.9728	1	11	72
CMPMT - EUCLIDEAN	22.2384	35.7748	1	9	72
CMPMT - NETWORK	21.2004	34.6340	1	9	72

Clustering Methodology	TOTAL COST DUCT	TOTAL COST FIBER	TOTAL COST AWGs	GRAND TOTAL	COST/ MBS
KMEANS	11610.976	759.456	264	12634.432	175.4782
CMPMT - EUCLIDEAN	11563.968	715.496	216	12495.464	173.5481
CMPMT - NETWORK	11024.208	692.68	216	11932.888	165.7346

Figure 2.10: **(a)** KMEANS Clustering **(b)**CMPMT-E **(c)** CMPMT-NW **(d)** Comparison**(e)** Cost per MBS **(f)** Layout Comparison

problem which is using Hillsman editing coupled with Teitz & Bart heuristics (details will be covered in the end of this chapter). As AWG and PS are having finite capacity so we used **maximize capacitated coverage strategy** which chooses facilities i.e PS or AWG such that all demands which are buildings and MBS can be served without exceeding the capacity of any facility. In addition to honoring capacity it selects facilities such that the total sum of weighted impedance i.e length of duct/fiber in meters is minimized. It is found that CMPMT-NW is just 12.89 % less than optimal solution, which is quite encouraging and near optimal result, furthermore enhanced dimensioning tool provides full end to end solution from initial planning till final deployment. It is also highlighted that finding optimal solution for less than 100 demands/ cluster elements is manageable but increasing demand points or facilities to select, put huge memory and computational requirements by optimization algorithm and yields no results, **which is not the case with our dimensioning tool**. As we all know demand points can be as high as 10000 (ten thousand) houses which requires almost 400 PS (1:32) i.e facilities to select. The details of results are shown in Fig. 2.11.



(a) (b)

Figure 2.11: **(a)** Optimizer Results using Hillsman editing coupled with Teitz & Bart Heuristics**(b)**CMPMT-NW results

2.3.4 Optimal MCO Placement Strategy

In our thesis we are considering that unprotected access network is already laid, so MCO location and required numbers are fixed and dictated by service provider. Our dimensioning tool however, also allows to find the optimal location and the number of MCO required to serve the area. It is pertinent to highlight that PSs and AWGs placements are dictated by clustering results as a bottom up approach but MCO placement and its required number is a top down approach. This problem can be modeled in two ways:-

- **Approach-1** When operator has already some location in the area, then we can find the optimal location and can calculate the penalty of not placing the MCO at optimal location then management can weigh the pros and corns of both locations and decide accordingly.

- **Approach -2** When operator doesn't have some location earmarked before start of project, which is the case in most of the projects. Optimal location of placing MCO can be found. Furthermore dimensioning tool also allows to see the impact of serving the area by two or more MCO this will surely decrease fiber/ duct and enhance network reliability and resilience, but operational expenditures will increase. Again management can weigh the pros and corns of both the approaches and decide accordingly either to go for 1x MCO or more.

To solve this problem we have employed ArcGIS location allocation module [Arc] which is one of combinatorial optimization, which means the number of potential solutions can grow quickly, thus exhaustive search techniques are impractical for finding good solutions within reasonable search times even a small problem like from 100 locations choose best 10 contains over 17 trillion combinations. Therefore, heuristics are employed to carry out faster searches. Location-allocation is a solver for the facility location problem which can be modeled as given N candidate facilities and M demand points with a weight, choose a subset of the facilities, P, such that the sum of the weighted distances from each M to the closest P is minimized.

The location-allocation solver starts by generating an origin-destination matrix of shortest-path costs between all the facilities and demand point locations along the network. It then constructs an edited version of the cost matrix by a process known as **Hillsman editing**. This editing process enables the same overall solver heuristic to solve a variety of different problem types. The location-allocation solver then generates a set of semi randomized solutions and applies a vertex substitution heuristic **(Teitz and Bart)** to refine these solutions creating a group of good solutions. A meta heuristic then combines this group of good solutions to create better solutions. When no additional improvement is possible, the meta heuristic returns the best solution found. The combination of an edited matrix, semi randomized initial solutions, a vertex substitution heuristic, and a refining meta heuristic quickly yields **near-optimal results**.

Both the strategies mentioned above for MCO placement and splitting the MCO into two regional MCOs have been highlighted in Fig. 2.12. Problem is designed to minimize weighted impedance, it chooses facilities i.e MCO such that the total sum of demands; which are AWGs, allocated to facility multiplied the impedance to the facility which is the network distance in meters is minimized. Dimensioning tool can also incorporate the location of international gateway exchanges or the general alignment of already laid core network for finding the best location of MCO or MCOs to minimize total length of required duct and fiber.

2.3.5 Fiber Layout

Fiber layout: Once the location and number of MCOs, PSs and AWGs have been defined, the fiber layout can be designed. Routing can be done using modified Dijkstra with duct

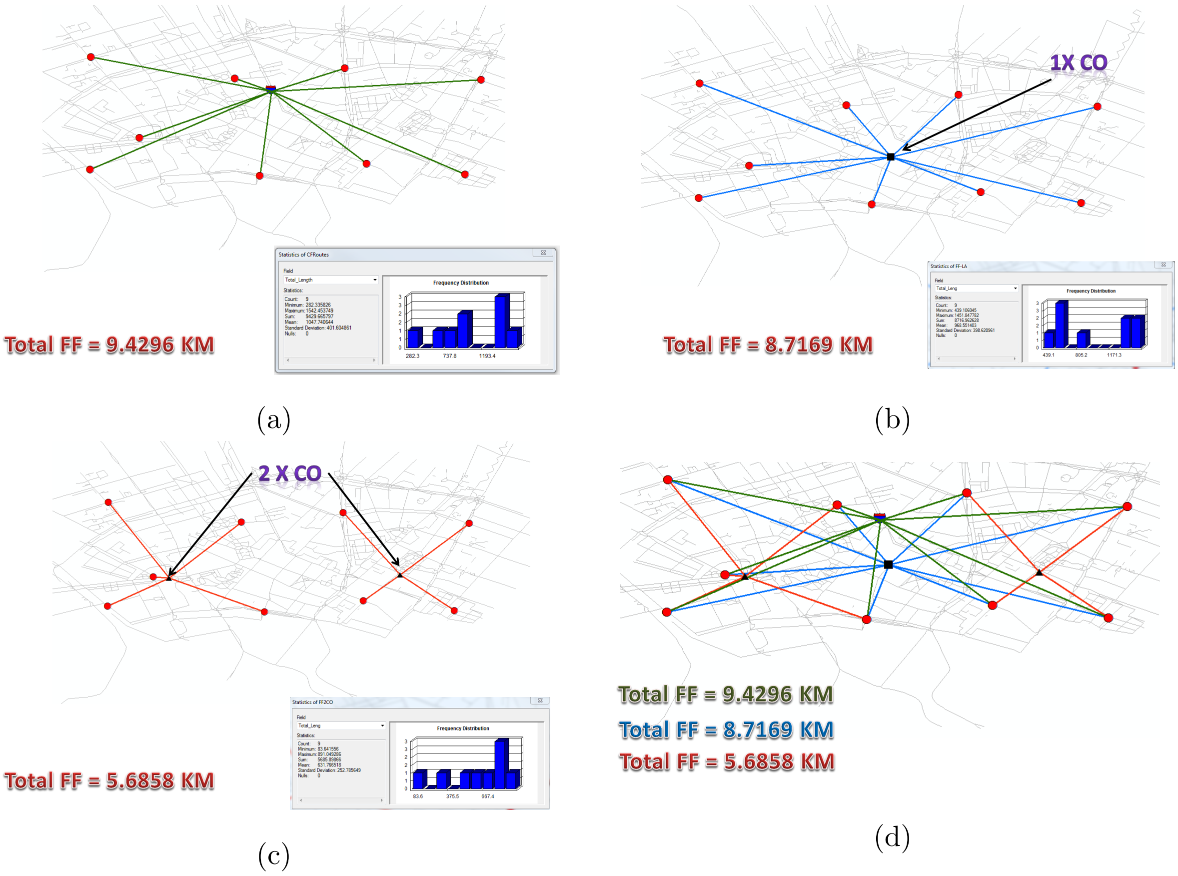


Figure 2.12: **(a)** MCO placement - Location pre decided by operator **(b)**Optimal MCO placement to reduce overall duct and fiber length from each AWG to MCO **(c)** Effect of splitting the MCO to two regional MCOs results in reduction of duct/fiber length and improving network reliability but OPEX may increase **(d)** Comparison of all the strategies

sharing or modified Dijkstra without duct sharing or Salesman Transport Problem or Ring, more details will be covered in *chapter 4* . It is performed in three steps as under and Fig. 2.13 also shows the dimensioning tool output explaining the fibers required to connect buildings and/or MBS to the MCO through different remote nodes:-

- Connect MCO to AWGs with Feeder Fibers (FFs).
- Connect AWGs to PSs and/or MBSs with the Distribution Fibers (DFs).
- Connect PSs to residential users with the so-called Last Mile Fiber (LMF).

2.3.6 Conduits Calculations

When all the fiber paths have been calculated/ identified the conduits which defines the diameter of tube containing the fiber pairs and also directly related to the how deep/ wide

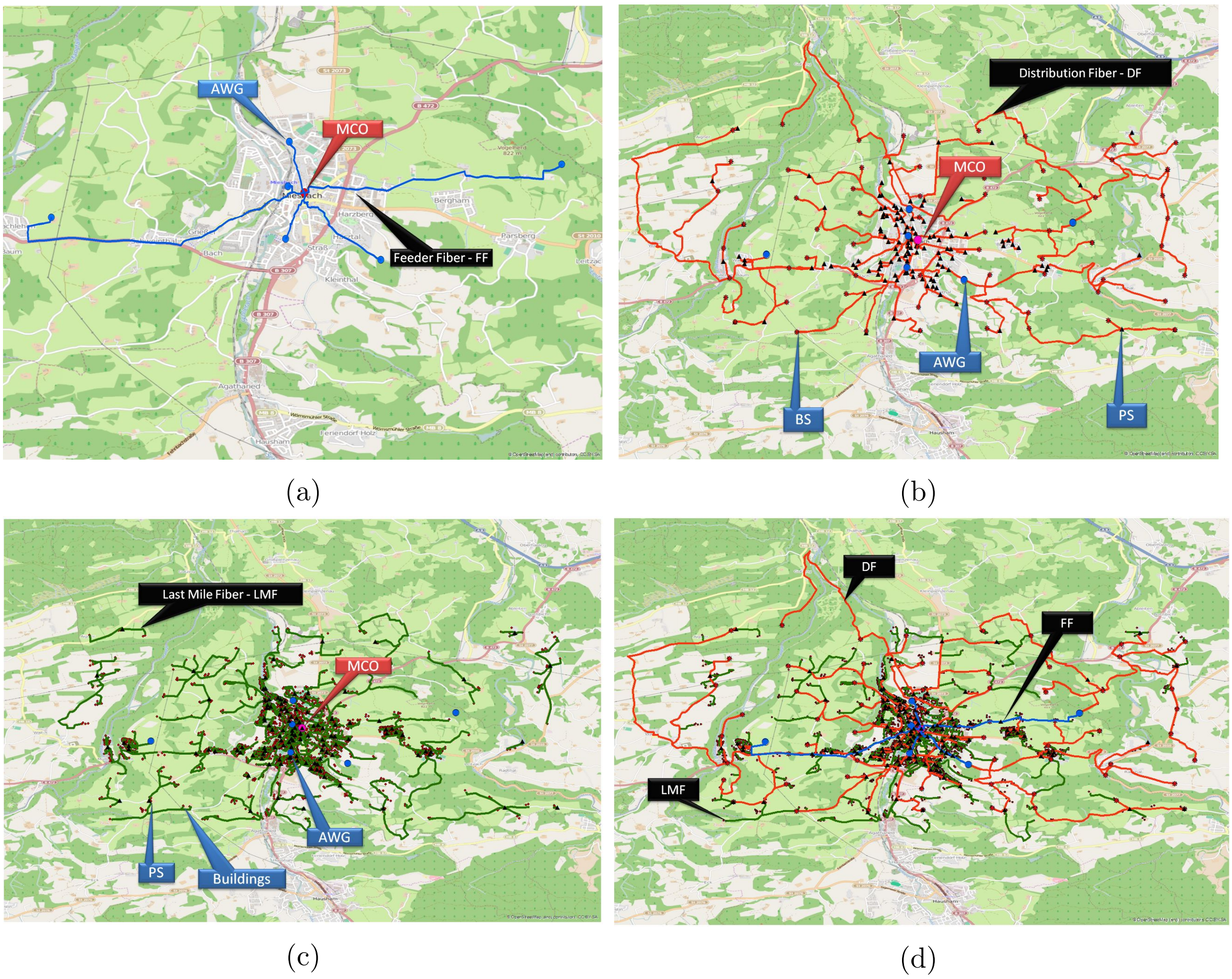
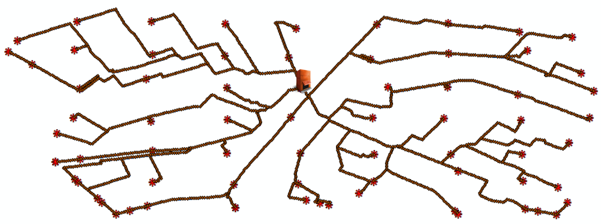


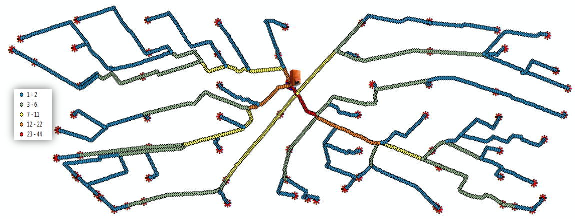
Figure 2.13: **(a)** Feeder Fiber - FF **(b)**Distribution Fiber - DF **(c)** Last Mile Fiber - LMF **(d)** Calculated FF (in blue), DF (in red) and LMF (in green)

will be the trenching to lay DUCT. Dimensioning tool also calculates this by generation of point features on calculated DUCT(reference:Fig. 2.14(a)), consequently by joining/ calculating all fiber paths each point acts as counter and calculates the required number of fiber pairs as shown in Fig. 2.14(b). In order to calculate the required length of each category of conduit, all points of specific category are combined as one line feature by merging/ dissolving. Fig. 2.14(c) shows that enough space is available in each type of conduit to blow the paths for future use and especially for protection fibers. So in order to lay protection fiber paths there is a high probability that no fresh digging will be required.

As result of the network planning, the dimensioning of components (MCO, AWGs and PSs) as well as the fiber and trenching length/diameter is obtained. In this thesis, we will focus on Macro Base Stations (MBSs) for mobile backhaul, which has a co-located ONU connected directly to AWG by a dedicated wavelength channel. The other types of



(a)



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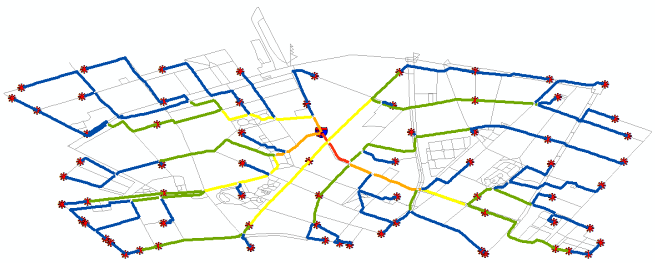


CONDUITS CALCULATIONS			
Actual Requirement	**Length Required**	**Availability in Market**	**Left/Spare for Protection Paths**
23-44 pairs	0.2294 km	96 pairs	At least 52, At most 73
12-22 pairs	0.70819 km	48 pairs	At least 26, At most 36
7-11 pairs	2.1094 km	24 pairs	At least 13, At most 17
3-6 pairs	5.872 km	12 pairs	At least 6, At most 9
1-2 pairs	12.754 km	4 pairs	At least 2, At most 3

(c)

Figure 2.14: **(a)** Generation of point features **(b)**Calculation of exact requirement of fiber pairs at each point**(c)** Converting point features to lines and calculation of required conduit lengths. at least and at most spare/ leftover pairs which can be used as reserve/ laying of protection fiber, are also shown in the table

cells which may not have base band processing function (e.g., small cells (SC) requiring fronthaul) and business users can also be connected in this manner. In next chapters we will discuss how these HPCANs can be protected by proposing, analyzing and implementing different end to end (E2E) protection schemes.

Chapter 3

Proposed End to End (E2E) Protection Schemes

In this chapter, we have proposed different E2E protection schemes for MBS/RN2, considering its high capacity and failure impact factor. However, all protection schemes can easily be extended to PSs/RN2, if required. The proposed schemes are based on fiber and microwave based solutions. Protection schemes and their reliability models have also been illustrated by Reliability Block Diagrams (RBDs). Following protection schemes have been proposed and analyzed, which will be implemented by our dimensioning tool in DU, U and R areas, to check its efficacy and suitability.Details of each will be covered in subsequent sections:-

- Disjoint Fiber Protection (DFP)
- Ring Feeder Fiber Protection (RFFP)
- Inter MBS DF Protection (IMBSP)
- Ring Inter MBS Protection (RIMBSP)
- Microwave MBS Protection (μWP)

Before dilating upon each protection scheme lets have a look about protection schemes specified in ITU-T G.983.1 [ITU15b], these are differentiated on the basis of which elements of the access network are protected/duplicated.Details are as under and also highlighted in Fig. 3.1:-

- **Type A:** The FF is duplicated this ensures protection from possible fiber failures in FF. The ONUs and OLTs are still without protection.
- **Type B:** In this type, OLTs are also duplicated (for simplicity and avoid cluttering/ repetition not shown in figure).

- **Type C:** This type involves a full duplication of OLT, fiber and all ONUs thus ensures to to recover from failures at any point of the network.
- **Type D:** In this case a partial duplexing on the ONUs can be done in case that only a limited number of end users e.g,. business users desires or require full reliability in their connection.

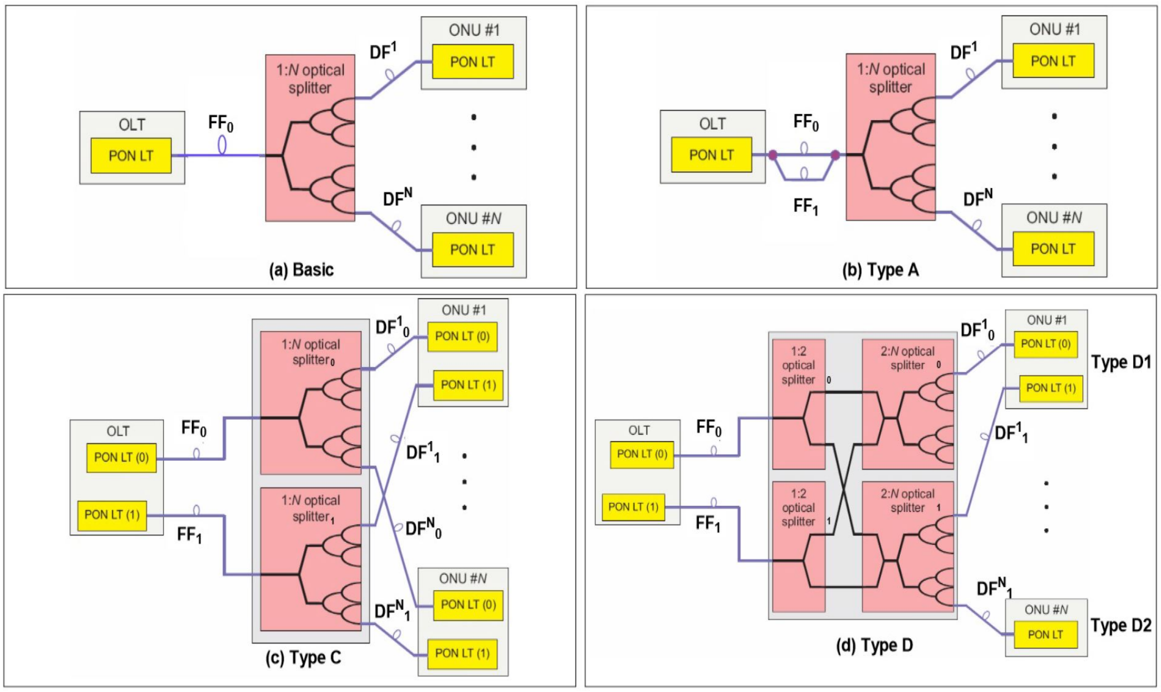
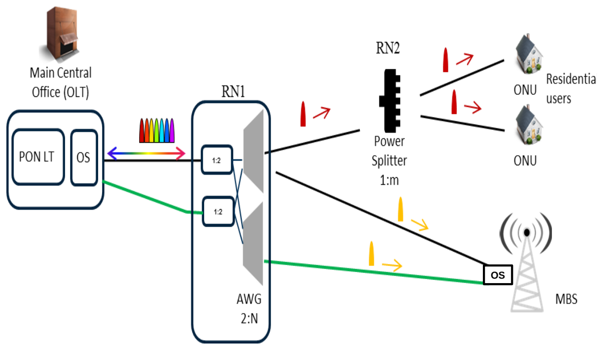


Figure 3.1: Protection schemes for Passive Optical Networks (Original Reference: [WCMK09])

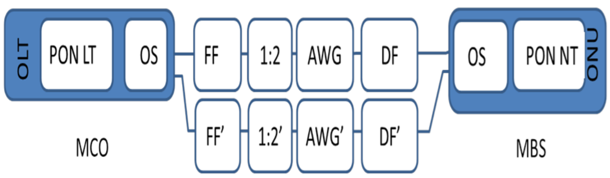
3.1 Disjoint Fiber Protection (DFP)

This scheme is based on Type A, protection scheme proposed in ITU-T G.983.1 (explained above), but applied to FF and DF of each MBS. As it is shown in Fig. 3.2(a), the scheme needs disjoint FF as well as DF to each MBS. This scheme requires an Optical Switch (OS) at the OLT to switch the signal to protection FF in case a failure occurs in the working FF and at RN1, two extra 1:2 couplers and two AWG to connect both working and protection FFs and DFs. At the MBS, one OS is required. Fig. 3.2 (b) shows the Reliability Block Diagram (RBD) for the connection between MBS and MCO in this scheme. RBD is a graphical representation of the system illustrating the relation between system components from the reliability point of view, and is often referred to as its connection availability model. The acronyms used are: **(MCO)** Main Central Office, **(OLT)** Optical Line Terminal,**(PON LT)** Passive Optical Network Line

Terminal,**(OS)** Optical Switch,**(FF)** Feeder Fiber,**(FF')**Protection Feeder Fiber,**(AWG)** Arrayed Waveguide Grating,**(AWG')**Protection Arrayed Waveguide Grating,**(DF)** Distribution Fiber,**(DF')** Protection Distribution Fiber,**(PON NT)**Passive Optical Network Network Terminal,**(MBS)** Macro Base Station,**(ONU)** Optical Network Unit. Fig. 3.2 (c-d) presents an example of the FF and DF layout for DFP scheme by using our planning & dimensioning tool.



(a)



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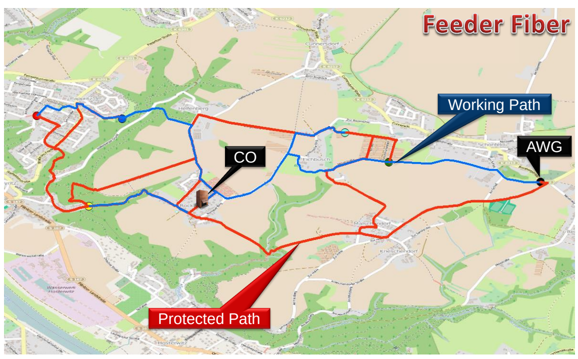

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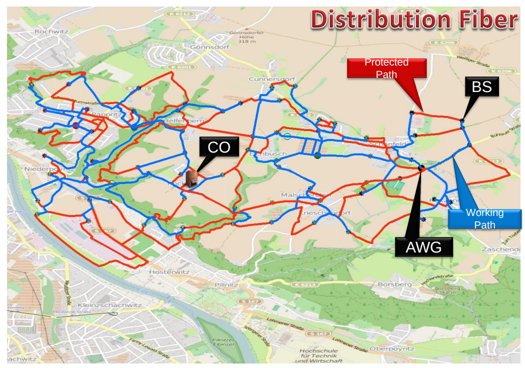


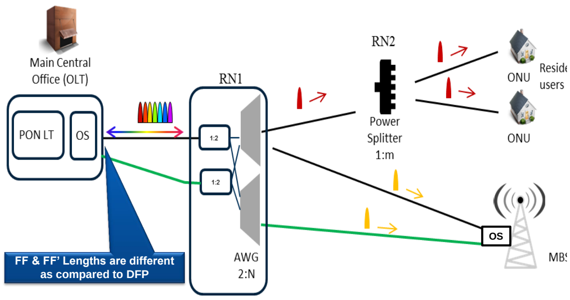
(d)

Figure 3.2: **(a)** Disjoint Fiber Protection (DFP) scheme **(b)**Reliability Block Diagram **(c)** Dimensioning tool results FF(d) Dimensioning tool results DF

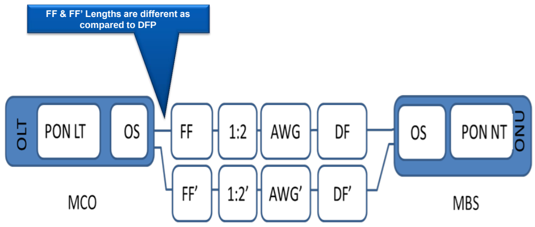
3.2 Ring Feeder Fiber Protection (RFFP)

This scheme proposes connecting all the AWG through a duct ring. The ring is computed using the Traveling Salesman Problem (TSP) by preserving the first and last node (either

AWG or MCO). Each AWG has two FFs towards the MCO: one clockwise and the other anticlockwise as shown in Fig. 3.3(c). The working FF is the shortest fiber path, whereas the protection is the longer one. Hence, the nodes colored in blue used the clockwise direction as working fiber, whereas the nodes colored in red use the anticlockwise direction. From AWG to the MBS, a disjoint DF as in DFP scheme is proposed. This scheme requires the same components and it has the same RBD as DFP but with different FF lengths, as shown in Fig. 3.3(a-b).



(a)



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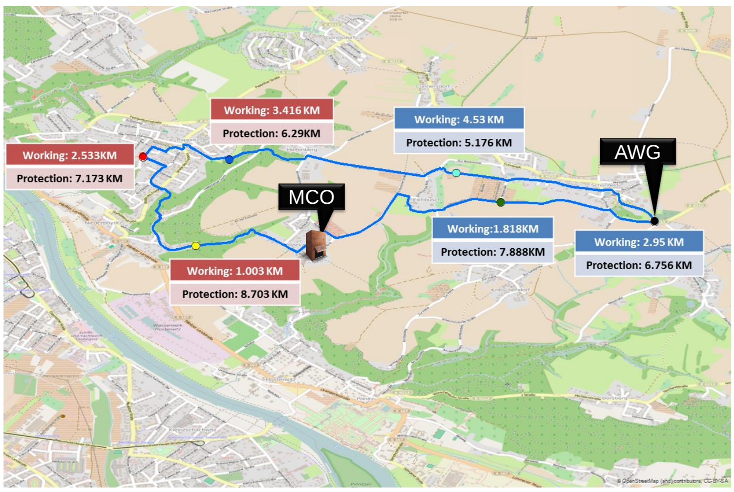
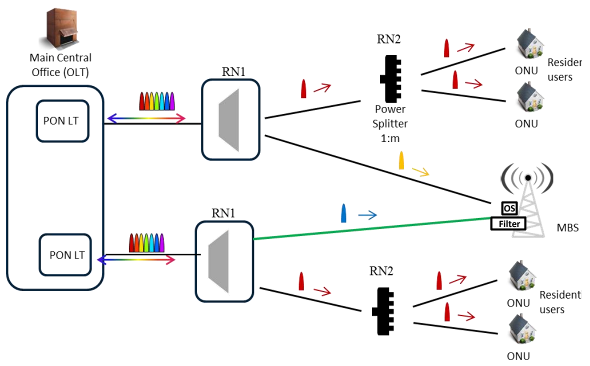


(c)

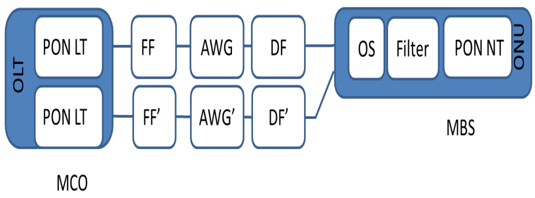
Figure 3.3: **(a)** Ring Feeder Fiber protection Scheme**(b)**Reliability Block Diagram **(c)** Feeder duct ring for the RFFP scheme (in blue the nodes connected through the anti-clockwise direction and in red the nodes connected through the clockwise direction to the MCO

3.3 Inter MBS DF Protection (IMBSP)

This protection scheme offers protection to MBS using a disjoint DF from the protected MBS to the closest disjoint AWG. In this case, a disjoint AWG is the one which does not share any duct with the FF and DF of the protected MBS (as depicted in Fig. 3.4(c)). This scheme requires an OS and a filter at the MBS. Fig. 3.4(a-b) shows protection scheme and RBD for the connection of MCO and MBS.



(a)



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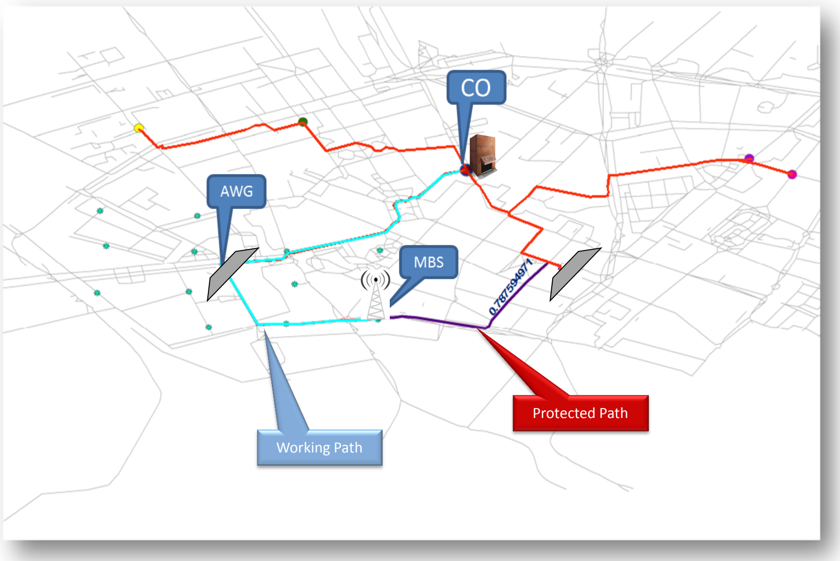
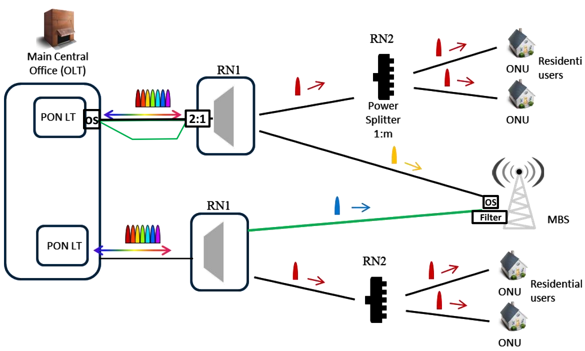


(c)

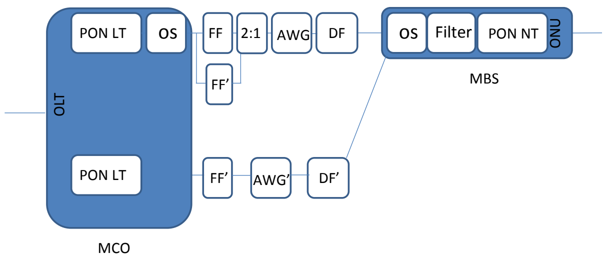
Figure 3.4: **(a)** Inter MBS Protection (IMBSP) Scheme**(b)**Reliability Block Diagram **(c)** Dimensioning tool example

3.4 Ring Inter MBS Protection (RIMBSP)

This scheme proposes connecting all the AWG through a duct ring as proposed in RFFP, so FF protection is ensured by the ring i.e shorter path in any of the clockwise or anticlockwise direction is taken as working path and the other is allocated for protection path. For DF protection Inter MBS DF protection is proposed as in protection scheme IMBSP. It is expected that by proposing this scenario the solution space/ probability of finding the nearer disjoint AWG to MBS is increased, thus DF required for protection will decrease as highlighted in Fig. 3.5(c). Furthermore as compared to IMBSP, this scheme also offers to protect only the FF thus it is modular, means it can be divided into modules, separate for FF and separate for FF& DF, this specially helps to offer flexibility in splitting funds and network rollout. Fig. 3.5(a-b) shows protection scheme and RBD for the connection of MCO and MBS. This scheme requires 1x OS at each PONLT, 1x coupler at each RN1 and 1x OS, 1x filter at each MBS.



(a)



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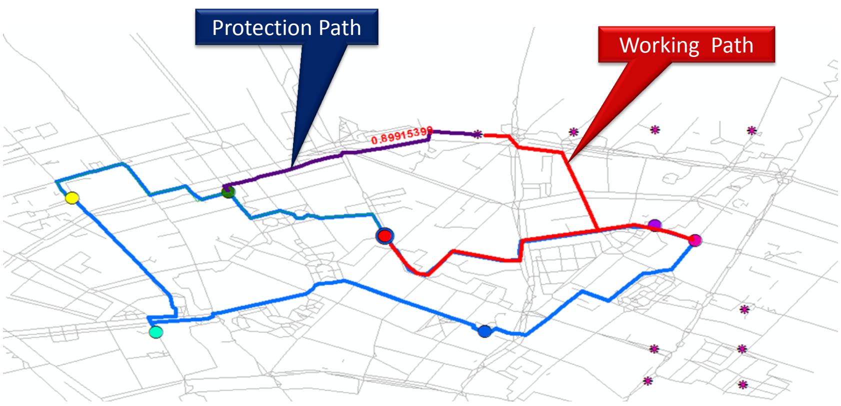


(c)

Figure 3.5: **(a)** Ring Inter MBS protection Scheme **(b)**Reliability Block Diagram **(c)** Implementation in DU area (Berlin)

3.5 Microwave MBS Protection (μWP)

This protection scheme proposes wireless solutions which have much lower deployment cost to offer protection links for feeder and/or distribution segments as highlighted in [FR11] and [YSWC14]. It offers protection to MBS based on a microwave link between two disjoint MBSs i.e. they do not share any FF or DF ducts. This scheme is shown in Fig. 3.6(a-b).One MBS can protect another MBS subject to following two constraints:-

- MBS are disjointly connected to the MCO
- MBS have a Clear Line of Sight (CLOS).

Forward and reverse bearings as shown in Fig. 3.6(a)) are required to be calculated for speedy deployment and network rollout after checking the CLOS results. The proposed solution provides E2E protection for MBS but it is not modular same as IMBSP.For meeting the high protection BW capacity, ease of installation and flexible deployment, we have proposed Point to Point (Pt $\rightarrow$ Pt) links, however Point to Multi point (Pt$\rightarrow$ Mpt) links can also be used to reduce total cost i.e CAPEX, IMPEX and OPEX. In this case the total number of links required will be equal to number of AWGs and number of Customer Premises Equipment (CPEs) will be equal to number of MBS.

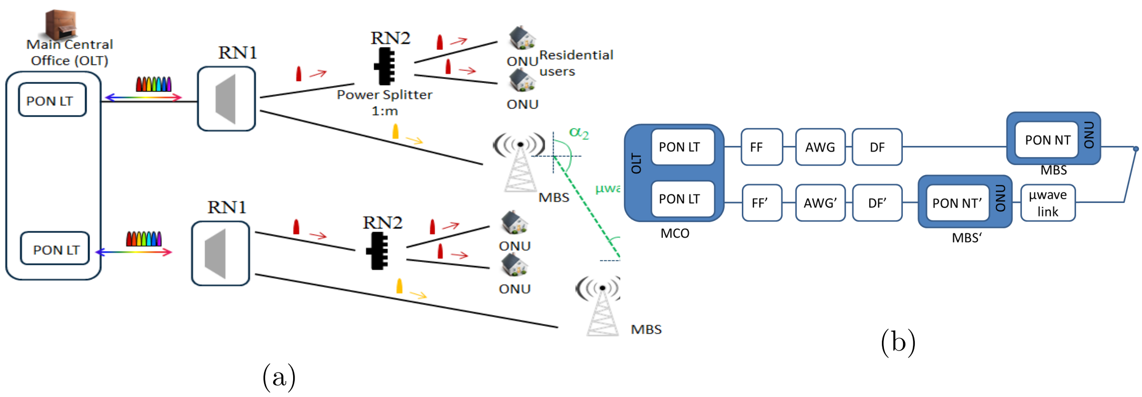


Figure 3.6: **(a)** μWave protection Scheme **(b)**Reliability Block Diagram

3.6 Indirect Improvement in Reliability of Residential Users

The reliability of residential users will indirectly improve or remain same depending upon the selected protection scheme. This indirect improvement is directly related to the modularity offered by the scheme. In our case DFP, RFFP and RIMBSP is modular means can protect FF,DF separately as well as combined. However IMBSP and μWP is not modular because it can't protect the only FF or DF.The reliability block diagrams of residential users with respect to selected E2E protection scheme for MBS protection are as shown in (Fig. 3.7 till Fig. 3.11).

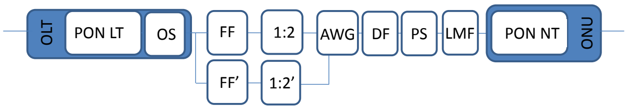


Figure 3.7: RBD of residential users when DFP is Selected

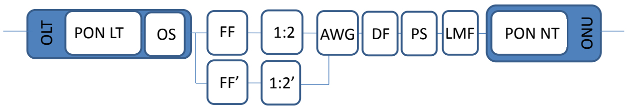


Figure 3.8: RBD of residential users when RFFP is Selected

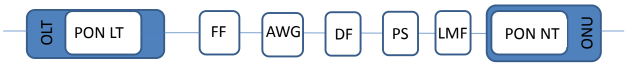


Figure 3.9: RBD of residential users when IMBSP is Selected

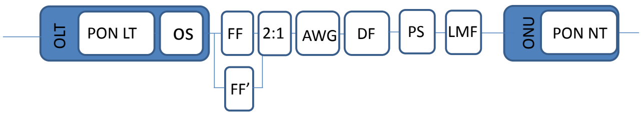


Figure 3.10: RBD of residential users when RIMBSP is Selected

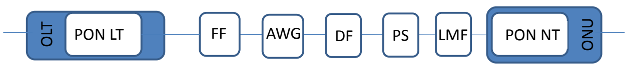


Figure 3.11: RBD of residential users when (μWP) protection is Selected

Chapter 4

Implementation Methodology & Parameters Definition

In this chapter, we have highlighted the methodology which will be used to implement the proposed protection schemes in Dense Urban (DU), Urban (U) and Rural (R) areas . Before proceeding to results and comparisons in next chapter, we have also defined different parameters at the end of this chapter, which are required to draw logical, fair and unbiased conclusions pertaining to different case studies.

4.1 Implementation Methodology

The protection schemes have been compared in three different areas representing DU,U and R scenarios, whose characteristics have been summarized in Table. 4.1 and Fig. 4.1 (a-b) , realistically the density of Buildings or MBS per KM^2 is more in DU area than U or R areas.

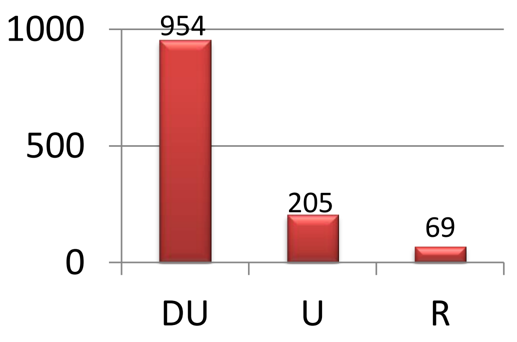
For HPCAN architecture, we have considered AWGs of 1:40 wavelengths and PS of 1:32 splitting ratio. The port utilization i.e. the maximum number/ upper ceiling of ports which are allowed to use, is set to 80%. The remaining 20% of the ports are left for protection or future use.Considering these values lower bound computation of the equipment needed in the field has been computed and summarized in Table. 4.2.

The step by step details of adopted methodology is as under:-

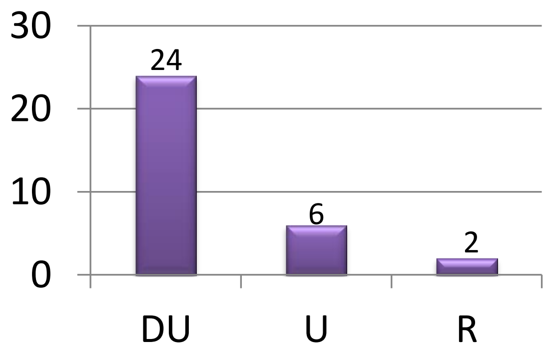
- Select the area of study from open street map from *https://www.openstreetmap.org* and save the file using export function. Use overpass API if file size is large *NOTE,* when it prompts to save file and ask location and name, don't forget to give extension .osm with file name (It is must!!) otherwise database parsing will not be possible

NAME	TYPE	AREA [KM²]	TOTAL BUILDINGS	BUILDINGS/ KM²	INTER MBS DISTANCE [METERS]	TOTAL: MBS	MBS/ KM²
BERLIN	DU	3	2863	954	200	72	24
HELFENBERG	U	12	2462	205	400	70	6
MIESBACH	R	45	3103	69	800	64	2

Table 4.1: Selection of Areas



(a)



(b)

Figure 4.1: **(a)** Buildings density/ KM^2 **(b)** MBS density/ KM^2

DU - BERLIN

TOTAL: BUILDINGS	TOTAL: BASE STATION	MINIMUM: POWER SPLITTERS REQUIRED	MINIMUM: AWG REQUIRED
2863	72	111	6

U - HELFENBERG

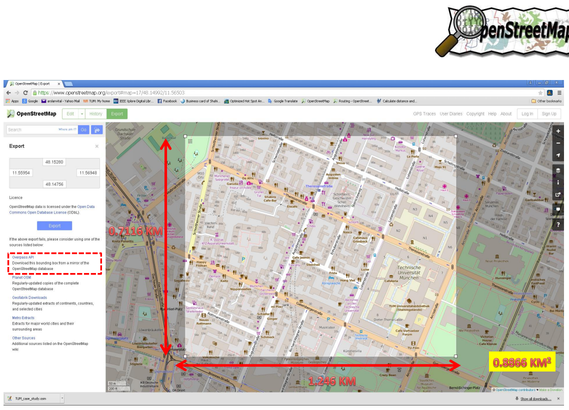
TOTAL: BUILDINGS	TOTAL: BASE STATION	MINIMUM: POWER SPLITTERS REQUIRED	MINIMUM: AWG REQUIRED
2462	70	95	6

R - MEISBACH

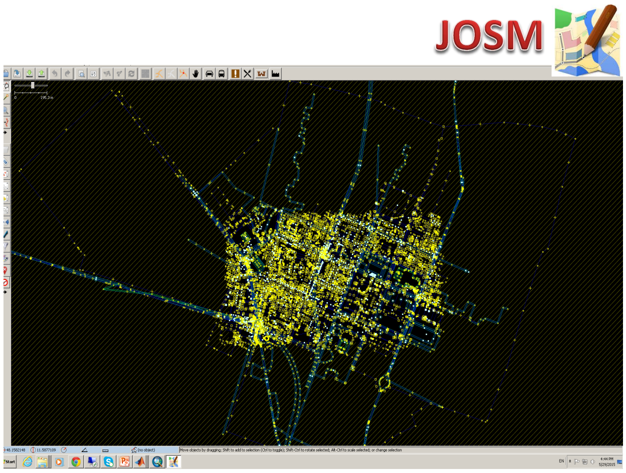
TOTAL: BUILDINGS	TOTAL: BASE STATION	MINIMUM: POWER SPLITTERS REQUIRED	MINIMUM: AWG REQUIRED
3103	64	120	6

Table 4.2: Minimum Equipment required for Optical Distribution Network(ODN)

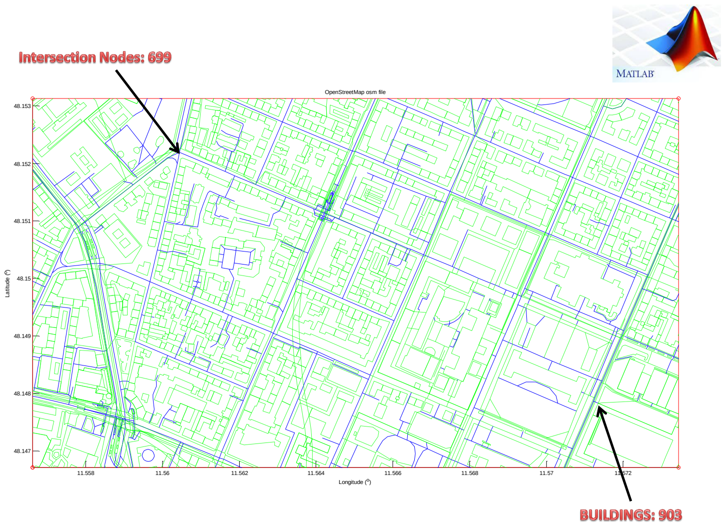
using either Matlab or ArcGIS. It is highlighted in Fig. 4.2. Example of parsed database of DU,U and R areas is also shown in Fig. 4.3 (a),(b) and (c) respectively.



(a)



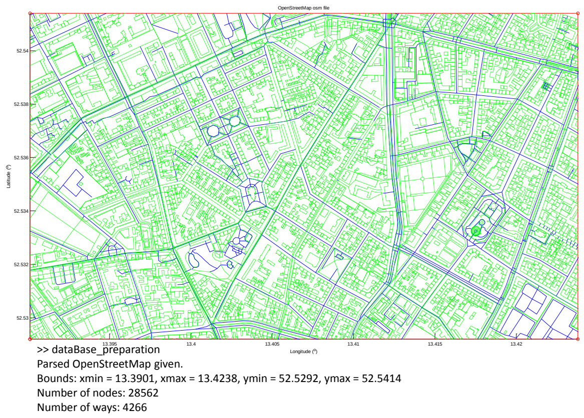
(b)



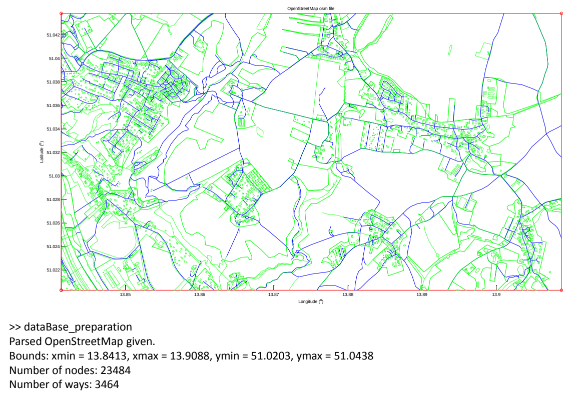
(c)

Figure 4.2: **(a)** Selection of geographical area from Open street Map **(b)**Java Open Street Map editor **(c)** Parsing of .osm file in Matlab for ways/ nodes details and confirmation of selected map bounds/ area of study

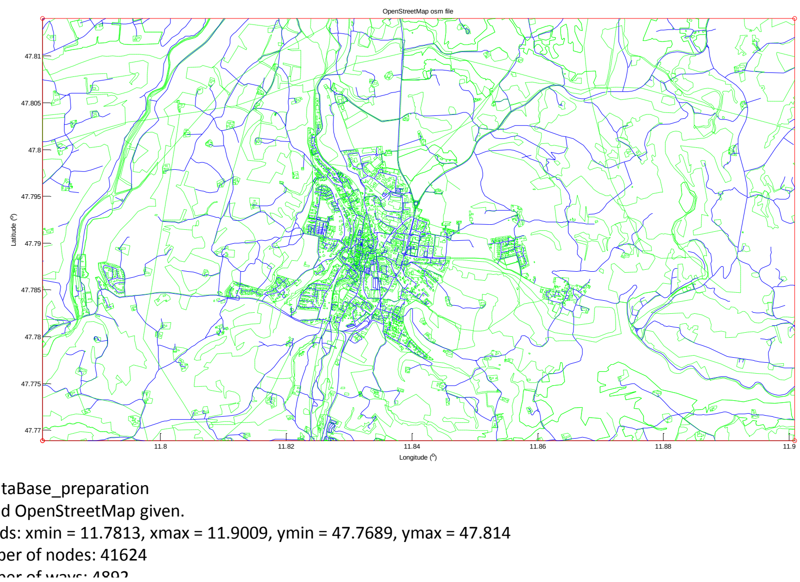
- For every building select random node or center point of buildings' polygonal data to convert it to point data. This is required to have the exact location of cabinet box (e.g., building basement) Reference Fig. 4.4(a).
- Associate the selected building node to nearest street/ road, so that every building should have its own distinct street node.Reference Fig. 4.4(b).



(a)



(b)



(c)

Figure 4.3: **(a)** Parsed Database of DU area **(b)**Parsed Database of U area **(c)** Parsed Database of R area

- When the MBS locations are unknown, the MBS can be placed based on a regular fishnet distribution. In that case, the MBS are also associated to the nearest "MBS street node".Reference Fig. 4.4(c).
- 1^{st} stage clustering using proprietary clustering algorithm of buildings to power splitters, given the splitting ratio and the port usage. Reference Fig. 4.4(d). Clustering algorithm as shown in Fig. **??** has been designed to generate clusters of fixed size with the possibility to dynamically adjust individual cluster size and/or total number

of clusters to maintain cluster quality and to reduce the required infrastructure.

- Place the PS at the closest street intersection node as this reduces required fiber and increase accessibility and facilitates finding alternative paths required for protection. Reference Fig. 4.4(e).
- 2^{nd} stage clustering of PS and MBS to AWGs based on the number of wavelengths and the port usage.Reference Fig. 4.4(g).
- Find the centroid of each cluster and place AWG to nearest intersection node.Reference Fig. 4.4(h).
- Compute the fiber layout of each fiber section (i.e. FF, DF and LMF). Based on the layout, the fiber required for each section as well as the duct can be computed. Furthermore, the cable size for each street segment can be computed as shown in Fig. 4.4(j) and Fig. 4.4(k).

So, the complete dimensioning process can be summarized in three steps: **(1)** Area selection and database parsing **(2)** Clustering for placement of Remote Nodes (PS & AWG) **(3)** Routing for fiber layout (Duct+fiber) of either working or protection.

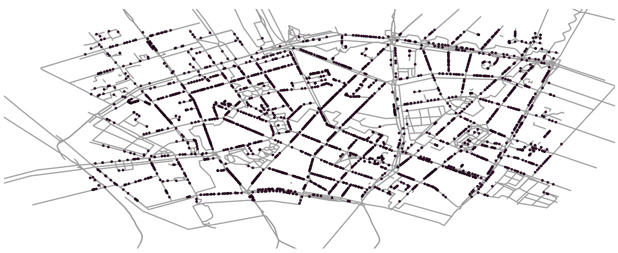
Note: For more details on functions used and how to configure different steps very detailed operating manual has also been prepared and attached as soft copy in CD.

4.2 Routing Approaches

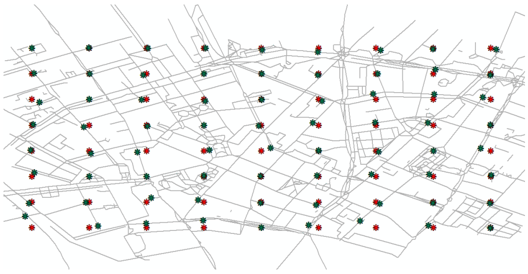
Enough has already explained for step 1 & 2 in chapters 2, 3 and also early part of this chapter. Routing determines the total length of duct and fiber and for this we have following options/ approaches:-

- **Dijkstra shortest path with duct sharing**: As the name highlights this routing strategy aims to minimize the total duct, which is directly related to on ground digging and considered as most costly factor , however this strategy results in to increase in total fiber length. This strategy suits best in the start of project when you want to cover maximum customers with minimum initial investment and maintain balance in cash inflows/ outflows. To implement this routing strategy weight reduction method or reduce the impedance value of selected segment is used, so that to increase it's chances to select by other remaining non connected nodes. It is evident that this routing strategy requires fine balance between two things, either to go for duct sharing and compromise on increase in fiber length or do new digging to decrease fiber length, but this will increase total duct length. Figure 4.4 a & b duly highlights this fact i.e. Duct sharing results almost 50% increase in fiber length, however it requires 7.2% less Duct than without Duct sharing. Using this strategy the biggest concern is that what if costs increases due to the total fiber length be

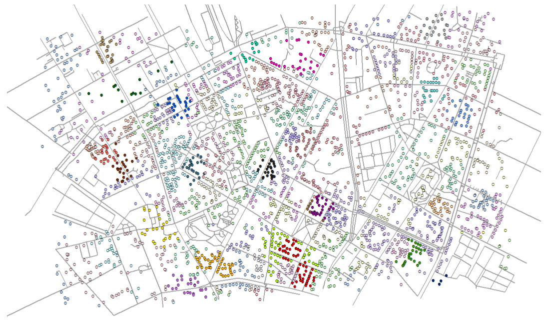
(a) Identify each building by one point



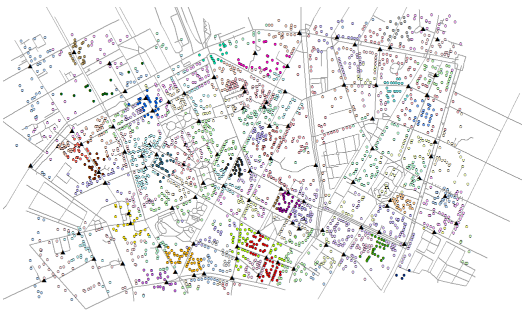
(b) Street nodes associated to the buildings



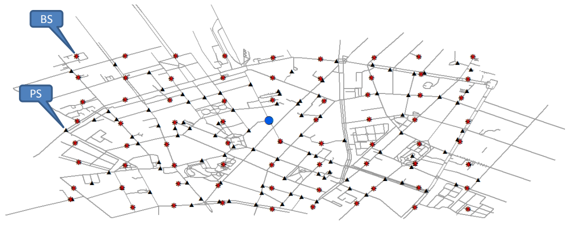
(c) Placement(red) and relocation of MBS (green)



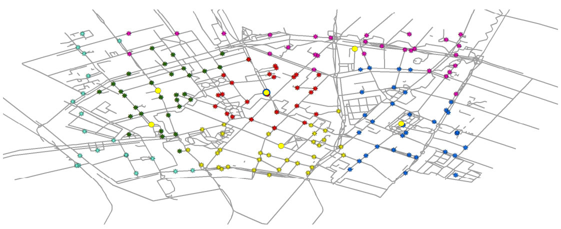
(d) 1^{st} stage clustering of buildings to power splitters (second splitting stage)



(e) Placement of PS (Black Triangles) at cluster centroid and push to nearest intersection node

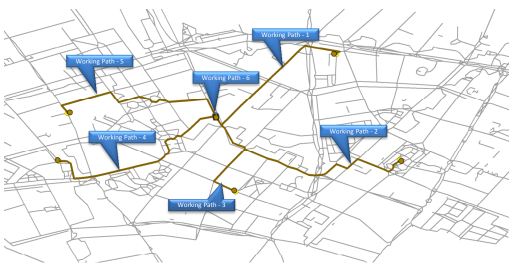


(f) Re located PS & MBS

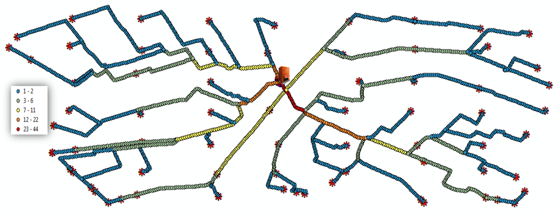


(g) 2^{nd} stage clustering

(h) Placement of AWG at cluster centroid (green) and push to nearest intersection node (yellow)



(i) Calculation of fiber paths and duct



(j) Cable size calculation: red (highest fibers/cable) blue (lowest fiber/cable)

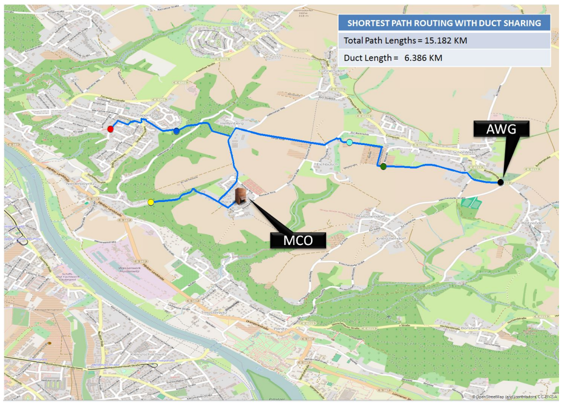
Figure 4.4: Step by Step Implementation Methodology

higher than the savings obtained by performing duct sharing. As highlighted earlier in [MD15] ,very fine balance can be maintained by decreasing the weights of selected segments by some weight reduction factor like 0.1, 0.2, 0.3, 0.4 etc and find the optimum value to reduce the overall cost.This optimum value is different for different areas like DU,U or R areas and solely depends the density of selected network data set i.e total length of roads/ KM^2.For better understanding/ comprehension of the reader, it is highlighted in [MD15] optimum value for DU area is around .10 or 10% and for R area it is approximately .30 or 30%.

- **Dijkstra shortest path without duct sharing**: This routing strategy aims to minimize the total path lengths of fiber segments and always follow the shortest path irrespective of what paths have already been selected, due to this it may or may not results in to increase in total required Duct.This strategy suits best when you have the laid network/ no more digging is required and you want to add more fiber connections e.g. disjoint protection paths.
- **Salesman Transport Problem (STP) & Ring** : Salesman Transport method finds the optimum path to connect all the points with minimum duct by calculating the best order of visiting all the points, however it results in to long fiber distances from source to a particular destination(s) like any Minimum Spanning Tree (MST) algorithm. This is used as the building block of finding the optimum ring for working/ protection paths. Ring requires more fiber and duct than Dijkstra (with and without duct sharing) but its length is quite comparable i.e. 7.034% more fiber length and 24.42% more duct length.It is pertinent to mention here that ring becomes a very useful technique when protection is also required **as it requires no more duct to lay additional fiber segments**.Optimum ring is generated by preserve 1^{st} & last point and allow reordering to rest of points.Ring is best suited for FF working/ protection paths as increase in fiber/ duct is quite comparable, however for DF working/ protection ring penalty (converting MST, generated by STP to Ring) is quite high. It is also recommended to place AWG at central cluster element rather than cluster centroid to reduce total duct/ fiber.

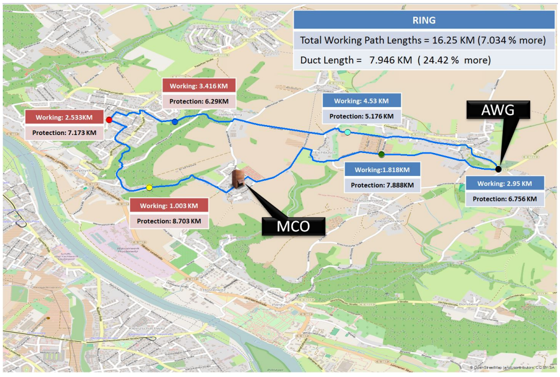
It is pertinent to highlight that this thesis compares different protection schemes only for MBS (due to its high capacity and failure impact factor), with respect to the extra fiber and additional components required e.g. AWG, OS, Splitters, filters etc. Hence the fiber and duct required for the unprotected scenario is not included for the comparison. Besides, we are looking into FTTB solution where all streets have already ducts for the unprotected case, and therefore additional trenching is not needed to lay protection FF or DF. So,following is the adopted strategy:-

- Dijkstra Shortest path with duct sharing is not used as it is optimizing a contradictory objective function against finding the disjoint paths.
- Dijkstra shortest path without duct sharing algorithm is used to find disjoint paths to reduce/ minimize the overall length of fiber segments for selected protection scheme,



(a)

(b)



(c)

Figure 4.5: **(a)** Dijkstra with Duct Sharing **(b)**Dijkstra without Duct Sharing **(c)** Ring Created by Salesman Transport Problem (STP)

except Ring.

- Ring is used for Protection schemes RFFP and RIMBSP for calculating the working and protection paths.Shortest path in any direction i.e. clockwise/ anticlockwise is working path and the other is taken as protection path.

4.3 Parameters Definition

After understanding the implementation methodology this section defines different parameters which are required, before going to next chapter which is Results and Comparison. Parameters definition are required mainly due to following reasons:-

- For understanding and better comprehension of the reader, especially of equations and formula's used.
- For consistent and fair comparison, which leads to logical conclusions in last chapter

of Conclusions and Future Outlook.

Following parameters have been defined:-

- ***FF*** ⇒ Feeder Fiber required for working paths.
- ***DF*** ⇒ Distribution Fiber required for working paths.
- ***FF′*** ⇒ Feeder Fiber required for protection paths.
- ***DF′*** ⇒ Distribution Fiber required for protection paths.
- **ΔW** ⇒ (*Fiber required for working paths in considered protection scheme - Fiber required for working paths by reference scenario*). Any protection scheme which is using ring i.e RFFP & RIMBSP will have this a positive value, rest of protection schemes will have this a zero value.
- ***DUCT*** ⇒ Duct required by unprotected scenario.
- ***DUCT′*** ⇒ Duct required by selected protection scheme.

Basing on these parameter definitions following equations have been derived for calculating of average protection fiber, which is required for results and comparison in next chapter:-

- **Average Protection Fiber Required - Availability Calculations**

$$(FF^{'} / \text{Total number of AWGs}) + (DF^{'} / \text{Total Number of MBS})$$

- **Average Protection Fiber Required - Cost Calculations**

$$(FF^{'} + \Delta W + DF^{'}) / \text{Total Number of MBS}$$

4.4 ArcGIS

For planning and implementation methodology, both Matlab and ArcGIS have been used. Both are compatible and results can be imported/ exported at any required point in time. Matlab is mainly used for clustering as it is one of the best to solve numerical problems. Readers are quite conversant with Matlab, however for better understanding and assimilation of ArcGIS (which is used mainly for constrained based routing) following are few of its details:-

> *"ArcGIS is a state of the art **G**eographical **I**nformation **S**ystem which realizes the advantage of location awareness. It collects and manages data in layers and shape files to perform advanced and sophisticated spatial analysis"*

Features and capabilities of Arc GIS as highlighted in [Arc15b], are as under and also shown in Fig. 4.6:-

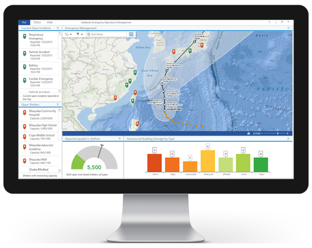
- **Planning & Analysis**: It carries sophisticated data analysis, optimize site and route selection and advanced predictive modeling.
- **Operational Awareness**: It allows to share and disseminate processed and unprocessed information to all concerned in a centralized or distributed way.
- **Field Data Collection**: It gives the capability to work with online or offline interactive maps. Technicians in the field can access maps and view real-time information which makes it easy to report problems, complete work orders, and update maintenance records.
- **Asset Management**: It ensures to track asset performance, maintenance history, improvement projects, and inspection plans.
- **Community Engagement**: It allows to create and share interactive maps containing valuable information with public/ community, so that every one is informed and well coordinated.

In this thesis we have extensively used its osm and network analyst extensions. OSM extension allows to download, parse, edit and upload the osm maps. ArcGIS Network Analyst provides network-based spatial analysis tools for solving complex routing problems. Salient features which have been used in our thesis are as under and highlighted in Fig. 4.7:-

- **Optimized Routes**: Find the shortest route depending on the impedance value selected for the solver. Routes can accumulate any number of cost values such as distance, time, slope, or other flow attributes. Solve for just two stop locations, or sequence many stops in the best order. *We have used this to calculate working/ protection Rings for RFFP and RIMBSP schemes.*
- **Find Closest Facilities**: Measure the cost of traveling between incidents and facilities to determine which are nearest to one other. Specify how many to find, whether the direction of travel is towards or away, and other constraints like search cutoff thresholds. *We have used this to calculate the working FF/DF of reference scenarios.*
- **Create Origin Destination Matrices**: The origin destination cost matrix produces a distance table, with least-cost paths along the network from many origins to many destinations. The ***cost values reflect the network distance, not the straight-line distance***. *We have used this feature to calculate the cost matrix of CMPMT-E or NW clustering algorithm.*

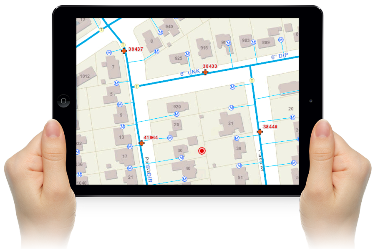
In order to to implement routing with or without duct sharing we have to decrease/ increase/ no change the weights/ impedance values of selected routes. This can be implemented by selecting the right barriers and its associated cost which can be scaled (high/ low) as well as restriction (off). So following is the adopted methodology:-

- For Dijkstra with duct sharing reduce scaled cost e.g 0.1 or 10 % etc.



(a) Planning & Analysis

(b) Operational Awareness



(c) Field Data Collection

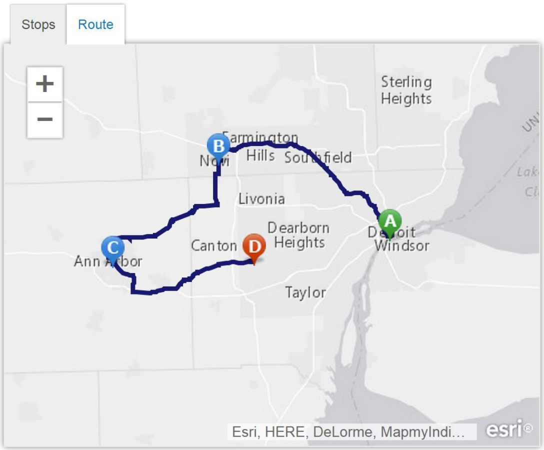
(d) Asset Management

(e) Community Engagement

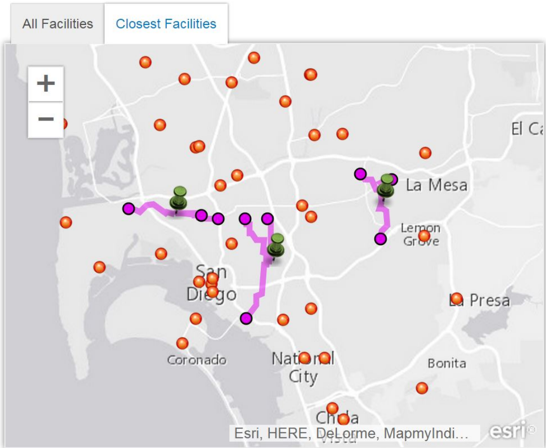
Figure 4.6: Arc GIS Features and Capabilities (Original Source: [Arc15b])

- For Dijkstra without duct sharing don't change the cost so no difference in already selected and going to be selected nodes, it will always find the shortest path irrespective what has been done in the past, so results into overall less fiber length.
- For finding the disjoint path restriction barriers are used.

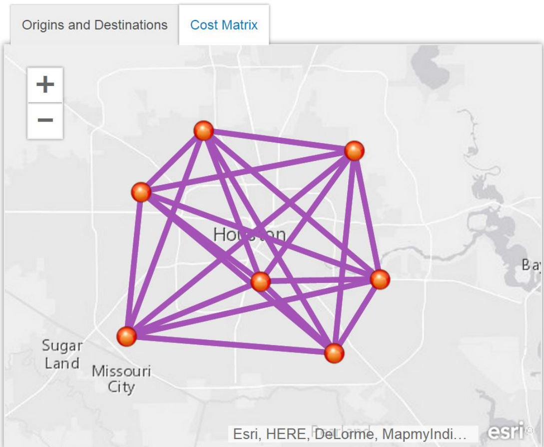
Barriers are feature classes in network analysis layers that restrict or alter impedance values of the underlying edges and junctions of the associated network data set. Barriers are split into three geometry types (point, line, and polygon) and are designed to model temporary changes to the network. *Barriers are mainly used to calculate the protection FF' and DF' paths.* The various types of barriers are described and shown in Fig. 4.8.



(a) Optimized Routes



(b) Find Closest Facilities



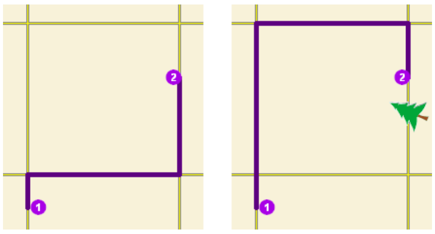
(c) Create Origin Destination Matrices

Figure 4.7: Network Analyst - Arc GIS Original Source: [Arc15c]

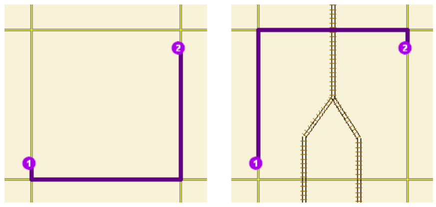
Before going to results and comparison let us summarize once again what we have done and learnt up-till this place:-

> *For HPCAN dimensioning we have used open street maps as data source and parsed in Arc GIS. We first clustered buildings to place PS.We distribute and locate MBS using fishnet polygons and then clustered PS and MBS to place AWGs. OLT is placed at user defined location. For calculation of working paths we have used Dijkstra shortest path with duct sharing and for protection paths we have used Dijkstra shortest path without duct sharing by selecting requisite type of barriers.*

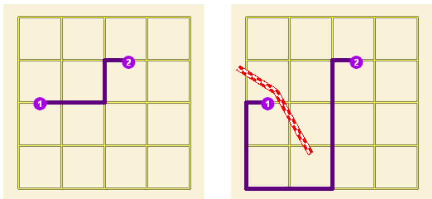
Using this methodology results have been calculated for all protection schemes in all type of areas (DU,U and R) and will be discussed in detail in next chapter, followed by all important results.



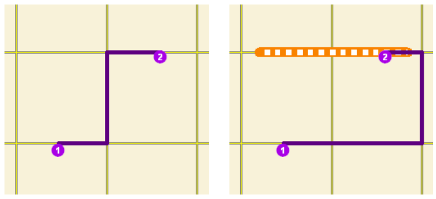
(a) Restriction Point Barrier



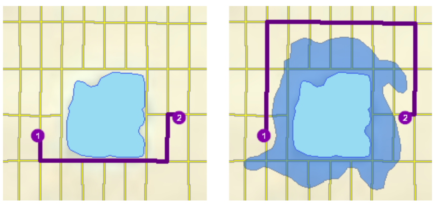
(b) Scaled Cost Point Barrier



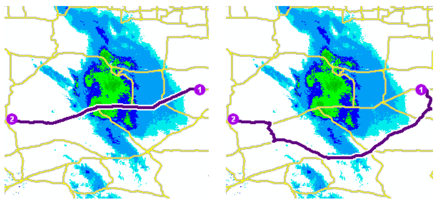
(c) Restriction Line Barrier.(*This type of barrier is used to find disjoint* FF' *and* DF' *paths*)



(d) Scaled Cost Line Barrier



(e) Restriction Polygon Barrier.(*This helps to convert STP into optimum ring topology*)



(f) Scaled Cost Polygon Barrier

Figure 4.8: Barriers (Original Source: [Arc15a])

Chapter 5

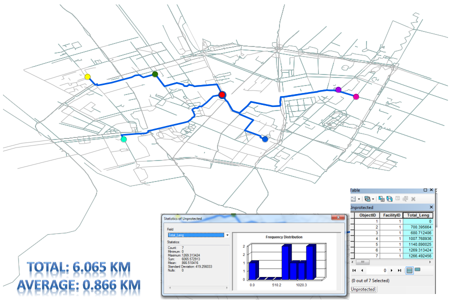
Results & Analysis

In this chapter, we have presented the results and analysis of all the proposed protection solutions and their suitability to different areas based on different parameters, namely Component cost, Power consumption, Connection availability, Indirect improvement in connection availability of residential users, Failure Impact Factor (FIF), Protection fiber length/MBS and the Additional fiber required for working paths from reference scenario. Preliminary results and analysis of each considered parameter will be followed by comparative and consolidated performance analysis of each protection scheme in DU, U and R areas at the end of this chapter.

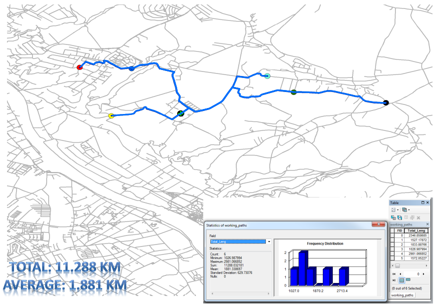
5.1 Fiber Length Calculation

As highlighted in Chapter 4, we have used ArcGIS network analyst and required barriers to calculate the average and total fiber required for Working and Protection paths in DU,U and R areas. These will be used to calculate different considered parameters, which are directly or indirectly dependent on working and protection fiber lengths. Details of calculated working and protection fibers are as under:-

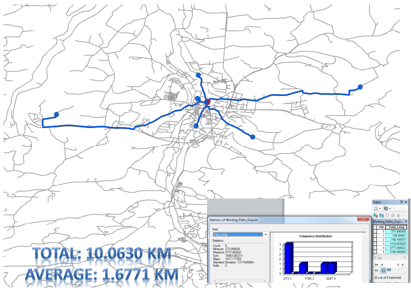
1. Unprotected FF Working Paths - *Reference, Fig. 5.1*
2. Disjoint FF Protection Paths - *Reference, Fig. 5.2*
3. Ring FF Working and Protection Paths - *Reference, Fig. 5.3*
4. Unprotected DF Working Paths- *Reference, Fig. 5.4*
5. Disjoint DF Protection Paths- *Reference, Fig. 5.5*
6. Inter MBS DF Protection Paths.- *Reference, Table. 5.1*
7. Ring Inter MBS FF & DF Protection Paths.- *Reference, Table. 5.1*



(a) Dense Urban Area - Berlin

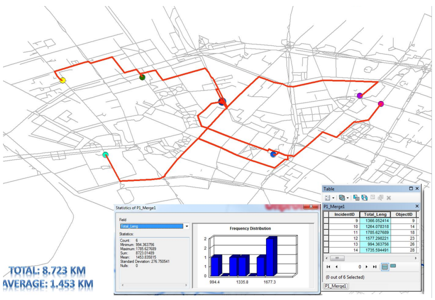


(b) Urban Area - Helfenberg

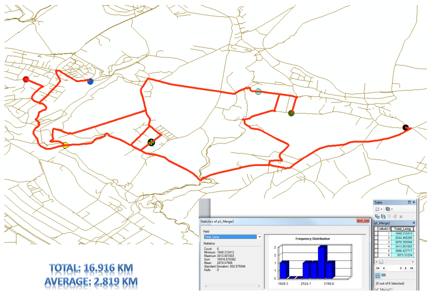


(c) Rural Area - Miesbach

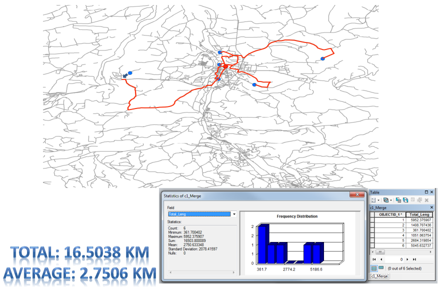
Figure 5.1: Calculation of Unprotected Working Paths - FF



(a) Dense Urban Area - Berlin

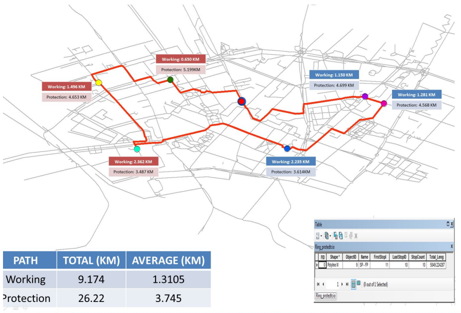


(b) Urban Area - Helfenberg

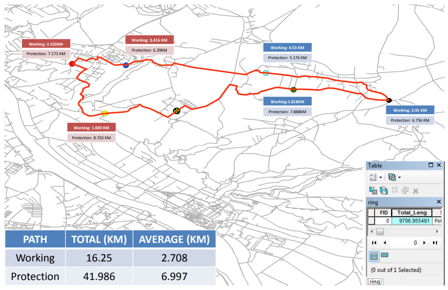


(c) Rural Area - Miesbach

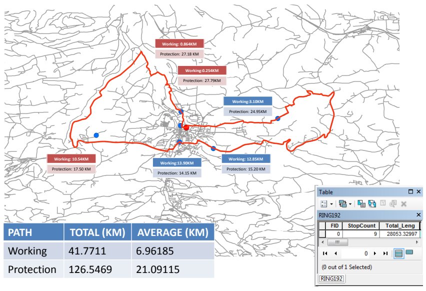
Figure 5.2: Disjoint FF Protection Paths



(a) Dense Urban Area - Berlin

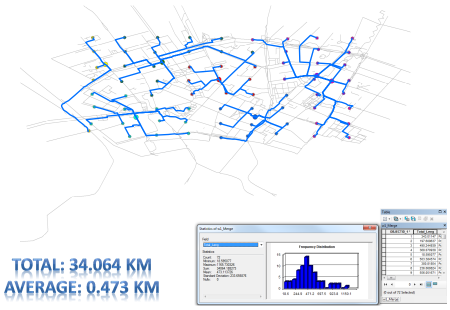


(b) Urban Area - Helfenberg

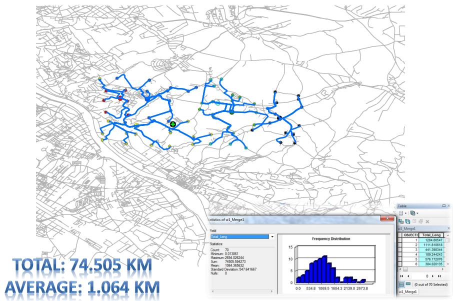


(c) Rural Area - Miesbach

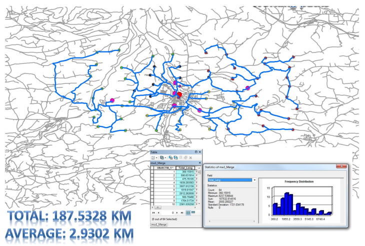
Figure 5.3: Ring FF Working and Protection Paths



(a) Dense Urban Area - Berlin

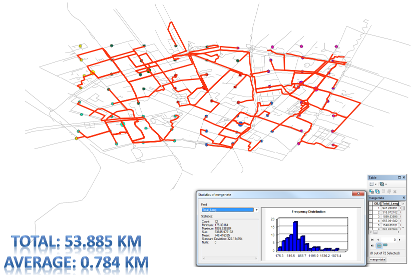


(b) Urban Area - Helfenberg

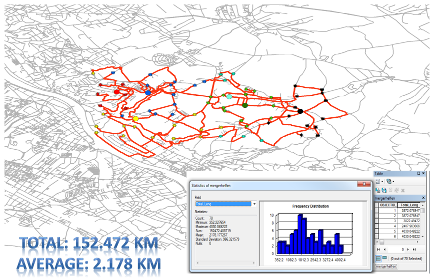


(c) Rural Area - Miesbach

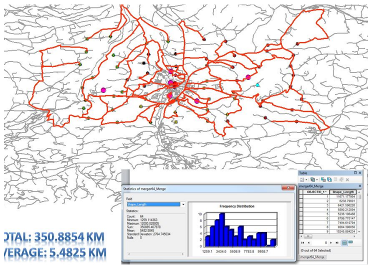
Figure 5.4: Unprotected DF Working Paths



(a) Dense Urban Area - Berlin



(b) Urban Area - Helfenberg



(c) Rural Area -Miesbach

Figure 5.5: Disjoint DF Protection Paths

The total protection fiber required and the average protection fiber required per MBS is the heart and soul to determine the efficiency of any protection scheme. More fiber requirement means more cost and less availability which is not desired by any operator/ customer. Summarized results are shown in Table. 5.1. It is highlighted that μWP does not require extra fiber, since it relies only on the microwave link between MBS (i.e. extra equipment cost).

Protection Scheme	DU				U				R			
	FF' + ΔW		DF'		FF' + ΔW		DF'		FF' + ΔW		DF'	
	SUM	AVG	SUM	AVG	SUM	AVG	SUM	AVG	SUM	AVG	SUM	AVG
DFP	8.72	1.45	53.89	0.78	16.92	2.82	152.47	2.18	16.50	2.75	350.89	5.48
RFFP	**29.30**	**3.75**	53.89	0.78	**46.95**	**7.00**	152.47	2.18	**158.18**	**21.09**	350.89	5.48
IMBSP	0.00	0.00	81.28	1.13	0.00	0.00	196.18	2.80	0.00	0.00	288.45	4.51
RIMBSP	**29.30**	**3.75**	66.47	0.92	**46.95**	**7.00**	156.15	2.23	**158.18**	**21.09**	307.60	4.81
µWP	-	-	-	-	-	-	-	-	-	-	-	-

Table 5.1: Average Protection Fiber Required per MBS. ΔW is only relevant to protection schemes which are using ring topology for FF working paths. ΔW values are 3.109 KM, 4.962 KM and 31.0781 KM in DU,U and R areas respectively.ΔW values are included in sum but not in average, Reference Section 4.3

5.2 Considered Performance Parameters

Comparison and analysis highlights the suitability of protection scheme to particular type of area and also compares the different protection schemes with regards to various performance parameters to determine and check the efficacy of each protection scheme. We have considered following parameters for comparison and analysis, Details of each will be covered in following subsections:-

- Components Cost/ MBS
- Connection Availability
- Additional Power Required/ MBS
- Failure Impact Factor(FIF)
- Fiber Length/ MBS
- Improvement in Availability of Residential Users
- Additional Fiber Requirement for Working Paths (ΔW)

5.2.1 Components Cost/ MBS

Table. 5.2 compares the cost associated to the additional components required for each protection scheme in different areas. The extra components required in each considered protection scheme are as under:-

1. DFP and RFFP requires following equipment:-
   (a) 1x OS at each PONLT and MBS.
   (b) 2x couplers and 2x AWGs at each RN1.
2. IMBSP requires 1x OS and 1x filter at each MBS.
3. RIMBSP requires following equipment:-
   (a) 1x OS at each PONLT.
   (b) 1x coupler at each RN1.
   (c) 1x OS and 1x filter at each MBS.
4. μWP requires one microwave link for each pair of MBS. Hence, for N MBS, N/2 microwave links are required since, the microwave link is considered to be bidirectional. It is pertinent to highlight that Pt $\rightarrow$ MPt solution may give more savings, but fulfilling the BW requirement will be a challenge, which in our considered case

is 10 Gbps, almost equal to the capacity of one free light wavelength capacity from AWG to each MBS.

Reference Cost Values	
Component	Cost
OS	2
AWG2:N	14.40
Coupler	1
Filter	1.5
µwave link	150

(a)

Protection Scheme	Component	Required Components		
		DU	U	R
DFP	OS	79	76	70
	AWG	14	12	12
	Couplers	14	12	12
RFFP	OS	79	76	70
	AWG	14	12	12
	Couplers	14	12	12
IMBSP	OS	72	70	64
	Filters	72	70	64
RIMBSP	OS	79	76	70
	Couplers	7	6	6
	Filters	72	70	64
µWP	µwave links	36	35	32

(b)

Protection Scheme	Total Cost [CU]		
	DU	U	R
DFP	373.60	336.80	324.80
RFFP	373.60	336.80	324.80
IMBSP	252.00	245.00	224.00
RIMBSP	273.00	263.00	242.00
µWP	5400.00	5250.00	4800.00

(c)

Protection Scheme	Cost/MBS [CU]		
	DU	U	R
DFP	5.19	4.81	5.08
RFFP	5.19	4.81	5.08
IMBSP	3.50	3.50	3.50
RIMBSP	3.79	3.76	3.78
µWP	75.00	75.00	75.00

(d)

Table 5.2: (a) Reference cost values (b) Additional equipment required by each protection scheme (c) Total cost (d) Cost per MBS

The costs values for different components shown in Table. 5.2(a) are given in Cost Units (CU) which are normalized to the cost of a GPON ONU i.e around 50 Euro. Following is the preliminary analysis:-

1. Cost associated to each protection scheme for additional equipment required, is not an area specific factor, it solely depends upon the total number of endpoints to be served.
2. DFP & RFFP is having same cost as architectural structure of scheme is the same as shown in Fig. 5.6.
3. RIMBSP is having less cost than DFP/ RFFP.

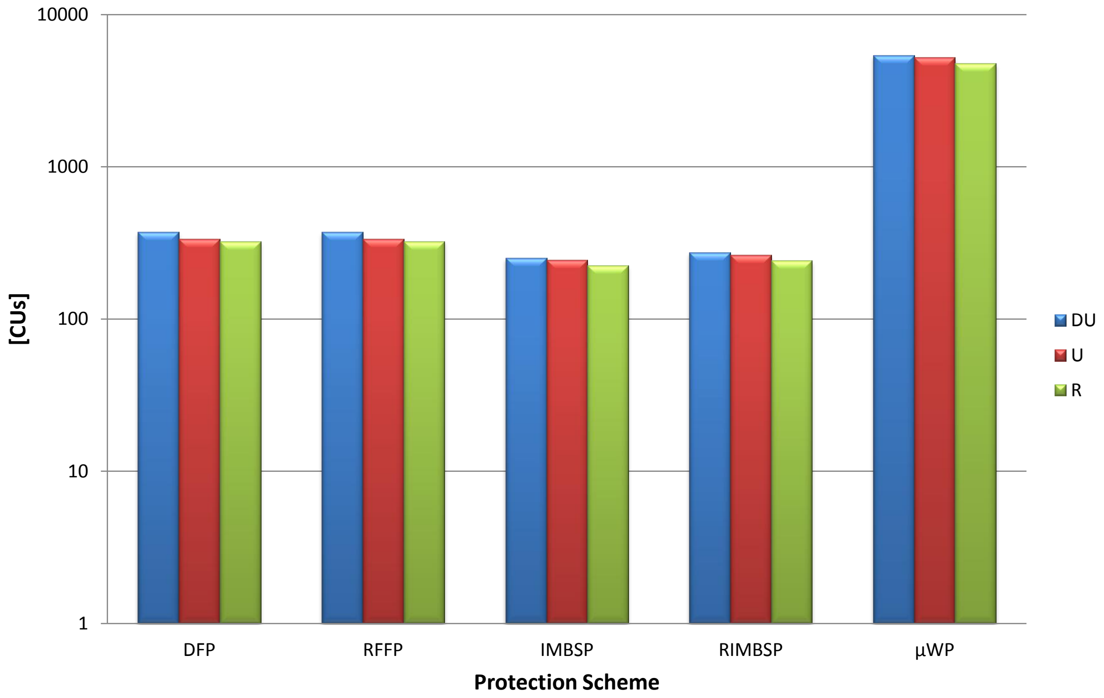


Figure 5.6: Total Additional Equipment Cost

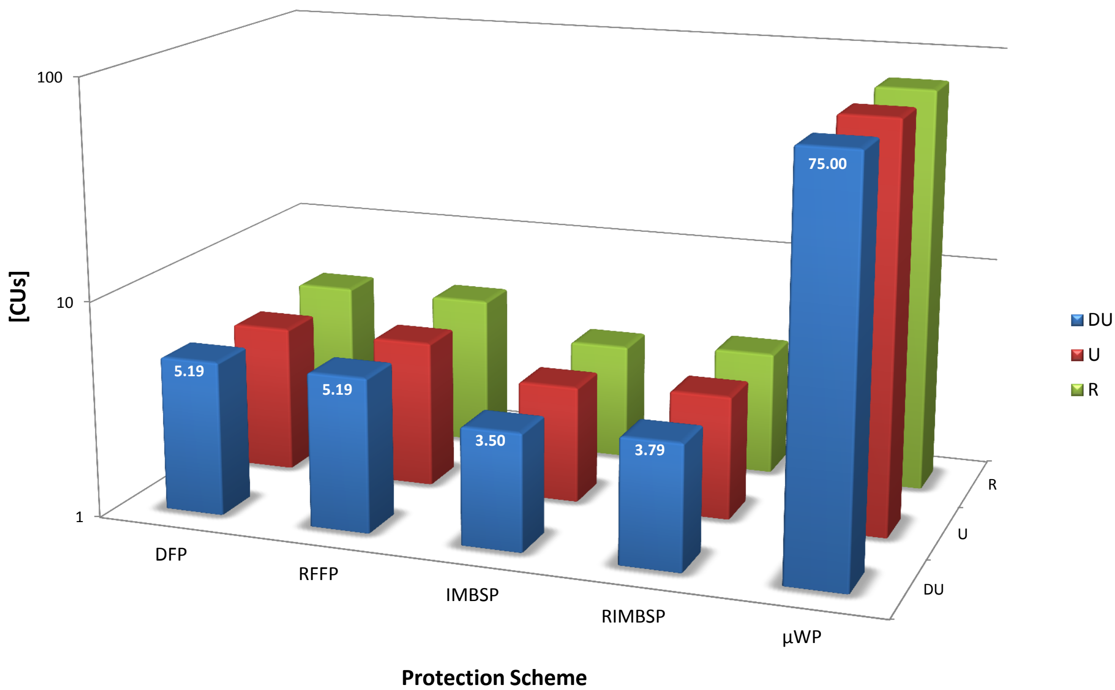


Figure 5.7: Additional Equipment Cost per MBS

4. IMBSP requires the minimum additional equipment, so it is the most economical as shown in Fig. 5.7.

5. μWP is the most expensive one, but it gives more flexibility and quick installation.

6. From scaling factor DFP& RFFP are most economical as these require only 1x OS for any additional MBS but, IMBSP/RFFP requires 1x OS & 1x filter for any additional MBS, as shown in Table. 5.2(b).

5.2.2 Connection Availability

The connection availability is defined as the probability of the connection being operational at any point of time. RBD is often referred to as the availability model of the system (in this thesis system corresponds to the connection between OLT and the MBS). Average length of protection fiber required per MBS for availability calculations has been calculated using following formula and results are shown in Table. 5.3 and Fig. 5.8:-

$$Average\ Fiber'/\ MBS = (FF^{'}/\ Total\ number\ of\ AWGs)+(DF^{'}/\ Total\ number\ of\ MBS)$$

From average protection fiber required per MBS for availability calculations, following can be deduced:-

1. Average Protection fiber required for IMBSP is almost half than DFP.

2. Protection fiber required by RFFP & RIMBSP is twice than DFP in DU and U areas.

3. Protection fiber required by RFFP & RIMBSP is thrice than DFP in R areas because, organizing OLT and AWGs in a ring has quite more penalty in R areas than DU & U.

Protection Scheme	DU	U	R
DFP	2.237	4.997	8.233
RFFP	4.529	9.175	26.574
IMBSP	1.128	2.803	4.507
RIMBSP	4.668	9.227	25.898
µWP	0.000	0.000	0.000

Table 5.3: Average Protection Fiber Required per MBS - Availability Calculation

The considered fiber availability is 0.999985725 per km or consequently unavailability is 0.000014275 per km. Average protection and working fiber lengths required for both FF

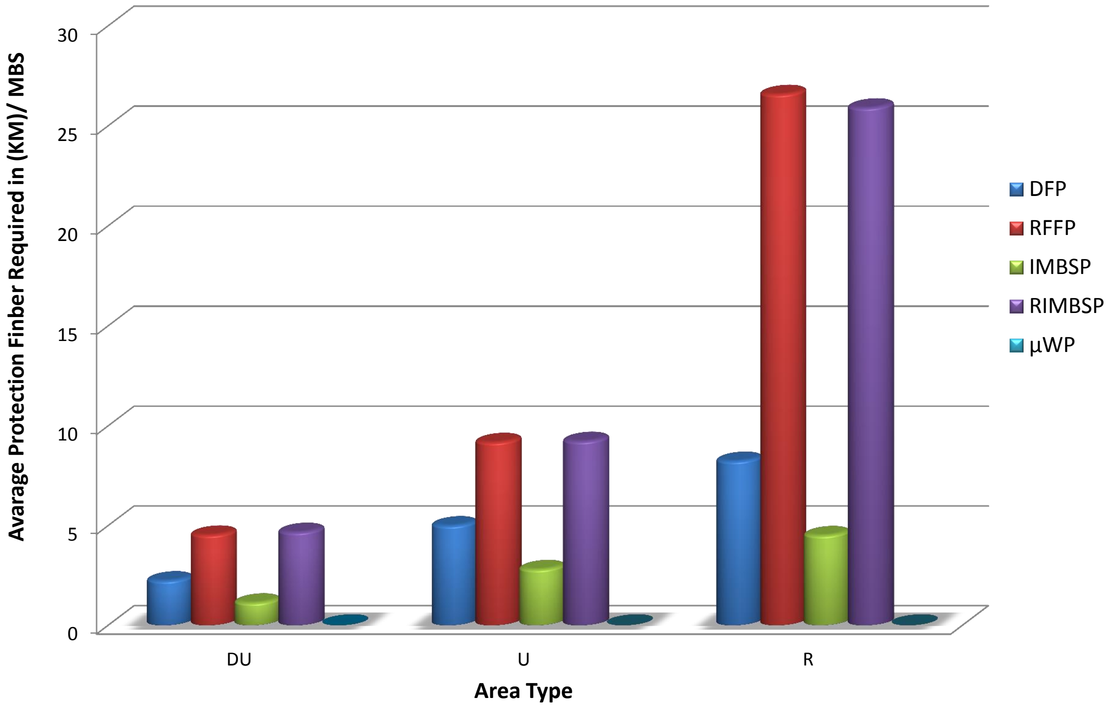


Figure 5.8: Average Protection Fiber Required per MBS - Availability Calculations

and DF are shown in Table. 5.4(a). Considering the fiber availability and unavailability/ km the results have been computed as shown in Table. 5.4(b & c). When we have these fiber availability and unavailability values, we have used availability/ unavailability of the different components involved in RBD as shown in Table. 5.5, the connection availability for MBS has been computed using expressions/ formulas described in Table. 5.6(a). The system unavailability and availability results are shown in Table. 5.6 (b & c) and compared in Fig. 5.10. Following are the deductions:-

1. IMBSP, RIMBSP & μWP schemes have higher connection availability due to the PONLT protection at the OLT.

2. μWP offers even higher availability due to the duplication of all the components (incl. PONNT).

3. DFP and RFFP have different fiber lengths, they show comparable connection availability. It means once the fiber is protected, the length of fiber has minor impact on connection availability.

Protection Scheme	DU				U				R			
	Average		Average		Average		Average		Average		Average	
	FF	FF'	DF	DF'	FF	FF'	DF	DF'	FF	FF'	DF	DF'
DFP	0.866	1.45	0.473	0.78	1.881	2.82	1.064	2.18	1.6771	2.75	2.9302	5.48
RFFP	1.3105	3.75	0.473	0.78	2.708	7	1.064	2.18	6.96185	21.09	2.9302	5.48
IMBSP	0.866	0.866	0.473	1.13	1.881	1.881	1.064	2.8	1.6771	1.6771	2.9302	4.51
RIMBSP	1.3105	3.75	0.473	0.92	2.708	7	1.064	2.23	6.96185	21.09	2.9302	4.81
µWP	0	0	0	0	0	0	0	0	0	0	0	0

(a)

Protection Scheme	DU				U				R			
	Average		Average		Average		Average		Average		Average	
	FF	FF'	DF	DF'	FF	FF'	DF	DF'	FF	FF'	DF	DF'
DFP	0.999987638	0.999979301	0.9999932	0.999988865	0.999973149	0.999959745	0.999984811	0.999968881	0.99997606	0.999960744	0.999958172	0.999921776
RFFP	0.999981293	0.99994647	0.9999932	0.999988865	0.999961344	0.999900079	0.999984811	0.999968881	0.999900624	0.999698983	0.999958172	0.999921776
IMBSP	0.999987638	0.999987638	0.9999932	0.999983869	0.999973149	0.999973149	0.999984811	0.999960031	0.99997606	0.99997606	0.999958172	0.999935621
RIMBSP	0.999981293	0.99994647	0.9999932	0.999986867	0.999961344	0.999900079	0.999984811	0.999968167	0.999900624	0.999698983	0.999958172	0.999931339

(b)

Protection Scheme	DU				U				R			
	Average		Average		Average		Average		Average		Average	
	FF	FF'	DF	DF'	FF	FF'	DF	DF'	FF	FF'	DF	DF'
DFP	1.23622E-05	2.06987E-05	6.752E-06	1.11345E-05	2.68511E-05	4.0255E-05	1.51886E-05	3.11192E-05	2.39405E-05	3.92558E-05	4.1828E-05	7.82245E-05
RFFP	1.87073E-05	5.35302E-05	6.752E-06	1.11345E-05	3.86562E-05	9.99207E-05	1.51886E-05	3.11192E-05	9.93762E-05	0.000301017	4.1828E-05	7.82245E-05
IMBSP	1.23622E-05	1.23622E-05	6.752E-06	1.61307E-05	2.68511E-05	2.68511E-05	1.51886E-05	3.99695E-05	2.39405E-05	2.39405E-05	4.1828E-05	6.43786E-05
RIMBSP	1.87073E-05	5.35302E-05	6.752E-06	1.3133E-05	3.86562E-05	9.99207E-05	1.51886E-05	3.1833E-05	9.93762E-05	0.000301017	4.1828E-05	6.86609E-05

(c)

Table 5.4: (a) Average protection and working FF/DF required [KMs] (b) Availability results for length of fibers, considered fiber availability is 0.999985725 per km (c) Unavailability results for length of fibers, considered fiber unavailability is 0.000014275 per km

Reference Values		
Component	Availability	*Unavailability
OLT	0.99996381	3.619E-05
PS 1:32	0.999999	1E-06
AWG 1:40	0.999994	6E-06
AWG 2:40	0.999994	6E-06
OS	0.999994	6E-06
Filter	0.999994	6E-06
coupler/ splitter	0.9999993	7E-07
wireless link	0.999967	3.3E-05
ONU	0.999961	3.9E-05

*Individual components unavailability $e_i<<1$

Table 5.5: Reference availability and unavailability values of different network components

Protection Scheme	MBS Availability Improvement $[a^t = 1-(e^t)]$
DFP	$e^t = e_{PONLT}+e_{OS}+((e_{FF}+e_{1:2}+e_{AWG}+e_{DF})*(e_{FF'}+e_{1:2'}+e_{AWG'}+e_{DF'}))+e_{OS}+e_{PONTNT}$
RFFP	$e^t = e_{PONLT}+e_{OS}+((e_{FF}+e_{1:2}+e_{AWG}+e_{DF})*(e_{FF'}+e_{1:2'}+e_{AWG'}+e_{DF'}))+e_{OS}+e_{PONTNT}$
IMBSP	$e^t = ((e_{PONLT}+e_{FF}+e_{AWG}+e_{DF})*(e_{PONLT'}+e_{FF'}+e_{AWG'}+e_{DF'}))+e_{OS}+e_{Filter}+e_{PONNT}$
RIMBSP	$e^t = ((e_{PONLT}+e_{OS}+(e_{FF}*e_{FF'})+e_{2:1}+e_{AWG}+e_{DF})*(e_{PONLT'}+ \text{Avg } e_{FF/FF'}+e_{AWG'}+e_{DF'}))+e_{OS}+e_{Filter}+e_{PONNT}$
µWP	$e^t = (e_{PONLT}+e_{FF}+e_{AWG}+e_{DF}+e_{PON\ NT})*(e_{PONLT'}+e_{FF'}+e_{AWG'}+e_{DF'}+e_{PON\ NT'}+e_{\mu WAVE\ LINK})$

(a)

	Unavailability		
	DU	U	R
DFP	8.7191E-05	8.71938E-05	8.7199E-05
RFFP	8.71923E-05	8.71983E-05	8.72471E-05
IMBSP	5.10043E-05	5.10092E-05	5.10141E-05
RIMBSP	5.10051E-05	5.10092E-05	5.10282E-05
µWP	1.3371E-08	1.92521E-08	2.64464E-08

(b)

	Availability		
	DU	U	R
DFP	0.999912809	0.999912806	0.999912801
RFFP	0.999912808	0.999912802	0.999912753
IMBSP	0.999948996	0.999948991	0.999948986
RIMBSP	0.999948995	0.999948991	0.999948972
µWP	0.999999987	0.999999981	0.999999974

(c)

Table 5.6: (a) Expressions/ formulas used to calculate system unavailability and availability (b) System unavailability results (c) System availability results

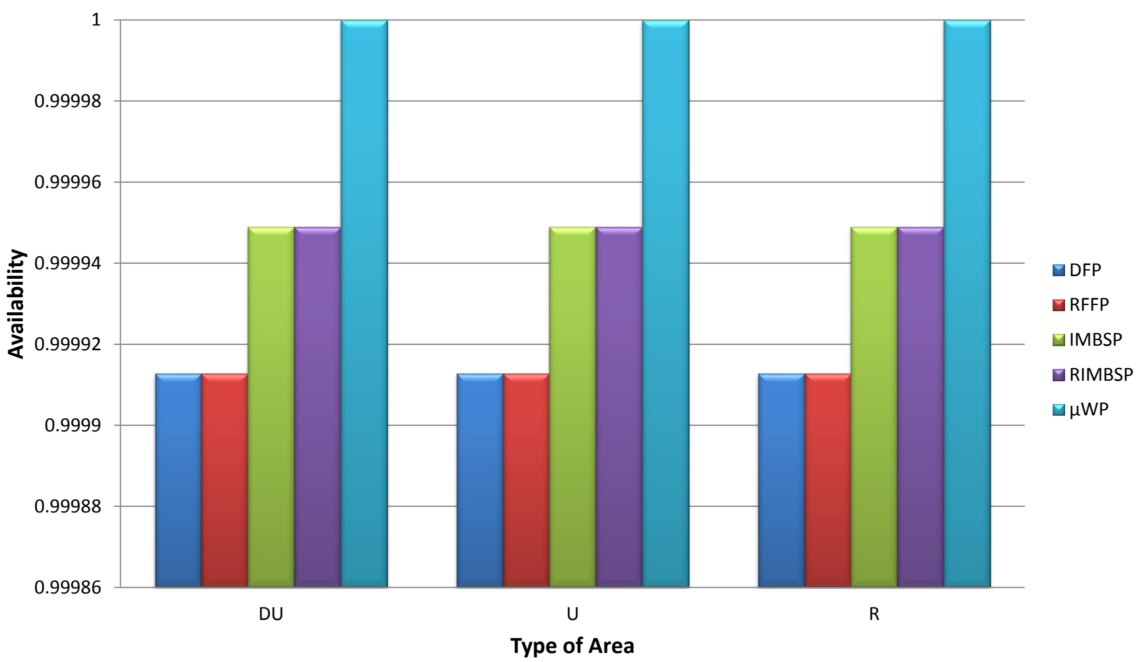


Figure 5.9: Comparative system availability calculation results for each protection scheme in DU, U and R area

5.2.3 Power Required/ MBS

The power consumption of telecommunication networks is currently dominated by the power consumed in access networks. Therefore, the extra power consumed by the different protection schemes has also been compared. Table. 5.7(a) summarizes the total as well as per MBS consumed power per year. It is pertinent to highlight that out of additional components which are being used for protection only OS and filters are the power consuming components. AWGs and couplers are passive components and does not consume any power. The reference power consumption values used for OS and Filters are also shown in Table. 5.7(b), [?] and [?]. Following is the preliminary analysis:-

1. Power consumption of OS is very less as compared to filter i.e, almost 10,000 times less.
2. Power consumption by DFP and RFFP is very less, as these schemes are not using any filters.
3. Power consumption of IMBSP and RIMBSP per MBS is same as shown in Fig. 5.11.
4. μWP scheme is the most power consuming protection scheme although it offers two modes of operation, sleep and active as highlighted in Table. 5.7(b). In sleep mode the power consumption is almost 4 times less than active. Power consumption has been calculated considering the availability and unavailability of wireless link.

Protection Scheme	Power Consuming Equipment	Required Components			Power Consumption All Components			Annual Power Consumption [kWh]			Annual Power Consumption/ MBS [kWh]		
		DU	U	R	DU	U	R	DU	U	R	DU	U	R
DFP	OS	79	76	70	0.00948	0.00912	0.0084	0.083	0.080	0.074	0.001	0.001	0.001
RFFP	OS	79	76	70	0.00948	0.00912	0.0084	0.083	0.080	0.074	0.001	0.001	0.001
IMBSP	OS	72	70	64	100.80864	98.0084	89.60768	883.084	858.554	784.963	12.265	12.265	12.265
	Filters	72	70	64									
RIMBSP	OS	79	76	70	100.80948	98.00912	89.6084	883.091	858.560	784.970	12.265	12.265	12.265
	Filters	72	70	64									
µWP	µwave links	36	35	32	144.017	140.016	128.015	1261.586	1226.542	1121.410	17.522	17.522	17.522

(a)

Reference Power Consumption Values		
Component	[Watts]	Remarks
OS	0.00012*	* DiCon MEMS Single Mode Cylindrical package
Filter	1.40 ^	^ DiCon MEMS Tunable Filter (Type A), Channel Spacing 100 Ghz
µwave link	18.00	Active mode
	4.00	Sleep mode

(b)

Table 5.7: (a) Power Consumption Calculations (b) Reference Power Consumption Values

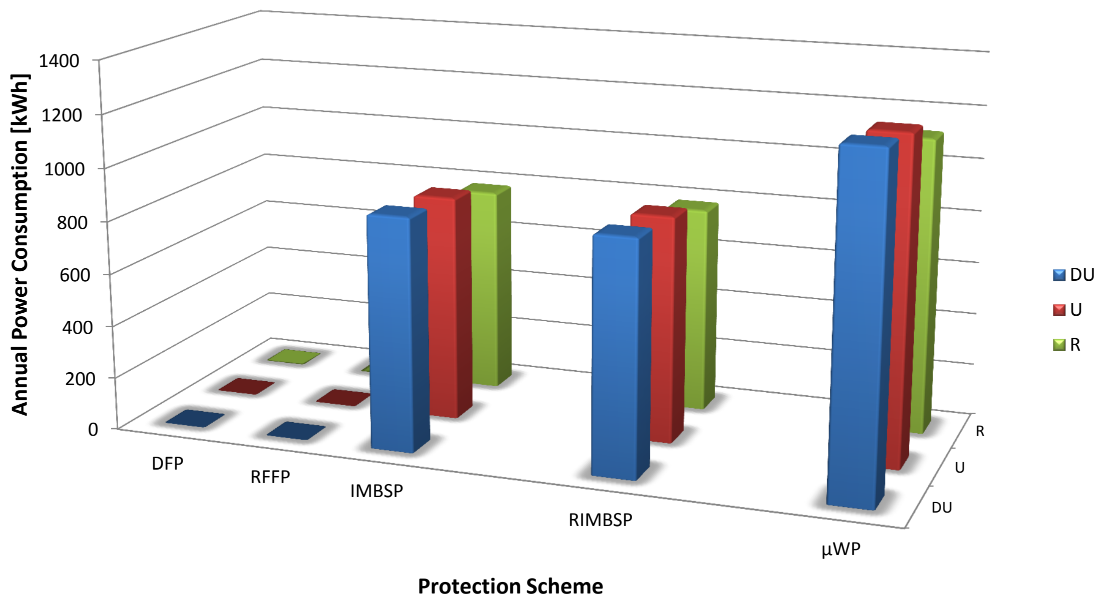


Figure 5.10: Annual Power Consumption Analysis - Total

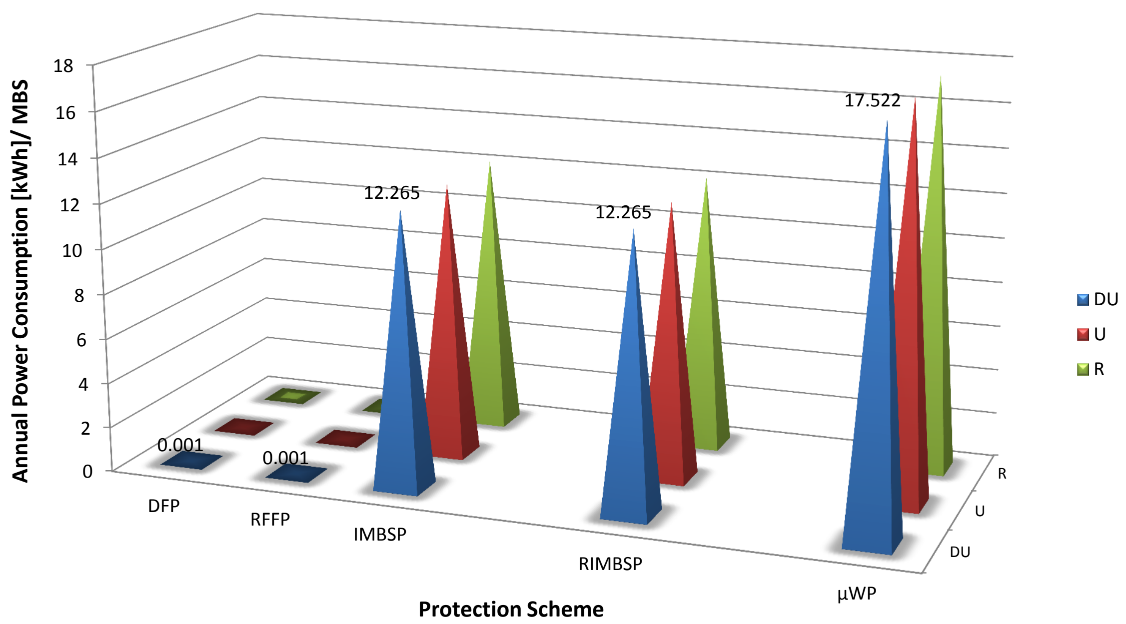


Figure 5.11: Annual Power Consumption Analysis/ MBS

5.2.4 Failure Impact Factor(FIF)

The Failure Penetration Range (FPR) is defined as the number of affected users/connections when a particular failure occurs. For example, a failure of the FF affects all users connected to this PON and hence, the FPR of an unprotected FF failure is the client count of this PON. The FPR of a DF failure is only one because its failure interrupts the connection of a single ONU/ MBS. In most of the cases, failures of the protection set are prioritized based on their impact so that operators start protecting the components with a higher impact. Failure Impact factor (FIF) takes into account the network components that are unprotected, their unavailability, and the impact that their failure may have (i.e. the number of users that will be affected by their failures). The FIF of a connection can be computed as the sum of the FIF of each unprotected component involved in the connection. Hence, the FIF of a fully protected connection is nil. The FIF of an unprotected component is computed as the product of its unavailability and its Failure Penetration Range (FPR), which is defined as the number of affected users/connections when this component fails. Since all the fibers to the MBS are protected, the FIF depends only on the components' FIF. Results are calculated and summarized as shown in Table. 5.8(a) & (b) respectively. Fig. 5.12 shows the comparative analysis of protection schemes in DU, U and R areas. Following is the preliminary analysis:-

1. FIF of μWP scheme is zero as all components are protected.
2. FIF of IMBSP and RIMBSP is very less as PONLT is protected in these schemes.
3. DFP & RFFP are having the highest FIF. As both schemes are using the same architectural scheme the FIF values are same.
4. FIF values are high in R areas than U and DU areas because the endpoints are different in each scenario, so as FPR values are different as already shown in Table 4.1.
5. Compared to unprotected scenario (FIF value = 0.0265186717), DFP & RFFP schemes has decreased FIF by almost 50%, IMBSP & RIMBSP has decreased the FIF by almost 50,000 times.

5.2.5 Fiber Length/ MBS

Fiber Length/ MBS means, how many kilometers of protection fiber is required per MBS? Average length of protection fiber required per MBS for cost calculations has been calculated using following formula:-

$$(FF' + \Delta W + DF')/ \textit{Total Number of MBS}$$

Average protection fiber required per MBS for cost calculations as shown in Table. 5.9 and Fig. 5.13, following can be deduced:-

	Unprotected Component	Components FIF		
		Dense Urban	Urban	Rural
DFP	PONLT	0.01517395	0.01527218	0.019102288
	OS1	0.002515714	0.002532	0.003167
	OS2	6E-06	6E-06	6E-06
	PONNT	3.9E-05	3.9E-05	3.9E-05
RFFP	PONLT	0.01517395	0.01527218	0.019102288
	OS1	0.002515714	0.002532	0.003167
	OS2	6E-06	6E-06	6E-06
	PONNT	3.9E-05	3.9E-05	3.9E-05
IMBSP	OS	6E-06	6E-06	6E-06
	Filter	6E-06	6E-06	6E-06
	PONNT	3.9E-05	3.9E-05	3.9E-05
RIMBSP	OS	6E-06	6E-06	6E-06
	Filter	6E-06	6E-06	6E-06
	PONNT	3.9E-05	3.9E-05	3.9E-05
µWP	-	0	0	0

(a)

FIF			
Scheme	DU	U	R
DFP	0.017734664	0.01784918	0.022314288
RFFP	0.017734664	0.01784918	0.022314288
IMBSP	5.1E-05	5.1E-05	5.1E-05
RIMBSP	5.1E-05	5.1E-05	5.1E-05
µWP	0	0	0

(b)

Table 5.8: (a) Unprotected component FIF Calculation (Component Unavailability * Failure Penetration Range) (b) Failure Impact Factor of different protection schemes in DU,U and R areas

1. DFP is the most economical solution in DU & U areas however IMBSP is the most economical solution in R areas.

2. RFFP, RIMBSP & IMBSP are having almost same cost in DU & U area but significantly different in R areas.

3. RFFP is more economical than RIMBSP in DU and U areas however, RIMBSP is more economical than RFFP in R areas.

4. As shape of graphs is not same in all areas therefore applying universal protection solution is not a good option. It is evident that implementation of any protection scheme requires more funds in U and R areas as compared to DU area because of less population and MBS density/ KM as already shown in Figure 4.1. Therefore % Increase in cost for Implementation in U and R areas, with reference to implementation cost of DU area, has also been calculated and shown in Fig. 5.14, following is

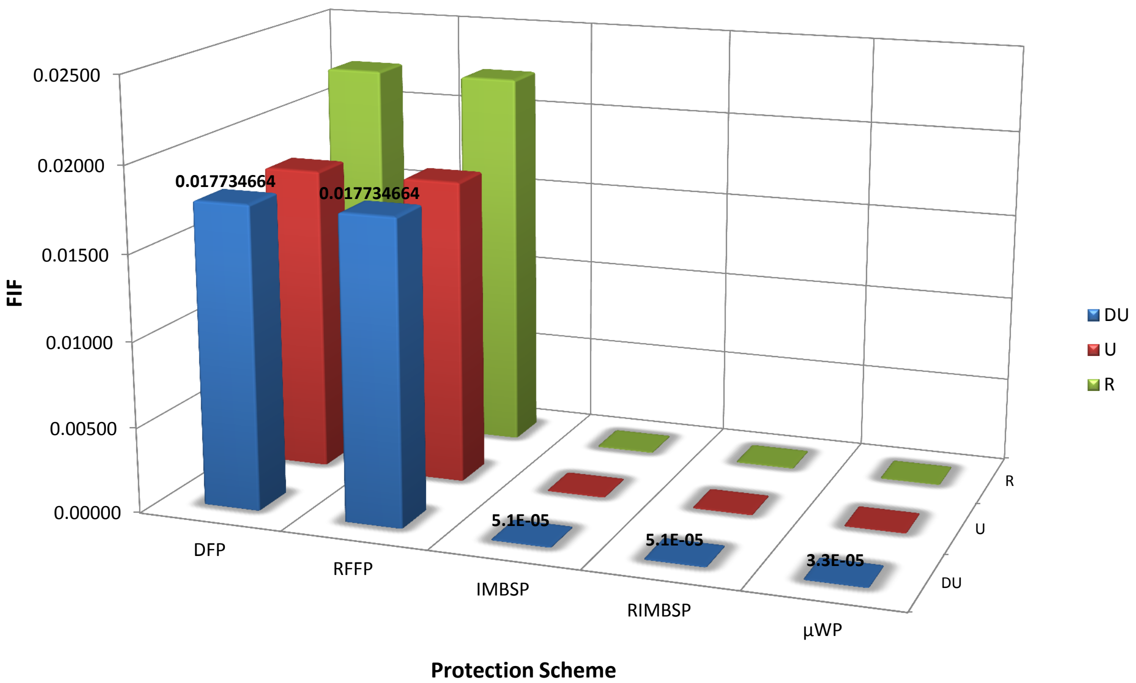


Figure 5.12: Failure Impact Factor of Different Protection Schemes in DU,U and R Areas

highlighted:-

- RIMBSP has minimum % increase in U areas considering reference as implementation cost in DU area.
- IMBSP has minimum % increase in R areas considering reference as implementation cost in DU area.

Protection Scheme	DU	U	R
DFP	0.870	2.420	5.740
RFFP	1.155	2.849	7.954
IMBSP	1.129	2.803	4.507
RIMBSP	1.330	2.901	7.278
µWP	0.000	0.000	0.000

Table 5.9: Average Protection Fiber Required per MBS - Cost calculation

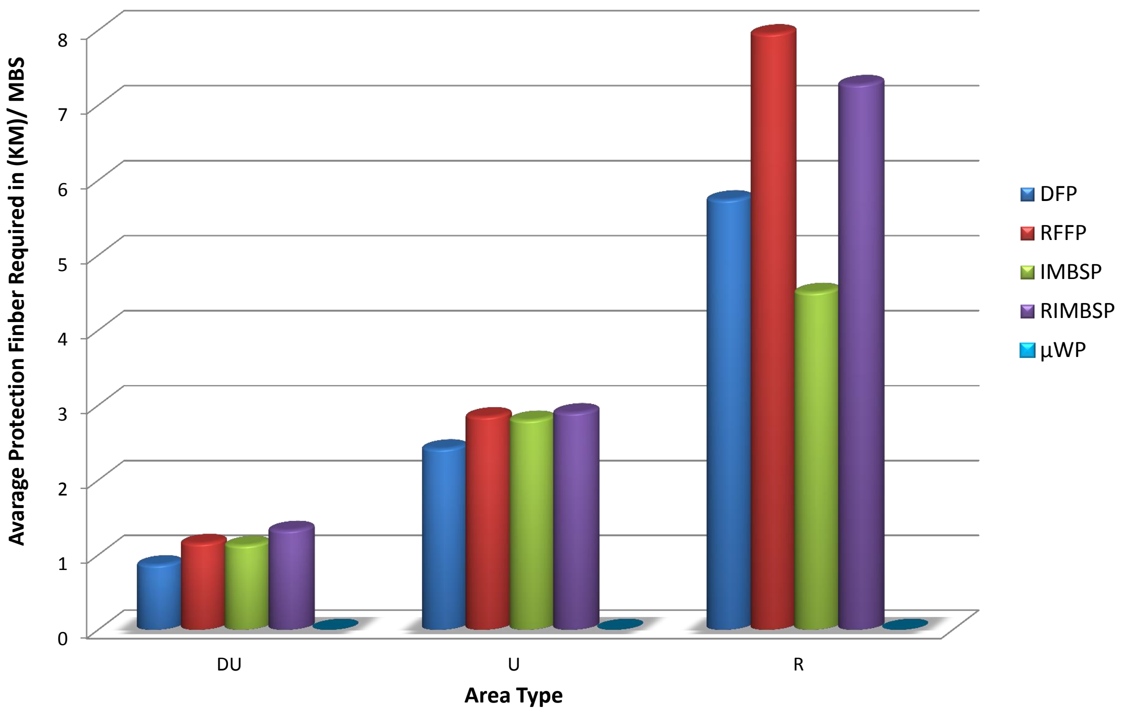


Figure 5.13: Average Protection Fiber Required per MBS - Cost calculation

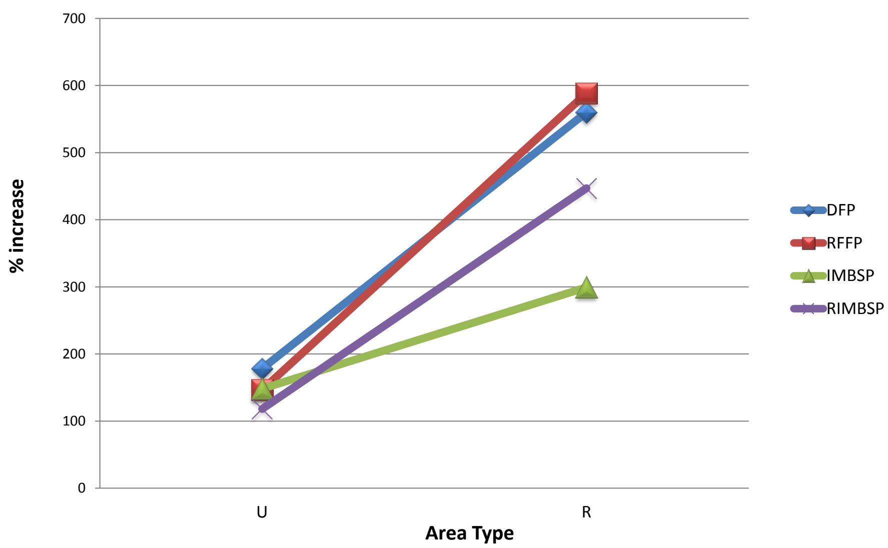


Figure 5.14: Percentage increase in cost for implementation in U and R areas, with reference to implementation cost of DU area

5.2.6 Improvement in Availability of Residential Users

As already explained in Section 3.6 DFP, RFFP and RIMBSP will also result into the availability improvement of residential users along MBS, because of protected FF which is common to MBS as well as residential users. However IMBSP and μWP will not able to enhance/ improve the residential users availability, so it will be same as unprotected case. Table. 5.10(a) shows calculated availability improvement of residential users using the expressions/ formulas used in Table. 5.10 (b). Fig. 5.15 highlights following:-

1. DFP, RFFP and RIMBSP results in improvement of availability of residential users.
2. The degree of improvement is different in DU,U and R areas as the length of FF and FF' is different in all areas.
3. IMBSP and μWP don't improve the availability of residential users. If it is desired to incorporate this feature, than following are the available options:-
   - **IMBSP** If protection of only FF is required it can be done either using disjoint or ring FF Protection, however this will require additional funds and will not result any further improvement in the availability of MBS.
   - **μWP** In order to protect only FF we have two options of either using fiber (Disjoint or Ring) or use additional very high capacity Microwave links, which are equal to total number of AWGs/ 2. Considering the quantum of traffic demand which is required to be protected, it can easily be concluded that with today's state of the art microwave technology it is not possible or extremely difficult to implement the microwave solution. Resultantly fiber is the only feasible solution for FF as highlighted and very well explained in [YSWC14].

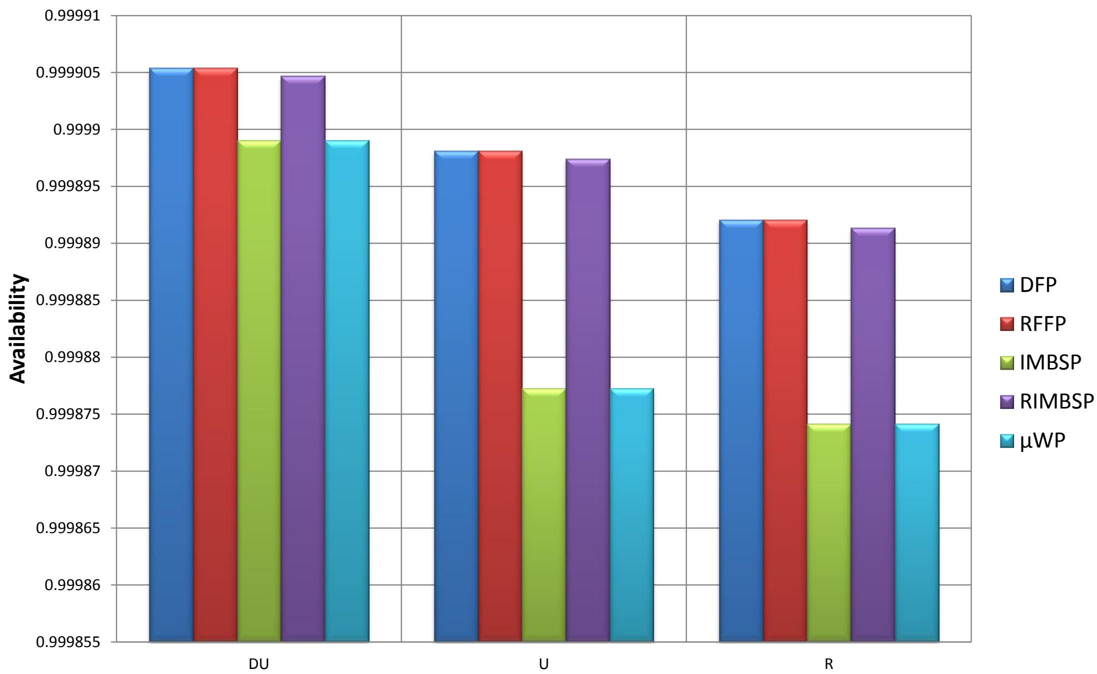


Figure 5.15: Residential users availability results for different protection schemes in DU, U and R areas

Residential Users Availability			
Scheme	DU	U	R
DFP	0.999905411	0.999898134	0.99989209
RFFP	0.999905411	0.999898131	0.99989206
IMBSP	0.99989905	0.999877284	0.99987415
RIMBSP	0.999904711	0.999897431	0.999891361
µWP	0.99989905	0.999877284	0.99987415

(a)

Unprotected Case	$e^t = e_{PONLT}+e_{FF}+e_{AWG}+e_{DF}+e_{PS}+e_{LMF}+e_{PONNT}$
IMBSP & µWP	$e^t = e_{PONLT}+e_{FF}+e_{AWG}+e_{DF}+e_{PS}+e_{LMF}+e_{PONNT}$
DFP & RFFP	$e^t = e_{PONLT}+e_{os}+((e_{FF}+e_{1:2})*(e_{FF'}+e_{1:2'}))+e_{AWG}+e_{DF}+e_{PS}+e_{LMF}+e_{PONNT}$
RIMBSP	$e^t = e_{PONLT}+e_{os}+(e_{FF}*e_{FF'})+e_{2:1}+e_{AWG}+e_{DF}+e_{PS}+e_{LMF}+e_{PONNT}$

(b)

Table 5.10: (a) Residential users availability results for different protection schemes in DU, U and R areas (b) Expressions/ formulas used for calculation of availability improvement of residential users

5.2.7 Additional Fiber Requirement for Working Paths (ΔW)

Considering the difference in working paths from reference scenario, ΔW can be calculated using following formula:-

(*Fiber required for working paths in considered protection scheme - Fiber required for working paths by reference scenario*)

Any protection scheme which is using ring i.e RFFP & RIMBSP will have this a positive value, rest of protection schemes will have this a zero value.Reference to Table 5.1, following is deduced:-

1. ΔW is almost 40-50 % in DU & U areas.
2. Its value is too high in R areas i.e almost 300 %.

5.3 Comparative Analysis & Consolidated Results

In this section we have done the fusion of results for comparative analysis and logical conclusions. Details will be covered in following subsections.

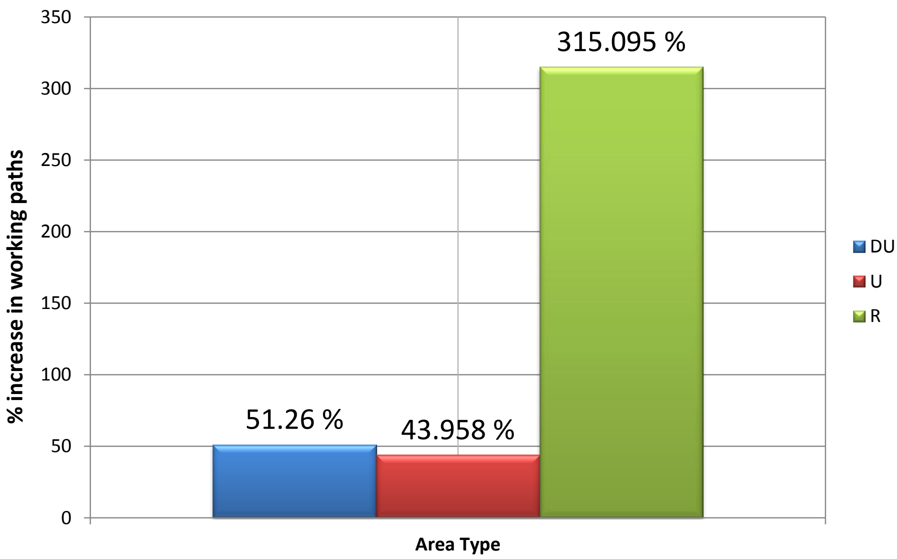


Figure 5.16: Additional Fiber Requirement for Working Paths(ΔW)

5.3.1 Net Spider Diagrams & Degree Definitions

We will compare protection schemes in DU, U and R areas using Net Spider Diagrams. These are used for the comparison with respect to the parameters already mentioned in section 5.2 and proposed degrees and ranges as mentioned in Table. 5.11. It is pertinent to highlight that **lower the degree, the better it is** i.e 1 is better than 4. Graphical representation of considered parameters with considered ranges are also shown in Fig. 5.17.

5.3.2 Comparison of Protection Schemes in DU Area

Degree definition and performance of different protection schemes in DU area have been shown in Table. 5.12 & Fig. 5.18. Following is the analysis:-

1. DFP is having lowest connection availability, highest FIF and comparable higher component cost. But it requires minimum additional power, lowest protection fiber length per MBS (considering fiber schemes only) , maximally improves residential users availability and also does not require any delta W. Reference Fig. 5.18(a).
2. RFFP is same as DFP, but it requires Δ W and length of protection fiber required per MBS is comparable more. Reference Fig. 5.18(b).
3. IMBSP is the suitable compromise of all considered parameters, except it does not improve the availability of residential users. Reference Fig. 5.18(c).

Protection Scheme	Components Cost/MBS			Availability			Power Required/MBS			FIF			Fiber Length/MBS			Residential users Improvement			Δ W		
	DU	U	R	DU	U	R	DU	U	R	DU	U	R	DU	U	R	DU	U	R	DU	U	R
DFP	5.19	4.81	5.08	0.999912809	0.999912806	0.999912801	0.00	0.00	0.00	0.017735	0.017849	0.0223142	0.87	2.42	5.74	0.999905411	0.999898134	0.99989209	0	0	0
RFFP	5.19	4.81	5.08	0.999912808	0.999912802	0.999912753	0.00	0.00	0.00	0.017735	0.017849	0.0223142	1.16	2.85	7.95	0.999905411	0.999898131	0.99989206	3.109	4.962	31.0781
IMBSP	3.50	3.50	3.50	0.999948996	0.999948991	0.999948986	12.27	12.27	12.27	5.1E-05	5.1E-05	5.1E-05	1.13	2.80	4.51	0.99989905	0.999877284	0.99987415	0	0	0
RIMBSP	3.79	3.76	3.78	0.999948995	0.999948991	0.999948972	12.27	12.27	12.27	5.1E-05	5.1E-05	5.1E-05	1.33	2.90	7.28	0.999904711	0.999897431	0.999891361	3.109	4.962	31.0781
µWP	75.00	75.00	75.00	0.999999987	0.999999981	0.999999974	17.52	17.52	17.52	3.3E-05	3.3E-05	3.3E-05	0	0	0	0.99989905	0.999877284	0.99987415	0	0	0

(a)

KEY	Components Cost/MBS	Availability	Power Required/MBS	FIF	Fiber Length/MBS	Residential users Improvement	Δ W
1	<= 3.5	> 0.999999974	<= 0	<= 3.3E-05	<1	> 0.999904711	0
2	> 3.5 && <=3.76	< 0.999999974 && >= 0.999948972	> 0 && <= 12.27	> 3.3E-05 && <= 5.1E-05	>1.0 && <=2.42	<= 0.99989134&& >=0.999897431	>0 && <=4
3	>3.76 && <=5.19	NA	NA	NA	>2.42 && <= 4.51	<=0.99989209 && >=0.999891361	>4 && <=30
4	> = 75	< 0.999948972	> = 17.52	> 5.1 E-05	> 4.51	No Improvement	>30

(b)

Protection Scheme	Components Cost/MBS			Availability			Power Required/MBS			FIF			Fiber Length/MBS			Residential users Improvement			Δ W		
	DU	U	R	DU	U	R	DU	U	R	DU	U	R	DU	U	R	DU	U	R	DU	U	R
DFP	3	3	3	4	4	4	1	1	1	4	4	4	1	2	4	1	2	3	1	1	1
RFFP	3	3	3	4	4	4	1	1	1	4	4	4	2	3	4	1	2	3	2	3	4
IMBSP	1	1	1	2	2	2	2	2	2	2	2	2	2	3	3	4	4	4	1	1	1
RIMBSP	2	2	2	2	2	2	2	2	2	2	2	2	2	3	4	1	2	3	2	3	4
µWP	4	4	4	1	1	1	4	4	4	1	1	1	1	1	1	4	4	4	1	1	1

(c)

Table 5.11: (a) Consolidated Results of Considered Parameters (b) Degree Ranges (c) Proposed Degrees

4. RIMBSP provides the best solution of all the considered factors.Reference Fig. 5.18(d).

5. μ WP is having the highest component cost, power requirement and does not improve the availability of residential users. But it has the highest connection availability, does not require any additional fiber for protection, lowest FIF and also does not result into any Δ W requirement. Reference Fig. 5.18(e).

5.3.3 Comparison of Protection Schemes in U Area

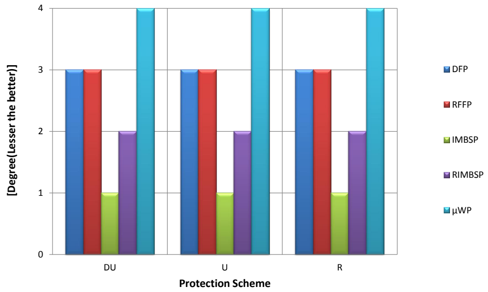
Degree Definition and Performance of Different Protection Schemes in U area have been shown in Table. 5.13 & Fig. 5.19. Following is the analysis:-

1. DFP is having lowest connection availability, highest FIF and comparable higher component cost. But it requires minimum additional power, minimum protection fiber length per MBS (considering fiber schemes only) , highest residential users improvement and also does not require any delta W. Reference Fig. 5.19(a).

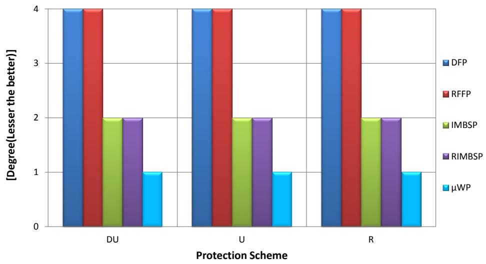
2. RFFP is same as DFP but it requires Δ W and length of protection fiber required per MBS is comparable more. Reference Fig. 5.19(b).

3. IMBSP provides the best solution of all the considered factors except it does not improve the availability of residential users.Reference Fig. 5.19(c).

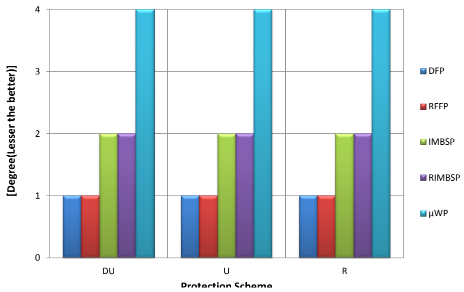
4. RIMBSP is the suitable compromise of all considered parameters. Reference Fig. 5.19(d).



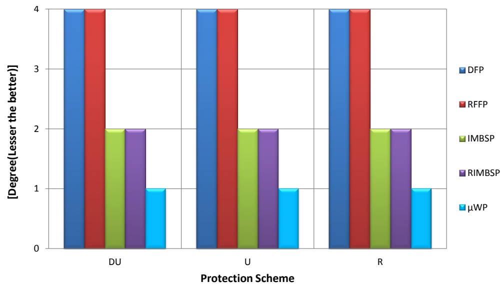
(a) Components cost/ MBS



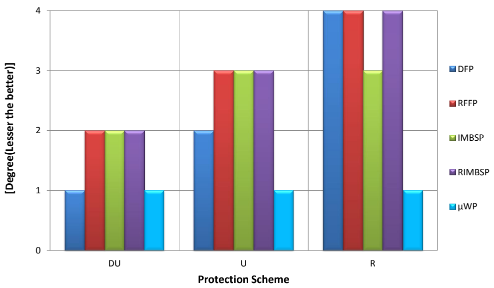
(b) Connection availability



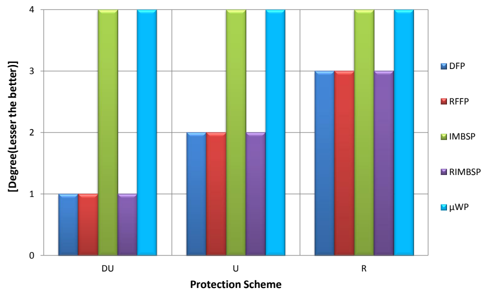
(c) Power requirement/ MBS



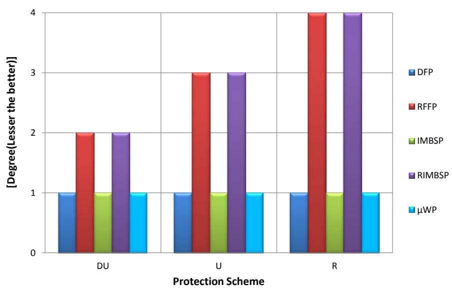
(d) FIF calculations



(e) Protection fiber length/ MBS



(f) Residential users availability improvement



(g) Δ W

Figure 5.17: Comparative analysis of different protection schemes in DU, U and R areas with reference to considered parameters with degree definitions

DEGREES DEFINITION DENSE URBAN AREA (LESSER THE BETTER)							
Protection Scheme	Components Cost/MBS	Availability	Power Required/MBS	FIF	Fiber Length/MBS	Residential users Improvement	Δ W
DFP	3	4	1	4	1	1	1
RFFP	3	4	1	4	2	1	2
IMBSP	1	2	2	2	2	4	1
RIMBSP	2	2	2	2	2	1	2
µWP	4	1	4	1	1	4	1

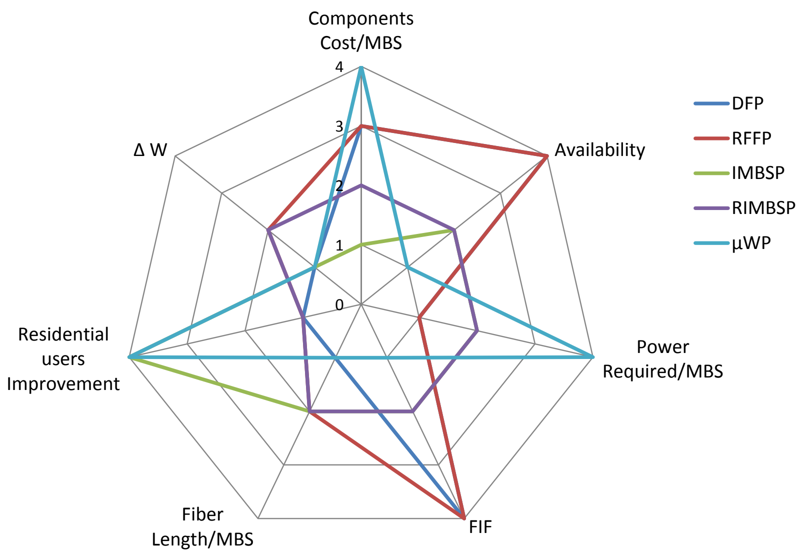


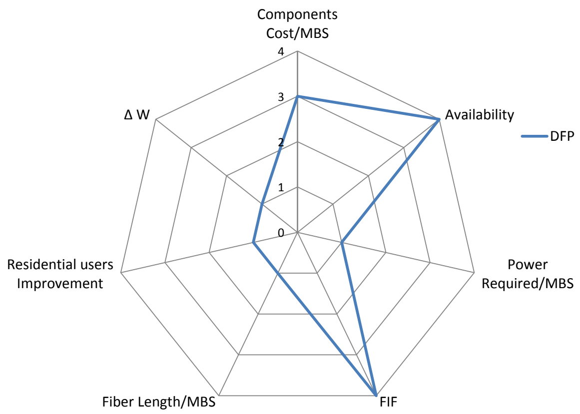
Table 5.12: Degree definition and performance of different protection schemes in DU area

5. μ WP is having the highest component cost, power requirement and does not improve the availability of residential user. But it has the highest connection availability, does not require any additional fiber for protection, lowest FIF and also not having any Δ W. Reference Fig. 5.19(e).

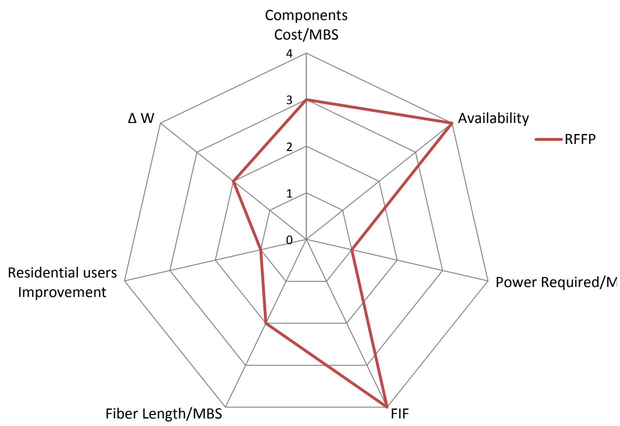
5.3.4 Comparison of Protection Schemes in R Area

Degree Definition and Performance of Different Protection Schemes in R area have been shown in Table. 5.14 & Fig. 5.20. Following is the analysis:-

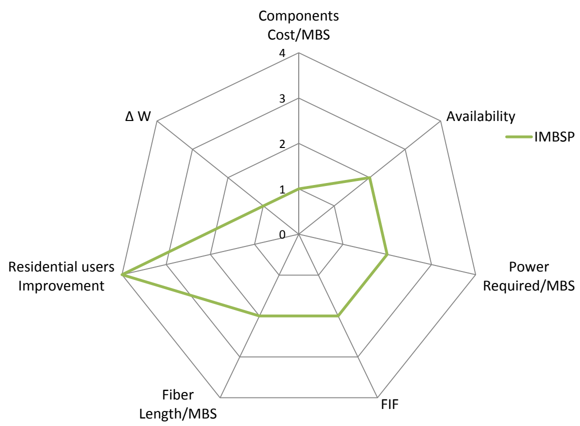
1. DFP is having lowest connection availability, highest FIF and comparable higher component cost. But it requires minimum additional power, minimum protection fiber length per MBS (considering fiber schemes only) , highest residential users improvement and also does not require any delta W. Reference Fig. 5.20(a).
2. RFFP is same as DFP but it requires ΔW and length of protection fiber required



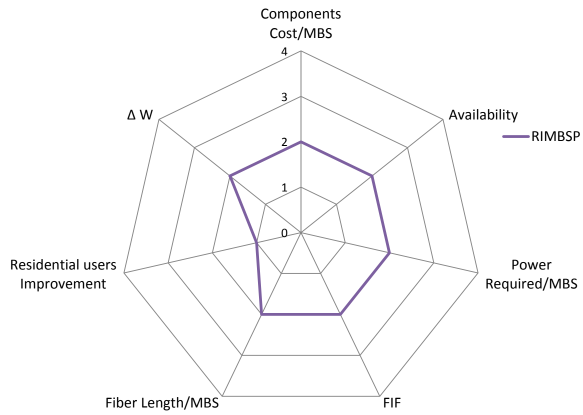
(a) DFP - Dense Urban Area



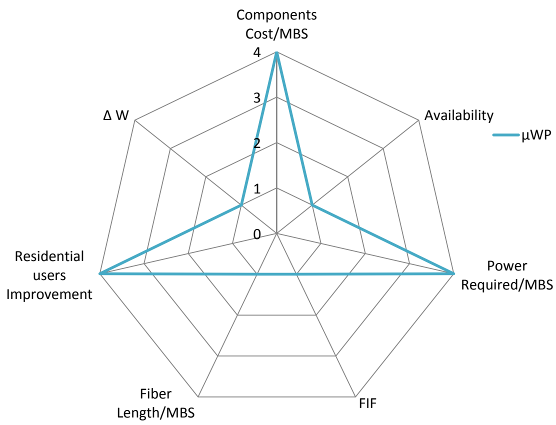
(b) RFFP - Dense Urban Area



(c) IMBSP - Dense Urban Area



(d) RIMBSP - Dense Urban Area



(e) μWP - Dense Urban Area

Figure 5.18: Comparative analysis of different protection schemes in DU areas with reference to considered parameters with degree definitions

DEGREES DEFINITION URBAN AREA (LESSER THE BETTER)							
Protection Scheme	Components Cost/MBS	Availability	Power Required/MBS	FIF	Fiber Length/MBS	Residential users Improvement	Δ W
DFP	3	4	1	4	2	2	1
RFFP	3	4	1	4	3	2	3
IMBSP	1	2	2	2	3	4	1
RIMBSP	2	2	2	2	3	2	3
µWP	4	1	4	1	1	4	1

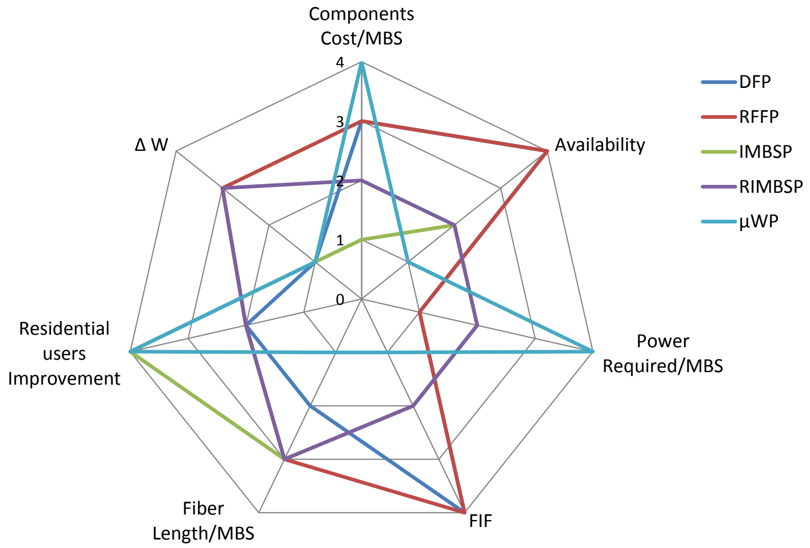


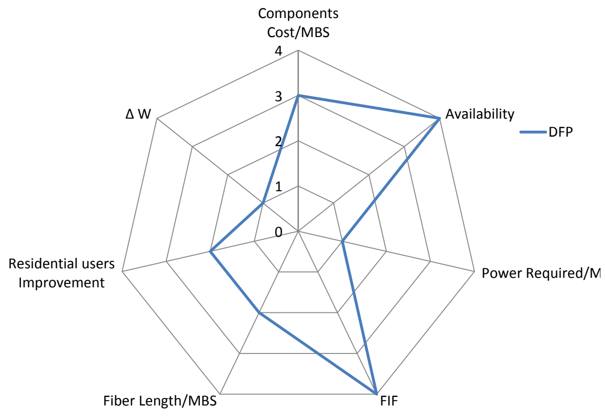
Table 5.13: Degree Definition and Performance of Different Protection Schemes in U area

per MBS is comparable more. Reference Fig. 5.20(b).

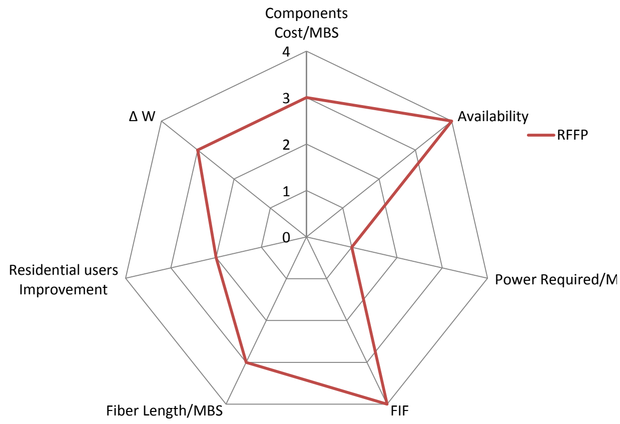
3. IMBSP provides the best solution of all the considered factors except it does not improve the availability of residential users. Reference Fig. 5.20(c).

4. RIMBSP is the suitable compromise of all considered parameters and also improves the availability of residential users also. Reference Fig. 5.20(d).

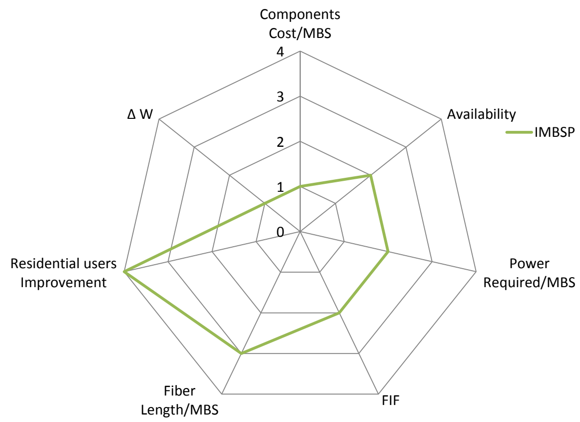
5. μ WP is having the highest component cost, power requirement and does not improve the availability of residential user. But it has the highest connection availability, does not require any additional fiber for protection, lowest FIF and also not having any ΔW. Reference Fig. 5.20(e).



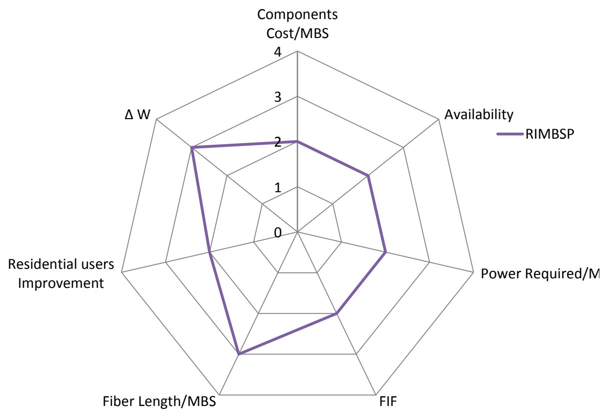
(a) DFP - Urban Area



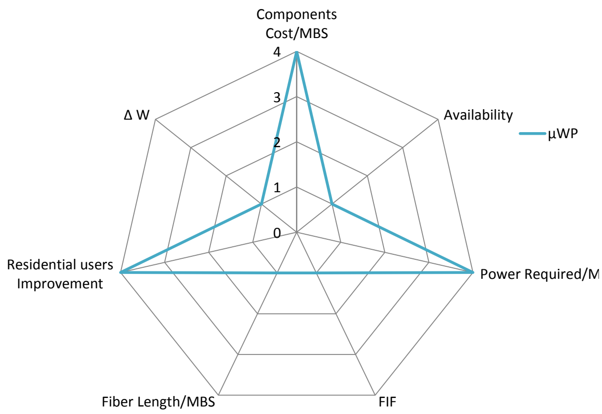
(b) RFFP - Urban Area



(c) IMBSP - Urban Area



(d) RIMBSP - Urban Area



(e) μWP - Urban Area

Figure 5.19: Comparative analysis of different protection schemes in U areas with reference to considered parameters with degree definitions

DEGREES DEFINITION RURAL AREA(LESSER THE BETTER)							
Protection Scheme	Components Cost/MBS	Availability	Power Required/MBS	FIF	Fiber Length/MBS	Residential users Improvement	Δ W
DFP	3	4	1	4	4	3	1
RFFP	3	4	1	4	4	3	4
IMBSP	1	2	2	2	3	4	1
RIMBSP	2	2	2	2	4	3	4
µWP	4	1	4	1	1	4	1

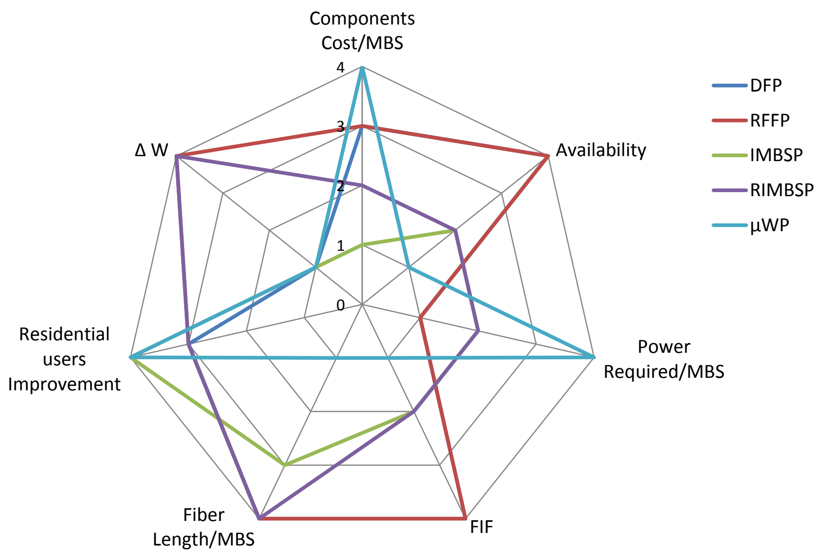
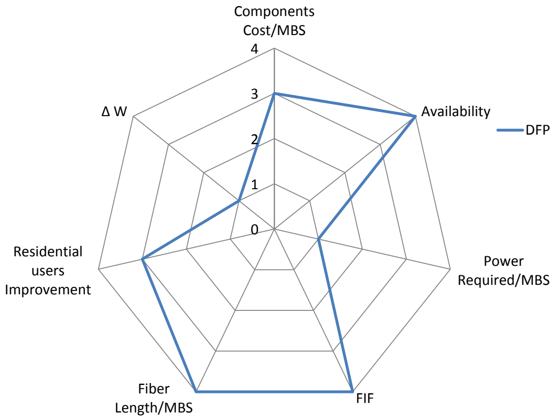


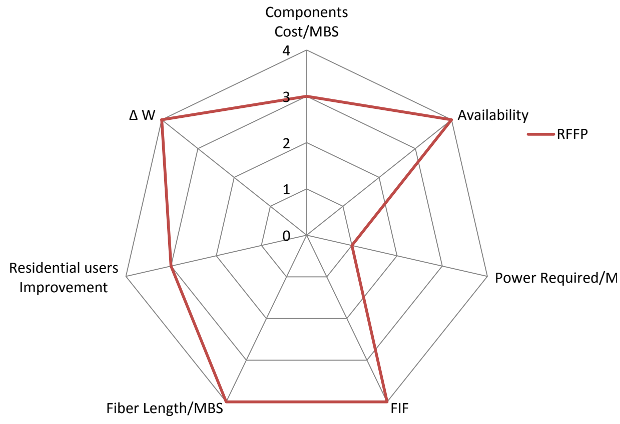
Table 5.14: Degree definition and performance of different protection schemes in R area

5.3.5 Protection Schemes Performance in DU, U and R Areas

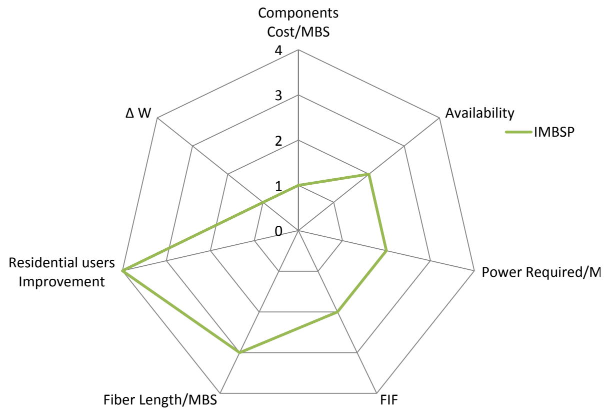
- **Disjoint Fiber Protection (DFP).** Rural areas require more fiber length/ MBS and improves less the residential users availability than the same scheme in DU and U areas. Reference Fig. 5.21.
- **Ring Feeder Fiber Protection (RFFP).** Rural areas require more ΔW, more fiber length/ MBS and improves less the residential users availability than the same scheme in DU and U areas. Reference Fig. 5.22.
- **Inter MBS DF Protection (IMBSP).** Rural areas require more fiber length/ MBS than the same scheme in DU and U areas. Reference Fig. 5.23.
- **Ring Inter MBS Protection (RIMBSP).** Rural areas require more ΔW, more fiber length/ MBS and improves less the residential users availability than the same scheme in DU and U areas. Reference Fig. 5.24.
- **Microwave MBS Protection (μWP).** It is same in DU,U and R areas as it is not



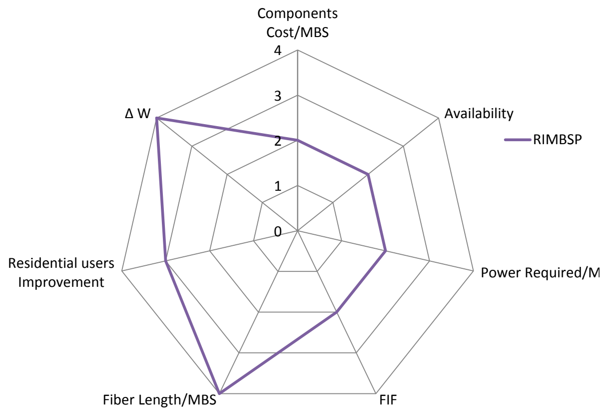
(a) DFP-Rural Area



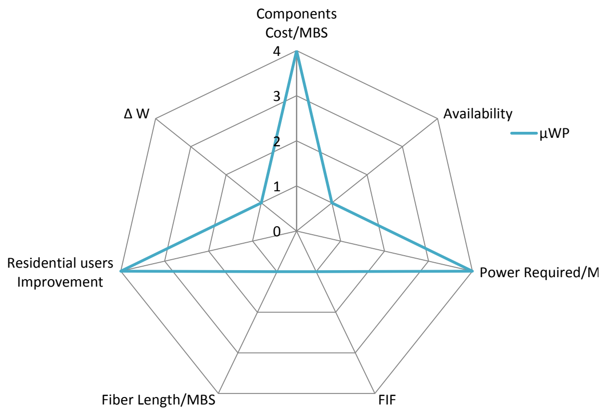
(b) RFFP-Rural Area



(c) IMBSP-Rural Area



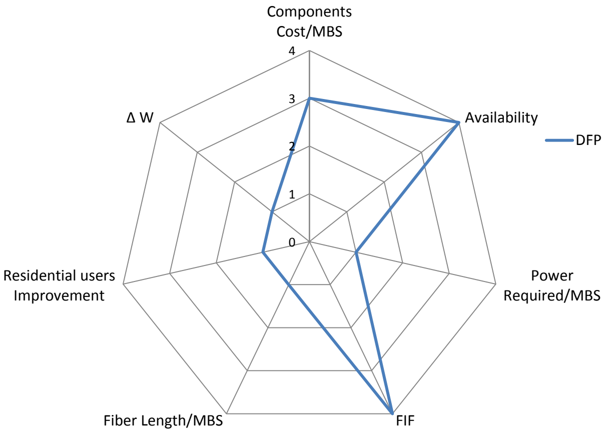
(d) RIMBSP-Rural Area



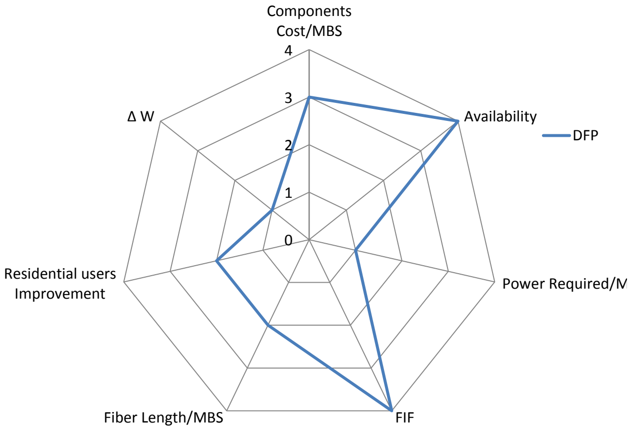
(e) μWP - Rural Area

Figure 5.20: Comparative analysis of different protection schemes in Rural areas with reference to considered parameters with degree definitions

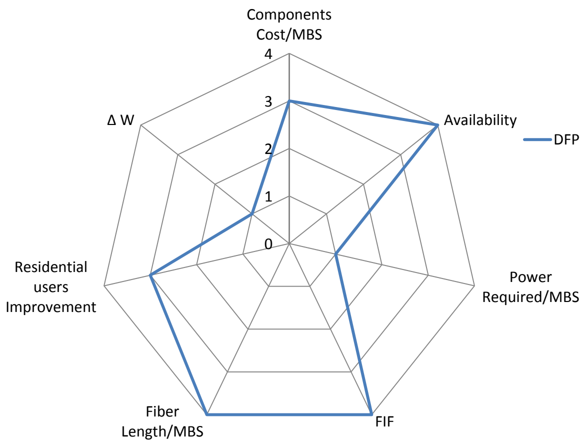
dependent on any of area specific parameter. Reference Fig. 5.25.



(a) DFP-Dense Urban Area



(b) DFP - Urban Area



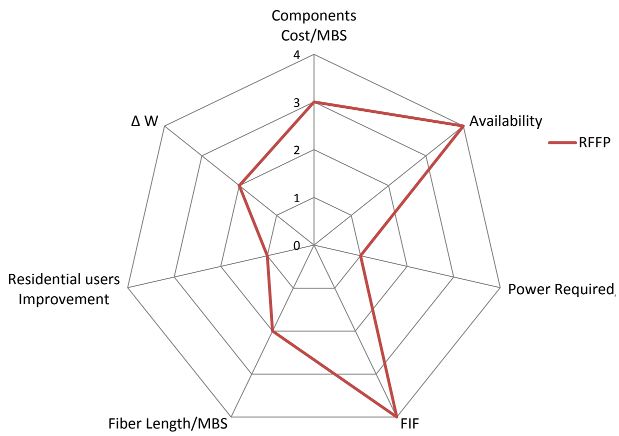
(c) DFP - Rural Area

Figure 5.21: DFP Performance

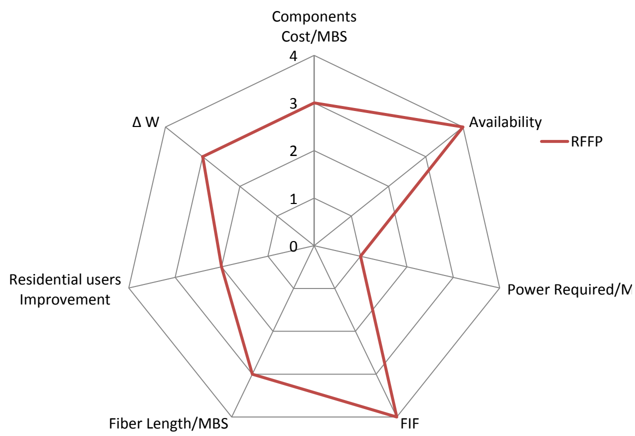
5.4 Consolidated Overall Performance

5.4.1 Even Weights Distribution.

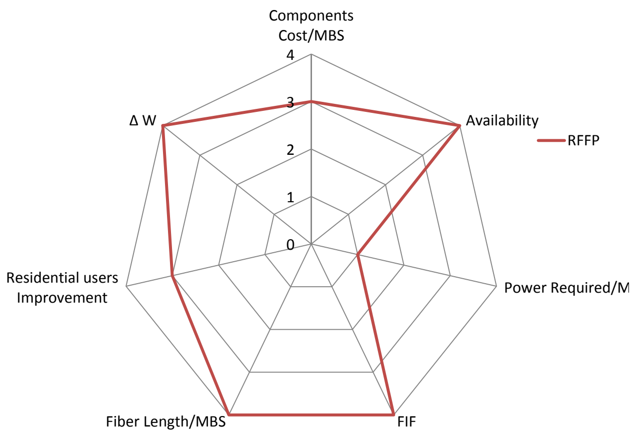
Considering all parameters i.e. component cost, power consumption, connection availability, indirect improvement in connection availability of residential users, failure impact factor, protection fiber length/MBS, additional fiber required for working paths from reference scenario and giving equal weights to each of the considered parameter (giving equal importance to each considered parameter). Fig. 5.26 shows the consolidated performance with even weights distribution, following are the results:-



(a) RFFP-Dense Urban Area



(b) RFFP - Urban Area



(c) RFFP - Rural Area

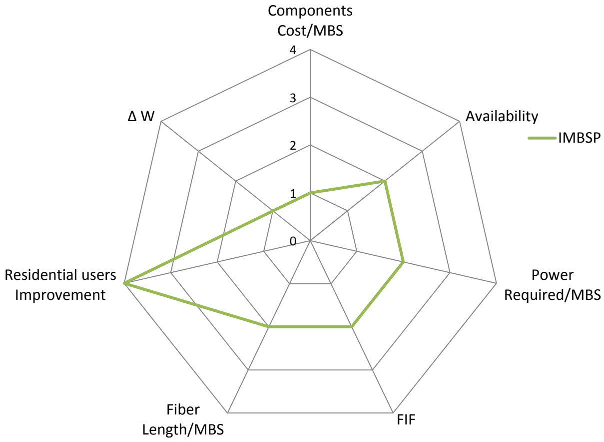
Figure 5.22: RFFP Performance

1. RIMBSP is the best protection scheme in DU area.
2. IMBSP is the best protection scheme in U & R areas.

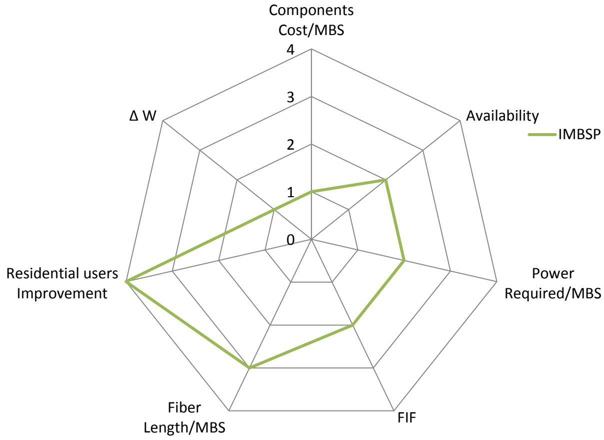
5.4.2 Uneven Weights Distribution (Parameter Wise)

However any operator can adjust these weighing parameters inline with its management policy, to meet the desired goal/ objective. Fig. 5.27 shows the consolidated performance with uneven weights distribution (Not giving equal importance to each considered parameter). Following are the results:-

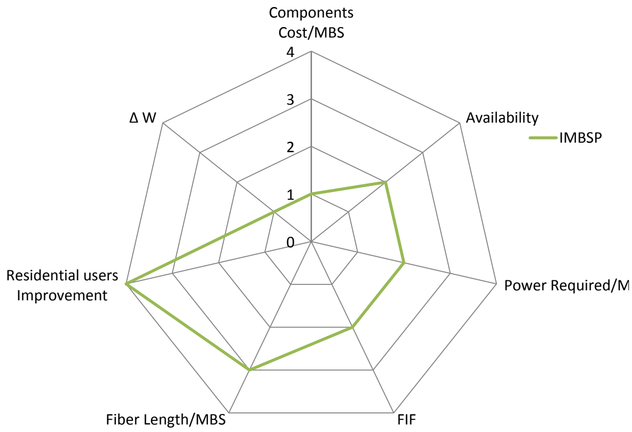
1. Fig. 5.27(a) shows that if operator/ service provider gives top priority to availability, fiber length/ MBS, ΔW and little importance to power required/ MBS, FIF and no



(a) IMBSP-Dense Urban Area



(b) IMBSP - Urban Area



(c) IMBSP - Rural Area

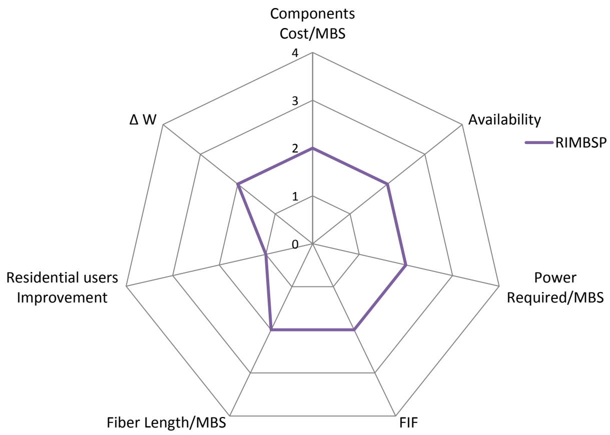
Figure 5.23: IMBSP Performance

importance to components cost, residential users improvement, than μWP is the best protection scheme in DU,U and R areas.

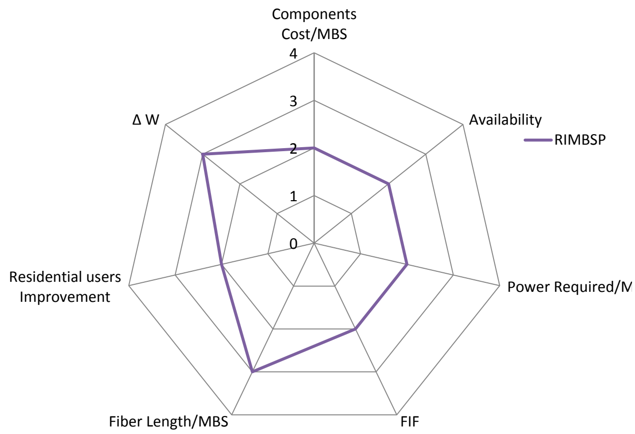
2. Fig. 5.27(b) shows that if operator/ service provider gives top priority to availability, fiber length/ MBS,residential users improvement and comparable less importance to power required/ MBS and no importance to components cost, FIF, ΔW, than following are the results:-

   - RIMBSP is the best protection scheme in DU areas.
   - RIMBSP and μWP both are having the same results and best in U areas.
   - μWP is the best protection scheme in R areas.

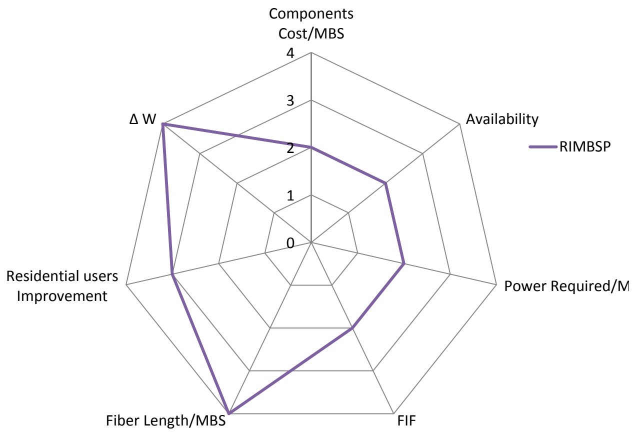
3. Fig. 5.27(c) shows that if operator/ service provider gives top priority to component



(a) RIMBSP-Dense Urban Area



(b) RIMBSP - Urban Area



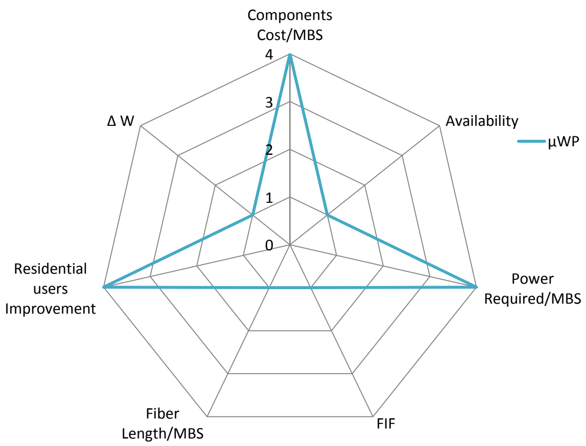
(c) RIMBSP - Rural Area

Figure 5.24: RIMBSP Performance

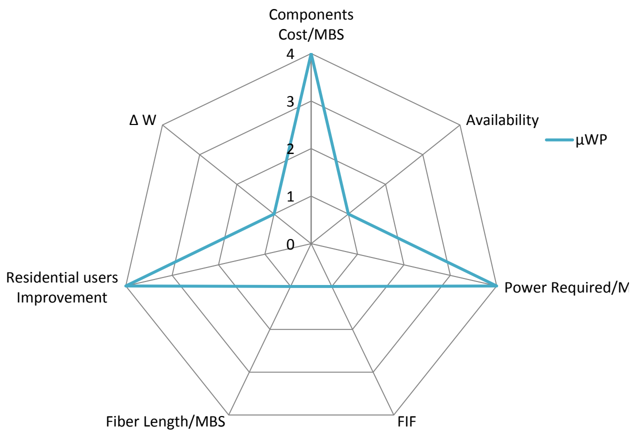
cost, availability, fiber length/ MBS and comparable less importance to ΔW and and no importance to power required/ MBS FIF, residential users improvement, than following are the results:-

- IMBSP is the best protection scheme in DU areas.
- RIMBSP and μWP both are having the same results and best in U & R areas.

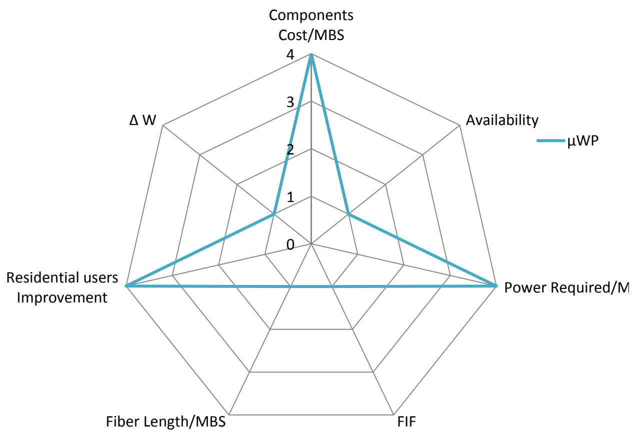
4. Fig. 5.27(d) shows that if operator/ service provider gives top priority to availability, component cost and comparable less importance to power required/ MBS, FIF, fiber length/ MBS and no importance to residential users improvement, ΔW, than IMBSP is the best protection scheme in DU,U and R areas.



(a) μWP-Dense Urban Area



(b) μWP - Urban Area



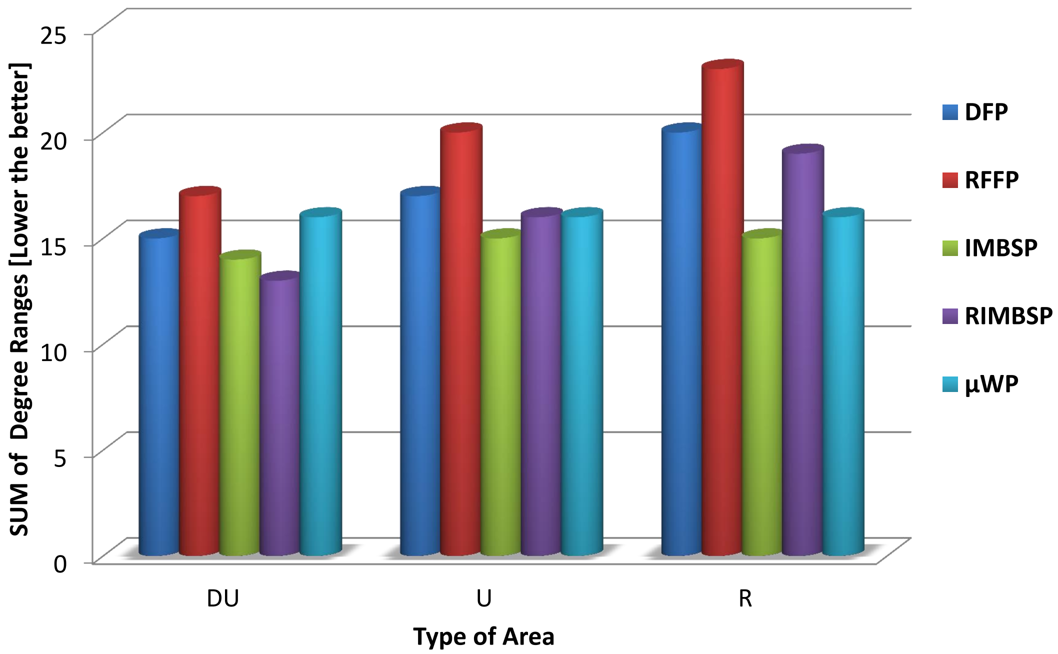
(c) μWP - Rural Area

Figure 5.25: μWP Performance

5.4.3 Uneven Weights Distribution (Category Wise)

For further in-depth analysis, the considered parameters can also be grouped into following distinct categories for logical conclusions from different perspectives:-

1. **Investments**
   - Component cost
   - Protection fiber length/MBS
   - ΔW
2. **Customer Satisfaction**
   - Connection availability



Components Cost/MBS	Availability	Power Required/MBS	FIF	Fiber Length/MBS	Residential users Improvement	Δ W
1	1	1	1	1	1	1

Figure 5.26: Consolidated Overall Performance-Even Weights Distribution

- Indirect improvement in connection availability of residential users

3. **OPEX**
   - Power consumption
   - Failure Impact Factor (FIF) which is directly related to SLAs (Service Lease agreements)

Fig. 5.28 shows the consolidated and comparative results, with uneven weights distribution when parameters are organized into categories as mentioned above. Following are the results:-

1. If operator/ service provider gives top priority to Investments than IMBSP is the best protection scheme in DU, U and R areas (Reference: Fig. 5.28(a)).
2. If operator/ service provider gives top priority to customer satisfaction than RIMBSP is the best protection scheme in DU and U areas. In R areas both RIMBSP and μWP are the best protection schemes (Reference: Fig. 5.28(b)).
3. If operator/ service provider gives top priority to OPEX than both RIMBSP and IMBSP are the best protection scheme in DU, U and R areas.(Reference:

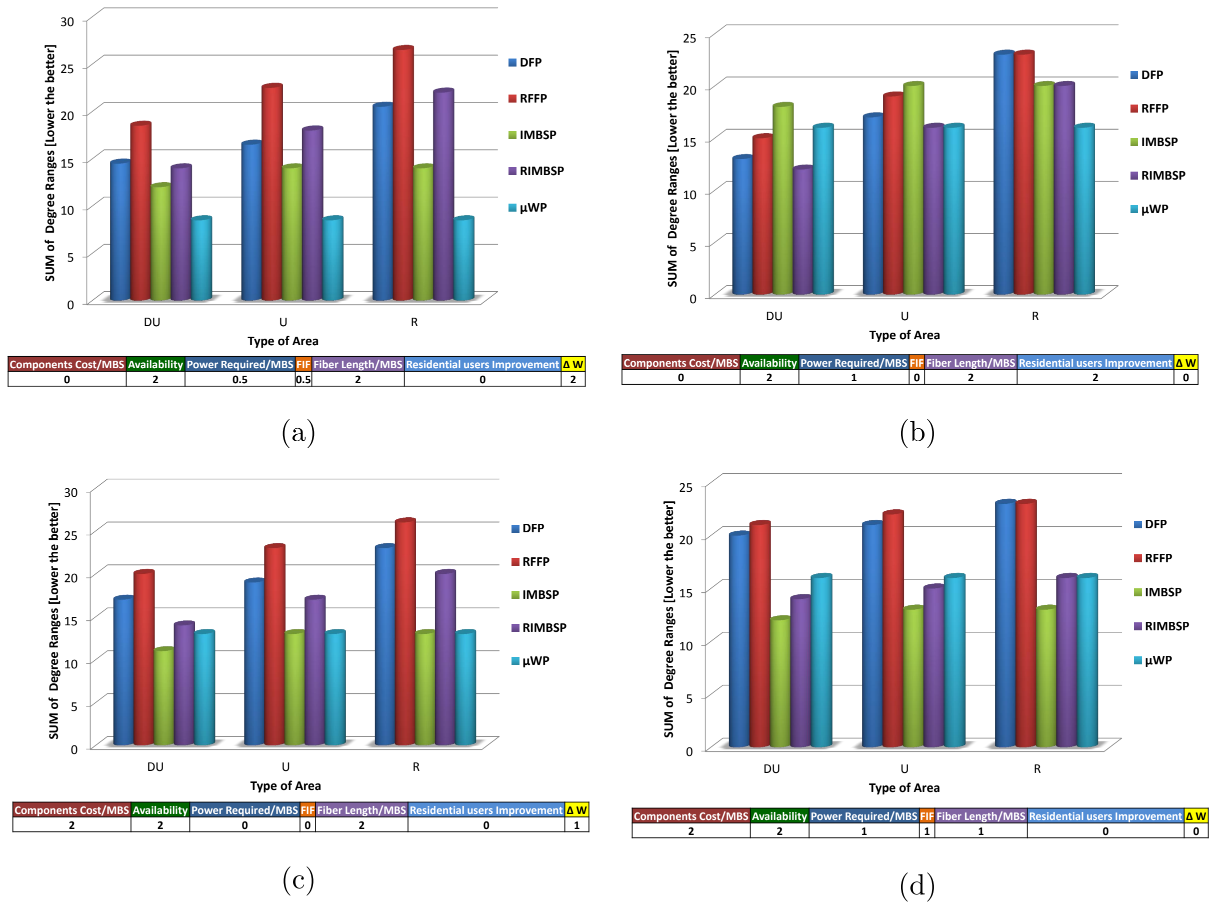
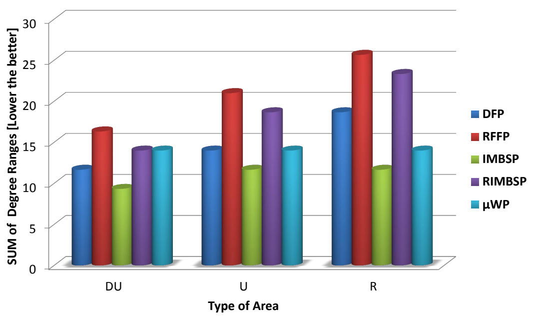


Figure 5.27: Consolidated Overall Performance - Uneven Weights Distribution (Parameter Wise)

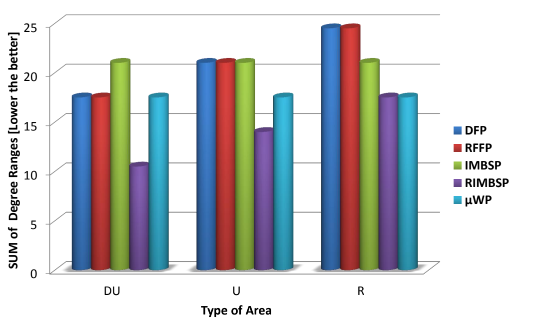
Fig. 5.28(c)).

4. If operator/ service provider gives top priority to Investments as well as OPEX than IMBSP is the best protection scheme in DU, U and R areas (Reference: Fig. 5.28(d)).



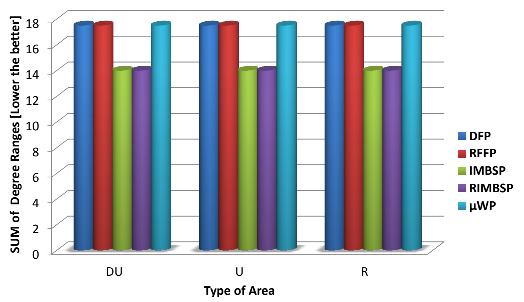
Components Cost/MBS	Availability	Power Required/MBS	FIF	Fiber Length/MBS	Residential users Improvement	Δ W
2.333333333	0	0	0	2.333333333	0	2.3333

(a) Investment Perspective



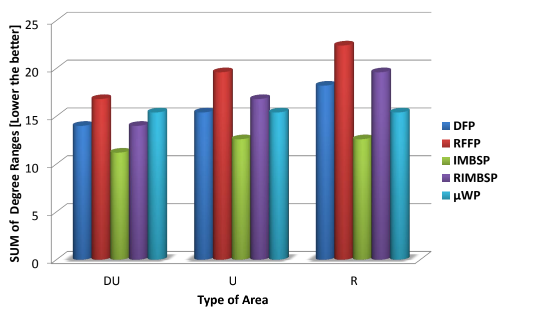
Components Cost/MBS	Availability	Power Required/MBS	FIF	Fiber Length/MBS	Residential users Improvement	Δ W
0	3.5	0	0	0	3.5	0

(b) Customer Satisfaction Perspective



Components Cost/MBS	Availability	Power Required/MBS	FIF	Fiber Length/MBS	Residential users Improvement	Δ W
0	0	3.5	3.5	0	0	0

(c) OPEX Perspective



Components Cost/MBS	Availability	Power Required/MBS	FIF	Fiber Length/MBS	Residential users Improvement	Δ W
1.4	0	1.4	1.4	1.4	0	1.4

(d) Investment and OPEX Perspective

Figure 5.28: Consolidated Overall Performance - Uneven Weights Distribution (Category Wise)

Chapter 6

Conclusions and Future Outlook

6.1 Conclusions

Optical access networks of today's network arena, offers much higher bandwidth per end point and considerable longer optical reach. Moreover, in this network centric society, the uninterrupted access to the network services is becoming crucial and therefore operators are now also considering to protect their access networks in addition to their aggregate and core networks. However, the cost factor is still very important due to the relatively low cost sharing in access segment. This thesis has presented five different protection schemes for Macro Base Stations (MBS) because of its high offered capacity and Failure Impact Factor (FIF) in a converged access network scenario based on Hybrid Passive Optical Networks (HPON). These protection schemes differ in terms of component cost, power consumption, connection availability, indirect improvement in connection availability of residential users, FIF and protection fiber length required/ MBS.

First and foremost, **C**onverged **A**ccess **N**etwork **P**lanning and **D**imensioning **T**ool (CANPDT) is developed, which is an Arc GIS based tool coupled with the numerical analysis power of Matlab for the optimal and cost effective network planning and dimensioning of converged access network. The tool extracts geographical location data of buildings and roads infrastructure from Open Street Map and builds network database for simple as well as constrained based routing. Proprietary clustering tool developed in Matlab executes two stage clustering according to two stage access architectures. The dimensioning tool also offers different enhancements like ports usage factor, filtration of inconsistent data, deployment of MBS specific to the needs of operator, finding the length of fibers, ducts and conduits. CANPDT also helps to implement different protection schemes and calculates, not only the Bill of Quantity (BoQ) but also provides exact layout of the network. CANPDT also allows the smooth integration with already developed software platforms through model builder.

Secondly, regarding the protection schemes, it is also shown that it is difficult to find a single solution best for all possible cases. The best protection scheme depends on the clear and concise requirements of the operator and the deployment area. Comparative and consolidated performance analysis of each protection scheme has been carried out with even and uneven weights distribution to select the best protection scheme in a particular scenario/ area. It has been shown that with even weights distribution, RIMBSP is the best protection scheme in DU area and IMBSP is the best protection scheme in U and R areas. Moreover weights can be adjusted considering each parameter individually (Power/MBS or Fiber length/ MBS etc.) or considering category wise (Investment, Customer Satisfaction or OPEX etc.) by network/ service provider to meet any specific goal/ requirement. It is also shown that by changing these weights the results significantly varies, thereby the best solutions in DU, U and R areas are also changed. Different case studies have also been presented for more in-depth analysis and lucid understanding of the subject.

Acknowledging the efforts and contributions, the following presentations/ publication have been prepared:-

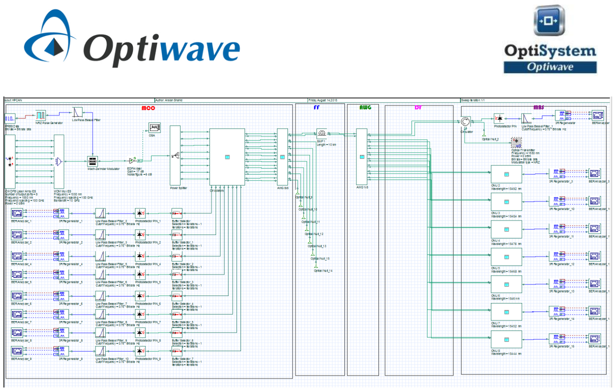
- CTTE Paper [SMMLJ15] and presentation in Nov 2015.
- CANPDT tool demo.
- Journal paper to be submitted at JOCN [SMM15].

6.2 Future Outlook

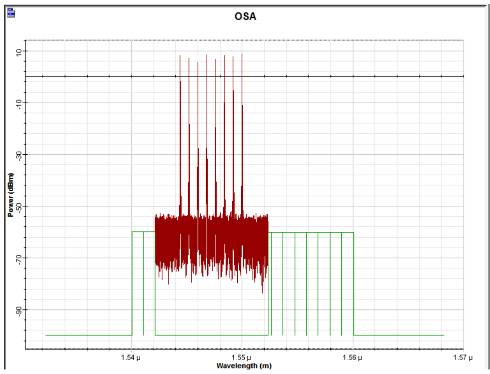
In this section we have highlighted different fields/ areas which can be explored to continue or further improve this work. Following are highlighted:-

6.2.1 Implementation of Protection Schemes

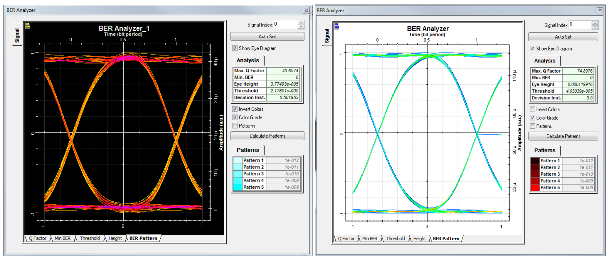
The protection schemes can also be implemented on real hardware or on simulation software to have more in depth knowledge like recovery time, BER and other nonlinear effects etc. Sideline efforts have also been made during Master thesis to implement this in **"Optiwave-Optisystems"** simulation software, which can be carried further in next coming projects. Fig. 6.1 shows the implementation of 8 Channels bidirectional WDM PON, representing 1x MCO and 8x MBS. It is also shown how to switch off any network element to represent the fault. Spectrum Analyzers, oscilloscopes, BER analyzers etc, can be used on schematic to have deeper understanding of working of optical network and measure different performance parameters of Optical Distribution Network (ODN) both in electrical and optical domains. Its optical and electrical components library provides access to all types of components required for protection schemes like OS, couplers, splitters, filters etc.



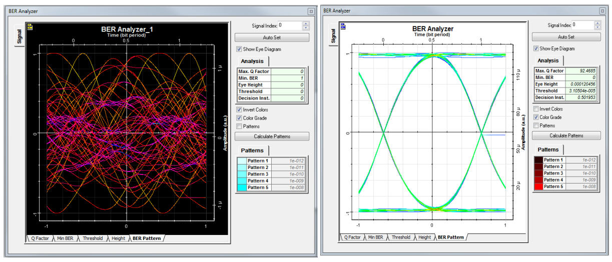
(a) Schematic



(b) Multiplexed Signal - 8 Channels



(c) BER at MCO (left) and ONU (right)



(d) BER at MCO when Tx of ONU is switched off (left)

Figure 6.1: Implementation of WDM PON - Optiwave

6.2.2 Fronthaul/ Backhaul Communication

Mobile operators/ service providers are one of the most important customers, who need backhaul/ fronthaul connectivity for their Radio Access Network for sending data back towards backbone network. In fronthaul scenario all end points are connected to the MCO as shown in Fig. 6.2(a), but in backhaul scenario some end points like Small Cells are connected to nearest MBS and not to the MCO as shown in Fig. 6.2(b)). Consequently data traffic of small cells are aggregated and sent to MCO by MBS. This adopted methodology may result into decrease in total fiber length/ duct, but for sure required number of RNs/ AWG will be decreased. For aggregation of traffic at MBS a remote OLT will be required for processing/ aggregation of traffic for further sending towards MCO and vice-versa. Dimensioning and Planning tool can be modeled further to cater for both fronthaul as well as backhaul communication.

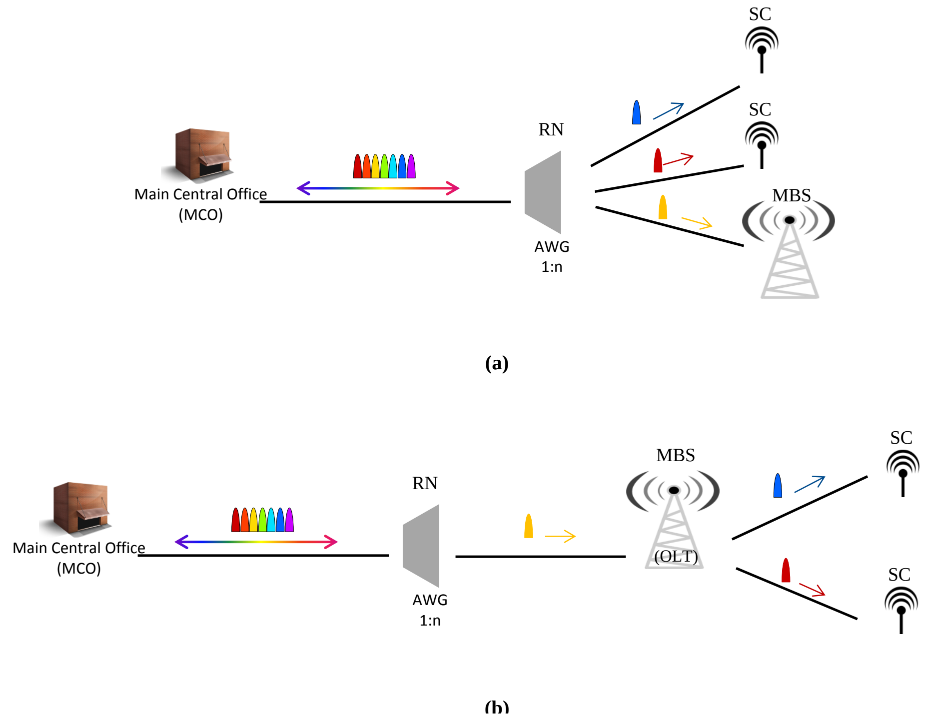


Figure 6.2: (a) Fronthaul (b) Backhaul

6.2.3 Dual Homing

In a dual-homing architecture, a host is connected to two different OLTs located at different locations as shown in Fig. 6.3 therefore, it is unlikely that the host will be denied access to the network. In the past, dual homing architecture and protection are studied separately. Protection schemes mentioned in this master thesis can be further improved, considering dual homing furthermore new protection schemes may also be proposed to further enhance the network resilience. Dual homing can be programmed/ implemented as already shown in Section 2.3.4.

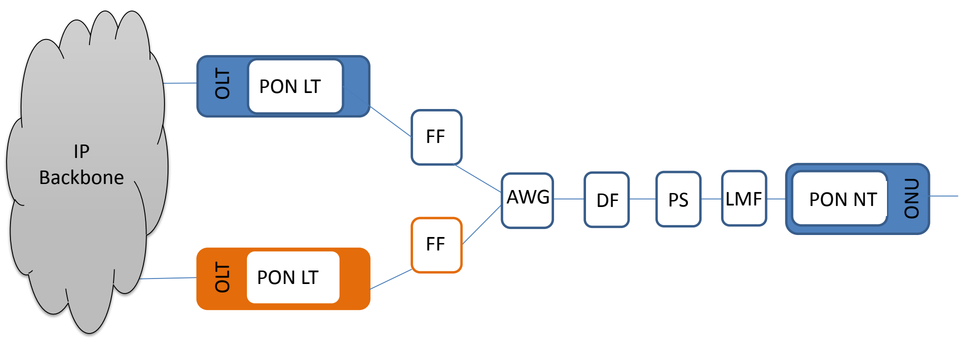


Figure 6.3: Dual Homing

6.2.4 Will Core Networks be a Bottleneck in future?

The capacity upgrade in the access networks may lead to a huge traffic demand increase in the core/aggregation networks [RDPP13]. Consequently, in the near future the core segment may become the bottleneck for the bandwidth upgrade per user. One way to address this problem is to keep the local traffic in the access network area as much as possible. It would prevent “feeding” the core network with the data belonging to the users in the same geographical locations and help to mitigate the increase of the capacity demand in the core/aggregation networks caused by the development of the access segment. Different techniques can be explored to limit the data in the form of geographical clusters having their own synchronized servers (like video streaming etc) to serve area specific users/ customers. Protection can also be planned for provision of backup services from nearest disjoint neighboring cluster.

6.2.5 Integration and development of GUI

The developed CANPDT tool can be integrated with other software packages through model builder and using built in functions etc. Another proposed future work can be to develop user interactive GUI, which takes the input from the user and gives the output results, duly supporting dynamic search forms. The developed application should able to install on windows terminals or support web based access. Different software can be used such as Visual studio, Matlab etc. An example of such an interface has also been prepared in Matlab and is shown in Fig. 6.4.

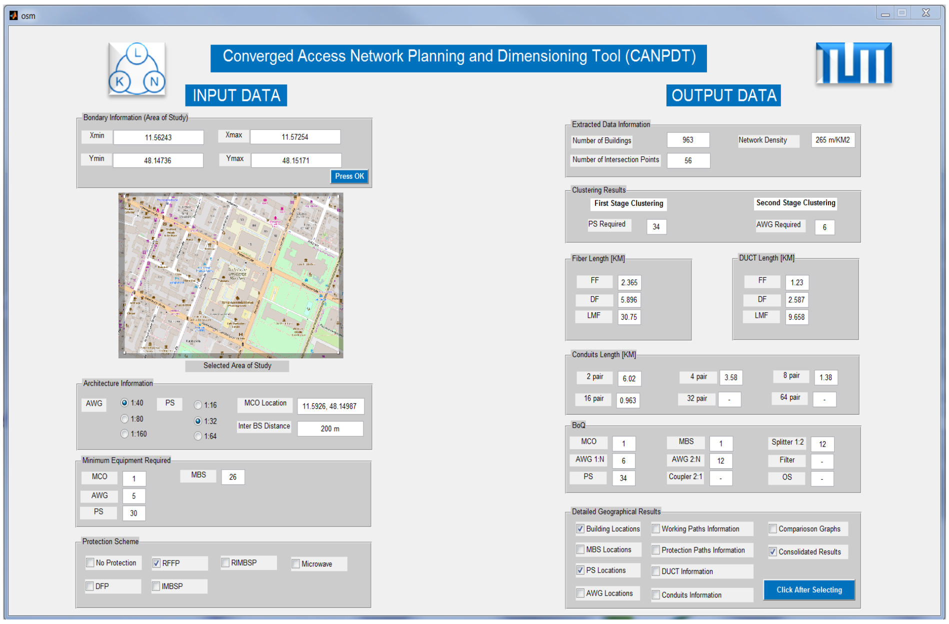


Figure 6.4: GUI-Matlab

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Appendix A

Matlab Code Files

The details of code files are as under:-

- CODE1 - CMPMT Network space. (Soft and hard copy)
- CODE2 - CMPMT Euclidean. (Only Soft copy - CD attached)
- CODE3 - Integration with already developed dimensioning tool based on following Matlab codes/ functions:-
    - Routing Modified DIJKSTRA with duct sharing (Only Soft copy - CD attached)
    - Associate RN2 with buildings (Only Soft copy - CD attached)
    - Associate RN1 with PS/MBS (Only Soft copy - CD attached)
- GUI Matlab CANPDT (Only Soft copy - CD attached)
- Arc-GIS project files including shape files and layers of DU, U and R areas (Only Soft copy - CD attached)
- Details of extensions and functions used of Arc-GIS during Master thesis (Only Soft copy - CD attached)
- Pdf file and Latex Code file of thesis report in zipped format (Only Soft copy - CD attached)
- Pictures and tables used in report (Only Soft copy - CD attached)
- Copy of Kick off, Midterm & final Presentation (Only Soft copy - CD attached)

%% CMPMT CLUSTERING USING NETWORK SPACE INSTEAD OF EUCLIDEAN SPACE %%

% **INPUT**: Cost OD Matrix generated by Network Analyst, Arc GIS 10.3 using Larger Network Dataset (LND) to increase the probability of finding the protection paths, especially for cluster outliers

% **OUTPUTS**: Clusters with associated list to each cluster element and cluster centroids for integration with already developed dimensioning tool as well as for Arcgis for further spatial analysis

% **FINDING THE OPTIMUM COST EFFICIENT CLUSTERING ORDER/ PENALTY MATRIX** %

%% **Note 1**: Number of paths from one cluster element to other elements is not fixed, which in case of Euclidean is always same, because of always available crow flights%%

%% **Note 2**: Distance in meters is the actual distance in network space which routing function will also use for calculation of fiber layout, so clustering & routing is in the same network space%%

```
load('Cost_matrix.mat', 'Cost_matrix'); % Cost matrix from Arc GIS

load ('B_C_L.mat','B_C_L'); % Cluster elements like Buildings, PS, MBS and AWG, It is Before Clustering List, B_C_L

SR=10;% Required size of each cluster which is limited by splitting ratio of either Power Splitter (PS) or Array Wavelength Grating (AWG) incorporating the port usage factor e.g 0.8 or 80% etc

count=1;
i=1;
accum_cost=0;
penalty_matrix=zeros(length(B_C_L),2);% what is the penalty in meters of length of fiber, if we start clustering from this seed master, so every cluster has one seed master and number of seed members limited by SR or Cost thresh hold
len=length(Cost_matrix);
while(i<=len)
    rank1= Cost_matrix(i,4);
    accum_cost=Cost_matrix(i,5);
    if (rank1==1)% Selected Seed master/member
        j=i;
        while(j<=(i+SR-2))
            rankSR1=Cost_matrix(j,4); %Current seed member rank to check whether it belongs to the same seed master

            rankSR2=Cost_matrix(j+1,4); %Next seed member rank to check whether it belongs to the same seed master

            accum_cost=accum_cost+Cost_matrix(j+1,5);
            if (rankSR2>rankSR1) % If seed master doesn't change
```

```
                index=j+1;
                j=j+1;
                continue;
            else
                index=j; % if seed member changed
                break;
            end
        end
        penalty_matrix(count,1)= Cost_matrix(index,2);
        penalty_matrix(count,2)= Cost_matrix(index,5); % Cost of the farthest
seed member

        penalty_matrix(count,3)= accum_cost; % Accumulated cost from seed
master to all seed members, doesn't incorporate the cost which will be
increased due to non-availability of any seed member due to selection by
already selected cluster

        count=count+1;
        i=j;
        continue;
    end
    i=i+1;
end
penalty_matrix;
%[B,I] = sort(penalty_matrix(:,2), 'descend'); % Ascending order is better
than descending, means address the worst cases first, considering the farthest
member cost

%[B,I] = sort(penalty_matrix(:,3), 'descend'); % Ascending order is better
than descending, means address the worst cases first,considering the
accumulated cost

%[B,I] = sort(penalty_matrix(:,2), 'ascend'); % Ascending order is better than
descending, means grab the best/ compact clusters first, considering the
farthest member cost

[B,I] = sort(penalty_matrix(:,3), 'ascend'); % Ascending order is better than
descending, means grab the best/ compact clusters first, considering the
accumulated cost

penalty_matrix_ascend = [I,B];
-------------------------------------------------------------
   %% AFTER FINDING THE PENALTY MATRIX NOW WE WILL FIND THE CLUSTERS%%
                        %% DEFINING CLUSTER PARAMETERS%%

CE=72; %Total no of Cluster Elements like buildings or MBS+PS

NR=7+3; %Maximum Number of Rows or Number of cluster, half of the clusters are
added if cluster element or total cluster cost will exceed the thresh hold
value

NC=10;  % Required size of each cluster which is limited by splitting ratio of
either Power Splitter (PS) or Array Wavelength Grating (AWG) incorporating the
port usage factor e.g 0.8 or 80% etc

BCount=1;
```

```
Threshold= 5000; % Thresh hold value to have check on each individual cluster
element cost to be included in current cluster or not

ClusterIDs=zeros(NR,NC); % IDs of cluster elements
ClusterCosts=zeros(NR,NC);% Cost associated to each cluster element
ClusterFlags=zeros(1,CE); % Whether building is available for clustering or
not

TotalClusterCost=zeros(NR,1);% For calculating the total cluster cost, same as
accumulated cost
------------------------------------------------------------------------------
                  %% SELECTION OF SEED MASTERS  & MEMBERS %%
N=1;
r=1;
cost_incurred=0;
while(r<=NR)
    if (BCount>CE)% Checking how many Cluster elements have been clustered and
how many left

        break;
    end
    c=1;
    TotalClusterCost(r)=0; % for calculating the total cost = total length of
fiber required in meters of each custer

    CBuildID=penalty_matrix_ascend(N,1); %For selection of Seed Master from
penalty Matrix, CBuildID= Cluster BuildID= Seed Master

    if (ClusterFlags(CBuildID)==0) % Boolean flags to check whethe cluster
element is available for clustering or not if==0 means available, if ==1 means
not available

        ClusterFlags(CBuildID)=1;
        ClusterIDs(r,c)=CBuildID;
        BCount=BCount+1;
        c=c+1;
        Count=1;
        while(c<=NC) % for checking the upper limit of each cluster which is
defined by splitting ratio

            if (BCount>CE)
                break;
            end
               CBuildID_row = min(find(Cost_matrix(:,2) == CBuildID)); % Find
the minimum row number of Seed master

                if  Cost_matrix(CBuildID_row,4) == 1 % Just to double check
before picking seed members, when seedmaster=seed member only then it will be
equal to 1

                    BuildID = Cost_matrix(CBuildID_row+Count,3); %For
selection of seed members from cost Matrix, BuildID= Seed Member

                end
               cost_incurred=Cost_matrix(CBuildID_row+Count,5); % Cost of
including the cluster element in the present cluster
```

```
            if (ClusterFlags(BuildID)==0)% checking whether it is available
for clustering or not

                if (cost_incurred>Threshold) % checking whether it is within
the thresh hold value

                    break;
                end
                ClusterFlags(BuildID)=1; % it will not  be available to be
clustered next

                ClusterIDs(r,c)=BuildID;
                ClusterCosts(r,c)=cost_incurred;
                BCount=BCount+1;
                TotalClusterCost(r)=TotalClusterCost(r)+cost_incurred;
                c=c+1;
            end
            Count=Count+1;
        end
        r=r+1;
    end
    N=N+1;
 end
AllClusterCost=0;
for i=1:r-1
    AllClusterCost=AllClusterCost+TotalClusterCost(i);% total clustering cost
which is the sum of all cluster costs, will incorporate the penalty also due
to non-availability of valid seed member

end
nClusters=r-1;
Final(CE)=struct('BID',0,'Xc',0.0,'Yc',0.0,'CNo',0);
i=1;
for r=1:nClusters
    for c=1:NC
        if(ClusterIDs(r,c)>0)
            BuildID1=ClusterIDs(r,c);
            Final(i).BID=BuildID1;
            Final(i).Xc=B_C_L(BuildID1,2);
            Final(i).Yc=B_C_L(BuildID1,3);
            Final(i).CNo=r;
            i=i+1;
        end
    end
end
Final;
[~,index] = sortrows([Final.BID].'); Final = Final(index); clear index
CNo = [Final.CNo].';
associated_cluster_rn2=CNo; % Associated Cluster list, which is required for
integration with already developed dimensioning tool
```

%% **CALCULATING THE CLUSTER CENTROIDS** %%%

```
Final1 = [Final.Xc; Final.Yc; Final.CNo].';
for i = 1:max(Final1(:,3))
    indices = find(Final1(:,3) == i);
```

```
   clusters(i,1) = mean(Final1(indices,1)); % For calculating X value of
centroid

   clusters(i,2) = mean(Final1(indices,2)); % For calculating Y value of
centroid

end
associated_cluster_rn2;
clusters;
%bar(TotalClusterCost)
```

Appendix B

Notations and Abbreviations

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

AWG	Arrayed Waveguide Grating
MBS	Macro Base Station
BW	Bandwidth
CAPEX	Capital Expenditures
CO	Central Office
MCO	Main Central Office
CU	Cost Unit
DF	Distribution Fiber
EPON	Ethernet Passive Optical Network
FDMA	Frequency Division Multiple Access
FF	Feeder Fiber
FMC	Fixed and Mobile Convergence
FTTB	Fiber To The Building
FTTH	Fiber To The Home
GIS	Geographic Information System
GPON	Gigabit Passive Optical Network
GSM	Global System for Mobile Communications
HPON	Hybrid Passive Optical Network
ICT	Information and Communications Technology
IP	Internet Protocol
ITU	International Telecommunications Union
LMF	Last Mile Fiber
LTE	Long Term Evolution
NGOA	Next Generation Optical Access
NGPON	Next Generation Passive Optical Network

OASE	Optical Access Seamless Evolution
ODF	Optical Distribution Frames
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Terminal
ONT	Optical Network Termination
ONU	Optical Network Unit
OPEX	Operational Expenditures
OSM	Open Street Map
PON	Passive Optical Network
POP	Point of Presence
P2P	Point to Point
PS	Power Splitter
QoS	Quality of Service
RE	Reach Extender
RN	Remote Node
SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access
TWDM	Time and Wavelength Division Multiplexing
UPS	Uninterrupted Power Supply
WiMAX	Worldwide Interoperability for Microwave Access
WDMA	Wavelength Division Multiple Access
XGPON	10 Gigabit Passive Optical Network

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