Infrastructure Cost Savings with Unbalanced PONs in Rural Areas

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***Abstract*—Deployment of Optical Access Networks (OANs) is still a costly process, specially in rural areas, and thus requires detailed and efficient planning. The deployment strategies in rural areas are subjected to challenges posed by demographic and geographical factors. Traditional Balanced Passive Optical Network (BPON) deployments, using symmetrical splitters, which incurs into an inefficient and costly solution due to the sparse user distribution. To address this issue, this paper presents an Hybrid Passive Optical Network (HPON) solution, which combines BPON and Unbalanced Passive Optical Network (UPON) architectures to provide optimal connectivity and reachability. The HPON leverages optical taps in the UPON for fine-grained power distribution. BPON and HPON models are compared in four rural scenarios with varying population densities. The results suggest that the HPON leads to reduced cost per Optical Network Unit (ONU) and cost per unit area compared to BPON, thus providing a solution for the economical deployment of an OAN in rural areas. In the considered rural areas, HPON assures cost savings of up to 25% over BPON deployments.**

***Index Terms*—Optical Access Networks, Network Planning, Passive Optical Network**

I. Introduction

Global internet traffic increased to almost 40% at the peak of the worldwide COVID-19 lockdown, illustrating the essential role of robust internet infrastructure [1]. Ever since then, high-speed internet connection has become the backbone of digital infrastructure both in rural and urban areas. The scaling number of online devices in the household, hybrid work culture, and the proliferation of Internet of Things (IoT) applications (e.g., smart agriculture and farming) have led to a significant increase in traffic demands in the access segment of the network, both in urban and rural areas. OAN is a popular technology which is responsible for delivering data between the Internet Service Provider (ISP) and the end users in these areas.

OAN requirements in urban and rural areas require distinct solutions according to varying geographical factors and demand. The OAN planning in urban areas is traditionally done using BPON architecture, depicted in Fig. 1a, which interconnects the Optical Line Terminal (OLT) located at the Central Office (CO) to the different ONUs, which are located at the buildings or homes/flats in Fiber to the Building (FTTB) and Fiber to the Home/Flat (FTTH/F) respectively. This method considers uniform power splitting from OLT at the Remote Nodes (RNs), that is, several ONUs are connected to the same RN according to the splitting ratio. This may force the sparsely placed ONUs to connect to a distant RN, leading to an increase in the overall infrastructure costs. In the rural scenario, the ONUs are sparsely placed so deploying BPON here, could be costlier, slower, and inefficient than in urban areas. In order to prevent a digital divide, which limits the social and economic opportunities for the development of the rural areas, we aim at reducing the BPON deployment costs by proposing the use of HPON.

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This paper addresses the issue of cost-efficient Passive Optical Network (PON) planning and deployment in rural areas by exploiting UPON, which offers a more flexible solution for power distribution than the BPON. A UPON, depicted in Fig. 1b, allows a variable power splitting ratio to connect few ONUs. In this way, UPON optimizes the optical power distribution allowing interconnecting more distant ONU in a daisy chain topology.We propose a combination of both BPON and UPON architectures, called HPON to be applied in rural areas. The objective is to minimize the required OAN infrastructure in rural areas.

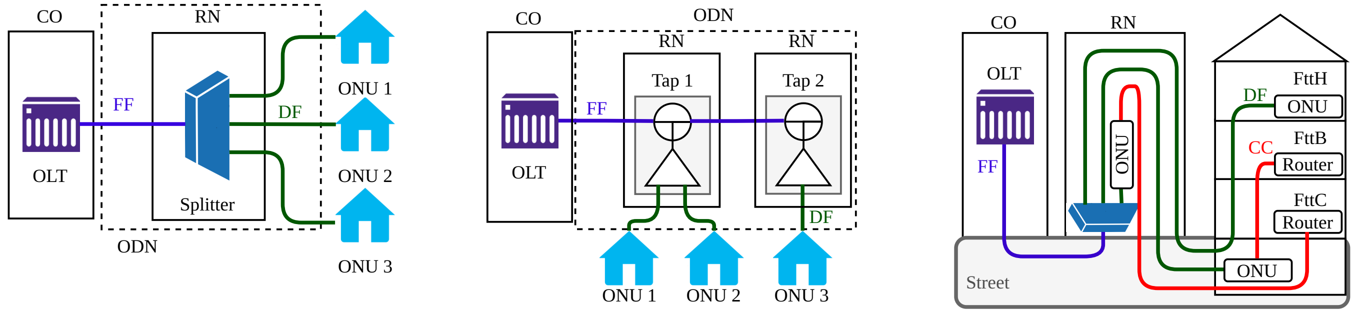
This paper is structured as follows: Section II overviews the BPON and UPON models and the state of the art. Section III covers the modeling techniques for BPON and HPON. The implementations of BPON and HPON are evaluated in Section IV. Finally, Section V concludes the paper.

II. Background

OANs are the preferred technology for ISPs in the access segment due to their higher bandwidth and reach performance than copper technologies. OANs are ideal for supporting bandwidth-intensive applications executed in the access segment of the network, such as high-definition video streaming, cloud access, home office, and online gaming. XGS-PON [2], the current ITU-T PON standard being deployed in Europe, can provide a symmetrical bandwidth of up to 10 Gbps and a reach of up to 20 km. There are ongoing standardization efforts at ITU-T for PONs reaching up to 400 Gbps.

A. (Balanced) Passive Optical Networks

A PON, hereafter referred to as BPON, depicted in Fig. 1a, is the traditional approach for realizing an OAN. The OLT, located at the ISP's CO, connects with the Feeder Fiber (FF)



(a) Balanced Passive Optical Network.

(b) Unbalanced Passive Optical Network.

(c) Fiber to the X architectures.

Fig. 1. Fig. 1a depicts the architecture for a BPON where balanced splitter located at the RN divides the incoming signal evenly into the output ports defined by its splitting ratio. Fig. 1b depicts the architecture for an UPON. The main difference with BPON is using optical taps instead of splitters, which enable fine-tuning the signal power distribution at every network stage. Fig. 1c shows FTTx, where the location of ONU defines the architecture.

to the splitters located at the RNs. The splitters are balanced as they divide the incoming optical signal evenly into the number of outputs determined by the splitters' splitting ratio. The Distribution Fibers (DFs) connect the splitters with the ONUs. The segment comprising the FFs, splitters, and DFs is the Optical Distribution Network (ODN), which consists solely of passive components. As depicted in Fig. 1c, the location of the ONU defines the FTTx architecture. The ONU is located at the customer premises in Fiber to the Home (FTTH). In FTTB and Fiber to the Cabinet (FTTC), the ONU is located at the building or cabinet, and the Copper Cable (CC) is re-used to connect the ONU to the customers' equipment. BPON is typically used in urban areas and is highly cost-efficient in areas with high customer density. Moreover, BPON scales up easily by adding ONUs in splitters' ports left for future use.

B. *Unbalanced Passive Optical Networks*

UPON is an OAN architecture that provides greater flexibility and efficiency in signal power distribution than BPON. As depicted in Fig. 1b, the components of the BPON and UPON are the same, except the splitters. The UPON uses optical taps with variable power splitting ratios, which enable network planners to optimize signal power distribution at every network stage, reaching distances up to 100 km. UPONs have been proposed as a cost-effective solution for connecting sparsely populated rural areas. However, network designs based on UPON tend to be more rigid than those based on a BPON, as altering an optical tap will affect the power distribution in all subsequent taps and ONUs in the chain. Hence, future network growth is critical in planning an UPON to leave room for flexibility in the design.

C. *State of the Art*

In [3], the authors propose a three-step process for evaluating the impact of the graphs and the methodologies on OAN planning. The work leverages the generalization capacity of Gabriel Graphs (GGs) to obtain graphs with properties similar to those of a city graph. The city graph and the generated GGs allow a comparison of the performance of Integer Linear Programming (ILP) formulations and state-of-the-art Heuristics for planning Unprotected, Type A, and Type B BPON in terms of total fiber length. Their results show that GGs can generalize the statistical properties of the city graph but struggle to capture the geometric grid layout typical of cities. In their evaluation, the ILP formulation required approximately 22% less fiber than the heuristic, showing the benefits of using exact methods over approximations. Moreover, the authors also showed how the network's sparseness drives the fiber length requirement, as planning BPON with the ILP in sparse GGs use, on average, 12% more fiber than over the original graphs, suggesting that BPONs are less efficient in rural areas.

UPONs are a recent initiative mainly driven by companies. In [4], VIAVI Solutions presents a white paper, comparing the advantages and deployment scenarios of BPON and UPON architectures. BPON is highlighted as a suitable solution for urban areas with high ONU density, as using balanced splitters ensures even signal power distribution for clusters of ONUs. The authors also evaluated UPONs, using optical taps in a daisy-chain topology, and concluded that they are more efficient in rural areas with low ONU density. The study also underscores the flexibility of UPON in extending the reach for optical signals. In [5], CommScope presents an application guide for optical taps in FTTx architectures for rural and urban areas. The guide describes how optical taps can reduce costs and make feasible FTTH architecture in rural areas. The guide also provides detailed specifications about different optical taps configurations and link loss computation. In [6], the technical paper reviews different ODN strategies, including the joint application of BPON and UPON, hereafter referred to as HPON. UPON is effective in lowering deployment costs and extending network reach, while BPON is effective in providing connectivity for clusters of ONUs. Taking cognizence from the state of the art, in this paper we propose HPON planning for the real rural areas and compare its cost-efficiency over BPON and across areas.

III. Methodology

This section presents a structured approach to gathering geographical data and modeling BPON and HPON.

A. Data Collection

Data Acquisition is crucial for accurate network design, visualization, and cost analysis. It involves two main tasks: (1) Obtaining street layout, generated using OpenStreetMaps (OSM), and (2) Getting building coordinates, ONUs, as shown in Fig. 2. The road network, including nodes and edges, is extracted. Nodes represent intersection coordinates, while edges represent the roads connecting these nodes. This data creates a real road network map, which will be used to plan the deployment of fiber optic cables. The second step is placing ONUs over a city layout. Every building is a polygon-shaped structure whose centroid is determined and treated as a potential ONU location. A desired percentage of ONUs is chosen from all the available building locations, known as the desired ratio. Hence, whenever the ratio of specified building types is below the desired mark, additional buildings can be added from the rest of the set.

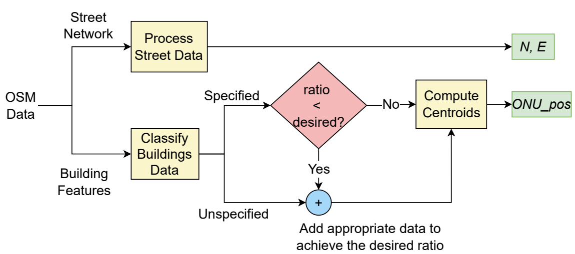


Fig. 2. Data Collection for Network Design

B. Network Modeling

BPON utilizes a single splitting method with symmetrical splitters to ensure uniform signal distribution across the network. In contrast, the HPON combines the attributes of BPON and UPON, which uses optical taps, to improve network flexibility and coverage. Both approaches are tailored for FTTB implementations, driven by the limited availability of detailed building data in the Data Collection phase.

1) BPON Modeling: The design of a BPON with an unprotected architecture, meaning no redundant FF and DF, is described in Pseudo-Algorithm 1. Line 1 loads the graph $G = (N, E)$ where N and E are set of intersection points and streets connecting them, respectively. Based on all building coordinates collected as ONU_pos, $G_{\text{with\_onus}}$ is generated by integrating each ONU to the end-points of the nearest edge, via adding two more edges in Line 2. The OLT is optimally positioned, Line 3, by determining closeness centrality of every node $n \in N$ in $G_{\text{with\_onus}}$. The most central node, as OLT, improves network scalability by becoming more accessible to the other nodes.

The commercially available symmetrical splitters in BPON are 1:2, 1:4, 1:16, 1:32, 1:64, and 1:128. A partial utilization of all the splitter ports is considered to ensure future network growth. So, $optimal\_connections$ is the number of ports a splitter can offer at this moment. The set of all ONUs is divided into an appropriate number of clusters, Line 6, using k-means clustering. The loop, 7-10, ensures assigning the closest node $n \in N$ to the centroid of each cluster as RN, and mapping all the ONUs in that cluster to this RN in a load-balancing way. $G_{\text{with\_onus}}$ is then used to calculate shortest FF and DF paths via Dijkstra's algorithm to obtain different performance metrics.

Algorithm 1 BPON Network Modeling

Require: N, E, ONU_pos, splitter_ports, utilization
Ensure: Designed BPON network with ONUs and RNs assigned
1: $G \leftarrow$ LOAD_GRAPH(N, E)
2: $G_{\text{with\_onus}} \leftarrow$ ADD_ONUS_TO_GRAPH(G, ONU_pos)
3: $OLT\_pos \leftarrow$ FIND_OPTIMAL_OLT($G_{\text{with\_onus}}$)
4: $optimal\_connections \leftarrow splitter\_ports \times utilization$
5: $n_clusters \leftarrow \lceil$COUNT_ONUS($G_{\text{with\_onus}}$)$/optimal\_connections\rceil$
6: $clusters \leftarrow$ APPLY_KMEANS_CLUSTERING($G_{\text{with\_onus}}$, $n\_clusters$)
7: **for** each cluster in $clusters$ **do**
8: $G_{\text{with\_onus}} \leftarrow$ ASSIGN_RNS($G_{\text{with\_onus}}$, cluster)
9: $G_{\text{with\_onus}} \leftarrow$ MAP_ONUS_TO_RNS($G_{\text{with\_onus}}$, cluster)
10: $splitter\_count \leftarrow$ CALCULATE_SPLITTERS_PER_RN($G_{\text{with\_onus}}$, cluster, $optimal\_connections$)
11: **return** $G_{\text{with\_onus}}$

2) HPON Modeling: As mentioned before, HPON integrates both BPON and UPON based on ONU density in an area. An example of a working HPON architecture is shown in Fig. 3, where a BPON splitter connection and a UPON with cascaded optical taps are depicted. A utilization parameter is also considered here so that the network can be scaled for future demands without any major infrastructural action.

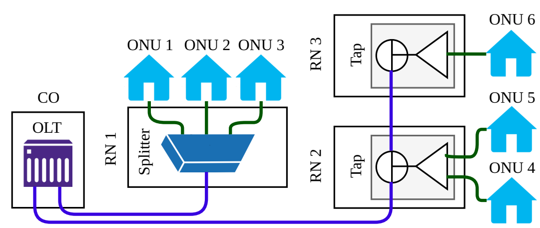


Fig. 3. Example of a HPON structure featuring a BPON with a symmetrical splitter and a BPON with an optical tap.

The modeling of HPON begins similarly to BPON, illustrated in Algorithm 2, by generating the graph $G = (N, E)$ which represents the rural area. The hybrid model simplifies the connections by directly linking each ONU to the nearest intersection point $n \in N$, directly designated as RN, within G in terms of geographical distance. The resulting graph is termed as $G_{\text{with\_onus}}$. OLT is placed in the same way as in BPON modeling. The next step is generating the Steiner Tree of G, called G_{Steiner}, with RNs as the set of terminal nodes, to have the shortest paths among all required nodes.

All the FFs, i.e., paths between RNs and the OLT, are then arranged in a manner where no path is a subset of any other path, hence called Unique Paths in Line 16. Starting with the longest unique path in terms of hop count, every unprocessed RN in the path is processed and determined if it requires a BPON splitter or an UPON optical tap, based on the number of direct ONUs connections it has. BPON is characterized by its direct fiber links from the OLT to each RN since higher capacity is needed while UPON uses the same optical fiber to feed different RNs with signals, by considering leaving a small portion of power in each RN. Hence, a power flow constraint is needed when designing RN with UPON.

Algorithm 2 HPON Network Modeling

```
Require: N, E, ONU_pos, splitter_ports, utilization
Ensure: Designed Hybrid Network with ONUs, and RNs assigned
G ← LoadGraph(N, E)
G_with_onus ← ADD_ONUS_TO_GRAPH(G, ONU_pos)
OLT_pos ← FIND_OPTIMAL_OLT(G_with_onus)
for node in G_with_onus do
    if node is not type ONU or OLT then
        Make node RN
    else
        Mark node as Intersection Point
G_Steiner ← SteinerTree(G, RNs)
Map_RNs_to_ONUs(G_Steiner)
for each RN in G_Steiner do
    for each ONU connected to RN do
        DF_paths ← GET_SHORTEST_PATHS(G_Steiner, RN, ONU)
for each RN in G_Steiner do
    FF_paths ← GET_SHORTEST_PATHS(G_Steiner, RN, OLT_pos)
unique_paths ← Save_Unique_Paths(FF_paths)
for path in unique_paths do
    for node in path do
        if node is unprocessed RN and has ≤ 8 ONUs then
            Start UPON design for RN node
            Choose right tap port based on the number of ONUs
            Find optimal tap loss ensuring power drop is within limits
            if power drop not within sensitivity then
                Initiate new fiber deployment for UPON
                Re-evaluate right tap port and tap loss
        else if node is unprocessed RN and has > 8 ONUs then
            Design using BPON
return G_Steiner
```

Each optical tap is equipped with two branches: a *thru leg*, which acts as FF to the other RN, and a *drop leg*, which acts as DF to the ONUs. The UPON design facilitates the sketch of daisy chain topology for each path, where several RNs are cascaded together until a desired count of ONUs, here 64, or the drop power limit of the optical tap is reached. The last successful node is reverted to a terminating tap, and the process is reset to the new, unique path. For each RN, the algorithm determines the appropriate tap ports based on the number of connected ONUs. It then finds the optimal tap loss by ensuring the power drop is within limits. The optimal tap loss process means leaving as much power as possible in the *thru leg* and as little as possible in the *drop leg* by trying every possible combination mentioned in [5] for 2-, 4-, and 8-port taps. This solution ensures that each RN receives the minimum required power to operate effectively, allowing the remaining signal to be utilized by subsequent RNs, which hence enhances network reachability. If no suitable tap loss is found, then the last successful node in the path is reverted to a terminating tap configuration, and the process resets from the current node. Once the optimal configuration is found for each RN, the design is finalized.

A fixed attenuator is applied to maintain the signal quality if the power drop exceeds the threshold. Passive components such as splitters, connectors, and fiber splicers, assumed every 5 km of fiber, contribute to signal attenuation. The fiber itself has its loss over distance, separately for both downstream and upstream communication. The power loss caused by every component is calculated arithmetically for every ONU on the network. The process outputs the final design, including the tap type, port ratios, *drop* power, and *thru* power values for each RN design with UPON. The hybrid model amalgamates UPON in less densely populated areas within the rural area and the BPON in more densely populated ones.

IV. Performance Evaluation

A. Simulation Setup

We perform our comparative analysis of the deployment costs of BPON and HPON on four rural areas with varying dimensions and population densities, summarized in Tbl. I. Data collection methodology mentioned in section III-A, and then BPON and HPON modelling are implemented in Python using different libraries. The created dataset with node coordinates, edges and building information are fed as input to the BPON and HPON models. In the BPON, the splitting ratio of 1:32 is considered at the RN, and this value is validated by distribution of the number of ONUs that a RN and the splitters can hold, considering 80% utilization. In the HPON, one optical tap per RN is considered, supporting a maximum of 8 ONUs. The power budget calculations are performed in both upstream and downstream with threshold ranging from -28 dBm to -8 dBm.

TABLE I
Geographical and Network planning parameters

	Bibertal	Petersaurach	Hollfeld	Renertshofen
Area [km]^2	27.3	41.81	80.66	93.11
Nodes, Edges	367, 477	317, 391	432, 522	390, 505
No. of ONUs	1592	1446	2663	2077
ONU Density per [km]^2	58.36	34.6	33	22.3

B. Cost Computation

Two major cost categories are considered: Street infrastructure and Node equipments costs. Street infrastructure cost includes installation of fiber optic cables, trenching activities, microduct deployment, and splicing the cable connections. Nodal equipment cost includes Subscriber Connector Angled Physical Contact (SC/APC) connectors, ONUs, OLT and splitters in case of BPON design or optical taps in case of UPON design. All costs within this analysis are normalized against the average market price of an ONU, which is 70€ [7], and are expressed in Cost Unit (CU). The considered costs are detailed in Tbl. II.

C. Deployment Cost Analysis

Fig. 4 and Fig. 5 present Street infrastructure elements and Node equipment, respectively, required in BPON and HPON deployment in the four different areas. First, we present

TABLE II
REFERENCE PRICES FOR COST CALCULATION [7]–[9]

Type	Price	Type	Price	Type	Price
Trenching	0.8 CU/m	ONU	1 CU	Distribution microduct	0.0159 - 0.07 CU/m
Splice cost per fiber	0.189 CU	OLT	28.57 CU	Splitter 1:32	1.87 CU
Cabinet	14.286 CU	SC/APC Connector	0.0646 CU	Feeder microduct	0.03-0.0629 CU/m
FTB	0.286 CU	Optical Tap	0.572 CU	Fiber cable	0.007- 0.07 CU/m

a detailed analysis of the BPON vs. HPON deployment in the Bibertal area as this area had more number of specified building types. Then BPON vs. HPON are compared based on sparsity of the four rural areas.

1) BPON and HPON Deployment Cost Comparison in Bibertal: We can see in the Fig. 4 for Bibertal area, that HPON uses 144% more of the feeder fiber length, and 76% lower distribution fiber length, than the BPON. The feeder duct length in the HPON is 10 km more, but the distribution duct length is 43% less than the BPON. HPON leverages more centralized fiber deployment closer to users' locations, minimizing the length of the distribution network. BPON uses a single RN for each cluster, leading to a shared duct among multiple ONUs, thus longer distribution fiber lengths. The total fiber length in HPON is 21% more than the BPON. However, the total duct length is 28% less than the BPON, which makes HPON more efficient in the sense that duct length/trenching is the major street infrastructure cost driving factor in the planning. The overall street segment cost of the HPON in Bibertal is 107493.97 CUs, which is 21.2% less than the BPON cost, because of the savings in the overall duct length and distribution segments' length, as shown in the Fig. 6a.

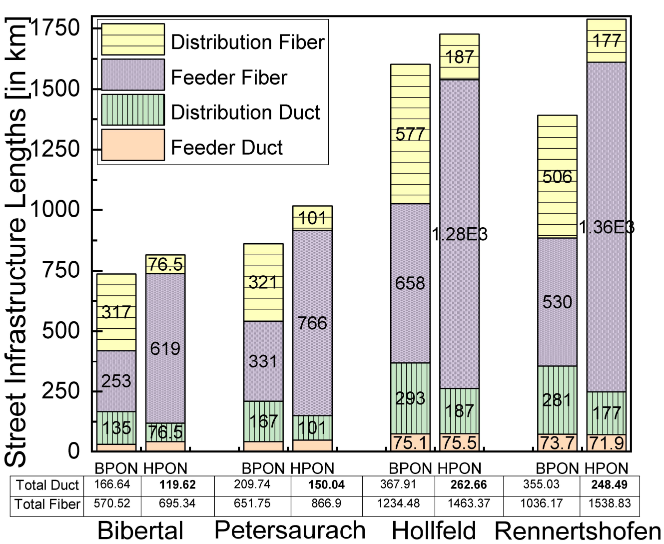


Fig. 4. Street Infrastructure's comparison across four rural areas, (length data less than 1% of the total length is not shown in this plot)

In Fig. 5, we can see that the BPON has 80% fewer RNs than the HPON, considering RNs at every intersection point. HPON has 24.9% more number of connectors than the

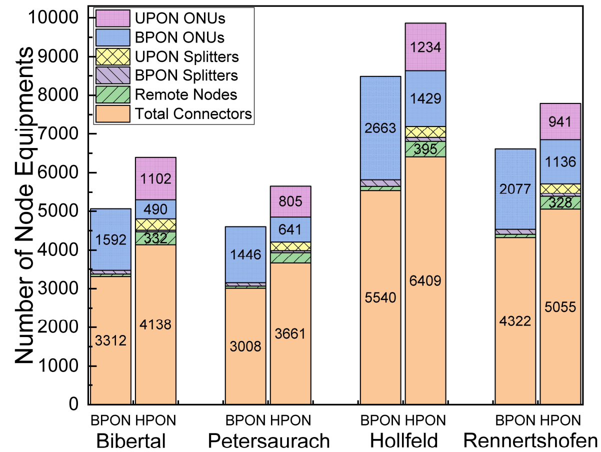


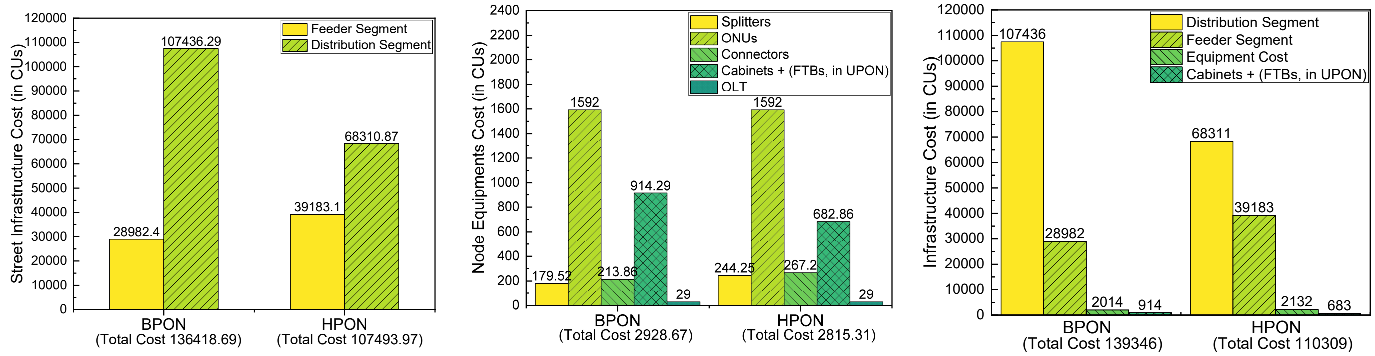
Fig. 5. Breakdown of Node Equipments in four rural areas, (data value less than 1% of the total number is not shown in this plot)

BPON, because of the increased complexity in BPON-UPON integration. HPON employs 290 HPON splitters to cater to 1102 ONUs and the remaining 490 ONUs are supported by the BPON splitters. In BPON, significantly lower number of traditional splitters are used serving all the ONUs but with a vast distribution network. In both the models, only 1 OLTs is considered. Analyzing the implications of these number on the overall equipment costs, HPON has 3.87% cost savings in the equipments deployed at the nodes than the BPON. This saving is present even after having more cost contribution from connectors (9.5%) and splitters (8.7%) because of lower costs of the optical taps on FTBs and less number of RNs with BPON. The cost share of ONUs has 54% and 56% contributions in BPON and HPON respectively, as shown in Fig. 6b.

Study of deployments in Bibertal for BPON and HPON, leads to this finding that considering total infrastructure costs, shown in Fig. 6c, HPON is 20.84% more cost efficient than the BPON. The main cost drivers in both HPON and BPON, are the distribution segment and feeder segments with trenching, duct and fiber costs.

2) Cost Analysis Area Wise: In this part, four different rural areas are compared to evaluate the economic benefits of employing the HPON over BPON design, considering different rural sparsity. The rural areas selected, have similar population sizes, but varying geographic expanses and the ONU densities, Tbl. I. In Fig. 4 and Fig. 5 we observed that the other three rural areas, Petersaurach, Hollfeld and Rennertshofen have similar variations between BPON and HPON in the feeder segment, distribution segment and no. of node equipments like Bibertal.

The plot in Fig. 7 illustrates how saving through the HPON increases as the rural areas become sparser i.e., decreasing ONU density. We observe that transition to more sparse areas, shows an increase in overall cost in both the BPON and HPON models. This reflects the higher expenses incurred in serving areas with lower ONU density. However, this trend is not true when we compare Hollfeld with Rennertshofen. This slight deviation suggests that local factors such as ONU locations, total



(a) Street Infrastructure Costs (b) Node Infrastructure Costs (c) Total Infrastructure costs

Fig. 6. Figs. 6a-6b present comparative breakdown of the costs contributing in BPON and HPON deployments' total infrastructure cost in the Bibertal Area. Figs. 6c gives a comparative view of the major costs driving the total cost, which are distribution and feeder street segments.

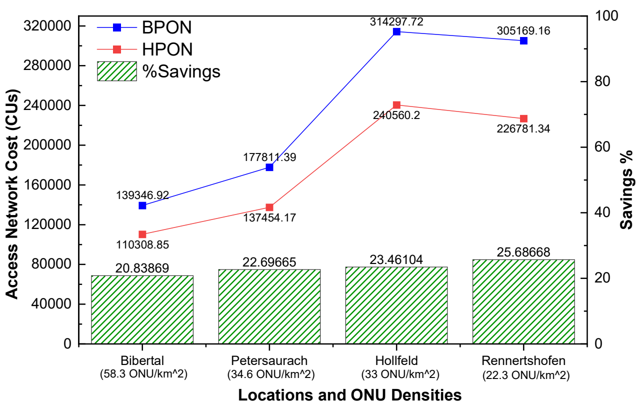


Fig. 7. Cost Comparison of rural areas

number of ONUs, and fiber deployment options (like clustering) might also influence cost-effectiveness. Furthermore, the HPON consistently shows a higher percentage of cost savings compared to the BPON across all areas. Starting with Bibertal, where the HPON shows a 20.84% cost reduction, and escalating to Rennertshofen, where the savings reach 25.69%. Cost/ONU and Cost/km^2 mimics the same percentage savings for HPON. The Cost/ONU, when using HPON for Bibertal, Petersaurach, Hollfeld and Rennertshofen are 69.29, 95.06, 90.33 and 109.19 CUs, respectively. Cost/km^2, when using HPON, for Bibertal, Petersaurach, Hollfeld and Rennertshofen are 4040.62, 3287.59, 2982.4 and 2435.63 CUs, respectively. This trend underlines the HPON model's efficiency in terms of cost, with more savings as the rural areas become sparser.

V. Conclusion

In this paper, we addressed the issue of cost-efficient access network planning in rural areas by considering the geographical and sparsity of the ONU distribution. We consider a BPON model, which uses symmetrical splitters and a HPON model that incorporates both BPON and UPON, using optical taps, solutions as an innovative fiber deployment technique. HPON allocate the power budget across less densely populated areas with fewer ONUs. Four rural areas were selected based on varying ONU densities and diverse geographical expanses. In Bibertal area, HPON emerged as a cost-efficient solution over BPON in both street infrastructure costs and node equipment costs. We also observed that Distribution Segment being the main cost contributor. There is an economic advantage of HPON over BPON in other rural areas as well. By analyzing the total access network costs across four areas, it is evident that the HPON not only reduced the cost per ONU but also offered significant savings on a cost per km^2 basis, ranging from 20.84% to 25.69% as the areas became sparser. Thus, we conclude that HPON is a more cost-efficient option than traditional BPON for OAN deployment in the rural areas. Future studies to further improve the HPON model may require consideration of multiple optical taps per RN, and efficient density-based clustering techniques.

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