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A Dijkstra Based Algorithm for Optimal Splitter Location in Passive Optical Local Area Network (POLAN)

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

Passive Optical Local Area Networks (POLANs) are integral to modern broadband communication systems, offering high bandwidth and immunity to electromagnetic interference. Designing an efficient POLAN requires careful consideration of splitter placement to minimize network costs. This paper presents an algorithmic approach using Dijkstra's algorithm and the Google Maps API to optimize splitter locations in a POLAN. By treating Optical Network Terminals (ONTs) as nodes in a graph and calculating walking distances between them, the algorithm identifies potential splitter locations that minimize fiber length. Using the Dijkstra's algorithm, the total fiber length used to connect every optical network unit is approximately 274km. Finally, a simulation of the full PON network was carried out and the BER and Q-Factor for each ONU was gotten. An average BER value of 1.8e-11 and Q-Factor value of 13.3 was gotten.

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Keywords: Djikstra algorithm; optical network terminal; optical network unit; passive optical network.

1. INTRODUCTION

Optical communications have been around since ancient and are currently the preferred transport method for broadband connections. Optical fibers enable the transmission of data through a long distance at very high speed and very low latency (Okeke et al., 2022). In order to provide an increase in bandwidth or information capacity, the evolution of electrical communication systems shifted to the use continually higher frequencies. The growing acceptance of optical communication can be attributed to the fact that optical frequencies are orders of magnitude greater than those utilized by electrical communication systems. A Passive Optical Local Area Network (POLAN) is a type of local area network that uses fiber-optic cables and passive optical components such as splitters and combiners to deliver signals between the central office and end-users. Unlike traditional LANs that use copper cabling, POLANs leverage the advantages of optical fiber, such as higher bandwidth, longer transmission distances, and immunity to electromagnetic interference.

In a POLAN, the central office contains the equipment necessary for converting electrical signals into optical signals and vice versa. Optical splitters are used to divide the optical signal into multiple paths, each leading to an end-user's location. At the end-user's location, an Optical Network Terminal (ONT) is used to convert the optical signal back into an electrical signal that can be used by devices such as computers, phones, or other networked devices.

In the design of a passive optical network, the location of the splitter is a design issue which can determine the cable cost and splitter cost. If the splitter is located close to an ODP (optical distribution cost), cable cost goes up since the optical node terminals will be connected to the splitter by separate optical lines. This however decreases the number of splitters but increases the length of fiber required. However, placing a splitter near the demand nodes may reduce the cost of fiber but increases splitter codes. Thus, there must be tradeoff between splitter and fiber cost

2. LITERATURE REVIEW

Okeke et al., (2021) developed a passive optical network (PON) for the University of Port-Harcourt, serving as the foundation for a LAN. They employed the Wavelength Division Multiplexing (WDM) technique due to its dedicated bandwidth for each subscriber and its flexibility in bandwidth management. The validation of the network was conducted using a virtual computation environment (Opti System).

Kim et al., (2011) dealt with a physical access network design problem of a fiber-to-the-home passive optical network (FTTH-PON). The design of the FTTH-PON access network sought the cost-effective location of optical splitters that provided optical connectivity from the central office to subscribers in a given service area. The problem was formulated as a multi-level capacitated facility location problem on a tree topology with non-linear link costs. To address the non-linear link costs, the paper proposed an objective function relaxation approach to obtain tight upper and lower bounds. It developed valid inequalities that enhanced the lower bound and proposed a local search heuristic procedure that improved the upper bound. The valid inequalities forced an integrality condition on the number of splitters placed at nodes, while the local search heuristic improved the initial greedy solution by placing splitters on the sub-root nodes of a given tree network. Computational results demonstrated the effectiveness of the proposed solution procedures.

The article by (Pehnelt and Lafata, 2017) outlined ideas and potentialities for an algorithm that applied graph algorithms to find the shortest path from Optical Line Termination to Optical Network Terminal unit. This algorithm employed a variety of methods to generate an optimal metric, thereby constructing an optimized tree topology primarily concentrated on minimizing the total trenching distance. Additionally, it addressed algorithms for determining the optimal placement of optical splitters using the K-Means clustering method and hierarchical clustering technique. The outcomes of the proposed algorithm were compared with those of existing methods.

Lohani and Prasad (2015) designed and simulated a hybrid WDM/TDM passive optical network. the performance of hybrid WDM/TDM PON is evaluated in terms of Q-factor and BER. The Q-factor and BER at OLT side is 4.04977 and 2.07621e-005 and at the ONU side is 4.03206 and 2.24227e-005. These values are low and be improved on.

In (Pal et al., 2014), the authors proposed a novel agglomerative clustering algorithm. The algorithm, along with ILP and heuristic models, attempted to minimize the total fiber cable required to connect sparse rural users to a drop PON splitter located up to several kilometers away from the user. The results showed that proper deployment strategies could increase the use of large last-stage splitter, thus increasing the sharing of fiber among users, while still minimizing the overall cable length. Additionally, the heuristic model was able to obtain similar results as the ILP (i.e., within an 8% margin), but could reduce the computation time by about 6 times, for the scenarios we considered.

This paper focused by (Chardy et al., 2012) on the optimization of FTTH deployment, which was of prime importance due to the economic stakes. The key design issue was locating splitters and routing fibers in an existing network infrastructure, represented as a graph with given capacities on the edges. No assumption was made about the structure of the graph. First, a mixed integer formulation was proposed for this decision problem, and it was proven to be NP-hard. Then, valid inequalities and problem size reduction schemes were presented. Finally, the efficiency of the solution approaches was assessed through extensive numerical tests performed on France Télécom-Orange's real-life data.

Branko (1999) discussed the local access network design problem for a full-optical network, where optical fiber connected the central office with all end-users. It analyzed the double-star tree topology and passive optical network (PON) architecture, with randomly placed optical splitters serving as star points. The optimization method selected for this study was the simulated annealing (SA) method, which was used to minimize the length of fiber cables in the full-optical network.

Eira et al., (2012) addressed the problem of identifying the least costly tree topology for time-division multiplexing PON (TDM-PON) deployment configurations, considering both equipment and installation costs (CAPEX) as well as operational exploration costs. To achieve this, an integer linear programming model was developed, which was capable of designing not only common single-stage PON configurations but also PONs with multiple stages of optical splitting. To reduce computation time for larger problems, a two-stage heuristic was proposed. Simulation results revealed that an optimal multistage splitting strategy could achieve up to 15% cost savings in CAPEX compared to the traditional single-stage approach. Additionally, the heuristic procedure provided results within acceptable bounds relative to the optimal solutions, validating its effectiveness for larger network sizes.

In this paper by (Zukowski et al., 2013), a nation-wide deployment case study of a 1024-way-split Long-Reach Passive Optical Network (LR-PON) for Ireland was examined. The effect of different splitter configurations in the Distribution Section on the PONs' utilization and the total fiber cable length required to cover the country was analyzed. The approach, which considered both densely and sparsely populated areas, was based on a clustering algorithm that aggregated end users into clusters representing different PON branches. Test scenarios were generated using a real dataset containing the exact positions of millions of buildings. The results showed how the optimal dimensions and positions of power splitters varied between densely and sparsely populated areas. The study identified which splitter configurations should be applied in urban and rural areas to minimize the number of PONs. Additionally, it demonstrated that by introducing cable branching near end users, a reduction of up to 40% in total fiber cable length could be achieved.

3. RESEARCH METHODOLOGY

The splitter location-allocation problem in Passive Optical Networks (PONs) involves determining the optimal locations for optical splitters to minimize network costs while meeting performance requirements. centralized splitting is used in this work and with the aid of Dijkstra’s algorithm the shortest path between each pair of ONTs is gotten in this work. Dijkstra's algorithm is a method for finding the shortest path from a starting node to all other nodes in a weighted graph. In the context of Passive Optical Networks (PONs), An improved Dijkstra's algorithm can be applied to find the optimal location for a splitter, which is a device used to split the optical signal from a single fiber to multiple fibers. To use Dijkstra's algorithm for finding the optimal location for the splitter, you can treat the ONTs as nodes in a graph as shown in Fig. 1, with the distance between two ONTs as the weight of the edge connecting them. The coordinates of each ONT are given in Table 1. The data is a secondary data gotten from Okeke & Idigo (2021).

Table 1. Coordinates of different ONTs

Longitude	Latitude
4.866352	6.973566
4.82567	6.956087
4.847137	6.991481
4.89677	6.976612
4.865044	6.93446
4.84592	6.96775
4.84009	6.982839
4.83361	6.984036
4.873571	6.998866
4.861064	7.007818
4.861188	7.001678
4.926687	6.936321
4.863698	7.005474
4.822736	6.989998
4.826498	6.97835
4.830989	7.01989
4.863786	6.975024
4.830131	7.02808
4.936852	6.948205
4.84388	6.995489
4.836445	6.992169
4.831056	6.991607
4.86592	6.971764
4.871235	6.960551
4.873325	6.967633
4.869661	6.929977
4.870598	6.937656
4.883155	6.930677
4.880579	6.937556
4.871082	6.919613
4.8759456	6.911113
4.847845	6.930874
4.896827	6.904349
4.885897	6.892871
4.879314	6.911096
4.880449	6.935425
4.888953	6.935421
4.884546	6.919824
4.890509	6.932446
4.899744	6.921622
4.884693	6.91381
4.836605	6.962732
4.86807	6.910196
4.874931	6.952569
4.8622	6.980034
4.874344	6.962228
4.805087	7.026585
4.806745	7.017185
4.850305	6.965294
4.846995	6.931832

The distance between two ONTs can be calculated using walking distance on the google map. Walking distance is used over great circle distance so as not to cut into buildings or encroach into right of ways thereby avoiding more cost. A google map API with the help of ‘googlemaps’ module on python is embedded into the code to automatically calculate these distances.

The Algorithm that can be used for the optimal splitter location.

1 Start
2 create a priority queue to store nodes

Set the distance of all nodes (except the starting OLT node) to infinity.

Set the starting OLT node's distance to 0 and mark it as visited.

While priority queue (PQ) is not empty:

Dequeue the node with the minimum distance from PQ (current node) using google maps API.

For each neighboring OLT:

Calculate the tentative distance to the neighbor: current distance + edge weight (distance to the neighbor)

If the tentative distance is less than the neighbor's current distance: Update the neighbor's distance to the tentative distance.

Set the current node as the neighbor's parent in the shortest path tree.

Enqueue the neighbor with its updated distance into PQ.

3 The shortest paths from the OLT to all other nodes are established in the shortest path tree
4 Identify potential splitter locations:

Traverse the shortest path tree from each leaf node (ONU) towards the OLT.

At each branching point (node with multiple children), identify the node as a potential splitter location.

5 Calculate total network cost:

Sum the distances of all edges in the shortest paths from the OLT to each ONU.

End

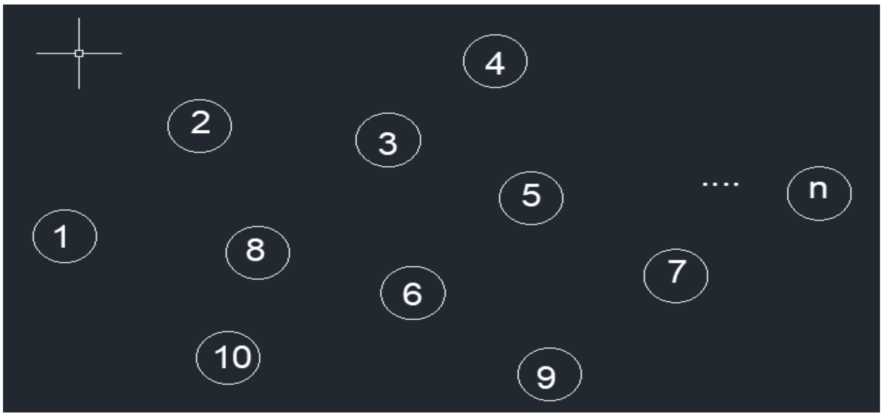


Fig. 1. Nodes which serve as ONTs

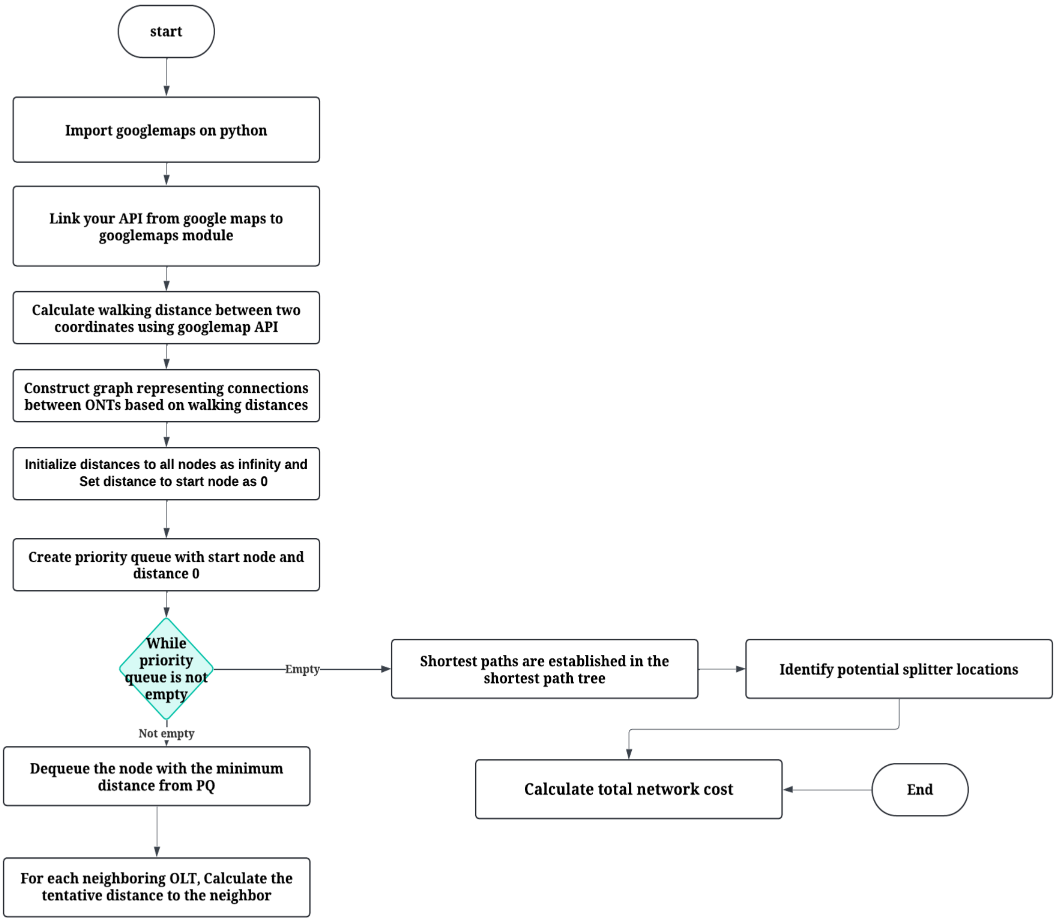


Fig. 2. Flowchart for Dijkstra Algorithm

Table 2 gives the distances covered by placing splitters in different location. The splitter location with the minimum distance is taken as the best location.

From Table 2, ONT 24 gives the minimum distance and therefore will give the best location as it will consume the lowest number of fiber length.

Table 2. Total distances covered by different ONTs

ONT 1	285.70 km
ONT 2	380.25 km
ONT 3	335.42 km
ONT 4	405.59 km
ONT 5	324.85 km
ONT 6	306.41 km
ONT 7	333.98 km
ONT 8	351.61 km
ONT 9	368.97 km
ONT 10	392.66 km
ONT 11	369.80 km
ONT 12	538.91 km
ONT 13	395.73 km
ONT 14	404.30 km
ONT 15	363.28 km
ONT 16	503.12 km
ONT 17	283.30 km
ONT 18	558.36 km
ONT 19	579.81 km
ONT 20	341.32 km
ONT 21	347.22 km
ONT 22	372.19 km
ONT 23	283.72 km
ONT 24	274.09 km
ONT 25	307.56 km
ONT 26	318.57 km
ONT 27	305.41 km
ONT 28	329.26 km
ONT 29	322.45 km
ONT 30	352.49 km
ONT 31	387.45 km
ONT 32	360.62 km
ONT 33	447.32 km
ONT 34	568.09 km
ONT 35	388.56 km
ONT 36	321.70 km
ONT 37	344.98 km
ONT 38	366.85 km
ONT 39	348.52 km
ONT 40	423.28 km
ONT 41	386.48 km
ONT 42	352.93 km
ONT 43	395.96 km
ONT 44	287.73 km
ONT 45	299.06 km
ONT 46	318.33 km
ONT 47	607.18 km
ONT 48	565.24 km
ONT 49	301.68 km
ONT 50	361.50 km

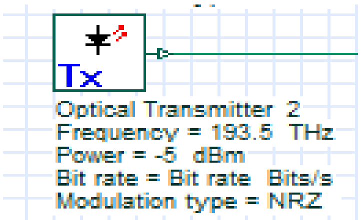
3.1 Simulation of Full Polan

A full PON network is simulated in this section. Each ONU distance from the splitter has been calculated and shown in Table 2. A total of 50 ONUs were used to find the optimal splitter distance. However, due to the limitation of Opti system worksheet space, only 20 ONUs are used for the simulation. The BER and Q Factor of each ONU are to be gotten from the simulation. The minimum BER expected is 10^{-9}. The distance of each ONU from the splitter is given in Table 3. The splitter coordinate is (4.871235, 6.960551). The distances are printed out in the Table 3.

Table 3. ONU distances from splitter

ONU	Distance from splitter
ONU1	2.2KM
ONU 2	6.62KM
ONU 3	5.33KM
ONU 4	5.28KM
ONU 5	3.96KM
ONU 6	3.52KM
ONU 7	5.14KM
ONU 8	5.94KM
ONU 9	5.04KM
ONU 10	6.34KM
ONU 11	5.68KM
ONU 12	8.79KM
ONU 13	6.33KM
ONU 14	7.41KM
ONU 15	6.09KM
ONU 16	9.89KM
ONU 17	2.21KM
ONU 18	11.10KM
ONU 19	9.20KM
ONU 20	5.60KM

The first component in the network is the optical transmitter with an input power of 5dBm, bit rate of 10gbps and an NRZ modulation type as shown in Fig. 3.



Optical Transmitter 2
Frequency = 193.5 THz
Power = -5 dBm
Bit rate = Bit rate Bits/s
Modulation type = NRZ

Fig. 3. Optical Transmitter

Since there are twenty ONUs to be supplied to, 20 transmitters are used. The frequency of the first transmitter is given as 193.1 THz and is increased by 0.2 THz down to the twentieth transmitter. The other parameters remain constant. The twenty transmitters are fed into a WDM multiplexer with 20 inputs as shown in Fig. 4.

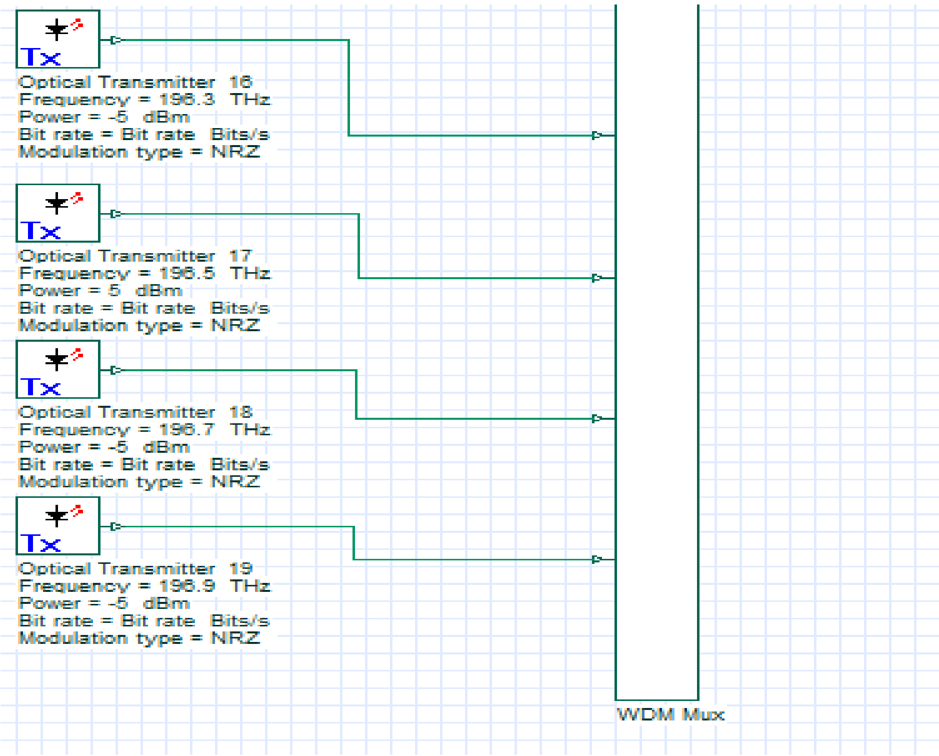


Fig. 4. Connection from Transmitters to WDM Mux

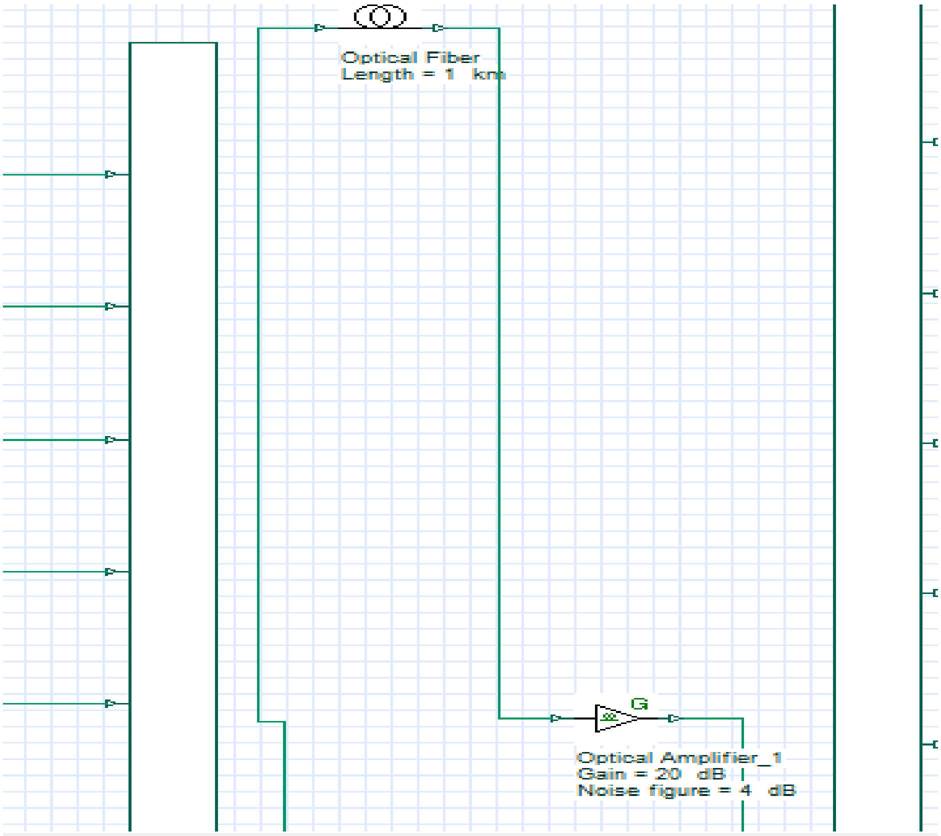


Fig. 5. Connection from WDM to optical amplifier to Splitter

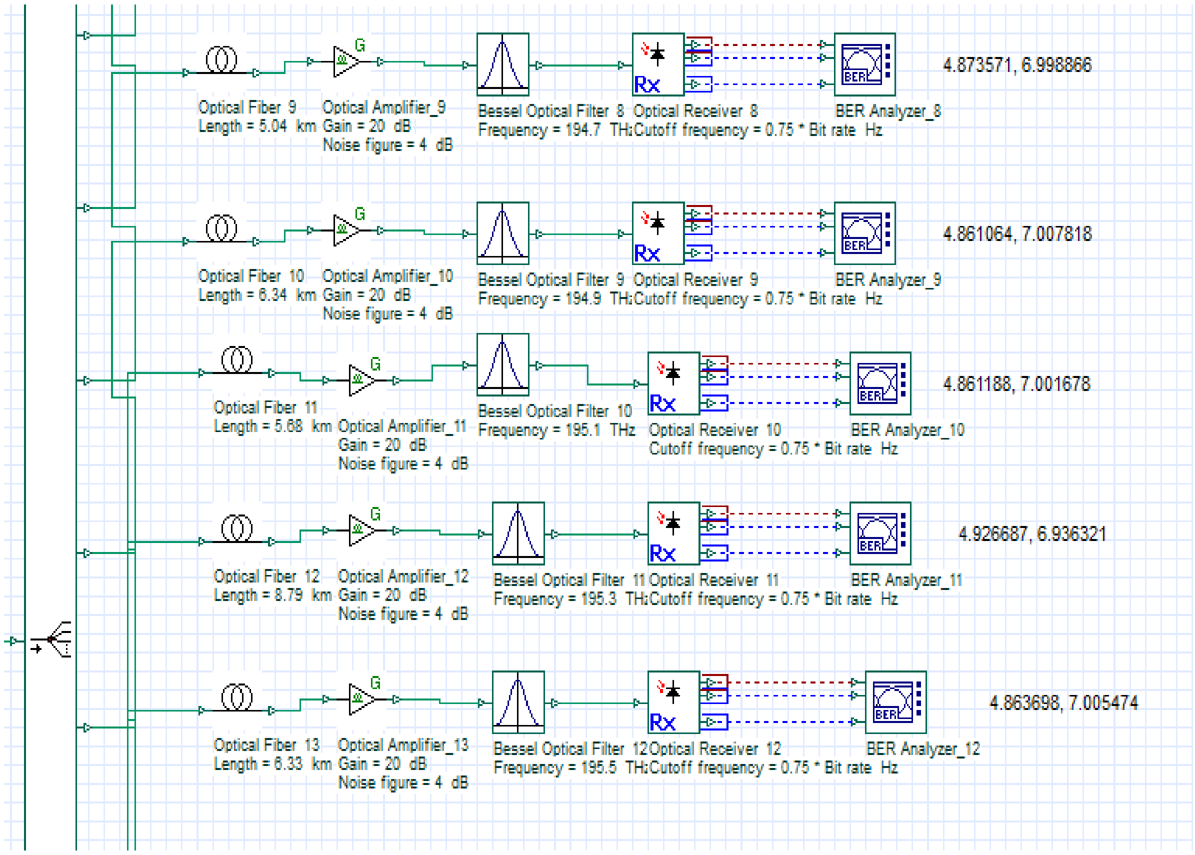


Fig. 6. Connection from splitter to various ONUs

The output from the multiplexer is connected to a 1km fiber cable which in turn is connected to a 20dB amplifier and then to a splitter (1xN) as shown in Fig. 5.

ONUs are supplied according to their appropriate distances and their coordinates given as seen in Fig. 6. A 20dB is added and then connected to the Bessel filter and optical receiver. The parameters used for the simulation are shown in Table 4.

Table 4. Simulation parameters

Parameter	Value
Transmit power	5dBm
Bit rate	10Gbps
Modulation type	NRZ
Amplifier gain	20dB
Receiver sensitivity	-25dBm
Maximum BER	10e-9

3.2 Link Budget Analysis

Link budget analysis is done to calculate the amount of light needed to design an optimal communications link. The four main parameters include transmit power, receiver sensitivity, insertion loss and fiber transmission loss. The budget link analysis for the PON network is shown below.

OLT to splitter distance = 1km

Fiber cables to each ONUs = 121.67km

Using the equation 3.14 below, the link budget can be gotten

$$\mathrm{P_T} - \mathrm{P_R} = (\mathrm{TFL} + \mathrm{TCL} + \mathrm{TSL} + \mathrm{TS_PL} + \mathrm{PM}) \quad (1)$$

$\mathrm{TFL} = \text{Total fiber loss} = \text{cable distance x loss}$
$\mathrm{TCL} = \text{Total connector loss}$
$\mathrm{TSL} = \text{Total splice loss}$
$\mathrm{TS_PL} = \text{Total insertion loss for splitter}$
$PM = Margin$

Attenuation coefficient = 0.3dB/km
Insertion loss = 0.5dB
Splice loss = 0.1dB
Insertion loss for splitter = 4.1dB

Transmit Power = 5dBm

$$TFL = (121.67km + 1km)\ x0.2(dB|km) = 26.9874dB$$

$$\begin{aligned} Total\ connectors &= 1\ connector\ at\ OLT \\ &+ 1\ connector\ at\ splitter \\ &+ 20\ connectors\ for\ ONU \\ &= 22\ Conncetors \end{aligned}$$

$$TCL = 22 * 0.5 = 11dB$$

$$TSL = 1 * 4.1 = 4.1dB$$

$$TS_pL = 1 * 0.1 = 0.1dB$$

Total FTTx Network loss (TFNL) = 25dB

$$TFNL = \begin{pmatrix} TFL + TCL + TSL + TS_pL \\ + PM \end{pmatrix} \tag{2}$$

$$= 11 + 4.1 + 0.1 + PM$$

$$PM = 9.8dB$$

$$P_R = -5 - 25 = 30dB$$

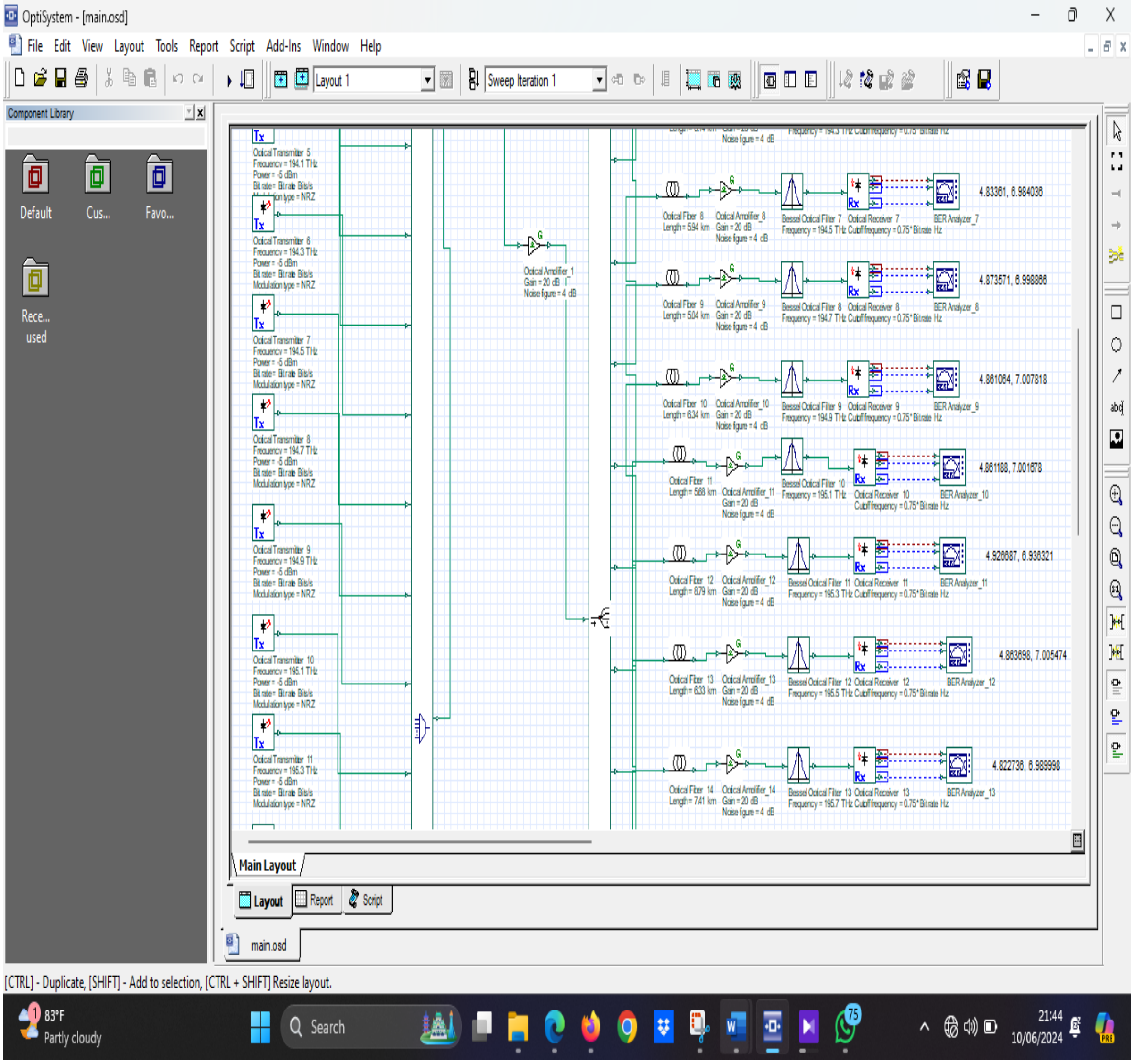


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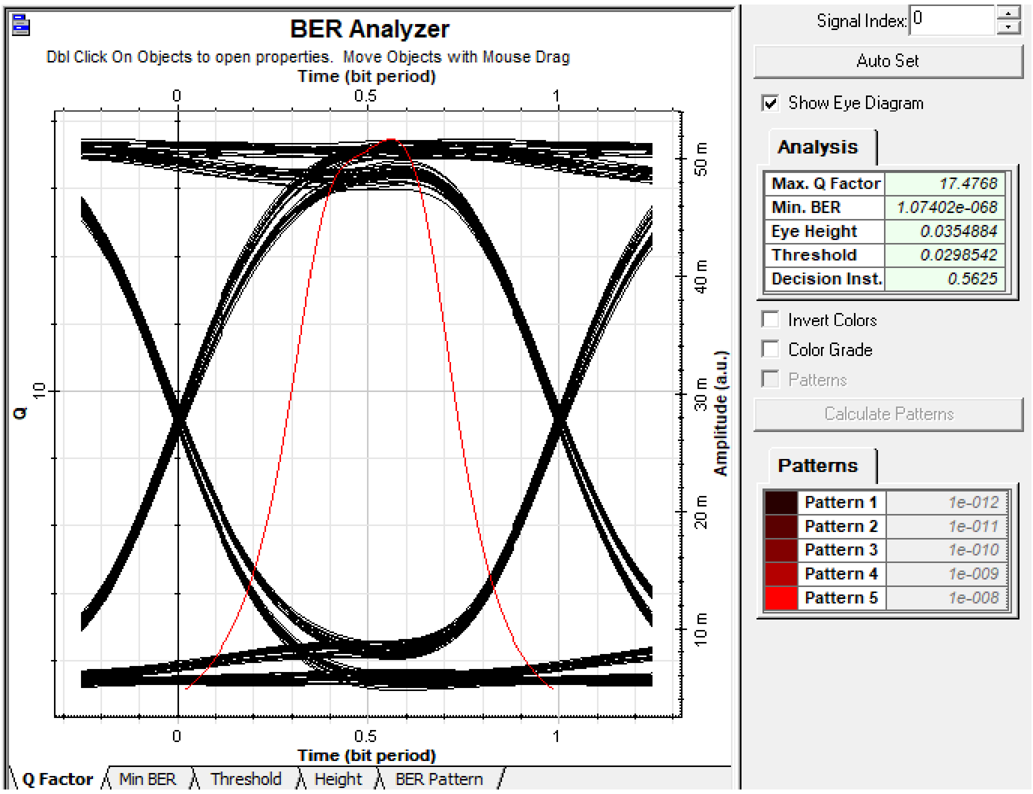
Fig. 7. Snapshot of the fiber network

4. RESULTS AND DISCUSSION

The complete Passive optical network was simulated (Fig. 7) to validate the efficiency of the system. There are twenty (20) ONUs that were connected to the network. Each ONU is evaluated with the Q Factor and bit error rates. The values for the parameters are given in Table 5 and shown in Fig. 8 to Fig. 14.



Signal Index: 0

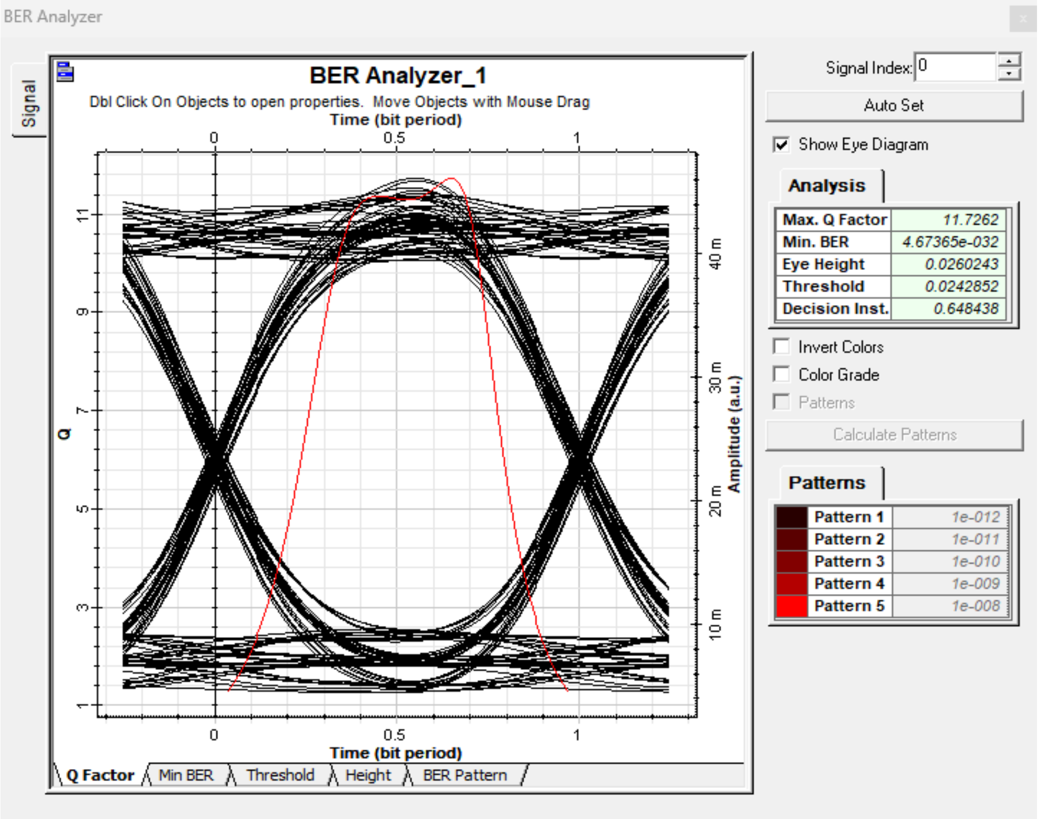
☑ Show Eye Diagram

Max. Q Factor	17.4768
Min. BER	1.07402e-068
Eye Height	0.0354884
Threshold	0.0298542
Decision Inst.	0.5625

☐ Invert Colors
☐ Color Grade
☐ Patterns

Pattern 1	1e-012
Pattern 2	1e-011
Pattern 3	1e-010
Pattern 4	1e-009
Pattern 5	1e-008

Fig. 8. Q Factor and BER values of ONU 1



Signal Index: 0

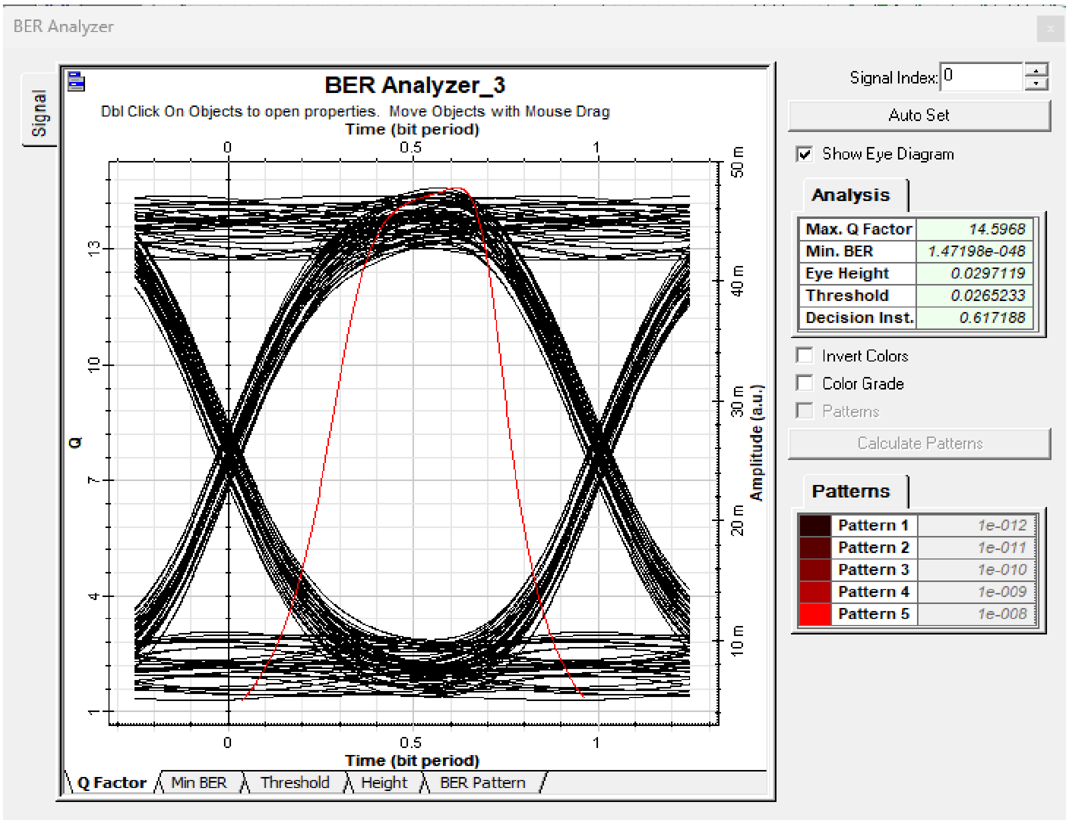
☑ Show Eye Diagram

Max. Q Factor	11.7262
Min. BER	4.67365e-032
Eye Height	0.0260243
Threshold	0.0242852
Decision Inst.	0.648438

☐ Invert Colors
☐ Color Grade
☐ Patterns

Pattern 1	1e-012
Pattern 2	1e-011
Pattern 3	1e-010
Pattern 4	1e-009
Pattern 5	1e-008

Fig. 9. Q Factor and BER values of ONU 2



Signal Index: 0

☑ Show Eye Diagram

Analysis

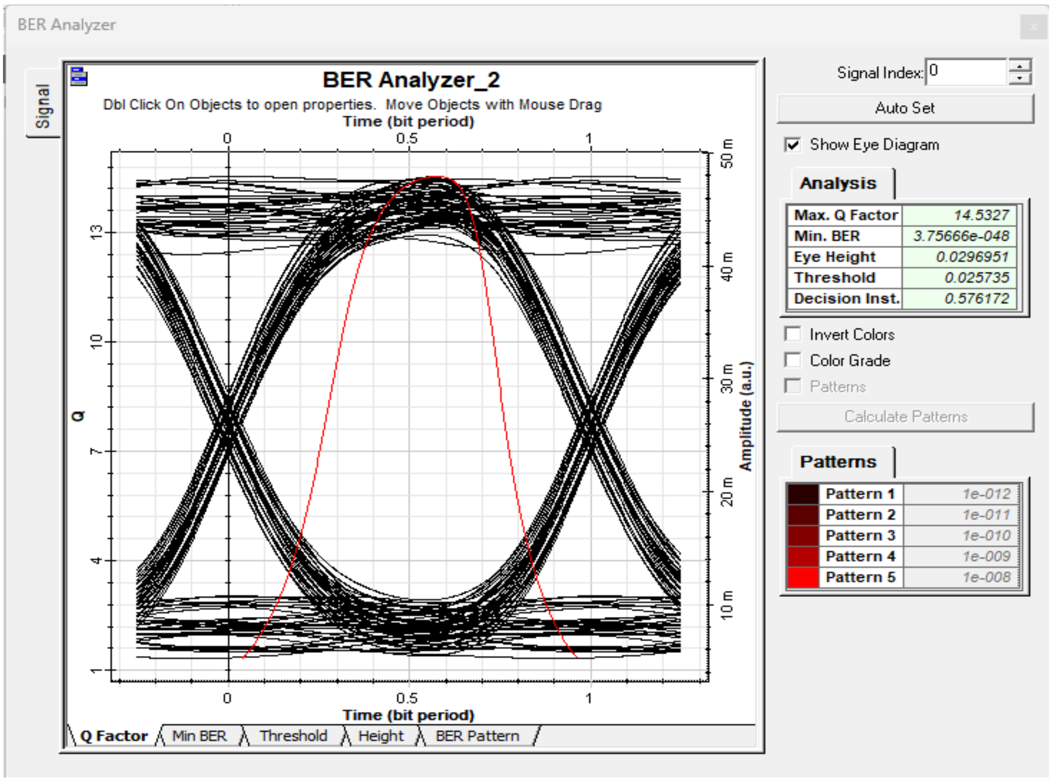
Max. Q Factor	14.5968
Min. BER	1.47198e-048
Eye Height	0.0297119
Threshold	0.0265233
Decision Inst.	0.617188

☐ Invert Colors
☐ Color Grade
☐ Patterns

Patterns

■	Pattern 1	1e-012
■	Pattern 2	1e-011
■	Pattern 3	1e-010
■	Pattern 4	1e-009
■	Pattern 5	1e-008

Fig. 10. Q Factor and BER values of ONU 3



Signal Index: 0

☑ Show Eye Diagram

Analysis

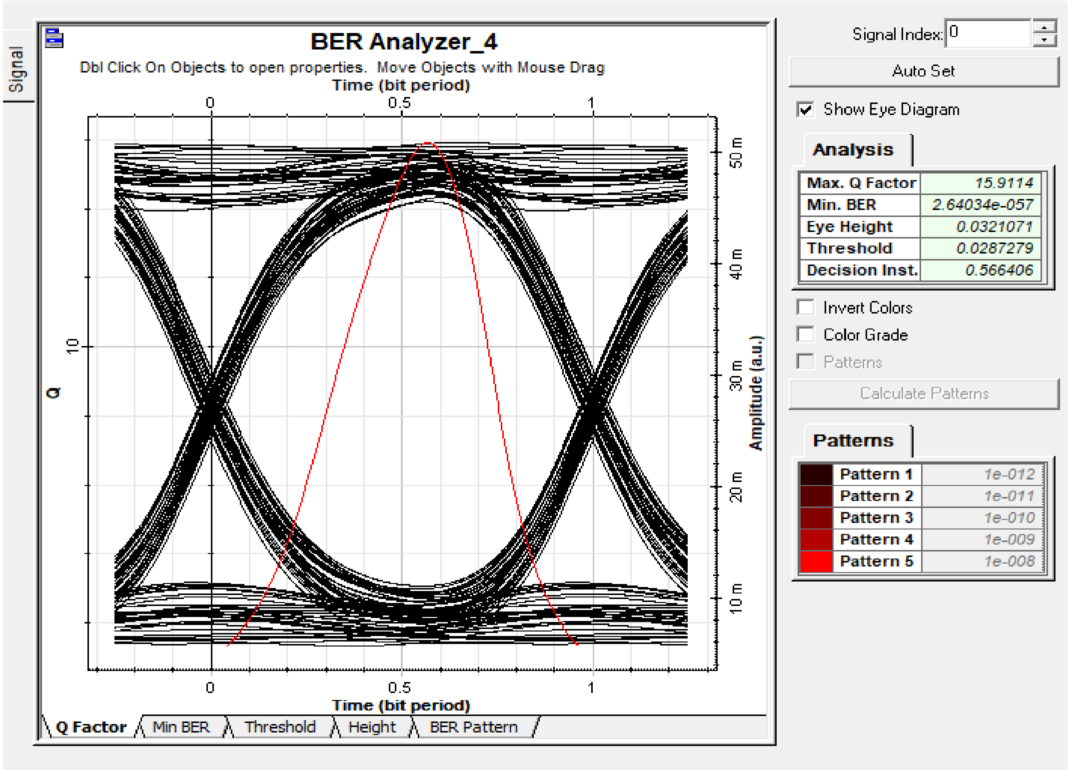
Max. Q Factor	14.5327
Min. BER	3.75666e-048
Eye Height	0.0296951
Threshold	0.025735
Decision Inst.	0.576172

☐ Invert Colors
☐ Color Grade
☐ Patterns

Patterns

■	Pattern 1	1e-012
■	Pattern 2	1e-011
■	Pattern 3	1e-010
■	Pattern 4	1e-009
■	Pattern 5	1e-008

Fig. 11. Q Factor and BER values of ONU 4



Dbl Click On Objects to open properties. Move Objects with Mouse Drag

Signal Index: 0

☑ Show Eye Diagram

Max. Q Factor	15.9114
Min. BER	2.64034e-057
Eye Height	0.0321071
Threshold	0.0287279
Decision Inst.	0.566406

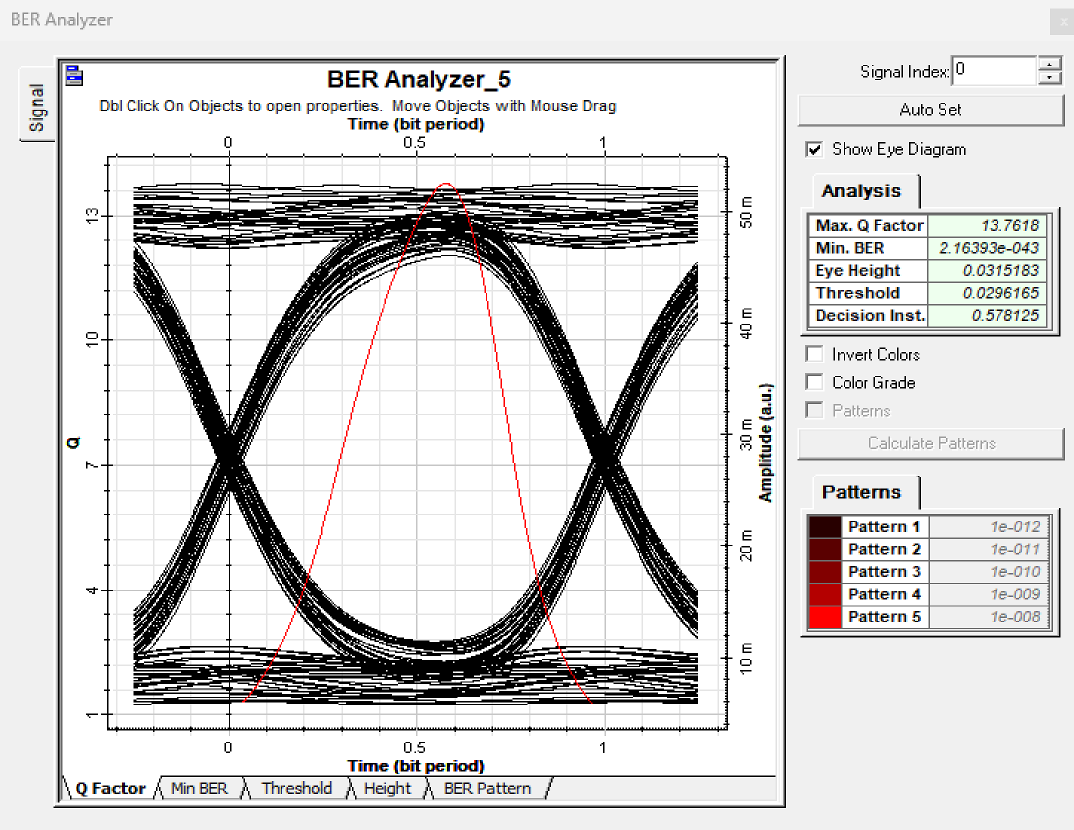
☐ Invert Colors

☐ Color Grade

☐ Patterns

■	Pattern 1	1e-012
■	Pattern 2	1e-011
■	Pattern 3	1e-010
■	Pattern 4	1e-009
🟥	Pattern 5	1e-008

Fig. 12. Q Factor and BER values of ONU 5



Dbl Click On Objects to open properties. Move Objects with Mouse Drag

Signal Index: 0

☑ Show Eye Diagram

Max. Q Factor	13.7618
Min. BER	2.16393e-043
Eye Height	0.0315183
Threshold	0.0296165
Decision Inst.	0.578125

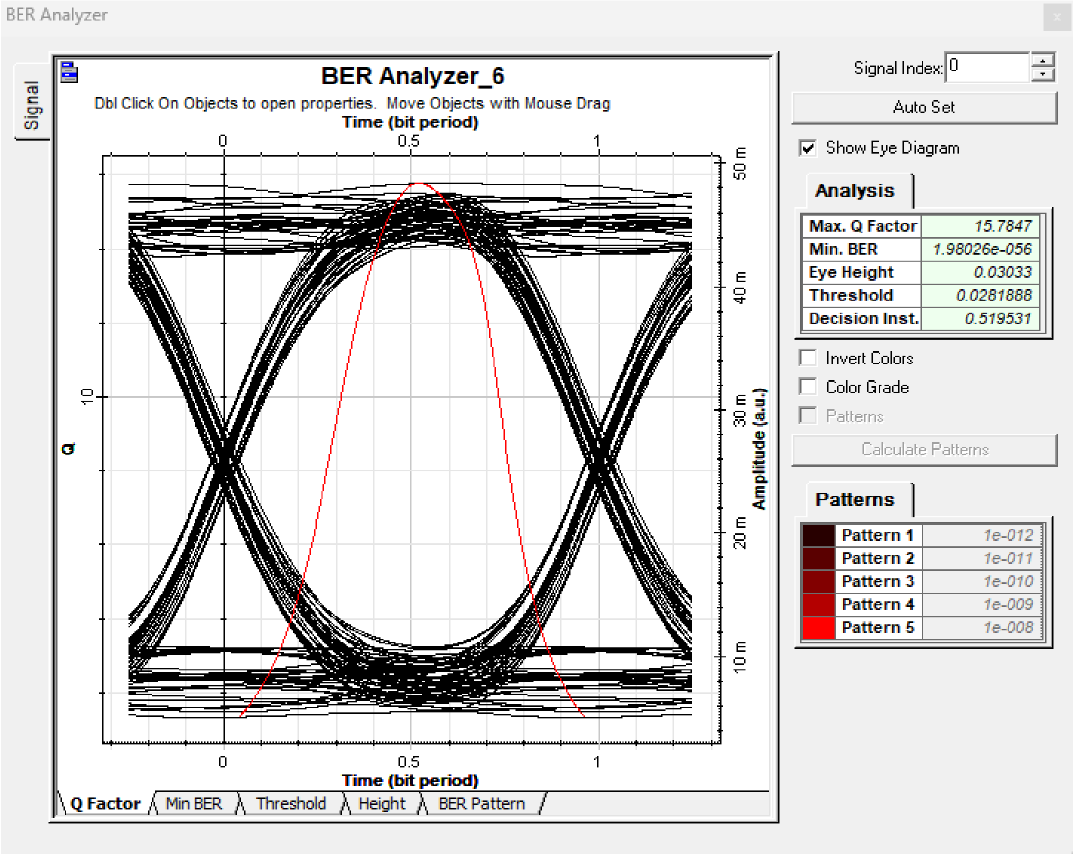
☐ Invert Colors

☐ Color Grade

☐ Patterns

■	Pattern 1	1e-012
■	Pattern 2	1e-011
■	Pattern 3	1e-010
■	Pattern 4	1e-009
🟥	Pattern 5	1e-008

Fig. 13. Q Factor and BER values of ONU 6



Signal Index: 0

☑ Show Eye Diagram

Analysis

Max. Q Factor	15.7847
Min. BER	1.98026e-056
Eye Height	0.03033
Threshold	0.0281888
Decision Inst.	0.519531

☐ Invert Colors

☐ Color Grade

☐ Patterns

Patterns

🟥	Pattern 1	1e-012
🟥	Pattern 2	1e-011
🟥	Pattern 3	1e-010
🟥	Pattern 4	1e-009
🟥	Pattern 5	1e-008

Fig. 14. Q Factor and BER values of ONU 7

Table 5. Q Factor and BER of various ONUs connected to the Splitter

ONU	Q Factor	BER
ONU 1	17.4766	1.07402e-068
ONU 2	11.7262	4.67365e-032
ONU 3	14.5968	1.47198e-048
ONU 4	14.5327	3.75666e-048
ONU 5	15.9114	2.64034e-057
ONU 6	13.7618	2.16393e-043
ONU 7	15.7847	1.98026e-056
ONU 8	13.0864	1.96967e-039
ONU 9	15.1964	1.86597e-052
ONU 10	12.4792	4.84518e-036
ONU 11	13.0684	2.48872e-039
ONU 12	14.7274	2.14574e-049
ONU 13	12.0405	1.08801e-033
ONU 14	10.4365	8.44328e-026
ONU 15	10.1057	2.60334e-024
ONU 16	9.83807	1.75755e-113
ONU 17	7.22618	2.48339e-013
ONU 18	29.202	9.02615e-188
ONU 19	8.01223	5.63197e-016
ONU 20	6.22729	2.36523e-010
Average	13.3	1.18e-11

The Q Factor and BER Values obtained are used to validate the POLAN design. The Q-Factor (Quality Factor) is a key performance metric in optical communication systems. It provides an indication of the quality of the signal received and is related to the Bit Error Rate (BER). A higher Q-Factor indicates better signal quality and lower BER. Q-Factor of 13.3 and an average Bit Error Rate (BER) of 1.18×10-11 together provide a detailed picture of the signal quality and reliability in an optical communication system. A Q-Factor of 13.3 ensures that the signal levels are well separated and the noise levels are minimal. This leads to very high signal integrity, meaning the system can accurately distinguish between binary 1s and 0s with an average BER of 1.18×10-11.

For every 1011 bits transmitted, only approximately one bit might be in error, which is negligible for most practical applications. the system is highly reliable.

5. CONCLUSION

In conclusion, the design of Passive Optical Local Area Networks (POLANs) presents a complex optimization problem, particularly regarding the placement of optical splitters to minimize network costs while meeting performance requirements. This study proposed the use of Dijkstra's algorithm, coupled with the Google Maps API, to determine the optimal splitter locations based on the shortest path between Optical Line Terminals (OLTs) and Optical Network Terminals (ONTs). By treating the ONTs as nodes in a graph and calculating the walking distance between them, the algorithm can identify potential splitter locations that minimize total network costs. The results demonstrate that this approach can effectively determine the optimal splitter locations, with the shortest path from the OLT to each ONT guiding the placement decision. The simulation of the entire PON network, followed by the measurement of BER and Q-Factor for each Optical Network Unit (ONU), provides a comprehensive assessment of network performance in realistic settings.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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