Optimum placement of optical amplifiers in a multi-wavelength hybrid network topology

SIMRANJIT SINGH[a], GAURAVPREET SINGH[*,a], GURPREET KAUR[a], RAMANDEEP KAUR[a], RAJINDER SINGH KALER[b]
[a]*Department of Electronics and Communication Engineering, Punjabi University, Patiala, India*
[b]*Department of Electronics and Communication Engineering, Thapar University, Patiala, India*

The present day widely used optical amplifiers, in spite of its numerous merits, are exorbitant to use and require maintenance, thus making network designers to recrudesce techniques to minimize the number of amplifiers for cost effective solution. In this paper, the count of the amplifiers has been reduced in proposed hybrid network topology by optimize its placement and further observed the acceptable performance. Last as soon as possible scheme has been employed for amplifiers gain splitting and its placement.

(Received December 15, 2014; accepted June 24, 2015)

Keywords: Amplifier placement, Hybrid network topology, Optical amplifiers, Wavelength Division Multiplexing

1. Introduction

The great demand in communication services make wavelength division multiplexing (WDM) network one of the preferred techniques to further upgrade architectures of present day and to support very high bandwidth service. The optical amplifier (OA) has made WDM very viable technology by means of increasing transmission distance and bit error rate in optical links. There are various types of optical amplifiers, but the most widespread-used ones are the erbium-doped fiber amplifiers (EDFA), it play a key role as power boosters, optical repeaters and preamplifiers in long distance optical fiber communications systems. ONU (Optical network Unit), it is a device that transforms incoming optical signals into electronics at a customer's premises in order to provide telecommunications services over an optical fiber network. Despite their advantages, they are very expensive devices and require maintenance [1-6]. These reasons make network designers to recrudesce techniques to minimize the number of amplifiers. Consequently many algorithms are proposed to find an optimal solution for this problem but global optimum method is the efficient solution to get the best solution of this problem by adding more noise parameters like fiber dispersion and noise margin of network. Following expression is used to understand the amplifier model as shown in [7].

$$\frac{p_{in}}{p_s} = \frac{1}{(G-1)} \ln\left(\frac{G_0}{G}\right)$$

where *Pin* is the total input signal power to the amplifier, P_s is internal saturation power, G_0 the small signal gain and G is gain, as also described in [8]. If G_m is the maximum small signal gain and P_m is the maximum output power an amplifier can supply.

$$G_o \leq G_m$$
$$GP_{in} \leq P_m$$

Optical amplifier placement can be optimize in optical networks by using different techniques. Ashraf *et al.* [8] introduced the optimal and heuristic solutions for the network provisioning problem by using mesh network topology for multicasting service. In this work, three schemes are used from which adaptive scheme outperforms in terms of number of OAs. Mercado *et al*. [9] compared various amplifier placement algorithms, like as soon as possible (ASAP), as late as possible (ALAP), late as soon as possible (LASAP) and distributed as soon as possible (DASAP), from which DASAP provides best results with better SNR. Singh *et al.* [10] proposed novel flat-gain OA using a hybrid configuration with an EYDWA and a SOA for 100 × 10-Gbps DWDM system at 0.2 nm interval. With an EYDWA-SOA hybrid amplifier, a flat gain of >14 dB is obtained across the effective bandwidth with a gain variation of the order of 0.75 dB without using any gain clamping techniques. Unfortunately, this work is limited to point-to-point system only. Randhawa *et al.* [11] resolved the designing issues in hybrid optical or wireless networks. In this investigation the objective was to minimize the network's deployment costs, while taking care of traffic or links capacity for different hybrid topologies like - ring, star, bus and mesh topologies. The various aspects of optical amplifiers are also discussed in [12-14]

Unfortunately, in these investigation the optical placements have been done in single type of topology only, as the currents network is a combination of various topologies. Moreover, the investigated topologies are limited to the number of users and wavelengths which disregards the bandwidth of optical fiber. In this paper, we extended the previous work by optimizing amplifier placement considering more noises with increased capacity and span distance. Hybrid network topologies viz. bus, ring and mesh are used with a point to multipoint network. The optimum solution of amplifier placement is calculated by using Global optimum method [5, 6] and constraints are found by MILP (Mixed integer linear program), the amplifiers are placed with LASAP scheme. This paper is organized into five sections. In Section 2 and Section 3, the problem formulation and system setup with solution approach is described. In section 4, results have been reported of the different end nodes and finally in Section 5 the conclusions are made.

2. Problem statement

Our objective is to find the minimum number of amplifiers required to operate the network and to find their exact placements. In general, when signals on different wavelengths originating from different transmitters arrive at an amplifier, their power levels could be very different. Due to the difference in power levels, the higher-powered wavelengths could saturate the amplifier and limit the gain seen by the lower-powered wavelengths. Moreover, allowing wavelengths in the same fiber to be at different power levels results in a mixed-integer nonlinear program [15] for the optimal amplifier placement problem, and it cannot be solved exactly. These problems can be bypassed by restricting all of the wavelengths at any given point in a fiber to be at the same power level.

We used certain steps to minimize the number of optical amplifiers, those are explained as : 1) To determine whether or not it is possible to design the network taking by consideration the limitations of the devices (e.g., the power budget of the amplifiers), 2) then generate a *linear* set of constraints to describe the problem settings, 3) use a MILP solver to determine the minimum number of amplifiers needed on our network, and 4) determine the exact placements of the amplifier in the network by using LASAP.

3. Sample network

The network consists broadcast type X stations and Y optical nodes. Transmissions of a station are received by every other station, which experiences losses as the signal passes through the fiber or network components. Each transmitted signal has to be received at receivers end at the power level greater than the sensitivity level, denoted by P_s. Attenuation on fiber is given by the parameter "α". The used parameters are described in Table 1. As shown in Fig. 1, the aggregate link 11-12 or 15-16 uses bus topology and nodes 1, 2, 3 and 4 use star topology separately and as a ring together.

Table 1. Considered parameters.

Parameter	Description	Value & Units Used
p_s	Minimum signal power at receiver or the amplifier sensitivity level	-30 dBm
G_m	Maximum small signal gain	20 dB
P_m	Maximum output power of amplifier and transmitter	0 dBm
α	Fiber attenuation	0.2 dB / km
P_s	Internal saturation power of amplifier	1.55 dBm
P_{max}	Maximum total output power in fiber	10dBm
D_p	Dispersion penalty	0.5dB/20km
M	Link loss Margin	3dB
L_l	Length of link *l*	Km
Gs_l	Total gain required on link *l*	dB
X	Number of stations or wavelengths in the network	-
Y	Number of stars in the network	-
L	Number of links in the network	-
A	Number of amplifiers in the network	-
λ_l	Number of wavelengths	-
n_l	Number of amplifiers on link *l*	-
D_a	Degree of star *a*	-
P_a	Output power of star *a* on each wavelength	-
Q	Number or nodes on the network	-

A. Solution Approach

Our solution approach consists of four steps -

- STEP 1 - Test the viability of the network.
- STEP 2 - Formulate the constraints
- STEP 3 - Solve the mixed integer linear program
- STEP 4 - Placement of amplifiers

- *Test the viability of Network*

First we need to check that whether our network have viable amplifier placement. To test the viability we require to send the signal from all transmitters and then to check that whether all the receiver are getting the signal having power level more than receiver sensitivity level. The feasibility has been checked as follows:

For each star in the network $1 \leq a \leq$ Q and for each input link *j* into the star *i*,

$$P_m + P_s \geq 10 \log_{10} (D_a - 1) + 10 \log_{10} (|\lambda_b|)$$

Then the network has viable amplifier placement else it is not viable

- *Formulate the constraints*

To calculate the linear constraints on various links or paths, it is required to determine the value of wavelength, fiber length, added noises, dispersion etc.

1. LINKS BETWEEN NODES

Here, two nodes *a* and *b* are connected to each other by using link *l*.

$$P_a - \alpha.L_1 - 10 \log_{10} (D_b -1) - D_p - M + Gs_l = P_b \quad (2)$$

$$G_m + Gs_l \leq 0 \quad (3)$$

$$G_m + Gs_l \geq - G_m (n_l) \quad (4)$$

Where $(D_b -1)$ is splitting loss at the node and G_m is based on the total input power via all wavelengths and total saturation power of an amplifier. G_m can be at its maximum when the input are at their lowest level i.e. p_s and the number of wavelength on that link i.e. λ_l so G_m for node to node is;

$$G_m = - p_s + 10 \log_{10} (|\lambda_l|) \quad (5)$$

2. LINK FROM STATION (ONU) TO NODE

Now a link *l* is used to connect any station *k* with node *b* and available gain on the transmitter on link *l* is given as;

$$P_m - \alpha.L_1 - 10 \log_{10} (D_a-1) - D_p - M + n_l (G_m) \geq p_b \quad (6)$$

Here, as we know that from ONU to node, a different frequency is used for every ONU then here only one frequency is used so by putting $\lambda_l = 1$ in (5) max gain available will be equal to the min received power i.e p_s then G_m will be shown as:

$$G_m = p_s \quad (7)$$

3. LINK FROM NODE TO STATION (ONU)

Link *l* is used to connect a node *a* to station *k*, we require that the necessary power on station for each wavelength will be at least equal to or greater than sensitivity level p_s

$$p_i - \alpha.L_1 + p_s - D_p - M + n_i (G_m) \geq p_s \quad (8)$$

Now here all the wavelengths from all the ONU of the network are receiving at a particular ONU so here we will consider the wavelengths from the whole network's stations i.e. N, so the max gain is as follows:

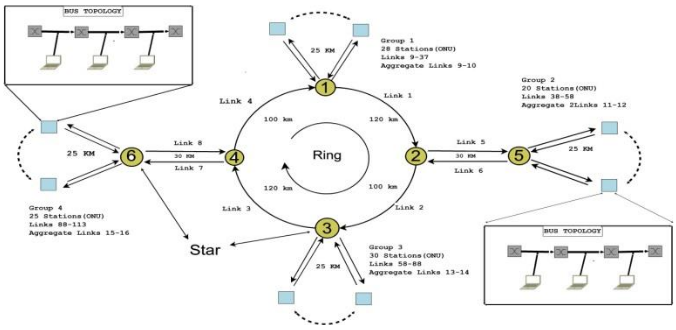


Fig. 1. Passive Hybrid topology based optical metropolitan area network.

$$G_m = p_s + 10 \log_{10} (N-1) \quad (9)$$

4. *NODE CONSTRAINTS*

For any node a, $1 \leq a \leq Q$, the necessary power on station for each wavelength should be at least equal to or greater than sensitivity level p_s,

$$P_a \geq p_s \quad (10)$$

To solve our formulation is its necessary that, for any star *a* via link *l* into star *b*, we ensure that the necessary output power p_j is acceptable

$$P_m - 10\log_{10} (D_b-1) - 10 \log_{10} (|\lambda_l|) \geq P_b \quad (11)$$

5. *MILP FORMULATION*

For any link *l*, n_l is a integer and to minimizing the number of amplifier is target function of our formulation which is as follows:

$$\text{Minimize } A = \textstyle\sum_{l}. n_l \quad (12)$$

- *Solve the Mixed-Integer Linear Program (MILP)*

Now the variable we formulate in the previous section can be fed into MILP solver *i.e.* mixed integer linear program, because the constraint or the value we found constraints (1- 12) are linear, we can write them as matrix equality of form $Ax \leq B$. These MILP solvers used branch and bound strategies to handle constraints.

- *Place the Amplifiers*

Three methods can be used to place the amplifiers on the link and split the gain between them, as follows:

1. *ASAP* - In this, as proposed in [5] link *l* was traversed and down-streamed then place first $n_l - 1$ amplifiers to provide the maximum gain with respect to constraint of the amplifier's output. Last amplifier is used to get the remaining link, so we will not let the power level go down to its least value.
2. *ALAP* - In this, as proposed in [5] method amplifier would by placed only when the power level becomes less than p_s else we will not place the amplifier.

3. *LASAP* – In this method, the *N*-1 first amplifiers are placed in the same way as in the ALAP scheme, but the last one is placed as soon as it is possible for it to give the remaining gain [8]. The best noise performance is obtained when LASAP method is used as compared to ALAP and ASAP, it provides around 26.8% better noise performance as compared to ALAP. So, for this investigation we have used LASAP scheme for amplifier placement.

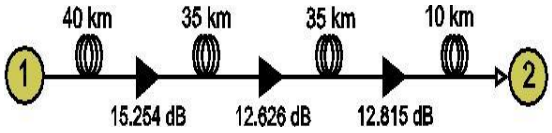


Fig. 2. Placement of amplifiers at link 1.

4. Result and discussion

Consider the sample network shown in Fig. 1. The network has N=103 stations and M=6 passive nodes. After the formulation of all constraints in MILP, number of amplifiers are n=17, maximum gain and per wavelength power is also acquired. The black triangles shown in Fig. 2 are the amplifiers located at its optimum place. The optimum placement of amplifiers have been done to get the desired or acceptable results. The gain and distance of each amplifier is shown in Table 2. For more clarity placement of amplifiers on link 1 between nodes 1 and 2 is shown in Fig. 2 with exact placement of OAs.

To validate the results from the proposed hybrid network the simulation is also done by the mean to evaluate the performance in the term of BER, received power etc. After the placement of amplifiers and to understand the performance of the network, the graph between BER and input power is plotted, as shown in Fig. 5(a) for aggregate links 9 and 13, the bit error rate is low which indicates the best performance. It is also observed that when power increases from -5 dBm to 1 dBm, the bit error rate increases continuously from 10^{-22} at group 1 user and it is maximum at group 3 user when power increase from -3 to -2.5 upto 10^{-9} which is also an acceptable value for optical transmission and Fig. 5 (b) shows the eye diagram of a user at particular aggregate link.

Table 2. Location and gain of amplifiers.

Link Number	Number of Links	Amplifier	Gain of Amplifier's	Distance
1 NODE 1 to NODE 2 120 KM	1	1	15.254 dB	40 km
		2	12.626 dB	75 km
		3	12.815 dB	110 km
2 NODE 2 TO NODE 3 100 KM	1	4	19.421 dB	30 km
		5	14.575 dB	75 km
3 NODE 3 TO NODE 4 120 KM	1	6	12.194 dB	40 km
		7	9.626 dB	75 km
		8	9.815 dB	110 km
4 NODE 4 TO NODE 1 100 KM	1	9	15.828 dB	30 km
		10	11.9765 dB	65 km
		11	12.1655dB	85 km
5 NODE 2 TO NODE 5 30 KM	1	12	15.528 dB	-
6 NODE 5 TO NODE 2 30 KM	1	13	12.4922 dB	-
		14	7.5 dB	22
7 NODE 4 TO NODE 6 30 KM	1	15	14.522 dB	-
		16	10.448 dB	18 km
8 NODE 6 TO NODE 4 30 KM	1	17	11.0102 dB	-

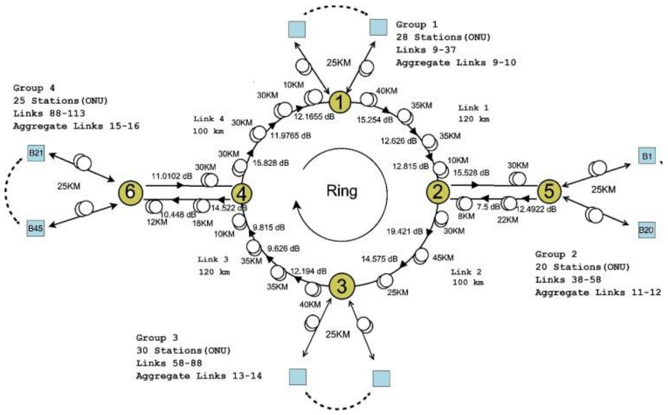


Fig. 3. Amplifier placement in network by using LASAP.

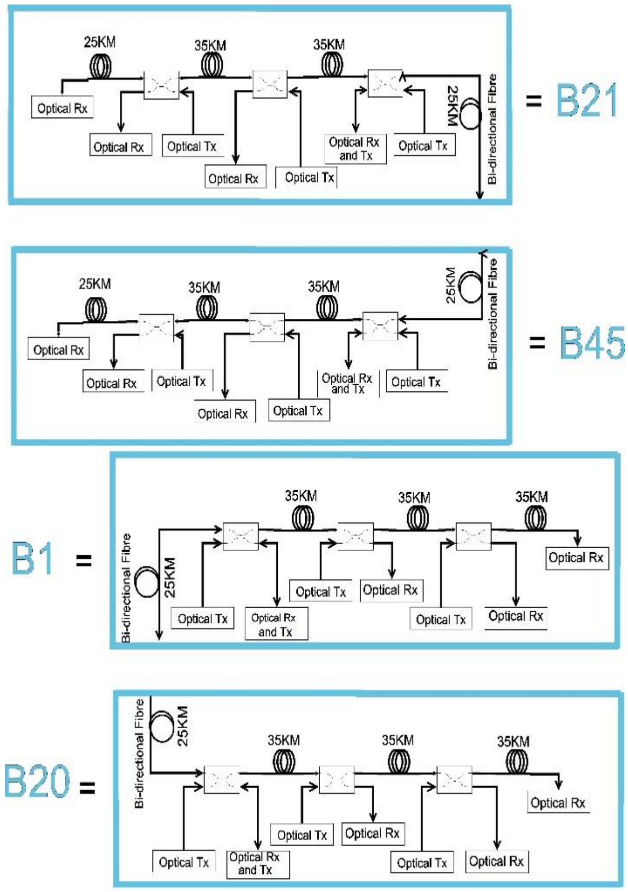
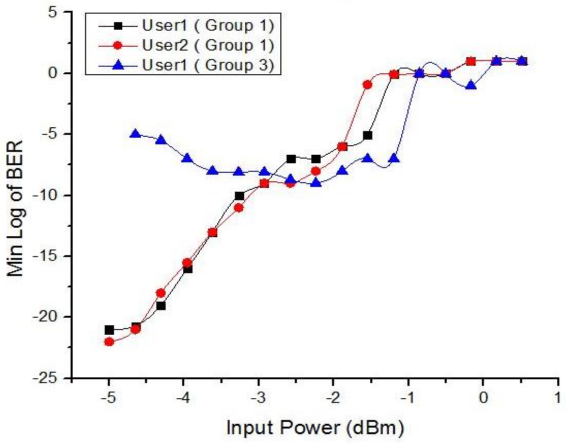
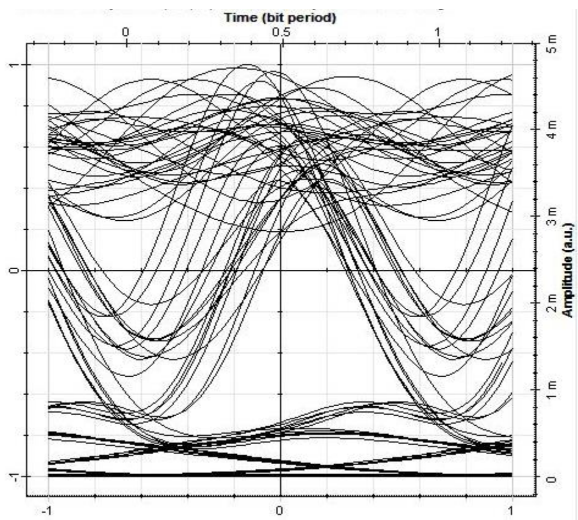


Fig. 4. Diagram of bus topology used at nodes B1, B20, B21 and B45.



(a)

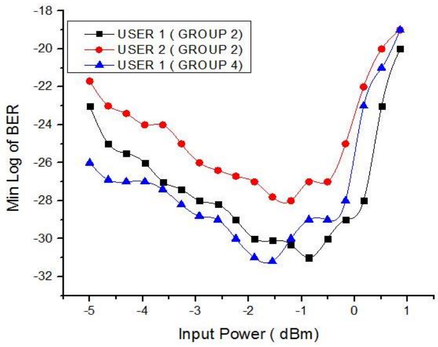


(b)

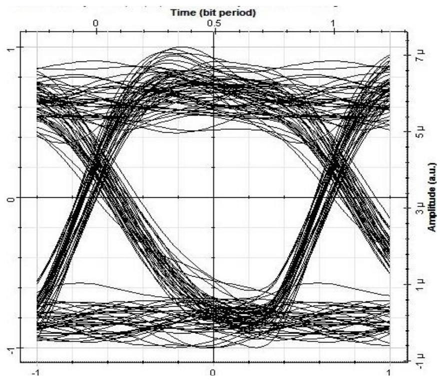
Fig. 5. (a) Input power vs. bit error rate for link 9 and 13, (b) Eye diagram at the link 12.

Fig. 6(a) show the graph between bit error rate and input power for aggregate links 11 and 15. In this figure, better results can be seen because these links are limited in distance. When the power increases from -5 dBm to 1 dBm, it decreases the bit error rate up to 10^{-31} which is a quite sufficient for optical transmission and Fig. 6(b) shows the eye diagram from a particular user under these aggregate links

Now Fig. 7(a) and Fig. 7(b) shows the eye diagram of received signal at the bus topology from the Fig. 3, the received signal degraded as the transmission is done from one receiver to another, opening of eye is decreases as the number of nodes or number of user increases.

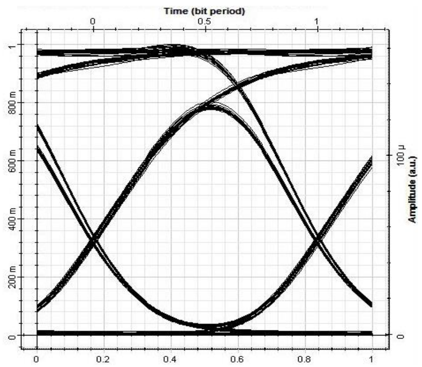


(a)

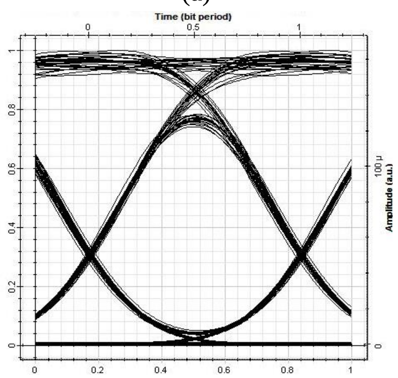


(b)

Fig. 6. (a) Input power vs. bit error rate graph for link 11-12 and 15-16, (b) Eye diagram of received signal from a particular ONU at the link.



(a)



(b)

Fig. 7. (a) Eye diagram of user at node B1, (b) Eye diagram of user at node B2.

Fig. 8 shows the change in output power as per the change in input power. Users in group 2 and group 4 have sufficient output power as compare to the users at group 1 and group 3. When input power increases from -10 to 5 dBm the received power slightly decreases for users at group 3 and 4.

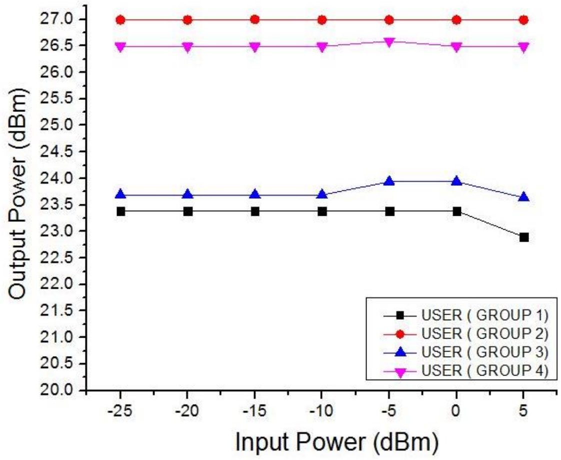


Fig. 8. Input power vs. output power for users at different groups.

5. Conclusion

The problem of optical amplifier placement and to minimize the amplifier's count in network has been examined. The placement scheme used is LASAP. After examining the network performance on various aspects with added noises resulted in a bit rate of up to 10^{-31} and the maximum transmission distance observed is 200 km. OCDMA and OTDMA techniques are planned to be worked upon in future, subsuming more noise and increasing transmission distance with more network topologies.

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*Corresponding author: gauravpreetsingh@hotmail.com