Placements of Hybrid/conventional optical amplifiers in a multi-wavelength dense metropolitan area network

SIMRANJIT SINGH*, R. S. KALER[a]
Department of Electronics and Communication Engineering, Punjabi University, Patiala, India
[a]*Department of Electronics and Communication Engineering, Thapar University, Patiala, India*

In this paper, we introduce optimal and heuristic solutions for the scaled-up and denser version of sample metropolitan area network (MAN). The solution is based on placing hybrid optical amplifiers for high capacity dense wavelength division multiplexed (DWDM) links and by placing conventional optical amplifiers over local links with the goal of minimizing the total number of optical amplifiers needed in the network, hence reducing its cost. The optimal solution is formulated as a mixed integer linear program and genetic algorithm. It is observed that, using the optimized low cost hybrid Raman- erbium doped fiber amplifier (EDFA), the numbers of conventional optical amplifiers are reduced over back-bone high capacity link.

(Received November 30, 2013; accepted July 10, 2014)

Keywords: Metropolitan area network, Conventional optical amplifiers, Hybrid optical amplifiers, Mixed integer linear program, Genetic algorithm

1. Introduction

The continuous increase on the demand of telecommunication services makes Dense Wavelength Division Multiplexing (DWDM) networks to be one of the preferred techniques to upgrade present architectures and to support high-bandwidth services [1]. The development of optical amplifiers has made DWDM a feasible technology by means of increasing transmission distances in optical networks. There are several types of optical amplifiers, but the most widespread-used ones are the Erbium-Doped Fiber Amplifiers (EDFAs). Despite their advantages, such as high gain, high bandwidth and low noise figure, EDFAs have some disadvantages. They are very expensive devices and need maintenance [2]. These reasons make network designers to develop techniques to minimize the number of amplifiers needed into the network. Several algorithms have been proposed to find an optimal solution to this problem [3-6]. On the other hand, hybrid optical amplifiers (HOAs) are an enabling and promising technology for future DWDM multiterabit systems. The HOAs are designed in order to maximize the span length, to minimize the impairments due to fiber nonlinearities, and to enhance the capacity of optical communication system [7, 8]. Also in [9] Hasan et al. reported that the EDFA-Raman HOA is the cheapest alternative for broadband amplification.

Recently, we have investigated the various HOAs for DWDM system at reduced channel spacing and high bit rate [10-12]. It was observed that the Raman-EDFA HOA is the best combination to achieve improved results. To take the advantage of Raman-EDFA further, various techniques have been addressed to achieve better gain flatness without using any costly components [13, 14]. Unfortunately, in our previous work or in literature, the hybrid optical amplifiers are investigated in point-to-point optical system. As today's technology is shifted towards multipoint network it is beneficial to take the advantage of HOAs by placing it into the networks. The original contribution of this paper is to propose the cost effective, denser and up-scaled network including the optimized hybrid and conventional optical amplifiers.

In this paper, we have extended the previous work by design the MAN network with the help of hybrid and conventional optical amplifiers for low cost solution. However, the HOAs are used to amplify the back-bone (large DWDM signals or star-to-star link) link, on the other hand, conventional optical amplifier are used to amplify the local network signals (between 10 to 20 Km). The proposed network shows improved/ cost-effective performance over other algorithms by reducing number of amplifier into network.

After introduction and defining the problem in Section 1 and 2, the solution approach is described in Section 3. Further the techniques used to place the conventional and HOAs are presented in Section 4. After taking the numerical example of MAN (see Section 5) the conclusions are made in Section 6.

2. Problem definition

In general, when signals on different wavelengths originating from different transmitters arrive at an amplifier, their power levels could be very different. This phenomenon is known as the near–far effect and it may result in inefficient utilization of an individual amplifier. 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. The near-far effect is mostly present between two passive stars connection (back bone connection) as many wavelengths from local stations are combining or splitting by these passive stars. In literature, various researches are evident that the hybrid optical amplifiers are the good alternative to achieve better gain flatness with minimum power variation among the effective wavelengths. Also the HOA is the best for broadband amplification as the conventional optical amplifiers (such as EDFA, SOA etc) are restricted to the wavelength band. Our goal is to find the minimum number of amplifiers required to operate the network and to determine their exact placements.

Our paper presents such methods to minimize the number of optical amplifiers over local links and backbone connections using mixed integer linear program (MILP) and optimized HOAs, respectively. The method works as follows (as also shown in Fig. 1): 1) determine whether or not it is possible to design the network taking into consideration the limitations of the devices (e.g., the power budget of the amplifiers, acceptable receiver sensitivity etc), 2) Optimize the HOA for corresponding transmission distances for broadband amplification with less variation of power. 3) generate a *linear* set of constraints to describe the problem setting for local links, 4) use a MILP solver to determine the global minimum number of amplifiers needed across the network, and 5) determine the exact placements of the amplifiers.

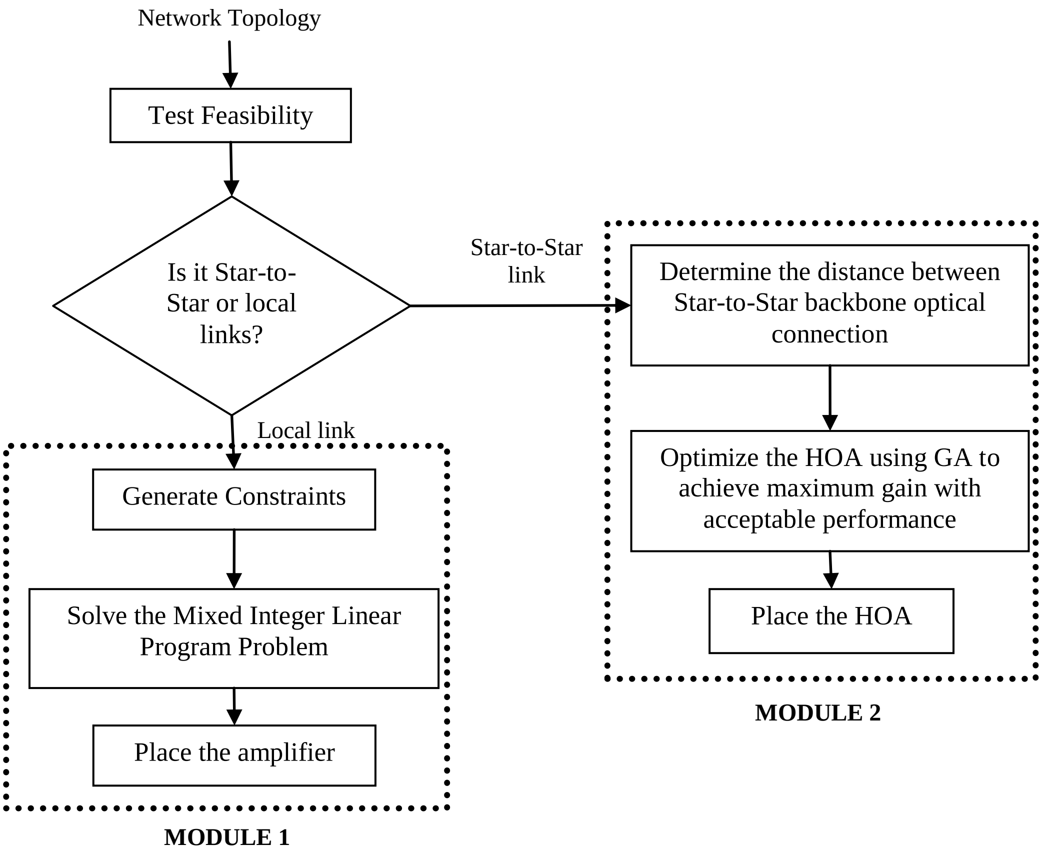

Fig. 1. Flow diagram of proposed algorithms for optimal placement of optical amplifiers.

3. Solution approach

The solution approach is divided into two modules after checking feasibility of network. *Module 1* corresponds to optimize the placement of conventional optical amplifiers for local connection (< 20 Km). On the other hand under *Module 2* the HOA is optimized for star-to-star link broadband amplification with less variation of power.

Testing of Feasibility of the Network:

We first determine whether the given network has a feasible amplifier placement. The feasibility test requires that all of the signals from all of the transmitters should be able to reach all of the destinations at a sufficiently high power level for detection. The attenuation loss (due to splitter, combiner, splicer, fiber etc.) suffered by the signals on any link can be compensated by using an adequate number of optical amplifiers. In this investigation the passive stars hubs have been used to combine or split the signals without any internal amplification. We only need to ensure that the power level of each input signal on every input link to a star is high enough to guarantee that the signal exits the star on every output link at a power level of at least P_{min}, as also reported in [3]. The test for feasibility can thus be written as follows:

$$P_{max} – 10 \log_{10} (S_i - 1) - 10 \log_{10} (|\lambda_n|) - 10 \log_{10} (S_p) \geq P_{min} \quad (1)$$

The description of various notations of parameters is described in Table 1. Means if the equation (1) for each star *i* in the network and for each input link *j* into the star *i* is achieved then the network has a feasible amplifier placement else the network is infeasible.

Selection of link type

In this step, the two types of links are treated individually. The placement of optical amplifier in local links, which connects the users to the star, is done by using MILP approach. On the other hand the optimization of hybrid optical amplifier for back-bone link, which connects the two stars placed at long distance, is done by using genetic algorithm (GA).

A. Generate the Constraints

(i)Computation of gmax (star to star)

The available gain at an amplifier is a function of the total input power aggregated across all wavelengths (P_{Total}), the maximum small-signal gain of the amplifier (G_{max}) and the total internal saturation power of the amplifier (P_{sat}). For any link *n*:

$$gmax_n = G(P_{Total}, G_{max}, P_{sat} \quad (2)$$

The various amplifier gain models can be used to obtain this function G. In this study, the amplifier EDFA gain modal has been taken from [3] for the case of local links**.** On the other hand the Raman-EDFA HOA gain has been calculated from equation A. 12 (see Appendix I) for the case of back-bone link.

For any back-bone link which connects star to star, there are $|\lambda_n|$ wavelengths in the link and hence the minimum total power across all these wavelengths is given by:

$$P_{Total} = P_{min} + 10 \log_{10} (|\lambda_n|) \quad (3)$$

From (2)

$$gmax_n = G(P_{min} + 10 \log_{10} (|\lambda_n|), G_{max}, P_{sat}) \quad (4)$$

(ii) Link Constraints (form station to star or star to station)

For any link *n* from any station *x* to the star *y* we can bound the power p_y by following expression:

$$P_{max} – \alpha \cdot L_l - 10 \log_{10} (S_y - 1) + gmax_n \cdot A_l \geq p_y \quad (5)$$

For any link *n* from star *y* to the station *p* we require that the received power at a station on each wavelength be at least the sensitivity level, i.e.

$$P_y - \alpha \cdot L_l + gmax_p \cdot A_l \geq p_{min} \quad (6)$$

Under the star constraint for each incoming link *n* into star *y*, we ensure that the required output power p_y is feasible, i.e.

$$P_{max} - 10 \log_{10} (S_y - 1) - 10 \log_{10} (|\lambda_n|) \geq p_y \quad (7)$$

Table 1. Description of used parameters.

Notation	Description
P_{max}	maximum power available from an amplifier in dBm
S_i	Number of output splitter ports
$\|\lambda_n\|$	Number of wavelengths carried by link *n*
S_p	Splicer loss
P_{min}	Minimum power required on a wavelength for detection in dBm.
$gmax_n$	Maximum per-wavelength gain that can be offered by an amplifier on link *n*.
G_{max}	Maximum small-signal gain of the amplifier
P_{Total}	Total input power aggregated across all wavelengths
P_{sat}	Total internal saturation power of the amplifier
P_n	Output power of star n on each wavelength.
Α	signal attenuation in dB/km.
L_l	Transmission distance
A_l	Number of amplifiers placed in the link
A	Total number of conventional amplifiers used in the network
B	Total number of HOAs used in the network
N	Total number of stations/ users
M	Total number of passive star

(iii) Star-to-Star Constraint

Under the star constraint for each incoming link *n* into star *y*, we ensure that the required output power p_y is feasible, i.e.

$$P_{max} - 10 \log_{10} (S_y - 1) - 10 \log_{10} (|\lambda_n|) \geq p_y \quad (7)$$

First the transmission distance has to be estimated then by multi-parameter optimization using global optimization technique (Genetic Algorithm) has been done to achieve large gain with less power variation. The implementation of GA is described in Appendix II.

(iv) Objective Function

Our objective is to minimize total number of amplifier

$$(A) = \sum_n A_n \quad (8)$$

Where number of amplifiers and per wavelength output power is variable.

4. Placement of conventional and HOAs

(i) Case 1: Placement of Conventional Optical Amplifier in Local Links (station-to-star or star-to-station)

The constraints (1)–(7) are found to be linear can be fed to a MILP solver (linear program solver version 1.11 has been used) to obtain the optimum values of the p_n's and A_n's. These MILP solvers typically employ branch-and-bound strategies [15] to handle the integrality constraints, thereby significantly cutting down the exponential search space. For the placement of conventional optical amplifier in local link we have used As-Soon-As-Possible algorithm, as explained in [5]. This method helps in reducing the amplifiers.

(ii) Case 1I: Placement of Hybrid optical Amplifier (Star-to-Star)

After determining the transmission distance and multi-parameter optimization the distributed Raman-EDFA HOA is placed between two stars. For multi-parameter optimization the Pump powers of Raman and EDFA has been considered. For the cost effective solution only one laser has been used as pump laser for Raman and EDFA, respectively. By adjusting the pump power we can achieve desired gain with better performance.

5. Numerical example of metropolitan area network

Fig. 2 presents the sample network which is a dense and scaled-up version of previous MAN networks [3-6]. The network has N= 80 stations and M= 5 passive stars. We describe below the operation of the two modules with this sample network. The input network topology is subdivided into the two modules after checking feasibility of the network. The feasibility of the network has been checked by determining whether the inequality of equation (1) holds good for this network. The feasibility is also checked according to the parameters with its value as described in Table 2. *Module I* is used to optimize the placement of conventional optical amplifier for local links (i.e $\leq$ 20 Km). In Module 1 it generates the constraints from the input for this network and contains the MILP solver and outputs the optimum value of the objective function. The complete MILP formulation and other related details such as precise amplifier locations have been omitted for clarity in the figures and can be found in [18]. At last the optimize placement of optical amplifier has been done as shown in Fig 2. *Module II* is used to optimize the Raman-EDFA hybrid optical amplifier for back bone star-to-star link which consist maximum number of channels. Under this module first we determine the distance between two stars and optimize the pump powers of Raman and EDFA using GA to achieve maximum gain (> 20 dB) with lesser variation (see Appendix II). After that this optimized HOA is placed into the backbone network as shown in Fig 2. As we observe from Fig. 2, the proposed optimum method pushes the conventional amplifiers toward the upstream side of the stars (away from the access links), thereby compensating for the splitting loss in advance.

Table 2. Important parameters used in this investigation.

Parameters	Range	Used value
P_{min}	-20 to -40 dBm [2]	-30 dBm
G_{max}	$\leq$ 25 dB [19]	20 dB
α	------	0.2 dB/Km
P_{sat}	-------	1.5 dBm

6. Cost analysis

Table 3 described the comparison between our proposed network with other sample networks reported in literature. It can be clearly observed that our proposed algorithm shows cost effective solution as compared to other even in the scenario of high capacity with large transmission distance. As [9] is evident that the combination of distributed Raman amplifier plus EDFA for large transmission distance is better as well as cost effective as compare to other conventional and hybrid optical amplifiers. In the sample network we have reduced the number of conventional optical amplifiers (see Table 3) by using only eight HOAs for instead of 14 [3], 16 [5]. For local links the number of conventional optical amplifier are same.

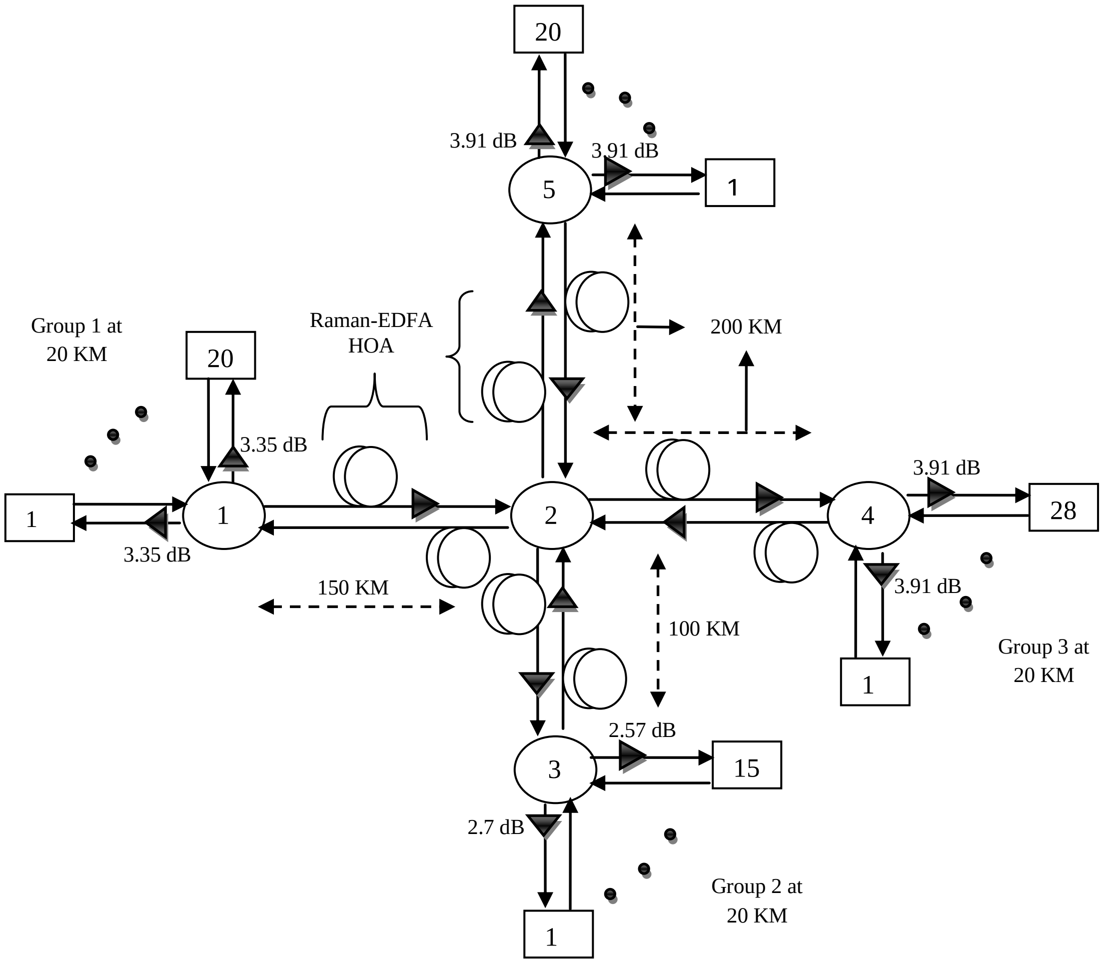

Fig. 2. Placement of hybrid and conventional optical amplifiers in high capacity MAN, scaled-up and denser version of [3-6].

Table 3. Comparison of amplifier placement algorithms.

Sample Network	Number of stars and distance between them	Total number of stations/ users	Number of used optical amplifiers for back-bone link	Used Algorithm
Ref. [3], Fig. 12	4 (100 to 150 Km)	68	14 (for 6 back-bone link)	MILP
Ref. [4], Fig. 10	5 (10 to 20 Km)	~60	~6 (for 8 back-bone link)	MILP
Ref. [5], Fig. 11	4 (100 to 150 Km)	63	13 (for 6 back-bone link)	Distributed ASAP
Ref. [5], Fig. 12	5 (100 to 200 Km)	29	16 (for 8 back-bone link)	Distributed ASAP
Current Work	5 (100 to 200 Km)	80	8 HOAs (for 8 back-bone link)	MILP + GA

7. Conclusion

We studied the amplifier placement problem with multiple types of amplifiers. It is observed that, using the optimized low cost Raman-EDFA HOA the numbers of conventional optical amplifiers are reduced over back-bone high capacity link. Although this increases the complexity of the amplifier-placement algorithm, numerical results show that certain networks do benefit significantly from this method by requiring fewer amplifiers.

References

[1] H. Suzuki, M. Fujiwara, K. Iwatsuki, J. Lightwave Technol. **24,** 1998 (2006).

[2] G. P. Agrawal, Fiber-Optic Communication Systems, John Wiley and Sons, Inc, New York *(*1992).

[3] B. Ramamurthy, J. Iness, B. Mukherjee, J. of Lightwave Technology, **16,** 1560 (1998).

[4] B. Ramamurthy, J. Iness, B. Mukherjee, IEEE/ACM Transactions on Networking, **6,** 755 (1998).

[5] G. M. de Mercado, I. de Miguel, F. González, P.

Fernández, J. C. Aguado, R. M. Lorenzo, J. Blas, E. J. Abril, M. López, Communications World (N. Mastorakis, ed), WSES-Press (2001).
[6] A. M. Hamad, A. E. Kamal, J. Opt. Commn. Netw. **1**, 204 (2009).
[7] J. H. Lee et al., J. Lightwave Technol. **23,** 3483 (2005).
[8] M. Karásek, M. Menif, A. Bellemare, International J. of Fiber Integr. Opt. **22,** 13(2003).
[9] S. Z. M. Hasan, V. Kalavally, R. Parthiban, T. Win, M. Premaratne, Optical Fiber Technology, **19**, 10 (2013).
[10] S. Singh, R. S. Kaler, Journal of Optical Engineering, **52**, 096102-1 (2013).
[11] S. Singh, R. S. Kaler, Fiber and Integrated Opt. **31,** 208 (2012).
[12] S. Singh, R. S. Kaler, Optical Fiber Technology, **19**, 428 (2013).
[13] S. Singh, R. S. Kaler, IEEE Photonics Technology Letters, **25**, 250 (2013).
[14] S. Singh, R. S. Kaler, IEEE Photonics Technology Letters, IEEE Photonics Technology Letters, **26**, 173 (2014).
[15] G. V. Reklaitis, A. Ravindran, K. M. Ragsdell, Engineering Optimization: Methods and Applications. New York: Wiley (1983).
[16] B. Ramamurthy, “Efficient design of wavelength division multiplexing (WDM)-based optical networks,” Ph.D. dissertation, Dep. Comput. Sci., Univ. California, Davis, CA (1998).
[17] R. P. Khare, Fiber Optics and Optoelectronics, Oxford University Press: New Delhi (2012).
[18] C. Headley and G.P. Agrawal, Raman Amplification in Fiber Optical Communication Systems, Elsevier Academic Press, California (2005).
[19] K. Magari, M. Okamoto, Y. Noguchi, IEEE Photon. Technol. Lett., **3**, 998 (1991).
[20] S. Singh, S. Saini, G. Kaur, R. S. Kaler, Optical Engineering, **53,** 016103 (2014).
[21] S. Singh, S. Saini, G. Kaur, R. S. Kaler, J. of Optical Society of Korea, **8,** (2014). (DOI: http://dx.doi.org/10.3807/JOSK.2014.18.2.0**)

*Corresponding author: simrankatron@gmail.com

APPENDIX I

Gain Model of Raman-EDFA HOA

In general the total gain of cascaded amplifiers is adding or product of individual gain. But in original the gain of second cascaded amplifier (net gain) is depend on the first amplifier gain as shown in Fig. A.1. So in this section we have derived the net gain modal by considering the actual conditions. The mathematical model is divided into two parts. In part A, an expression of variation of pump power and signal power along the EDFA length is determined while, in part B, after considering the effect of Raman output power on EDFA power, an expression for a net signal gain is established.

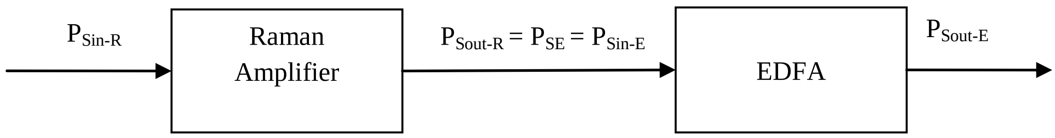

Fig. A.1 Net Gain/ Power evaluation.

After considering the rate equations of EDFA and Raman from [17, 18] and taking the actual condition to calculate the net gain of proposed HOA, we have:

$$G_{Total} = \exp\left\{ \begin{array}{l} -\Gamma_s\, \sigma_{sa}[exp(g_0 L_R - \alpha_s L_R)] N_t L_E + \\ \Gamma_s\, (\sigma_{sa} + \sigma_{se}) exp[g_0 L_R - \alpha_s L_R] N_{2avg} \end{array} \right\} \quad (A.1)$$

where $N_{2avg} = \frac{N_t[\omega_P + \omega_{sa}]L_E}{\left[\frac{1}{\tau_{sp}} + \omega_P + \omega_{sa} + \omega_{se}\right]}$, pump rate $\omega_p = \frac{\sigma_{pa} P_{PE}}{a_p h \nu_p}$, ω_{sa} is stimulated absorption rate, ω_{se} is stimulated emission rate.

The notations can be found in [17, 18].

APPENDIX 2

Multi-parameter optimization using genetic algorithm (GA)

The implementation of GA begins with the initialization of the various parameters for GA i.e. Cross over probability, mutation probability, selection parameter, the number of generations and population size. The broad description of GA can be found in [20, 21].

Applying this simple GA for optimization of HOA can be broadly sub-divided into following steps and their sequence can be represented by a flow diagram as shown in Fig. A.2.

Step 1: Initialization of GA parameters and population for various system parameters i.e. Raman length, EDFA length and its pump powers. During this stage, the range for the parameters i.e. the limits of the search space is defined. The parameters for the GA and range of values for HOA are as given in Table A.1 and A.2 respectively. Set the number of generations after which the algorithm will converge to optimum solution.

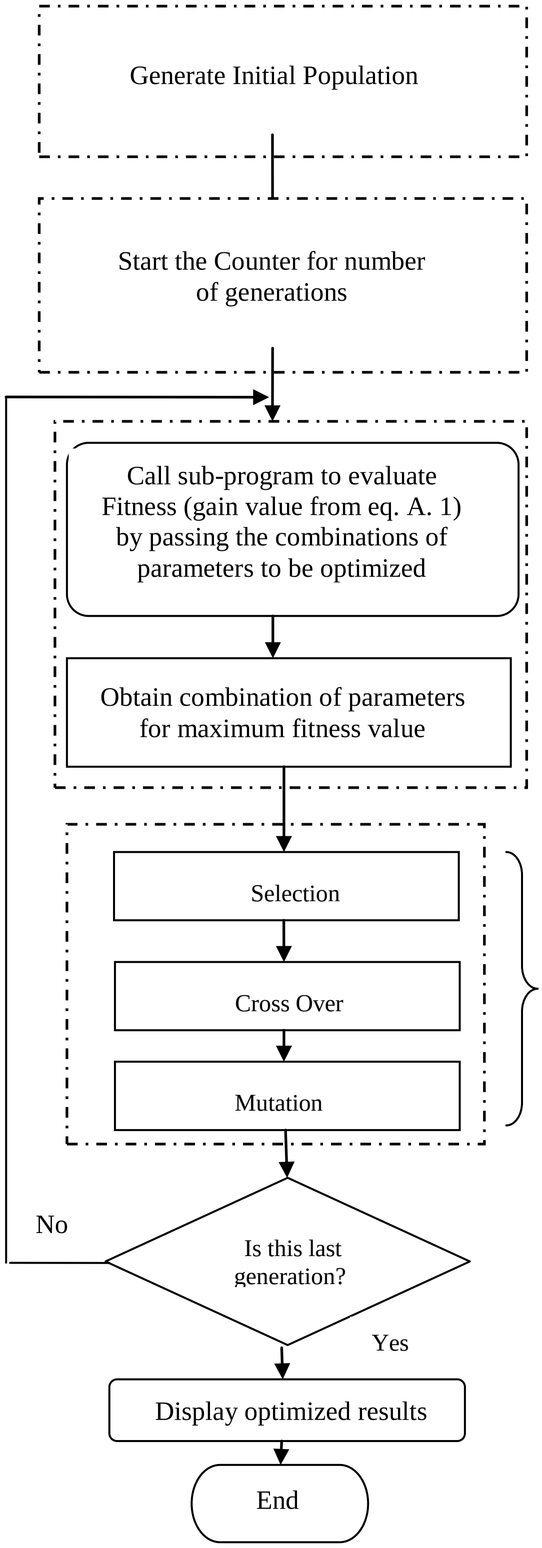

Fig. A.2 Basic genetic algorithm flow diagram applied for Raman-EDFA HOA optimization.

Table A.3. Optimized parameters from GA which are used in proposed scale-up sample network.

Raman Length (Km)	EDFA length (m)	Raman Pump Power (mW)	EDFA Pump Power (mW)	Gain (dB)
200	20	283.17	168.32	21.72
100	27.48	160.76	212.58	26.62
150	12.53	232.33	390.60	31.10

Table A.1. Parameters for the GA.

Parameter	Value
Cross over Probability	80%
Mutation Probability	2.5%
Tournament selection Parameter	75%
Number of generations	20
Population	400 individuals
Fitness function	Maximum gain

Table A.2. Range of values for HOA parameters.

Number of pumps	1
Maximum total power for counter-propagating pumps (mW)	500
Maximum Raman length(Km)	200
Maximum EDFA length(Km)	30

Step 2: At this stage, the counter is started for the number of generations at the beginning. The generations proceed iteratively until the final generation is reached.

Step 3: Within the above counter established for number of generations, there are sub-stages to evaluate the fitness value (i.e. Gain) and then modify the set of parameters for achieving maximum gain. Evaluation of amplifier gain for various possible combinations of parameters is performed by calling HOA model as a sub-program. The set of parameters obtained from a randomly generated population are passed within the function call to the sub-program one by one for the whole population. This sub-program on receiving the combination of all the parameters to be optimized, evaluate the gain using equation (A. 1). The average gain is returned to the program. The current fitness value is compared with the previous fitness and if it is greater than the previous one, then the set of parameters is taken as the better solution.

The previous combination is discarded and new combination is tracked during the current generation by comparing the previous results with the current.

Step 4: During the next sub-stage, the current population of individuals is modified by appropriately employing tournament selection. The fitness value and tournament select probability are passed to call the function. Here the fitness is an array of gain values respective to the set of all parameters in current population. Tournament selection chooses a random value for chromosomes depending upon small probability as defined in Table A. New chromosome pairs are obtained from these selected chromosomes by crossover method. These newly generated chromosomes form a temporary new population which replaces the original population after performing a mutation operation on each of the new chromosomes. Finally a new improved population is obtained. As the analogy of GA with proposed optical communication is concerned the tournament of individuals (in this case pump powers of Raman and EDFA) has been done.

Again step 3 followed by 4 is repeated until the final generation is reached. It can be determined that amplifier gain increases with the succession of the generations. Since, the proposed method of employing GA includes tournament selection, crossover method and mutation adopted collectively, so it converges towards maximum gain in a few generations and then further modification is not desirable.

Table A.3 shows the results obtained from genetic algorithm as a function of the expected gain of more than 20 dB. These optimized parameters are used for the HOAs placed in the sample network shown in Fig. 2 with its respective transmission distance.