A novel fiber-optic subscriber access network and Optical Amplifier placement

Yatindra Nath Singh, Arvind Kumar, A. Sakthivel, Vandana Singh

Abstract— **In this work, a new subscriber access network architecture has been proposed. It uses optical add-drop multiplexer (OADM) and wavelength division multiplexing (WDM). In order to alleviate the limitation on supportable number of users use of OAs has been investigated. It is found that with all the degradations in OAs, the number of users for a typical network is limited to 384.**

Keywords— **Subscriber Access, Fiber-optic network, Optical amplifier, WDM**

I. Introduction

ALL-OPTICAL networks are of interest because they are suppossed to use large available bandwidth in fiber to provide large capcities. The all-optical networks in subscriber access has been studied and experimented widely. They are of interest because services requiring very high bandwidth can only be provided to subscribers using fiber. Their had been many fiber-optic subscriber access network proposals e.g. FTTH (fiber to the home), FTTC (fiber to the curb), TTOSS (totally transparent optical subscriber system) [1], TPON (Telephony Passive Optical Network) [2], and PPL (Passive Photonic Loop) [3].

Any subscriber loop architecture for wideband applications should have certain desirable properties. The access equipments in subscriber premises should be low cost and easy to maintain. The high cost equipments should be in central office. This reduces the cost per subscriber for the network. The network should provide large bandwidth to the subscribers. Further, as all the subscribers will not initially subscribe to high bandwidth services, the architecture should be able to provide low bandwidth services at much cheaper price. Later when the subscriber would like to upgrade to a high bandwidth service, the service provider should be able to do so at a small additional cost. The protocol used must be simple and scalable. This is very important, as the number of active subscribers will change and protocol should efficeintly accomodate all the changes while keeping the network usage as high as possible. Further, the protocol overhead should be low. As the bandwidth demand will increase in future, the carrier company should be able to provide more capacity on the same fiber. This can be done using WDM technology.

In this paper a new scheme which will be useful as subscriber access network has been proposed. Any such network will suffer from split losses which reduces the number of subscribers that can be attached to the sytem. In view of this, the use of optical amplifiers in the proposed architecture has also been investigated in this paper.

All corresspondence with Dr.Y.N.Singh, Electrical Engineering Department, Indian Institute of Technology, Kanpur-208016, India. Email:ynsingh@ieee.org, Phone:0512-597944, Fax:0512-590063

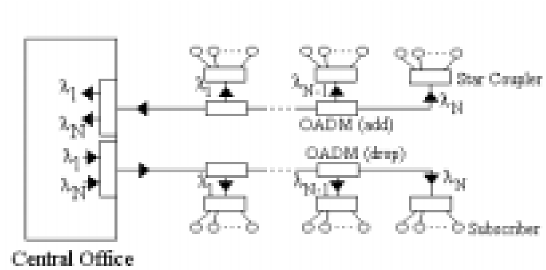

Fig. 1. Dual bus topology for SAN

II. Architecture

In any subscriber access network, there is a central office (CO). The subscribers are connected to central office and all the communication takes place through it. The central office does all the management including metering and billing. The proposed architecture for fiber optic subscriber access network is shown in Fig.1.

In this architecture, the subscribers are partitioned into groups. Each group uses a common shared wavelength to communicate to the central office. The wavelength can be shared among the subscribers in the group using a suitable access protocol. An example of such a protocol is given in [3], and many more can be designed.

There are two fibers running from central office through all the subscriber groups. One fiber carries as many wavelengths as the groups for downstream transmission. The second fiber is used for upstream traffic. For providing the group the access to one of the wavelength in the fiber, use of wavelength add-drop multiplexers is proposed. The above topology is dual bus topology. One can use the add-drop multiplexers in ring configurations also as shown in Fig.2. In ring configuration, while a wavelength is dropped for downstream transmission, the same wavelength can be added for upstream transmission. The advantange of this configration is that only one fiber is needed unlike two fiber in dual bus topology.

After a wavelength has been dropped at add-drop multiplexer, it is broadcasted to all the subscribers in a group using star coupler. There is another parrallel broadcast network for collecting upstream traffic from all the subscribers.

In this network, the number of users which can be supported will be limited by split loss of star coupler and insertion loss of add-drop multiplexers. While WDM will be providing large bandwidth, to use it effectively the network need to support large number of users. This can be done by placing the optical amplifiers appropriately.

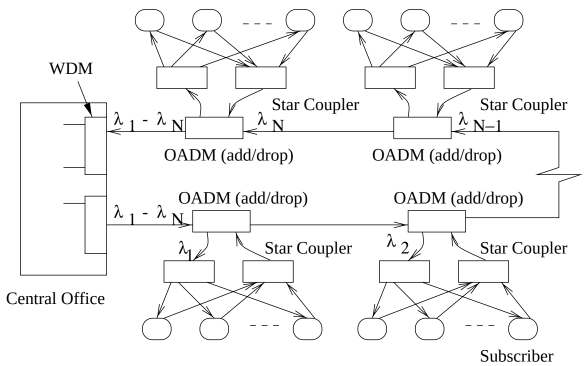

Fig. 2. Ring topology for SAN

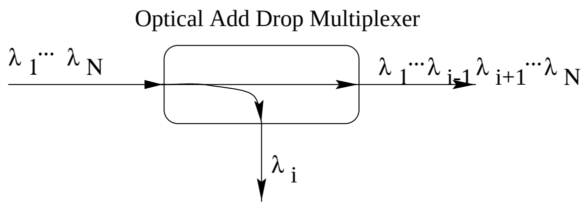

Fig. 3. drop function in OADM

A. Optical Add Drop Multiplexers

Optical add-drop multiplexer can be made using accousto-optic effect or interferometeric effect [6]. In an add-drop multiplexer there are three ports: input port, add-drop port and output port. Assuming that there are $\lambda_1 \ldots \lambda_{n-1}, \lambda_n$ wavelength at the input and λ_i is dropped, then at the add-drop port λ_i is diverted. At the output port all the other wavelengths $(\lambda_1 \ldots \lambda_{i-1} \lambda_{i+1} \ldots \lambda_{n-1} \lambda_n)$ will be there (Fig.3). When wavelength λ_i is added then at the input port λ_i should not be there (i.e., input has $\lambda_1 \ldots \lambda_{i-1} \lambda_{i+1} \ldots \lambda_{n-1} \lambda_n$). At the output port all the wavelengths $(\lambda_1 \ldots \lambda_{n-1} \lambda_n)$ will be there (Fig.4)

B. Semiconductor Optical Amplifier

Semiconductor optical amplifiers (SOA) are made using semiconductors (e.g., InGaAsP). The basic principal behind optical amplification is stimulated emission. In order to have stimulated emission, population inversion is needed, which is created by electrical bias in SOA. The gain and noise in these are modelled by the following equations

$$G = G_0 \exp\left(-(G-1)\frac{P_{in}}{P_{sat}}\right) \quad (1)$$

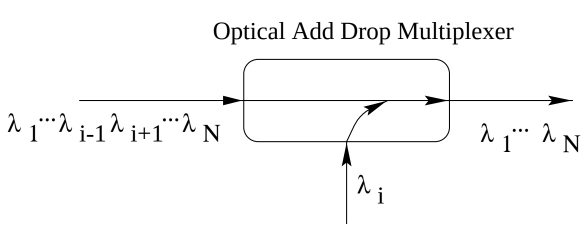

Fig. 4. add function in OADM

and

$$S_{sp} = n_{sp} h\nu (G-1) \qquad watts/Hz. \quad (2)$$

In the above eqautions, G is SOA gain, G_0 unsaturated gain, P_{in} input power to SOA, P_{sat} saturation power level, S_{sp} amplifier sponataneous emission (ASE) noise power spectral density, n_{sp} spontaneous emission factor, h Plank's constant, and ν optical frequency.

In the next section the placement algorithm of the OAs is given and thereafter main results are discussed.

III. OA placement in proposed architecture

In the proposed dual bus architecture, one can place optical amplifier all along the bus wherever required or after the signal is dropped from OADM. Using the OA in the bus gives the advantage that a single amplifier can amplify multiple wavelength and hence less number of amplifier will be needed. While if SOA is placed in signal path after dropping from downstream or before adding the wavelength in upstream direction, it will amplify only one wavelength. Consequently, OA placement only in the bus has been considered. The basic algorithm which has been used is as follows.

Only one amplifier is placed at a time. Let us term each group as branch. First of all using computational analysis number of branches which can be supported without OAs are determined. The criterion for supporting a branch is that BER should be less than 10^{-9}. Let i branches are supported without OAs. This means that if we want to place an OA, there are $i+1$ positions. Now the OA is placed in each of the $i+1$ positions and number of branches that can be supported are computed. Thereafter the OA is placed in the position which leads to maximum number of branches. In case if there are more than one position supporting same number of branches, the position leading to minimum BER in the worst affected branch is choosen.

Once the position of first OA is fixed, let the supportable number of branches be j. In that case j possible positions for placement of OA are there. This is with the assumption that more than one OA cannot be placed between two consecutive branches. In computational procedure, the next OA is placed at each of the position and supportable number of branches alongwith the maximum BER (denoted as BER for that OA position) among all the branches are computed. The position which gives maximum number of branches and thereafter minimum BER is choosen. This algorithm is followed till no more increase in number of branches is there.

The computational model considers three cases; network with a) unsaturated OAs, b) average gain saturated OAs and c) OAs with average gain saturation as well as gain fluctuations. The computational model is given in more details in [8], [9] and has been adopted from [10].

IV. Computational Model

In computation, one of the most important thing is loss model. If the transmitter power is known (say P_T) and SOAs are not there between CO and receivers for which

BER is computed, the loss (in dB) between transmitter and receiver assuming that receiver is in i_{th} group starting from CO is given by

$$L_{TR} = L_W + L_{sp}(2i+5) + i\alpha l + (i-1)L_m + L_{12} + L_i \log_2 n + 10\log_{10} n. \quad (3)$$

In the above equation, L_W is insertion loss of wavelength multiplexer at CO, L_{sp} splice loss, α fiber attenuation per unit length, L the length of fiber between two consecutive OADMs, L_m insertion loss of OADM, L_{12} insertion loss for drop signal in OADM, L_i insertion loss of 2×2 couplers used for making star coupler, and n the number of users in a group.

The loss (in dB) between transmitter at CO and first OA is used to find the input power to SOA. If the first SOA is placed before the i^{th} group the loss between transmitter and first SOA is given by

$$L_{TA_i} = L_W + 2iL_{sp} + i\alpha L + (i-1)L_m. \quad (4)$$

If the two consecutive amplifiers are placed before i^{th} and j^{th} OADM respectively, then loss (in dB) between them is given by

$$L_{A_iA_j} = 2(j-i)L_{sp} + (j-i)L_m + (j-i)\alpha L. \quad (5)$$

Further loss (in dB) between a receiver in l^{th} branch and nearest amplifier (which is before t^{th} OADM) is given by

$$\begin{aligned} L_{A_tR} &= [2(l-t)+4]\,L_{sp} + (l-t)L_m + L_{12} + (l-t)\alpha L \\ &\quad + L_i \log_2 n + 10\log_{10} n \qquad ; t < b \\ &= [2(l-t)+2]\,L_{sp} + (l-t)L_m + (l-t)\alpha L \\ &\quad + L_i \log_2 n 10\log_{10} n \qquad ; t = b \quad (6) \end{aligned}$$

Here b is total number of branches in the network.

In order to compute the gain saturation, it is assumed that bits in all the channels are synchronised. In order to find the impact of other channels, two cases have been considered. In one case, average value of saturated gain has been used. In the other case BER for every bit pattern in interefering channels is computed. Thereafter, average BER is computed.

V. Results and Conclusions

For a sample network with typical values of various parameter as given in table I, results were computed. Main results are as follows. Without OAs only two branches can be supported. Each branch is assumed to have 32 users. In the case with unsaturated OAs, when first OA is placed, the optimal position is before first OADM. It increases the number of branches to 19. Second OA leads to maximisation of branches when placed before fifth OADM. After adding sixth OA only one branch adds up. With seventh OA, there is no increase in number of branches (It remains 38). Table II, III, IV, V and VI shows the results in tabular form.

With a) average gain saturation as well as b) average gain saturation with gain fluctuation, the trend is similar. For the later case there is no improvement after placing more that three OAs.

In this work a novel subscriber access network architecture has been proposed and OA placement problem has been investigated. Cosidering the average gain fluctuation with gain fluctuation case, only three amplifier can be used. This means network can support 384 users per access fiber. The system will need 12 WDM channels while providing very good bandwidth (100Mbps) to each of the subscribers.

TABLE I

Typical parameter values

Maximum allowed transmitter power	P_T	0 dBm
Desired Bit error rate		10^{-9}
Insertion loss of single 2×2 coupler	L_i	0.5dB
Fiber attenuation coefficient	α	0.2 dB/km
Insertion loss of splice	L_{sp}	0.5dB
Distance between branches	L	5 km
Insertion loss for dropping signal in OADM	L_{12}	0.5dB
Insertion loss for passing signal in OADM	L_m	0.7 dB
Receiver load resistance	R_L	100 Ω
Operating wavelength	λ	1.55 μm
Optical Bandwidth	B_o	25 GHz
Electrical Bandwidth	B_e	2.5 GHz
Receiver temperature	T	300^o K
Electron charge	e	1.602×10^{-19} C
Quantum efficiency of photodiode	η	1
Responsivity of photodiode	R_o	1.28
Number of users per branch	n	32

TABLE II

P_e for without OA

$\epsilon \rightarrow$	P_e			
$b \downarrow$	0.00	0.05	0.10	0.15
1	1.0×10^{-39}	8.1×10^{-33}	3.9×10^{-27}	1.9×10^{-22}
2	3.9×10^{-19}	6.1×10^{-16}	2.6×10^{-13}	3.9×10^{-11}

b is number of branches, ϵ extinction ratio

References

[1] Khoe G.D., and Dielman, A., "TTOSS: An Integrated Subscriber System for Direct and Coherent System," *IEEE/OSA Journal of Lightwave Technology,* Vol.9, No.7, July 1986, pp.768-784.

[2] Stern, J.R. *et.al,* "Passive Optical Local Networks for Telephony Applications and Beyond," *Electronics Letters,* Vol.23, No.24, Nov.1987, pp.1255-1257.

[3] Faulkner, D.W., "Optical Networks for Local Loop Applications," *IEEE/OSA Journal of Lightwave Technology,* Vol.LT-7, No.11, Nov.1989, pp.1741-1751

[4] A. Yariv, *Optical Electronics,* 4th Ed., Saunders College Publishing, 1991.

TABLE III

Number of supported branches after placing first ideal amplifier.

$\epsilon \rightarrow$	Number of supported branches, P_e			
$P \downarrow$	0.00	0.05	0.10	0.15
I	19, 8.7×10^{-11}	18, 4.7×10^{-18}	18, 4.8×10^{-15}	18, 1.5×10^{-12}
II	18, 8.9×10^{-21}	17, 4.7×10^{-18}	17, 4.8×10^{-15}	17, 1.8×10^{-12}
III	17, 8.9×10^{-11}	16, 4.8×10^{-18}	16, 4.9×10^{-15}	16, 1.5×10^{-12}

P is position of amplifier placement, ϵ extinction ratio

TABLE IV

P_e WITH ONE OPTICAL AMPLIFIER

$b \downarrow$	P_e			
$\epsilon \rightarrow$	0.00	0.05	0.10	0.15
for $b = 1$ to 16, P_e is very small				
17	$2.8{\times}10^{-45}$	$2.4{\times}10^{-37}$	$7.4{\times}10^{-31}$	$1.7{\times}10^{-25}$
18	$1.0{\times}10^{-21}$	$4.7{\times}10^{-18}$	$4.8{\times}10^{-15}$	$1.5{\times}10^{-12}$
19	$8.9{\times}10^{-11}$	$*$	$*$	$*$
20	$*$	$*$	$*$	$*$

b number of branches, $*$ means BER is greater than 10^{-9}.

TABLE V

SUPPORTED b AND P_e AFTER SECOND IDEAL AMPLIFIER

Extinction ratio → / No. of amp ↓	No. of supported branches/Pe per user of respective branch			
	0.00	0.05	0.10	0.15
I	27/5.947 × 10^[illegible]	22/3.846 × 10^[illegible]	22/3.846 × 10^[illegible]	21/2.474 × 10^[illegible]
II	26/4.805 × 10^[illegible]	25/1.407 × 10^[illegible]	25/2.745 × 10^[illegible]	25/5.588 × 10^[illegible]
III	27/3.336 × 10^[illegible]	26/6.336 × 10^[illegible]	26/4.642 × 10^[illegible]	26/6.735 × 10^[illegible]
IV	28/5.736 × 10^[illegible]	27/4.736 × 10^[illegible]	26/5.407 × 10^[illegible]	25/5.822 × 10^[illegible]
V	29/2.174 × 10^[illegible]	28/5.803 × 10^[illegible]	27/5.674 × 10^[illegible]	27/1.312 × 10^[illegible]
VI	28/4.525 × 10^[illegible]	27/3.065 × 10^[illegible]	27/4.744 × 10^[illegible]	26/4.736 × 10^[illegible]
VII	27/4.750 × 10^[illegible]	27/2.927 × 10^[illegible]	26/3.753 × 10^[illegible]	26/2.645 × 10^[illegible]
VIII	27/6.384 × 10^[illegible]	26/5.128 × 10^[illegible]	26/9.635 × 10^[illegible]	25/3.237 × 10^[illegible]
IX	27/3.963 × 10^[illegible]	26/3.480 × 10^[illegible]	26/4.725 × 10^[illegible]	25/7.227 × 10^[illegible]
X	27/3.659 × 10^[illegible]	26/1.714 × 10^[illegible]	26/5.826 × 10^[illegible]	25/6.639 × 10^[illegible]
XI	26/1.283 × 10^[illegible]	26/4.834 × 10^[illegible]	25/5.734 × 10^[illegible]	25/4.274 × 10^[illegible]
XII	26/2.748 × 10^[illegible]	25/6.904 × 10^[illegible]	25/7.567 × 10^[illegible]	25/5.835 × 10^[illegible]
XIII	26/1.470 × 10^[illegible]	25/6.963 × 10^[illegible]	25/3.384 × 10^[illegible]	24/5.473 × 10^[illegible]
XIV	26/3.537 × 10^[illegible]	25/4.736 × 10^[illegible]	25/5.365 × 10^[illegible]	24/1.473 × 10^[illegible]
XV	25/3.272 × 10^[illegible]	25/5.737 × 10^[illegible]	24/4.845 × 10^[illegible]	24/4.451 × 10^[illegible]
XVI	25/1.265 × 10^[illegible]	24/3.057 × 10^[illegible]	24/7.451 × 10^[illegible]	24/5.225 × 10^[illegible]
XVII	25/2.945 × 10^[illegible]	24/7.364 × 10^[illegible]	24/6.467 × 10^[illegible]	23/1.585 × 10^[illegible]
XVIII	24/4.524 × 10^[illegible]	23/5.876 × 10^[illegible]	23/7.989 × 10^[illegible]	23/4.075 × 10^[illegible]
XIX	23/5.337 × 10^[illegible]	23/8.271 × 10^[illegible]	23/6.074 × 10^[illegible]	23/4.967 × 10^[illegible]
XX	23/6.836 × 10^[illegible]	⊗	⊗	⊗

⊗ means the $P_e > 10^{-9}$ or amplifier cannot be placed.

[5] G. P. Agrawal, *Optical Communication Systems,* John Wiley, 1992.

[6] Takashi Mizuochi *et.al*, "Interferometric crosstalk free optical add-and-drop multiplexer," *IEEE J. Lightwave Technology,* Vol.16, No.2, Feb.1998.

[7] Rajiv Ramaswami, Kumar N. Sivarajan, *Optical Networks: A practical perspective,* Morgan Kauffmann, California, 1998.

[8] Arvind Kumar, *Placement of optical amplifiers in optical networks,* M.Tech. Dissertation, Electrical Engineering Department, IIT Kanpur, April 1999.

[9] A.Sakthivel, *A new architecture for fiber-optic subscriber access network and effect of semiconductor optical amplifiers (SOAs) in it,* DIIT Dissertation, Electrical Engineering Department, IIT Kanpur, July 1998.

[10] Y.N.Singh, V.K.Jain, H.M.Gupta, "Semiconductor optical amplifiers in WDM star networks," *IEE Proceedings- Optoelectronics,* Vol.143, No.2, April 1996, pp.144-152.

TABLE VI

NUMBER OF SUPPORTED BRANCHES VS. NUMBER OF AMPLIFIERS

No. of amplifiers	Supported branches after placing the amplifier at optimum position
5th	37
6th	38
7th	38