PID No. PP-FIO-54

Upper Limit on the capacity of Subscriber Access Networks

T.M.Prasanna*[a], Rajiv Srivastava[a], Yatindra Nath Singh[a]
Department of Electrical Engineering, Indian Institute of Technology, Kanpur, Uttar Pradesh, India 208016

ABSTRACT

WDM is an answer to increasing bandwidth requirement, as it carves up the huge bandwidth of single mode fiber into channels whose bandwidths are compatible with peak electronic processing speeds. The paper deals with the unidirectional aspect of the Dual Bus Architecture for Subscriber Access Network with passive optical splitting being employed at the Optical Network Unit (ONU). The aim is to give an upper bound on the number of WDM channels that can be transmitted, and the number of subscribers that can be accommodated (by maximizing the number of power splits) for broadcast applications. Three cases discussed in this paper are (i) Analog broadcast channels along with unicast transmission (which are also called switched services). (ii) Digital broadcast channels with switched services. (iii) The hybrid of both analog and digital broadcast channels with switched services.

Keywords: Access Network, Modulation Schemes, EDFA and WDM.

1. INTRODUCTION

Increased demand for bandwidth arises from a proliferation of applications such as voice, video and data traffic as well as by the bootstrapping effect of increased consumption resulting from lower rates. The term ‘Broadband Services’ is coined for the hybrid transfer of data, voice and video services. Technologies like video on demand, teleconferencing and virtual reality that requires enormous bandwidth can be now realized. This dream is envisaged by optical communication along with Wavelength Division Multiplexing (WDM) technology. The deployment of networks [1] for sharing gave birth to operators providing the full service encompassing the triple play- voice, video and data. With services being classified as broadcast or switched, with the former one meaning the distribution of the same information to all subscribers as in CATV and the latter one as subscriber specific data being transmitted in the last leg like in internet and telephone services; paved the way for the classification of networks. The final links between the service provider’s facility to the home or business is called the Access Network [2]. The architecture, which has been considered, is shown in figure 1.

2. SALIENT FEATURES OF THE ARCHITECTURE

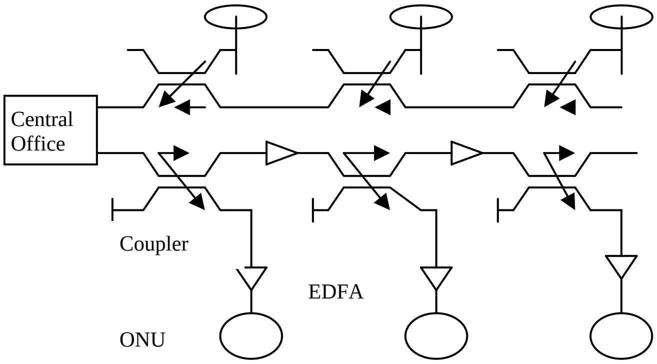

Figure1 Schematic of the architecture for access network

In this architecture, different wavelengths can be transmitted simultaneously and each wavelength contain many channels mounted on it, like, one wavelength may be containing broadcast data and the rest may contain unicast transmission data and all these channels are subcarrier multiplexed.

On the Bus, EDFAs are employed to maximize the number of branching out of it using a 3-dB coupler. This coupler is wavelength flattened, which allows WDM in the network. This is a very cost effective approach, as more and more subscribers can be adhered to without incurring too much of loss.

tmprasanna@gmail.com; Phone +91 9886471891

As in any network, upstream and downstream traffic requirements are different, so, in upstream traffic, there is no requirement of preamplifier as we did in downstream traffic, by using EDFA as preamplifier in each branch.

3. ANALYSIS OF THE ARCHITECTURE

3.1 ANALYSIS OF ALL ANALOG BROADCAST ALONG WITH SWITCHED SERVICES

Analog Broadcast can be either AM-VSB (Vestigial Side Band) or FM-SCM along with switched services. First branch has to be designed; for that we aim at designing the EDFA as a preamplifier in order to maximize the number of power splits, while still achieving the target Carrier-to-Noise Ratio (CNR).

3.1.1 DESIGNING OF A BRANCH IN SUBSCRIBER ACCESS NETWORK

For AM-VSB signals, the received signal power at the receiver (at the photo detector) is [3]

$$P_{signal} = \frac{m^2 R^2 G^2 (P_s^{in})^2 L^2}{2}$$

where m is the modulation depth per channel, G is the gain of EDFA as a preamplifier, R is the responsibility of the photo detector, P_s^{in} is the input signal to the preamplifier. Also, $R = \eta e/(h\nu_s)$, where η is the photo detector quantum efficiency.

By using noise variances, we can write different NCR (Noise to Carrier ratio) as [3]

$$NCR_{shot} = 2h\nu B_e/\eta GL(P_s^{in}/N)\mu^2 \quad NCR_{sig-sp} = 8h\nu n_{sp}(G-1)B_e/2G(P_s^{in}/N)\mu^2 \quad NCR_{sp-sp} = 4h\nu n_{sp}B_0 B_e(G-1)^2/G^2(P_s^{in})^2\mu^2/N$$

$$NCR_{thermal} = i_e^2 B_e/R^2L^2G^2(P_s^{in})^2\mu^2/N \quad CNLD^{-1} = \mu^3\exp(-1/2\mu^2)/\sqrt{2\pi}(1+6\mu^2) \qquad NCR_{RIN} = (RIN)B_e/(\mu^2/N) \tag{1}$$

$$NCR_{total} = NCR_{shot} + NCR_{sig-sp} + NCR_{sp-sp} + NCR_{RIN} + NCR_{thermal} + CNLD^{-1} \tag{2}$$

To maximize CNR, the rms modulation index needs to be optimized; this can be obtained by differentiating equation (2) w.r.t. μ.

Using L=1/M, and the values from table 1 in equation 1 and 2 we get the relation between number of AM-VSB receivers (M) and the number of AM-VSB channels (N) as

$$M = G*(61996.28)*((P_s^{in}/N)-3.39e-5) \tag{3}$$

TABLE-1

Parameter	Value	Parameter	Value
Signal Wavelength λ_s	1550 nm	Pump Wavelength λ_p	1476 nm
Pump Power	50 mW	Signal Power	1, 3.2, 5, 10 mW
Target CNR	48 dB	PhotodetectorQuantum Efficiency η	0.8
Equivalent circuit noise current density i_c	10 pA/$\sqrt{Hz}$	Relative Intensity Noise RIN	-152 dB/Hz
Optical Bandwidth B_o	25 nm	Excess loss	$\gamma\log_2 N$
S (Gain Loss Product)	1	B_e	5MHz

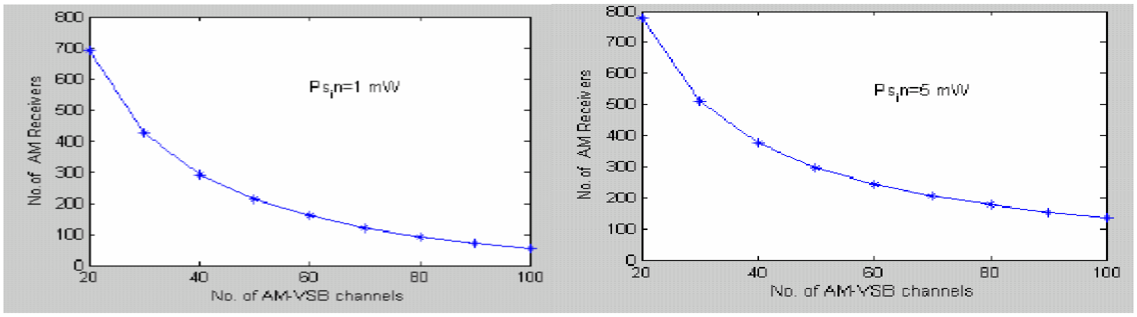

Figure 2 Number of subscribers in one branch w.r.t. Number of AM-VSB channels for All Analog Broadcast.

It is clear from the graph as the signal power increases more number of receivers and channel can be accommodated

3.1.2 DESIGNING OF BUS OF A SUBSCRIBER ACCESS NETWORK

The number of EDFAs on the bus cannot be arbitrary large because this number is limited by the ASE noise accumulation of the amplifiers. For N EDFAs, bus can support $(N+1)M$ number of users in SAN where M is the number of subscribers in one branch.

Let P_o be the ASE generated out of the first EDFA, and the gain of each EDFA on the bus is assumed constant, delivering constant power. The SAN will support N EDFAs under the condition

$$\left(P_o\left(\frac{S^N-1}{S-1}\right)\right) \le \frac{P_{ASE}^{upper\ \lim it}}{N_{ch}} \qquad \text{where} \qquad P_o = h\nu_s(G-1)B_o\eta$$

$$N_{ch} \le \left[\log_e\left(\frac{P_{ASE}^{upper\ \lim it}.(S-1)}{N_{ch}.P_o}\right)+1\right].\frac{1}{\log_e S} \tag{4}$$

S is the loss-gain product. N_{ch} represents the number of WDM channels G is the gain of an EDFA as an inline amplifier on the bus. $P_{ASE}^{upper\ \lim it}$ is calculated at specified and BER. In SAN the total power is the sum of broadcast and switched channels. Since, switched channels account for very less power as compared to analog broadcast ones, so, there will not be much changes in the power budget in the network, with the number of switched services channels.

3.2 ANALYSIS OF ALL DIGITAL BROADCAST (M-QAM/QPSK) WITH SWITCHED SERVICES

For all digital broadcast service, power involved is less, so the system will be less prone to nonlinear effects, thus justifying the use of a directly modulated laser diode for good linearity. Relative Intensity Noise becomes the main limitation to subcarrier-multiplexed systems. In the calculation it is assumed that all other noise sources are independent of each other. The target SNR was calculated according to the achievement of BER of 1e-9 at the receiver end [3].

$$BER = 0.5.\exp(-\alpha.SNR) \qquad \alpha = 0.25,\ 0.5,\ 1 \text{ for ASK envelope detection.} \tag{5}$$

TABLE-2

Modulation Scheme	SNR (dB)	RMS modulation index	Modulation Scheme	SNR (dB)	RMS modulation index
QPSK	16	0.7005	16-QAM	24	0.4754
64-QAM	30	0.3936	256-QAM	36	0.3408

Following the same set of mathematical expressions (1)-(4), we shall find the relation between the number of digital channels and the number of digital receivers. There is a phenomenal increase in the number of channels on one wavelength in a subcarrier multiplexed fashion, thus making it technology for the future, where thousands of channels with an equal number of subscribers in one branch may be required, as compared to the analog video broadcast case. Figure (3,4) shows the number of digital receivers with the number of digital channels mounted on one wavelength for QPSK and M-QAM modulation schemes where M takes values as 16, 64 and 256.

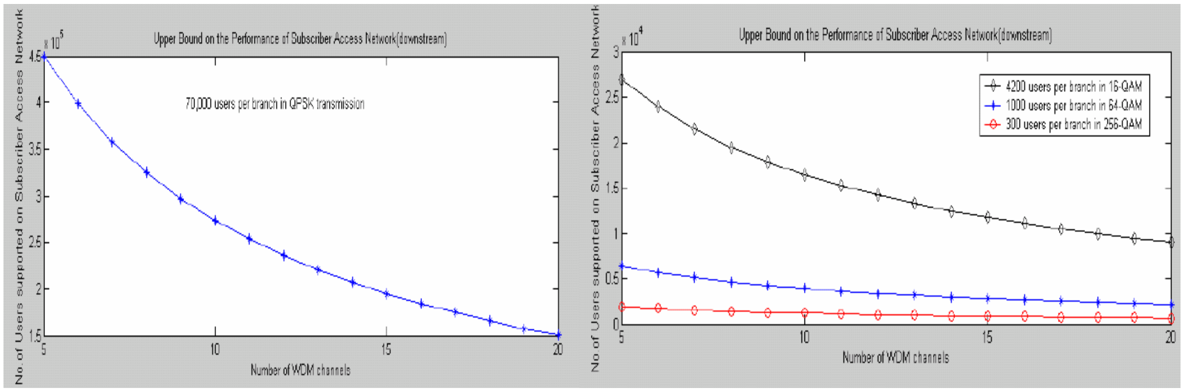

Figure 3 Number of Subscribers in SAN with Number of WDM channels in all Digital video Broadcast along with switched services.

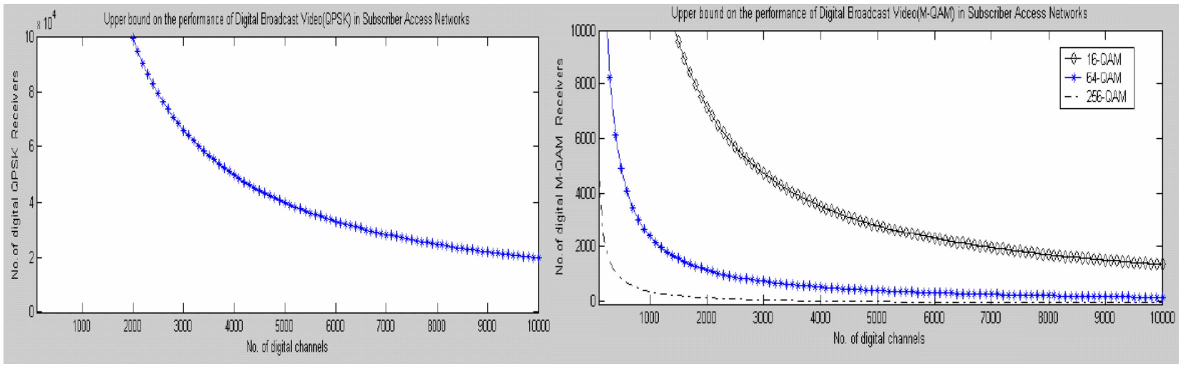

Figure 4 Number of Digital Receivers with number of digitally modulated channels mounted on one wavelength

3.3 ANALYSIS OF HYBRID MULTICHANNEL AM-VSB/M-QAM VIDEO LIGHTWAVE TRANSMISSION SYSTEMS WITH SWITCHED SERVICES

For hybrid analog/digital transmission over an optical fiber, the induced in-band clipping noise will significantly degrade the reception performance of M-QAM signals. This BER degradation is mainly caused by clipping behavior of laser diode. The analytic expression for the uncoded BER of M-QAM signal in a hybrid multichannel AM-VSB/M-QAM is [5]

$$P_e = \frac{1-(\frac{1}{\sqrt{M}})}{\log_2 \sqrt{M}} . \left\{ \gamma \left[erfc \frac{\Delta_1}{\sqrt{2}} + 2.25\gamma \frac{\phi_3(\Delta_3)}{(2+\gamma G)^2} + 5.25\gamma^2 \frac{\phi_5(\Delta_3)}{(3+\gamma G)^3} \right] + (1-\gamma) erfc \sqrt{\frac{1.5\Gamma_g}{(M-1)}} \right\} \tag{6}$$

$$\Delta_i = \sqrt{\frac{3\Gamma_g}{(M-1)(1+i\gamma^{-1}G^{-1})}} \quad i=1,2,3 \quad \Gamma_g = P_{av}/(\sigma_g^2 R_S) \quad \phi_k(z) = H_k(z).\frac{\exp(-z^2)}{2\sqrt{2\pi}} \tag{7}$$

Where $H_k(z)$ are Hermite polynomials. γ is the clipping index denoting the clipping probability per symbol interval. σ_g^2 is the Gaussian noise variance.

The average power per channel is

$$P_{av} = \frac{m_q^2.(RGLP_s^{in})^2}{2} \tag{8}$$

The different noises variance are [3]

$$\sigma_g^2 = i_c^2 + 2e(RGLP_s^{in}) + (RIN)(RGLP_s^{in})^2 + 4R\eta e n_{sp}(G-1)L^2GP_s^{in} \tag{9}$$

The first term in Equation (8) corresponds to thermal noise followed by shot noise, Relative Intensity Noise and beat noise respectively. The clipping noise that was modeled as Poisson statistics, the variance of which can be given as

$$\sigma_I^2 = (4\tau / 3).\pi^{(-3/2)}.\mu^5.\exp(-1/\mu^2).(RGLP_s^{in})^2 \quad where;\ \mu^2 = N_1.m_a^2 + N_2.m_q^2 \tag{10}$$

m_a, m_q are RMS modulation indices of AM and QAM channels.

N_1, N_2 are the number of AM and QAM channels respectively. μ^2 is the RMS modulation index, τ is the mean duration of clipping impulses [6] [7] that can be expressed mathematically as

$$\tau = erfc(1/\mu).(1/2\gamma.R_s) \tag{11}$$

R_s is the symbol rate (Baud Rate) of M-QAM. Equations (9) and (10) show that the clipping noise has got contributions from both AM and QAM clipping distortions. However, the dominant part will be from the clipping of AM signals because the QAM signals normally require much less power than AM signals.

$$CNR_{total}^{-1} = CNR_{shot}^{-1} + CNR_{thermal}^{-1} + CNR_{sig-sp}^{-1} + CNR_{RIN}^{-1} + CNLD^{-1} \tag{12}$$

Two cases are of interest in the design of the framework, the power from the transmitter can be high or low, but there exists an optimum value below which CNR decreases with the increase in QAM modulation index. Although, at that point, the required parameters are satisfied like BER=1e-10, but being less power involved, less number of EDFAs will be supported on the bus and consequently, reduced number of subscribers in SAN. Since QAM signal power is kept at lower level than AM signal power, so in a fully loaded hybrid AM-VSB/M-QAM, the AM CNR degradation is due to clipping distortion from both AM and QAM channels upto the point when the CNR starts to increase again, then power of QAM channels become high enough (and QAM channels also act as additional AM channels as at that point and beyond that, QAM channels have got a pretty high modulation index). The key assumption still holds here, i.e. , Linearity in EDFA gain with the input signal power. $GP_s^{in} = P_s^{out}$ is the parameter that differs in high and the low power case. Once the power is low, this P_s^{out} decreases with increasing OMI, but in high power case, the increase results in increased CNR. This high power regime will be the region of operation, since enhanced number of EDFAs is supported resulting in increased number of subscribers in SAN. This power that differentiates into two different regimes of operation has to be found out through repeated simulations where the onset of CNR creeps in, although this decrease and increase in power is very small, as such QAM channel being very less, its going to have very negligible effect. The reason these two cases are considered is that, the transmission of the QAM channels in a hybrid multichannel AM-QAM system has a strong dependence on the RF power ratio between the AM and QAM channels

There are two approaches to the start of the design.

Step 1: Fix up the AM modulation index and find the number of AM channels accordingly. This maximum AM modulation depth is chosen such that CNLD criterion is satisfied Once the AM modulation index is fixed up, let the number of AM channels be varied till the desired CNR of 49.5 dB (as in this case) is obtained at the receiver end. Fix the number of AM channels and find AM modulation index accordingly. Once this number is fixed, then optimum modulation index of AM can be found out, that gives many number of AM channels with CNLD criterion fixed and CNR $\geq$ 49.5 dB. That may come out to be the value of modulation index less than or equal to the maximum AM modulation depth, the way it was found in other alternative.

Step 2: The number of subscribers and the number of QAM channels have to be determined for BER< 1e-9 and SNR > 28 dB.

Step 3: Find out the optimum modulation index of M-QAM at the minimum probability of error.

Step 4: Find out $P_{upper\lim it}^{ASE}$ in the similar fashion as was done in the previous case, it can be inferred that the optimum QAM modulation index came out to be 2.5 for probability of error of 1e-10; this parameter was fixed, the plots were taken so as to set the minimum to 1e-10 and rest of the parameters were found out from that point. It can also be inferred that 42 AM-VSB channels and 72 64-QAM channels are supported. The AM modulation index was fixed at 4.35% and the clipping index was taken as 0.008. The CNR corresponding to that point is 49.5037 dB, which is as per the requirement of SAN, with power also 12.25 dBm and 2000 subscribers per branch. As the OMI of M-QAM signal increases, the BER first reduces, reaching a minimum point, and then increases again, as the clipping of M-QAM signals begins to take effect. The minimum BER increases when the channel number increases while the optimum OMI decreases. With users per branch being 2000, the implementation of Step 4 of the algorithm, gives the number of subscribers for 64-QAM case, employing the same set of steps, optimum modulation index of 2.40 is obtained. The difference in the result, from the earlier 64-QAM case (in which the 64-QAM channels' power was less as compared to AM channels' power) is that SNR has gone up, because of the increase in power resulting in better performance of SAN in terms of the number of WDM channels that can be transmitted and number of subscribers that be accommodated. The optimum modulation index has dipped a little because, as the number of QAM channels increases that can be increased by increasing the QAM power, the optimum OMI of M-QAM decreases with the increase in BER. Rest of the analysis remains the same, with the increase in QAM channels' power resulting in increment in the number of QAM channels supported to 76 in number. Figure (5) depicts the user base size and number of WDM channels obtained from the design of the bus network. The results can be seen as maximum number of WDM channels supported as 12 and number of EDFAs supported on the bus as 15, and consequently some 30,000 number of subscribers can be accomodated without going for optical regeneration in a SAN. The results are plotted in figure5.

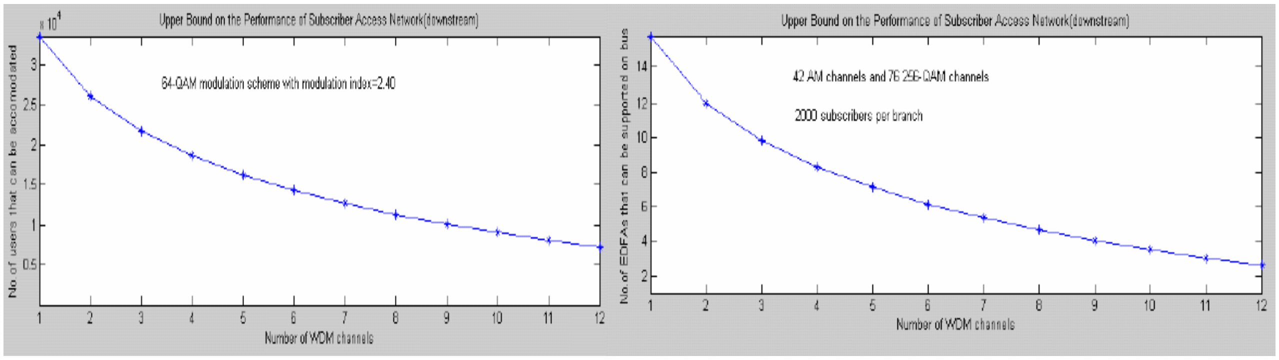

Figure5 User Base Size and Channel capacity in AM-VSB/64-QAM in SAN when 64-QAM signal is comparable as compared to AM-VSB signal power.

4 CONCLUSIONS

The future convergence of services will be a mixture of broadcast and unicast services. With digital modulation techniques already being penetrated deep into the communication sector owing to its numerous advantages, this paper accounts for digital broadcast as well as analog broadcast so as to maintain the backward compatibility with many channels that are still analog transmission based. The AM-VSB is the main modulation scheme for analog video transmission, while digital video broadcast is carried out using M-QAM/QPSK scheme. This paper gives the upper bound on the performance measures if the particular scheme is adopted and how the network can be modified to get the best performance using the WDM, also called as 'Data in a Rainbow' concept. Thus, the paper gives results for designing future light wave networks catering to the ever increasing demand for bandwidth supporting convergence of voice, video and data applications.

5 REFERENCES

[1] Andrew S.Tannenbaum: *Computer Networks*; Pearson Education.
[2] Paul Green: *Fiber Optic Networks*; Prentice Hall, Englewood Cliffs, NJ.
[3] Emmanuel Desurvire: *EDFA: Principles and Applications,* John Wiley and Sons Inc.
[4] Shiro Ryu, Shu Yamamoto, Hidenori Taga, Noburu Edagawa, Yoshihisa Yoshida, Hiroharu Wakabayashi, "Long-Haul Coherent Optical fiber Communication Systems Using Optical Amplifiers", *Journal of Lightwave Technology, Vol. 9, No. 2, February 1991.*
[5] Qun Shi, " Asymptotic Clipping Noise Distribution and its impact on M-ary QAM transmission over optical fiber", *IEEE Transactions on Communications, Vol. 43, No. 6, June 1995.*
[6] Lu, Darcie, "Broadband AM-VSB/64-QAM CATV system over HFC Network, *IEEE Photonics Technology Letters, Vol. 7, No. 4,. April 1995*
[7] K.Maeda, Morikura, "Study of BER of 64 QAM signal and OMI window of feasible operation in Analog/Digital Hybrid SCM Transmission Systems, *Journal of Lightwave Technology, Vol. 17, No. 6, June 1999.*