UPPER BOUND ON THE PERFORMANCE OF SUBSCRIBER ACCESS NETWORKS FOR DOWNSTREAM TRAFFIC CONSIDERATIONS FOR BROADBAND APPLICATIONS

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CERTIFICATE

This is to certify that the work contained in this thesis entitled "**Upper Bound on the Performance of Subscriber Access Networks for Downstream Traffic Considerations for Broadband Applications**", has been carried out by **T M Prasanna** (Y3104100) under my supervision and that this work has not been submitted elsewhere for a degree.

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Abstract

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 and optical fiber enjoys monopoly in providing long distance communication with a remarkable error rate performance. Optical communication is driven by WDM technology that employs Erbium Doped Fiber Amplifiers. WDM carves up the huge bandwidth of single mode fiber (SMF) into channels whose bandwidths are compatible with peak electronic processing speeds. The thesis deals only 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. The receiver sensitivity is compared for different detection schemes. Three cases arise as (i) Analog broadcast channels along with unicast transmission (also called switched services) (ii) Digital broadcast channels with switched services (iii) Hybrid Multichannel case. The analog broadcast is AM-VSB (Vestigial Side Band) and digital broadcast is M-QAM or QPSK modulated and they are sub-carrier multiplexed. The thesis also analyses the benefit of AM/OFDM than AM/M-QAM hybrid service in terms of bit error rate performance and proposes other schemes like Forward Error Correction coding. The simplified gain model of EDFA as a preamplifier has been adopted to exemplify its application in optical communication, and algorithm is given for the design of Subscriber Access Network, with an example design also carried out. Thus, the Wavelength Division Multiplexing (WDM) also called, as "Data in a Rainbow" concept will cater to the eventual needs of greater capacity and faster access.

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Chapter 1
Introduction

The evolution of communication technologies has envisaged the better connectivity and better services between different places in the globe. Internet and Cable Television (Common Antenna Television-CATV) has become a household name now. There is an insatiable hunger for bandwidth.

1.1 Why there is a need for more and more bandwidth?

Increased demand for bandwidth arises from a proliferation of applications such as voice, video and data as well as by the bootstrapping effect of increased consumption resulting from lower rates. The video transfer may be either of still images over internet or have moving pictures as in cable television networks. There has been a phenomenal growth in data traffic because of myriad of web pages available and their continuously increasing usage. Also, the transfer of voice traffic has increased to great limits with decreasing costs and introduction of new technologies like Voice over IP (VoIP) [Bib 1]. The emergence of digital trends in communication has given birth to better quality of audio and video standards like HDTV. The data traffic is mainly of SONET/SDH rates and trends are of packet transmission in connectionless IP networks.

FTTH (Fiber to the Home) is considered as a technology for future answering to the increasing bandwidth requirements. 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 require enormous bandwidth can be now realized. This dream is envisaged by optical communications along with Dense Wavelength Division Multiplexing (DWDM) technology.

Optical Communication using optical fibers has a virtual monopoly when bit rate exceeds a few Mbps or distances exceed a few hundred meters. WDM became the transmission technology of choice with the commercial availability of Erbium Doped Fiber Amplifiers (EDFA). Transmission System Engineering has a come a long way since then by improvements in modulation, coding, dispersion compensation and combating fiber nonlinearities' techniques. Thus, the coming lightwave transmission technologies will enhance the scope of broadband (voice, video, WWW) applications.

1.2 The race for Bandwidth continues with WDM…but how?

With the public network at crossroads, since data traffic is surpassing voice traffic, the bottleneck at the physical layer started being felt and multiplexing schemes were thought of as a viable solution. With Space Division Multiplexing (SDM), Time Division Multiplexing (TDM) and WDM being in the picture, the question was to employ which multiplexing scheme so as to make the best use of the vast bandwidth available in the optical fiber, and WDM technology was the preferred choice owing to some engineering reasons.

DWDM is a transmission technology that utilizes a composite optical signal carrying multiple information streams, each transmitted on a distinct optical wavelength. The concept of sending the whole traffic over one fiber in a multiplexed fashion instead of using multiple fibers in parallel is a very cost effective approach. The traffic carried on an optical wavelength is frequently generated by some SDH (Synchronous Digital Hierarchy) equipment containing mostly voice that is the mainstay of conventional telecommunication networks. The Time Division Multiplexing (TDM) functionality of SDH, i.e, combining lower rate streams into higher rate streams is available with the DWDM equipment and this integration of TDM multiplexing functionality with DWDM contributes to the cost savings in the network economy. The single DWDM amplifier replaces multiple SDH regenerators, thus reducing the unit cost of bandwidth. Also, since WDM supports many channels of lower bit rates, the distance limit due to chromatic dispersion is much larger for WDM systems than for equivalent TDM systems. Similarly, Polarization Mode Dispersion (PMD) does not impose significant distance limitations at lower bit rates. The WDM approach results in an increase in transmission capacity in a modular fashion by adding wavelengths whenever the capacity increase is required rather than having the whole big infrastructure in the starting itself as of in TDM approach. WDM systems being transparent to different bit rates and protocol formats (Data Link Layer and Network Layer issues) is an added advantage as it follows the complete layered approach enabling the upgrade in the network without many intricacies. TDM is limited by electronics speeds, because to have the receiver electronics operating at very high bit rates places pressure on today's VLSI technology, although the electronics for lower bit rates are being deployed successfully, thus making WDM a practical option. WDM carves up the huge bandwidth of single mode fiber (SMF) into channels whose bandwidths are compatible with peak electronic processing speeds. Reliability issues give WDM an edge over higher speed TDM systems as the latter's reliability is not that well quantified. Also, WDM Add Drop Multiplexers/ Demultiplexers (ADMs) can be used to bypass through traffic without terminating them in SONET equipment, thus reducing the number of Synchronous Optical Network (SONET) ADMs needed in the network resulting in network cost savings effectively. Needless to say, today's fiber based access networks use a combination of these access schemes with WDM-SCM combination (Appendix A) already being deployed on most of the regional and access networks, thus employing the benefits of both.

With DWDM being adopted on backbone/trunk routes; the physical layer constraints have been reduced to a lot more extent. Thus, this "Data in a Rainbow" concept will cater to the eventual needs of greater capacity and faster access and will leapfrog to an Ultra Long Haul DWDM technology for transoceanic distances in the near future.

1.3 Fiber based Access Networks- An Overview

The plethora of information being available stimulated the deployment of networks [1] for sharing, thus giving 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 conventional telephone networks and cable television networks differ in many respects like in bandwidth considerations and switching techniques, but with the merging of services, the access networks were made to be compatible with all types of traffic. Access networks can be further classified as feeder networks; the one that is between Hub/Head-end and the Remote Node, and distribution networks between the Remote Node (RN) and the Network Interface Unit (NIU). Distribution networks are classified as broadcast and switched networks. Broadcast networks are well suited for broadcast services with all

NIUs being identical and intelligence in them only, accounting for their easy deployment. On the contrary, switched networks being more suitable for switched services, with much easier fault location than the former one and NIUs being simpler, resulting in the intelligence in the network

Classification of traffic according to their nature as bursty, like internet traffic or non-bursty, as telephony or video, has driven the classification of feeder networks accordingly. Bursty services do not require the dedicated bandwidth link, as it will be more efficient to share a total large bandwidth among many NIUs, with some form of media access control (MAC) [1] protocol being required to coordinate access to the shared bandwidth by the NIUs. The disadvantage of the approach is that the receiver electronics has to operate at the total bandwidth of the network as opposed to the bandwidth needed by the NIU as in dedicated bandwidth link. Dedicated bandwidth link based networks are able to give each NIU a certain Quality of Service (QoS) guaranteed.

The future access networks are aimed towards supporting the convergence of services with Integrated Services Digital Network (ISDN) providing 128 Kbps and Asymmetric Digital Subscriber Line (ADSL) [1] providing higher bandwidths than the former one being already deployed. But with ISDN suffering from bandwidth limitations and ADSL being limited by distance in the final leg, it led to the development of FTTC/FTTB/FTTH technologies as access networks for the third and fourth generation lightwave systems. The FTTC/B/H approach has a higher initial cost, but provides bandwidth deeper in the network and proves to be a better long time solution.

With nowadays networks being classified as Broadcast and Select for broadcast services and Wavelength Routed Networks [2] for switched services, the future calls for the hybrid of both to support the hybrid of services. The distribution network need not be a point-to-point link specifically. It can be any network in itself like star, bus, mesh, ring [3] or hybrid of them. For example, the ONU can give connection to an Ethernet Local Area Network (LAN) [1] or Fiber Distributed Data Interface (FDDI) networks [2]. The ONU may be a simple passive device such as an optical star coupler or a static wavelength router. The number of NIUs/RNs that can be supported in a network is limited by the splitting loss in the star coupler. The design of networks as regional or access networks is different in approach owing to some long distance impairments like chromatic dispersion being dominant in the former one. Also, power budgets play a significant role in the design.

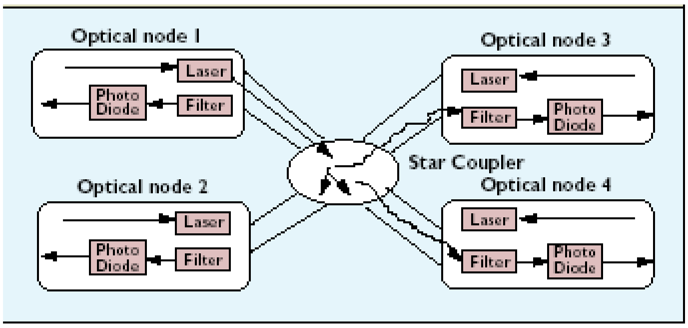


Fig 1.1 Broadcast and Select Network.

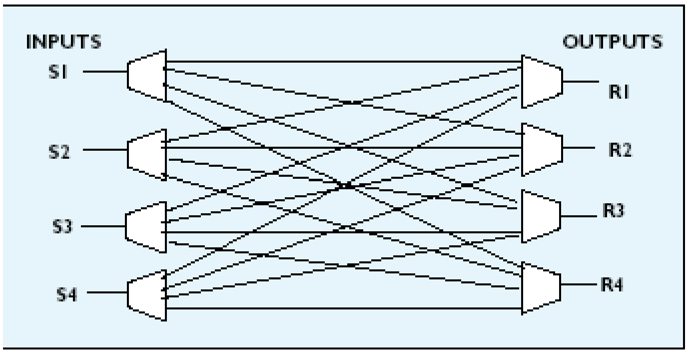
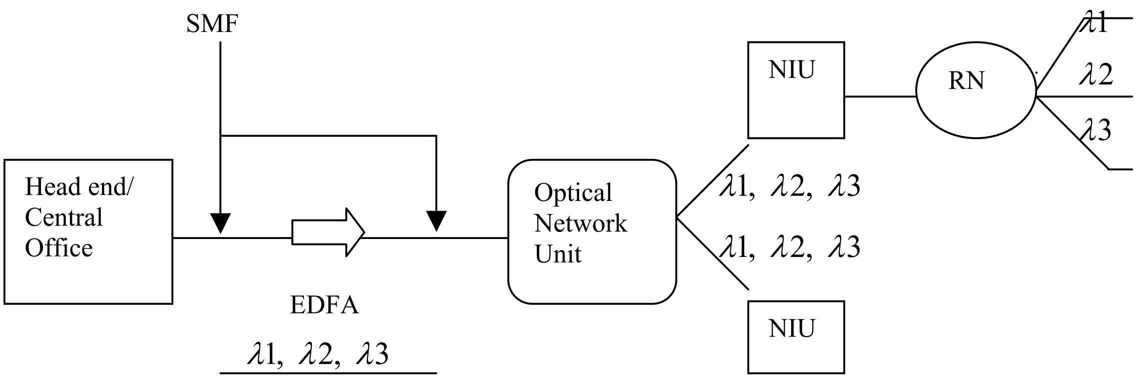


Fig 1.2 Wavelength Routed Network

(Figures 1.1 and 1.2 taken from Communications of the ACM, Vol 42, No.6, June 1999)

A wavelength routed network carries data from one access station to another without any intermediate optical to electronic conversion and is referred to as an 'All Optical Network'. The following figure shows a rough sketch of access network as employed in this thesis. It is a wavelength-routed network in the distribution part and a broadcast network in the feeder part thus catering to the hybrid requirements of Broadband communications.



1.4 Migration towards Broadband Applications

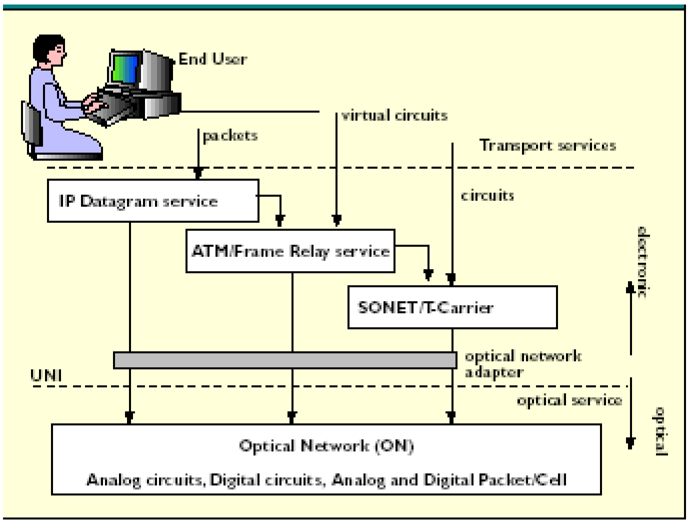


Fig 1.3 Broadband Services in a nutshell.
(Figure taken from the website: http://www.ini.cmu.edu/ITC/TPRCpaper_final.pdf)

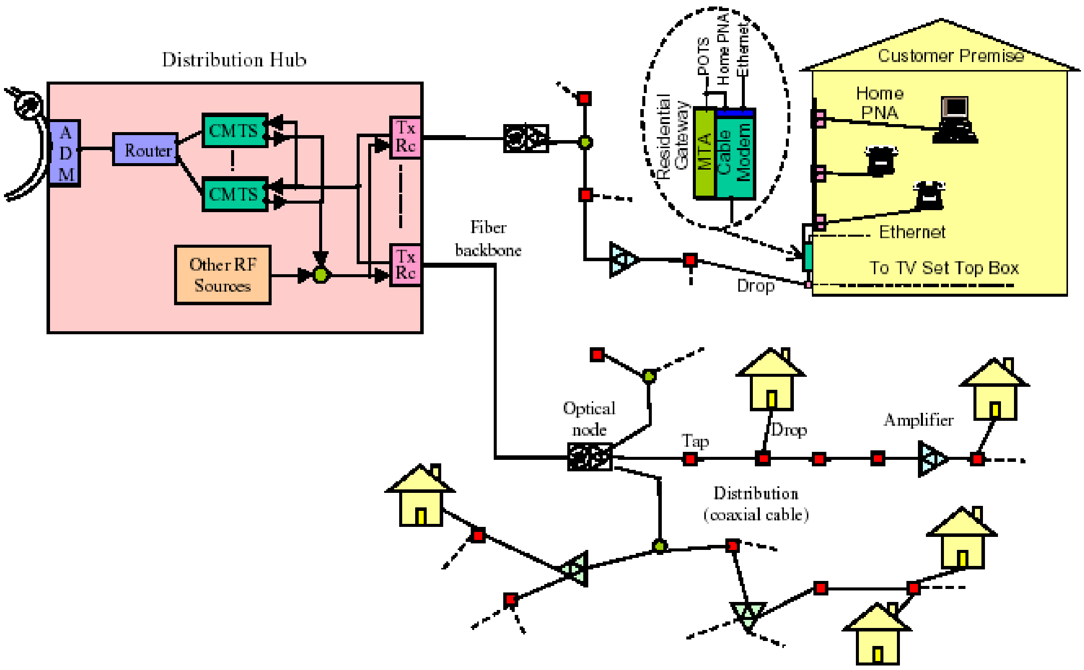


Fig 1.4 Overview of a fiber based optical Network
(Figure taken from the website: http://www.ini.cmu.edu/ITC/TPRCpaper_final.pdf)

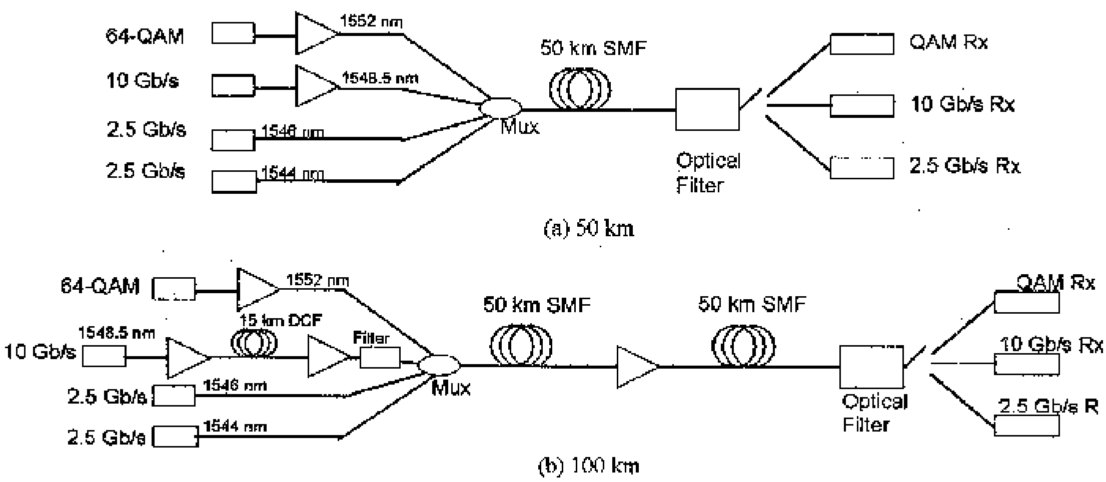


Fig 1.5 Simplified schematic of Broadband Network.

A broadband network is different from the conventional telephone or CATV networks in the sense that it has to support the high data rate in addition to low bandwidth requirements with certain QoS. The broadband networks are bi-directional with applications being classified as symmetric or asymmetric ones. To achieve the low installed costs, Sub Carrier Multiplexing (SCM) [4], [Bib 2]; passive optical splitting, FTTC techniques are being employed. The network is designed to provide high quality broadband services, while simultaneously achieving low installed fiber costs and affording graceful migration to High Definition Television (HDTV) and digital video. The use of passive optical splitting at the ONU enables the cost of transmitter and fiber plant to be shared by various subscribers. The upstream requirements differ from the downstream ones in the bandwidth requirement, as the latter ones account for more. The upstream transmission can be carried out at different wavelengths so as to avoid interference as the same fiber is used for both, thus enabling full duplex operation. The passive splitter at the ONU should also include the provision for switching other than the star coupler that acts as a splitter. With CMOS switches being well adopted for this purpose, the switching requirement is satisfied for switched applications along with broadcast ones. Although the designing of a whole broadband networks involve issues of other layers like network protocols (Network Layer), signaling protocols (Data Link Layer), use of Transmission Control Protocol (TCP)/ Internet Protocol (IP) as a part of transport layer in networks, this work aims at the topic from the physical layer point of view and involvement of other layers in the design can be taken as an extension of the same providing full fledged services. Other possible extensions of the work is in making it bidirectional and introduction of queuing analysis in the networks to account for latency in the delivery of packets from the source or among peer-to-peer transmission in the network.

1.5 Issues pertaining to System Design

The design of any network whether it is a long distance regional network or a short distance LANs, involves many issues to be taken care of. Topology, size of the network, receiver base size, transmitter and receiver tuning characteristics, choice and placement of amplifiers, power budget driving the number of amplifiers/regenerators are some of the cardinal factors ruling this design arena [3]. Designing has to very well complement the optimization of resources; the most important ones are maximum transmitter power and the optical fiber bandwidth. Many of the factors are interdependent.

- The receiver must receive the minimum required power for a given Bit Error Rate (BER) so that the number of users that can be supported can be made maximum. The power distribution to receivers must be done in such a fashion that receivers with smaller dynamic range can be used.
- With amplifiers' cost being reflected in the unit cost of the bandwidth, the design should try to reduce their number without compromising much on power budget. Also, other passive components like Multiplexers, Demultiplexers and couplers should be minimized.
- Transmission has to be carried out in the proper window. With optical fibers being less lossy in 1550 nm window, the transmission needs to be done in this range. This low loss in the fibers, resulting in more power at the receiver will straightly help in the enhancement of the number of users.
- Topology must be designed in such a manner that it can be easily upgraded at a later date when demand arises. For this, MAC protocol that helps to coordinate the sharing of common resources should be made independent of the number of users.
- Topology Selection should be aimed towards increasing the users base. Transmitters and Receivers can be made variably tuned to support WDM transmission, but attention must be given to the fact that protocols need to be modified depending upon the number of channels covered by the tunable range.

- Receiver Sensitivity, i.e, the average optical power required to achieve a certain bit error rate at a particular bit rate has to be taken special care of. Error Control Coding can be done to improve coding gain resulting in an improvement in receiver sensitivity, thereby improving the power budget. Choice of receivers as p-I-n FET or Avalanche Photo Diode (APD) governs this issue.
- Similarly choice of transmitters like distributed feedback laser with externally modulated or directly modulated governs the power budget. Modulation schemes have a say in BER limitations. Other impairments like crosstalk, nonlinearities in fiber bound the system parameters.
- Types of fiber like Single Mode Fiber, Multi Mode Fiber or Large Effective Area Fiber (LEAF) decide the dispersion factor, choice of amplifiers like EDFA or Semiconductor Optical Amplifier (SOA) and their placement strategies play a significant role in the design of modern day networks.
- Cascaded amplifiers' impairments like Amplified Spontaneous Emission (ASE) noise and interchannel spacing issues need to be considered. Interchannel spacing must be kept optimum so as to maximize the number of channels transmitted as well as to reduce the Inter Symbol Interference (ISI) problem.
- Bandwidth narrowing of cascaded multiplexers/demultiplexers places a stringent requirement on laser wavelength stability and accuracy. Equalization for the variation of signal powers and Signal-to-Noise Ratios (SNR) must be dealt with. Last but not the least; the proper wavelength planning is required.

1.6 Thesis Outline

Chapter Two deals with the need of Sub-Carrier Multiplexing and the concept of All Fiber Video Distribution (AFVD) and the brief description of Erbium Doped Fiber Amplifiers along with the bird's eye view of detection schemes, architectural considerations, the details of which can be found in standard textbooks.

Chapter Three gives the results for all analog broadcast, all digital broadcast and hybrid services. It gives the analysis of the number of subscribers along with the number of EDFAs and number of WDM channels that makes towards convergence of services.

Chapter Four deals with the onset of new technologies in this arena like the employment of Orthogonal Frequency Division Multiplexing (OFDM). This chapter also accounts for the practical issues that crop up during the design of a practical subscriber access network like dispersion, non-linearities and other impairments like laser phase noise.

Chapter Five deals with conclusions and explores the future scope of extension that can be carried out in this work. They can be taken as improvements/extension of this work and can be carried out as a sequel to it.

Appendices deal with the details of the derivations and the summary of relevant topics, to get oneself familiarized with and to get started, the references of which are appropriately stated as and when.

Chapter 2

Overview of the System

The application of broadband SCM system to both passive and optically amplified distribution networks has envisaged the All Fiber Video Distribution concept. The advent of new technologies in the field of optical communications has made the concept of broadband networks good player for practical deployment and not confining it to the four walls of research laboratories.

2.1 Subcarrier Multiplexed Lightwave Systems:

Subcarrier Multiplexing, when applied in conjunction with passive optical splitting makes up as a cost effective approach for broadband networks. Broadband Networks are the ones that support the transfer of high bandwidth data, being a good contender of services like Video on Demand. The concept behind the SCM technique is the transmission of microwave signals over optical links. SCM systems have the ability to accommodate both analog and digital modulation, to handle voice data, video, digital audio, high definition video and any future combination of services. This enormous flexibility makes them attractive option for broadband applications, for services originating from different service providers, each using different modulation formats and requiring varying amounts of bandwidth. The elementary concept behind this SCM technique is shown in Fig. 2.1.

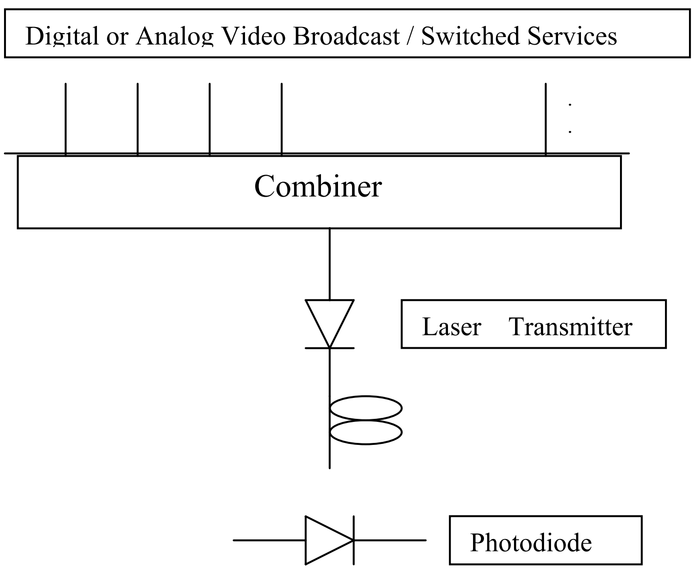


Fig. 2.1 Basic Schematic of Subcarrier Multiplexing

Optical amplification can be successfully used in SCM distribution systems to increase the number of subscribers without optical regeneration. Good number of subscribers can be accommodated by making reasonable assumptions about the amplifier gain characteristics and link budgets. SCM networks have the inherent capability to cater to the needs of enhanced bandwidth, utilizing the enormous bandwidth in single mode fiber. SCM scores high over conventional Time Division Multiplexing as the preferred approach for broadband subscriber distribution. In a nutshell, SCM offers a technique for transmitting data of many gigahertz bandwidth on each optical carrier, and allows for flexible allocation of bandwidth in response to subscribers' demand.

The key All Fiber Video Distribution (AFVD) technologies are wideband optical transmitters/receivers, multichannel video tuners and optical amplifiers. Optical amplifier performance is the key to advanced AFVD systems based on the tree branch topology because of the higher level of branching loss compensation that is required. The whole systems can be explained crudely as, the emitted light is amplified by an EDFA and distributed by the optical splitter. At the user's premises, the received light is converted back to electrical signals. Tuners are needed to select the desired channels, along with filters so as to separate out analog and digital signals.

2.2 Erbium Doped Fiber Amplifiers (EDFA):

The advent of optical amplifiers has brought a phenomenal revolution in high speed All Optical Networks, thus removing the constraints on E/O and O/E conversions, resulting in the removal of bottleneck at these nodes. Semiconductor Optical Amplifiers (SOA) and EDFAs have been instrumental in making the cost effectiveness of bandwidth today, with contribution to telecommunication and future data networks as well as convergence of services. EDFAs are superior to SOAs, although their weak points lie in their large size and difficulty in integration. The five superiorities are:

- High Output Light Power.
- Low Noise.
- Multichannel Amplification simultaneously.
- Low Distortion.
- Low Polarization dependency.

The physics behind the amplification is given in Appendix-B.

More details about this amplifier can be found in standard references [2], [3], [4] and [7]. Erbium ions in the EDFA are excited by a pumping light at a wavelength of 1480 nm or 980 nm. The weak input light, whose wavelength is 1550 nm, stimulates emission and amplified light is the output. Reflection induced CNR degradation is taken care of by input and output isolators. The long wavelength pass filter is necessary in forward pumping schemes to isolate the pumping light source. Forward pumping leads to a lower noise figure and a lower pumping light to signal light conversion efficiency than backward pumping. In forward pumping scheme, both signal and pump lights propagate in the same direction through the fiber whereas in the backward pumping, they propagate in the opposite direction. The forward pumping direction provides the lowest noise figure. In fact, the noise is sensitive to the gain and the gain is the highest when the input power is the lowest. Backward pumping provides the highest saturated output power. Bidirectional pumping scheme has a higher performance than the other two by combining the lowest noise figure and the highest output power advantageous although it requires two pump lasers. The signal gain is uniformly distributed along the whole active fiber. The flatness of EDFA gain over wavelengths is important for multiwavelength simultaneous amplification. The gain flatness of saturated EDFAs, however degrades due to gain hole burning. This gain flatness degradation limits the multiwavelength transmission system performance.

The deployment of EDFAs in Subscriber Access Networks requires the optimal design of EDFA in terms of maximization of post amplification loss, that maximizes splitting ratio while maintaining a target CNR at the receiver. The length that maximizes the gain is close to the length that maximizes the post amplification loss, so that they can be taken to be equal [10]. The computationally simplified model is assumed so as to facilitate the design process, that makes for the upper bound in the performance. The pump power and the signal power are assumed as input parameters for the design of EDFA. The output signal power can be computed from the following set of equations [10]. Q_s^{out} is in photons/second, while P_s^{out} is measured in watts ($P = h\nu Q$)

$$\alpha_p \ln(\frac{Q_s^{out}}{Q_s^{in}}) - \alpha_s \ln(\frac{Q_p^{th}}{Q_p^{in}}) + (\frac{\alpha_p}{Q_s^{IS}} - \frac{\alpha_s}{Q_p^{IS}})(Q_s^{out} - Q_s^{in}) + (\frac{\alpha_s}{Q_p^{IS}} - \frac{\alpha_p}{Q_s^{IS}})(Q_p^{in} - Q_p^{th}) = 0 \tag{2.1}$$

where the known wavelength dependent constants are α_s, α_p.

$Q_s^{IS}, Q_p^{IS}, Q_p^{th}$ are absorption constants and intrinsic saturation powers of signal and pump, and threshold power of pump (power required to invert an infinitesimally short piece of fiber) respectively. $Q_s^{in}, Q_s^{out}, Q_p^{in}$ are signal input and output power and pump input power respectively.

$$Q_p^{th} = \frac{\alpha_s Q_s^{IS} Q_p^{IS}}{(\alpha_p Q_p^{IS} - \alpha_s Q_s^{IS})} \tag{2.2}$$

The equation (2.1) that is transcendental in nature can be simplified in linear form as:

$$\begin{aligned}(\frac{\alpha_s}{Q_p^{th}} - \frac{\ln(0.7)}{0.3}\frac{\alpha_p}{Q_p^{in}})Q_s^{out} &= \frac{\alpha_s}{Q_p^{th}} Q_s^{in} + \frac{\alpha_s}{Q_p^{th}}(Q_p^{in} - Q_p^{th}) + \alpha_s \ln(\frac{Q_p^{th}}{Q_p^{in}}) \\ &- \ln(0.7)\frac{\alpha_p Q_p^{in}}{Q_s^{in}} - \frac{0.7}{0.3}\ln(0.7)\alpha_p\end{aligned} \tag{2.3}$$

The value of Q_s^{out} can be used to obtain the optimum length of EDFA as

$$l_{G\max} = \frac{1}{\alpha_p}[\ln(\frac{Q_p^{in}}{Q_p^{th}}) - \frac{(Q_s^{out} - Q_s^{in})}{Q_p^{IS}} + \frac{(Q_p^{in} - Q_p^{th})}{Q_p^{IS}}] \tag{2.4}$$

Given the pump and signal powers, using Equations (2.1)-(2.3) can give gain as

$$G_{\max.} = \frac{Q_s^{out}}{Q_s^{in}} \tag{2.5}$$

Designing of Networks require the knowledge of amplifier's spontaneous noise coefficient that can also be approximated as Equation (2.6). The minimum value of the spontaneous noise coefficient, n_{sp} can be obtained by letting the pump power tend to infinity, $P_p^{in} \to \infty$, thus achieving constant inversion, and yielding

$$n_{sp}(\min) = \frac{\alpha_p \gamma_s}{(\alpha_p \gamma_s - \alpha_s \gamma_p)} \tag{2.6}$$

The parameters taken are $\begin{matrix} P_s^{IS} = 0.1435mW, P_p^{IS} = 0.3106mW \\ \alpha_s = 0.9244m^{-1}, \alpha_p = 0.8286m^{-1} \end{matrix}$

γ_s, γ_p are signal and pump gain coefficients respectively, can be evaluated from

$$\begin{aligned}\gamma_s &= \zeta / Q_s^{IS} - \alpha_s \\ \zeta &= Q_E A / \tau\end{aligned} \tag{2.7}$$

Q_E is the density of erbium atoms, A is the area of the active region, τ is the spontaneous lifetime of the inverted atoms in the upper level. ζ is taken as 2.60e+15 $m^{-1}s^{-1}$.

The model of EDFA considered is linear, whereas it results in saturation. This assumption along with the lower bound on amplifier's spontaneous noise coefficient results in the upper bound in the performance of Subscriber Access Networks.

2.3 Comparision between different Detection schemes:

Detection at the receiver end is an important consideration, since it plays a role in the receiver noise consideration. Detection schemes are compared on the basis of the receiver sensitivity, that is the number of photons required to detect a bit correctly, that has a direct relation to bit error rate. The following schemes will be compared [8],[16]:

1. Optical Preamplification with Direct Detection (for both two level signals and non two level signals).
2. Optical Preamplification with Avalanche Photodetection.
3. Optical Preamplification with Coherent Detection.

The comparision schemes involve the study of the effect of both zero and non-zero extinction ratios and signal power shall be plotted against the EDFA gain for all schemes of detection.

2.3.1 Optical Preamplification with Direct Detection (Not applicable for two level signals):

The electrical SNR can be expressed as:

$$SNR_e = \frac{P_s^2}{\frac{h\nu_s}{\eta G}2B_e(P_s+2P_o)+4P_sP_o\frac{B_e}{B_o}+2P_o^2\frac{2B_e}{B_o^2}(B_o-\frac{B_e}{2})+\frac{4kTB_e}{R}(\frac{h\nu_s}{e\eta G})^2} \tag{2.8}$$

$$where; P_o = n_{sp}h\nu_s B_o$$

The above equation is solved for 16 dB electrical signal-to-noise ratio, which is decent for many applications. P_o is an equivalent noise power, with parameters fixed as $T = 300K, B_o = 2B_e = 40GHz, R = 200\Omega, k = 1.38e-23J/K$. Assumed RZ coding with data rate of 10 Gbps. Optical Preamplification can improve the detector electrical SNR by 3 dB inspite of the fact that optical SNR is necessarily degraded by 3 dB in the process.

$$P_s^2-(SNR_e)[\frac{2h\nu_sB_e}{\eta G}+\frac{4P_oB_e}{B_o}]P_s+(SNR_e)[\frac{2P_oh\nu_s(2B_e)}{\eta G}+\frac{2P_o^2(2B_e)}{B_o^2}(B_o-\frac{B_e}{2})+\frac{4kTB_e}{R}(\frac{h\nu_s}{\eta eG})^2]=0 \tag{2.9}$$

The above quadratic equation can be plotted for signal power with the preamplifier EDFA's gain in Figure (2.2).

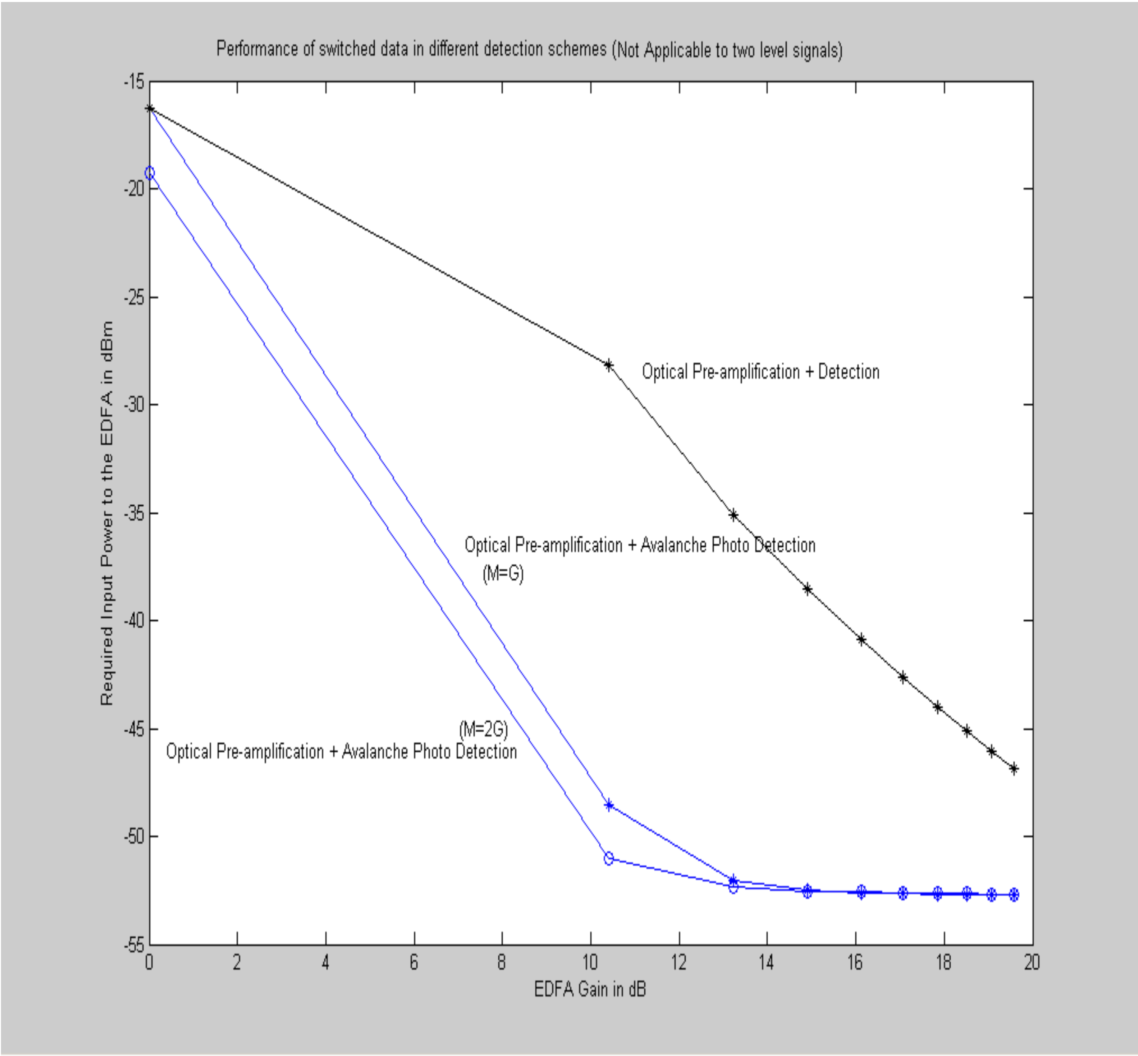


Fig. 2.2 Comparision between different Detection schemes with Optical Preamplification.

2.3.2 Optical Preamplification with Avalanche Photodetection:

As in the previous case, the electrical SNR w.r.t. EDFA gain can be expressed as:

$$SNR_e = \frac{P_s^2}{\frac{h\nu_s}{\eta G}2B_e(P_s+2P_o)F_{ex} + 4P_sP_o\frac{B_e}{B_o} + 2P_o^2\frac{2B_e}{B_o^2}(B_o-\frac{B_e}{2}) + \frac{4kTB_e}{R\langle M\rangle^2}(\frac{h\nu_s}{e\eta G})^2} \qquad (2.10)$$

$$where; P_o = n_{sp}h\nu_sB_o$$

$$\langle M\rangle : AvalancheGain$$

$$F_{ex} = ExcessNoiseFactor = \frac{\langle M^2\rangle}{\langle M\rangle} = k_i\langle M\rangle + (1-k_i)(2-\frac{1}{\langle M\rangle})$$

$$k_i = \alpha_h/\alpha_e = 0.01$$

k_i is the ionization ratio (assuming electron injection). The above equation is plotted for input signal power with respect to the EDFA gain, and for $\langle M \rangle = G, \langle M \rangle = 2G$ and plotted in Figure (2.2). $\langle M \rangle$ is the average value of Avalanche Gain and G is the preamplifier gain. However, at high data rates, receivers with optical preamplifiers are considerably more sensitive than coherent and APD receivers.

2.3.3 Digital Coherent Detection:

The IM-DD system is more susceptible to spontaneous emission from the optical amplifiers, so that the use of optical filters, which limits the bandwidth of the spontaneous emission, becomes necessary, whereas in a coherent system with optical amplifiers, the beat noise between the local oscillator light and the spontaneous emission is predominant over the beat noise between the spontaneous emission. As a result, beat noise limited state between the local oscillator light and the spontaneous emission can be achieved, which greatly reduces the requirement for the bandwidth of optical filters. Also, the waveform distortion due to fiber chromatic dispersion, which limits the transmission distance at high data rate system, can be compensated by using optical equalizers in the IM-DD systems. However, it can be electrically compensated more simply by using delay equalizers in the intermediate frequency stage of a heterodyne receiver.

Optical data is modulated in ASK, FSK or PSK formats. The total noise variance can be expressed by set of equations (2.11).

$$
\begin{aligned}
&\sigma_d^2 = \sigma_{shot}^2 + \sigma_{LO-ASE}^2 + \sigma_{s-ASE}^2 + \sigma_{ASE-ASE}^2 + \sigma_{th}^2 \\
&where; \sigma_{shot}^2 = \eta e.2B_e.(I_{LO} + GI_s + I_N) \\
&where; I_N = en_{sp}GB_o \\
&\sigma_{LO-ASE}^2 = 4\eta^2 I_{LO} I_N \tfrac{B_e}{B_o} \\
&\sigma_{s-ASE}^2 = 4\eta^2 G I_s I_N \tfrac{B_e}{B_o} \\
&\sigma_{ASE-ASE}^2 = 2\eta^2 I_N^2 \tfrac{2B_e}{B_o} \\
&where; I_s = \frac{eP_s}{h\nu_s}, I_{LO} = \frac{eP_{LO}}{h\nu_s}
\end{aligned}
\tag{2.11}
$$

If local oscillator power is high enough, local oscillator shot noise overcomes the detector thermal noise, then

$$SNR_e = SNR_{shot} = \frac{\eta P_s}{h\nu_s B_e}$$

$$SNR_e = \frac{SNR_{shot}}{\eta F_o(1+\frac{GP_s}{P_{LO}}) + 2(\frac{1}{G}+\eta n_{sp})\frac{GP_o}{P_{LO}} + \frac{h\nu_s \sigma_{th}^2}{\eta e^2 .2B_e GP_{LO}}} \quad (2.12)$$

$$where; F_o = 2n_{sp} + \frac{1}{\eta G}$$

$$P_o = n_{sp} h\nu_s B_o$$

P_o is the equivalent noise power. $BER = 0.5\exp(-\alpha SNR_e)$ (2.13)

where the different values of α as 0.25, 0.50 and 1 correspond to ASK envelope detection, FSK dual filter detection and CPFSK or DPSK delay demodulation, so that SNR can be obtained accordingly for BER of 1e-9. The plot of input signal power with the preamplifier EDFA gain can be expressed as Figure (2.3).

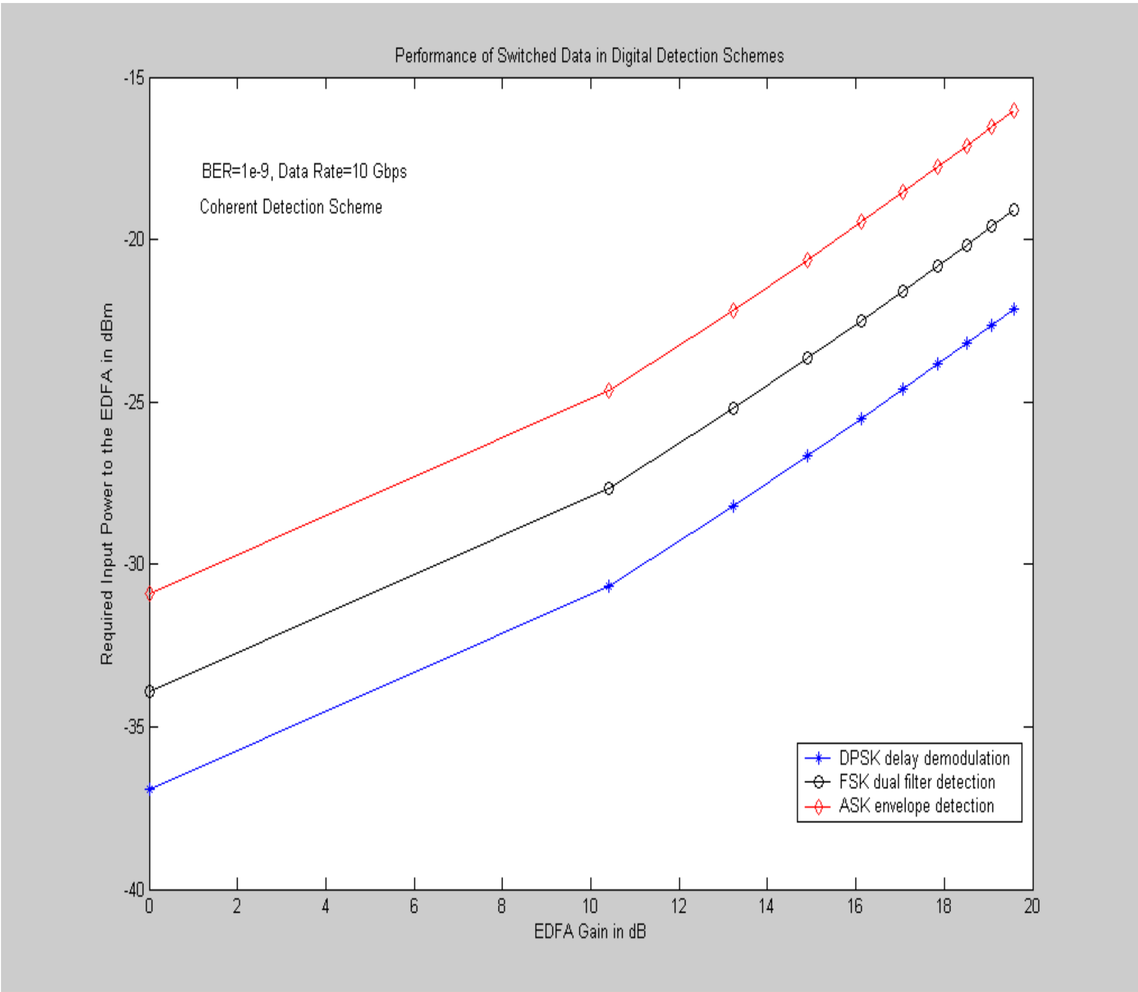


Fig. 2.3 Detection Performance in Coherent Detection Analysis.

The power penalty is defined as the receiver sensitivity degradation in decibels at the fixed BER as compared to the sensitivity without the amplifier. Higher output power in

IM-DD system will lead to undesired phenomena by the nonlinear effects of an optical fiber. However, coherent systems are used in this low amplifier output power mode to alleviate this problem of fiber nonlinearities. However, the effect of fiber dispersion is the least detrimental posing problem in IM-DD systems that accrue for its wide usage, as compared to other propositions. The above results are evaluated without the use of the polarizer at the detector. The analysis does not account for any distortion of the received data pattern caused by optical fiber. There is large frequency deviations and optical bandwidths greater than data rates causing negligible distortion.

2.3.4 Digital Direction Detection (Two Level Signals are considered with Finite and Infinite Extinction Ratios):

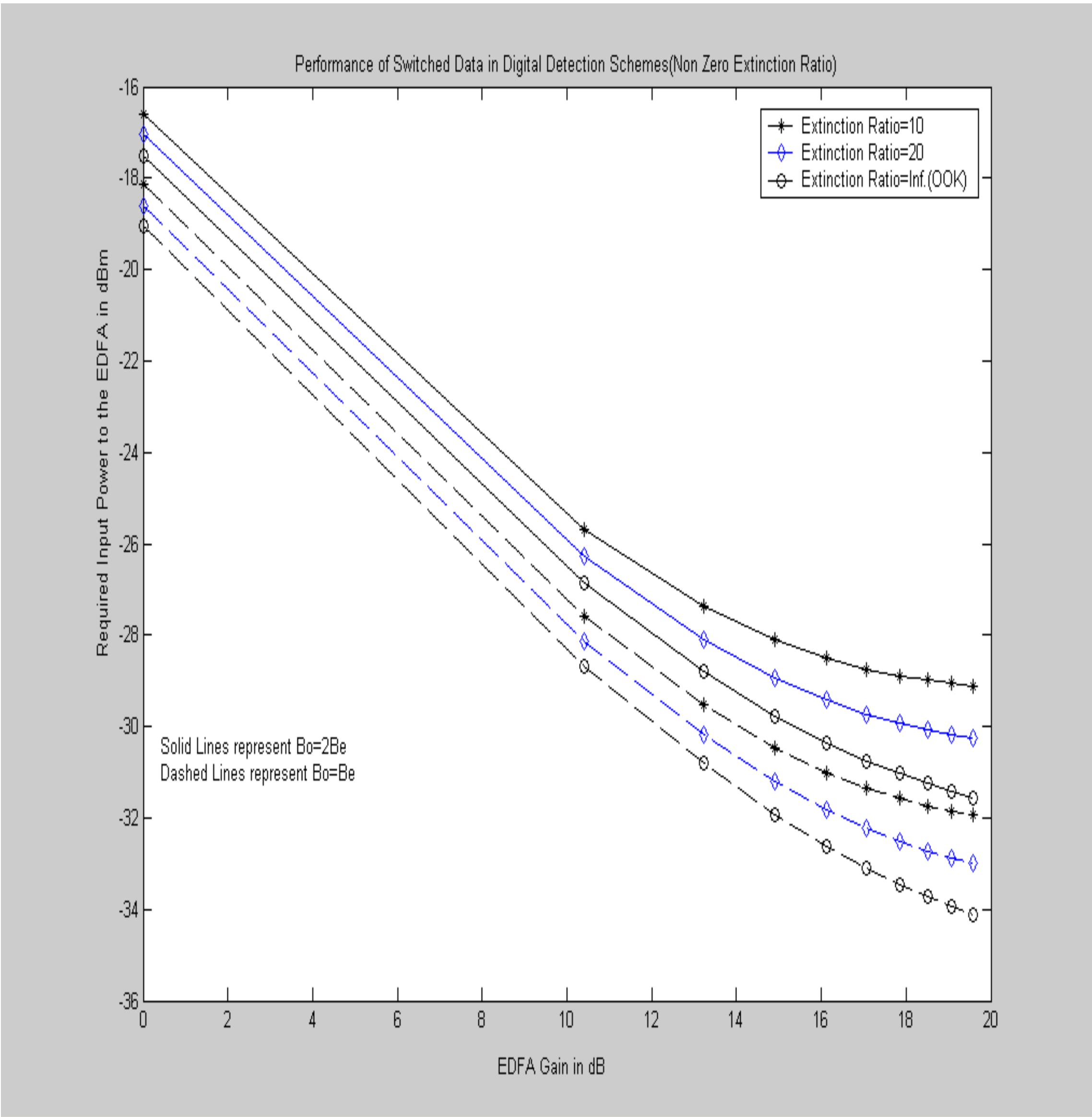


Fig. 2.4 Performance Analysis in Digital Direct detection when both finite and infinite Extinction ratios are considered.

The analysis remains the same as it was for previous cases, however, the extinction ratios are considered to be finite and the analysis are valid for two level signals.

$$BER = \frac{1}{\sqrt{2\pi Q}} \exp(\frac{-Q^2}{2})$$
$$Q : Personick' sfactor$$
$$Assume\_ASK\_scheme \tag{2.14}$$
$$N_1 = 2Q^2 (NF).k_r.\frac{(1+K_{1-0})}{(1-K_{1-0})^2} + [\frac{2Q.(NF)}{(1-K_{1-0})^2} * \sqrt{4K_{1-0}Q^2 k_r^2 + (1-K_{1-0})^2 k.k_r.k_{th}}$$

N_1 is the photons per bit for “1”. $B_e = k_r.B_r$ where B_r is the data rate and $k_{r,\min} = 0.5$, $B_{opt} = K.B_r$ where $K_{\min} = 1$, $k_{th} = (1 + \frac{i_{th}^2}{i_{ASE}^2})$, $NF = 2n_{sp}$ that gives fundamental limit on the performance.

K_{1-0} is the extinction ratio and different values of extinction ratios are considered in this work.

$$D(decision\_threshold) = \frac{\sigma_1 \langle i_0 \rangle + \sigma_0 \langle i_1 \rangle}{\sigma_0 + \sigma_1}$$
$$Q = \frac{\langle i_1 \rangle - \langle i_0 \rangle}{\sqrt{\sigma_0^2} + \sqrt{\sigma_1^2}}$$
$$SNR(1) = (\frac{\sigma_1}{\sigma_0} + \frac{\sigma_0}{\sigma_1})^2 .Q^2$$
$$Optical\_noise\_figure = \frac{(1/\eta) + 2.n_{eq}.G}{G}$$

Since the electronic bandwidth B_e of photo detectors, i.e., of the p-I-n type is fixed by carrier transit time and intrinsic capacitance, the reduction in the optical passband causes enhancement in receiver sensitivity.

2.4 Considerations of Architecture employed in Subscriber Access Network:

Architecture plays a key role in the design of the Subscriber Access Network. The choice of architecture plays a cardinal role in the better cost effective, protection enabled and restoration capable design of network that can help us in a long way to attain the objective of enhanced subscriber base coupled with better throughput. There are many architectures that can be employed, each one leading to different performance with different subscriber base.

The architecture can be drawn as:

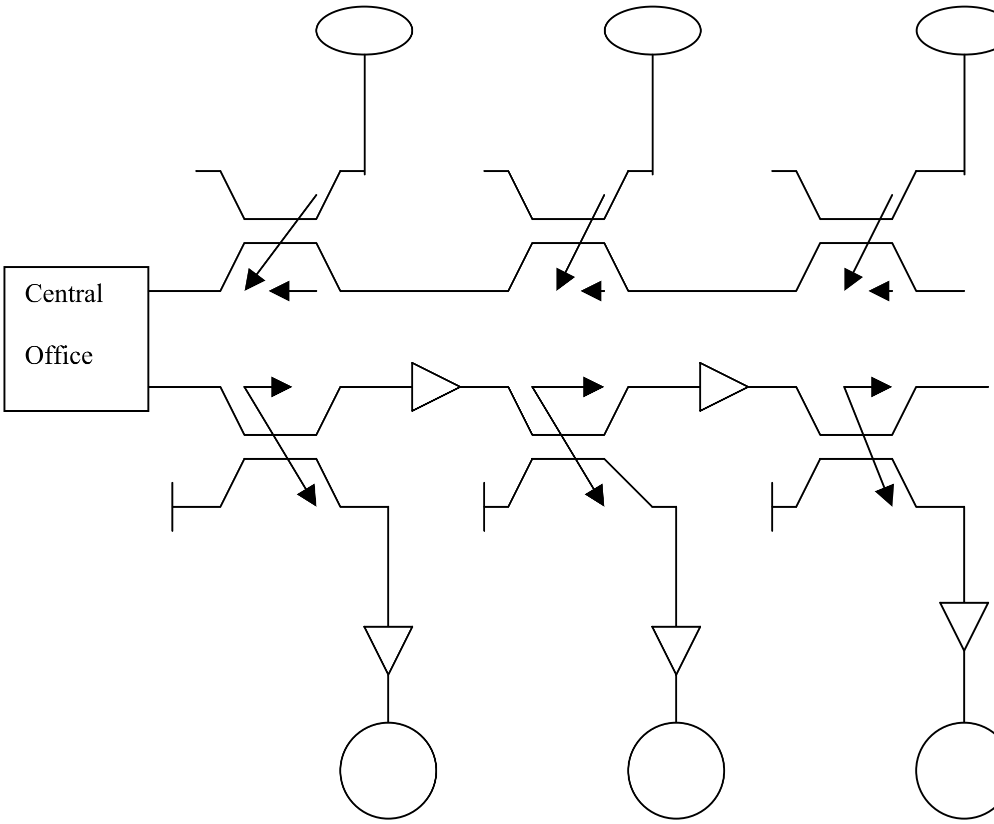


Fig. 2.5 Architecture employed in this work for the design of Subscriber Access Network.

The couplers used in the design of the subscriber access network is wavelength flattened 3-dB coupler that is capable of giving 50:50 division at all wavelengths in the desired window of transmission that makes it a suitable candidate for use in the WDM environment. The dual bus topology is used in which two separate fibers are used for upstream and downstream transmission; the other variant of this architecture is the use of the single fiber for both upstream and downstream traffic.

Ring architecture [2] has also gained the sufficient popularity for the design of the network, due to its self-healing characteristic. Fiber Distributed Data Interface (FDDI) employs fiber as a transmission medium, in these self-healing rings; creating alternate paths and providing isolation of faulty links increase reliability. FDDI uses two counter rotating rings. It employs a loop back mechanism for high reliability in case of node failures. Passive optical rings can provide high reliability because failure of a node does not break the ring. But the power budget poses a limitation on the number of users that can be alleviated using optical fibers. Star topology is an old player in this area that distributes optical power equally at output ports; therefore it results in the support of maximum number of users without amplifiers as compared to other topologies. Star couplers can be implemented in different topologies in itself like transmissive and reflective star coupler. The existing conventional topologies can be modified so as to support more number of users and to support different services.

The architecture that is employed in this work suits better for Subscriber Access Network for convergence of services in terms of simplicity in design and better performance. Other variants of the same architecture can be employed to obtain different performance, as per requirements. The above architecture can be modified to multilevel accordingly, so that more number of users can be accommodated. However, for analysis purpose, the above architecture is considered and the results can be extrapolated, to give much higher user bound.

Chapter 3
Performance Analysis of Subscriber Access Networks

This chapter gives an upper bound on the performance analysis of the Subscriber Access Networks. The reason it is called upper bound is that all impairments are not taken into account, thus practically; it will yield lesser performance, when all of them are accounted for.

3.1 Salient Features regarding the architecture:

- This is a WDM environment, i.e., many channels of different wavelengths can be transmitted simultaneously and each wavelength can contain many channels mounted on it, like, one wavelength may be containing broadcast data and the rest may contain switched data and all these channels are subcarrier multiplexed.
- This architecture forms the basis for subscriber access networks that can be used in FFTC/FTTB/FTTH concepts.
- On the Bus, we can employ EDFAs to maximize the number of branching out of it using a 3-dB coupler. We considered the splitting loss, excess loss, fiber splice loss in the network. However, we cannot employ any number of EDFAs in the network, as the upper limit is placed by the accumulation of the Amplified Spontaneous Emission Noise that progresses by accumulation along the fiber.
- Input to each EDFA on the bus that is employed as an inline amplifier is kept constant, so that gain of each EDFA is also assumed constant.
- This is a very cost effective approach, as more and more subscribers can be adhered to without incurring too much of loss.
- 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.

- For upstream considerations, we can transmit at 1310 nm window also. Although, we are using dual bus topology, the same wavelength window can also be used in downstream transmission.
- Upstream traffic will not be dense wavelength division multiplexing scenario, so that we can consider even an employment of Semiconductor Optical Amplifiers (SOAs) in the upstream bus part of the Subscriber Access Network. Employment of SOAs in the upstream traffic will be more cost effective than employing EDFAs that are more suitable for dense WDM application; as EDFAs are more costly.
- Remote Nodes contain tunable optical bandpass filter so as to separate out data of switched applications.
- At Optical Network Units, we consider losses due to splitting only, so that it has a wavelength flattened 1 x N splitter.
- Only downstream transmission will be considered, although upstream analysis will be similar and lot more easy as compared to downstream transmission.
- This work aims towards convergence of services as in next generation broadband fiber access networks, like triple play-voice, video and data.

3.2 Analysis of All Analog Broadcast along with Switched services:

Analog Broadcast can be either AM-VSB 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 post amplification loss, while still achieving the target Carrier-to-Noise Ratio (CNR).

3.2.1 Designing of a branch in Subscriber Access Network

The linearly approximated model of EDFA, as given in Chapter 2[10] is considered. For AM-VSB signals, the received signal power at the receiver (at the photo detector) is:

$$P_{signal} = \frac{m^2 R^2 G^2 (P_s^{in})^2 L^2}{2}. \tag{3.1}$$

where m is the modulation depth per channel, G is the gain of EDFA as a preamplifier, R is the responsivity 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 photodetector quantum efficiency. The impairments we consider are

$$\sigma_{shot}^2 = 2eRGLP_s^{in}B_e \text{ , where } B_e \text{ is the noise bandwidth} \tag{3.2}$$

$$\sigma_{sp-sp}^2 = 4R^2(h\nu_s n_{sp}(G-1)L)^2 B_o B_e \tag{3.3}$$

$$\sigma_{sig-sp}^2 = 4R\eta e n_{sp}(G-1)L^2 GP_s^{in}B_e. \tag{3.4}$$

We assumed that there is no polarizer used at the detector end; else this spontaneous-spontaneous noise term is reduced by half.

$$\sigma_{thermal}^2 = i_{th}^2 B_e \tag{3.5}$$

Where i_{th} is the equivalent circuit noise current density expressed in pA/$\sqrt{Hz}$.

$$\sigma_{RIN}^2 = (RIN)(RGLP_s^{in})^2 B_e \tag{3.6}$$

Where RIN is the laser Relative Intensity Noise, given by RIN=$< I_s^2 > / I_s^2$ expressed in dB/Hz and B_e is the receiver electronic bandwidth. We shall assume that nonlinear distortion is due to the clipping alone. Nonlinear distortion is caused by large excursions in peak modulation current.

$$CNLD = \sqrt{2\pi}.\left(\frac{1+6\mu^2}{\mu^3}\right).\exp(\frac{1}{2\mu^2}) \tag{3.7}$$

Where CNLD is the carrier to nonlinear distortion ratio and μ is the rms modulation index per channel related to number of AM-VSB channels and peak modulation index per channel, as

$$\mu = m\sqrt{N/2} \tag{3.8}$$

Nonlinear distortion includes intermodulation of all orders. It is a steep function of rms modulation index, that is, distortion rises rapidly as the usable index is surpassed. This accounting of nonlinear distortion is better than employing CSO (Composite Second Order Distortion) or CTB (Composite Triple Beat Distortion).

$$\sigma_{total}^2 = \sigma_{RIN}^2 + \sigma_{shot}^2 + \sigma_{sig-sp}^2 + \sigma_{sp-sp}^2 + \sigma_{thermal}^2 + \sigma_{NLD}^2 \tag{3.9}$$

Other sources of nonlinear distortion are not considered here, like Four Wave Mixing, Stimulated Brillouin Scattering and Self Phase Modulation. We shall find out the CNRs by dividing the signal power received as in Eq (1) and the individual noise variances. The reason we are assuming these noise variances as noise powers is that these noise sources are considered as zero mean random process. We shall look at the inverse of CNR, i.e., NCR noise to carrier ratio; we need to minimize the NCR, as that will result in maximization of CNR.

$$\begin{aligned}
NCR_{shot} &= 2h\nu_s B_e /(\eta GL(P_s^{in}/N)\mu^2) \\
NCR_{sig-sp} &= 8h\nu_s n_{sp}(G-1)B_e /(2G\mu^2(P_s^{in}/N)) \\
NCR_{sp-sp} &= 4B_e B_o (h\nu_s n_{sp}(G-1))^2 /((\mu^2/N)G^2(P_s^{in})^2) \\
NCR_{RIN} &= B_e(RIN)/(\mu^2/N) \\
NCR_{thermal} &= B_e i_c^2 /(R^2G^2L^2(P_s^{in})^2(\mu^2/N)) \\
CNLD^{-1} &= \mu^3.\exp(-1/(2\mu^2))/(\sqrt{2\pi}.(1+6\mu^2))
\end{aligned} \tag{3 .10}$$

We shall adopt the graphical method to find out the minima point of the total NCR. First the rms modulation index has to be found out followed by the number of receivers and the number of channels. The input signal power and the input pump power are prior information required for the design of the EDFA as a preamplifier in the branch.

$$NCR_{total} = NCR_{shot} + NCR_{sig-sp} + NCR_{sp-sp} + NCR_{RIN} + NCR_{thermal} + CNLD^{-1} \tag{3.11}$$

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 CNR_{target}	48 dB
Receiver Bandwidth B_e	5 MHz
Photodetector Quantum 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

The excess loss of the passive splitter can be given as $\gamma \log_2 N$, so that even if there are some large numbers of subscribers, then since the excess loss of single 3-dB coupler is of the order of 0.1 dB, the net excess loss can be neglected. The target CNR of 48 dB is well suited for many CATV applications, although the notion of CNR is mainly subjective, yet the value of CNR as 48 dB corresponds to a picture subjectively judged excellent. With the target CNR being fixed, the number of receivers and number of AM-VSB channels that can be transmitted on one wavelength has to be found out. Starting with the equation of NCR_{total}, we need to find out the value of rms modulation index that results in maximum CNR or minimum NCR. Differentiating that equation w.r.t. μ will be mathematically cumbersome, so we shall resort to graphical approach where we plot individual NCRs with respect to the rms modulation index. The individual NCRs are plotted for a input signal power of 5 mW, that is shown in the following Figure 3.1, from which rms modulation index can be found out.

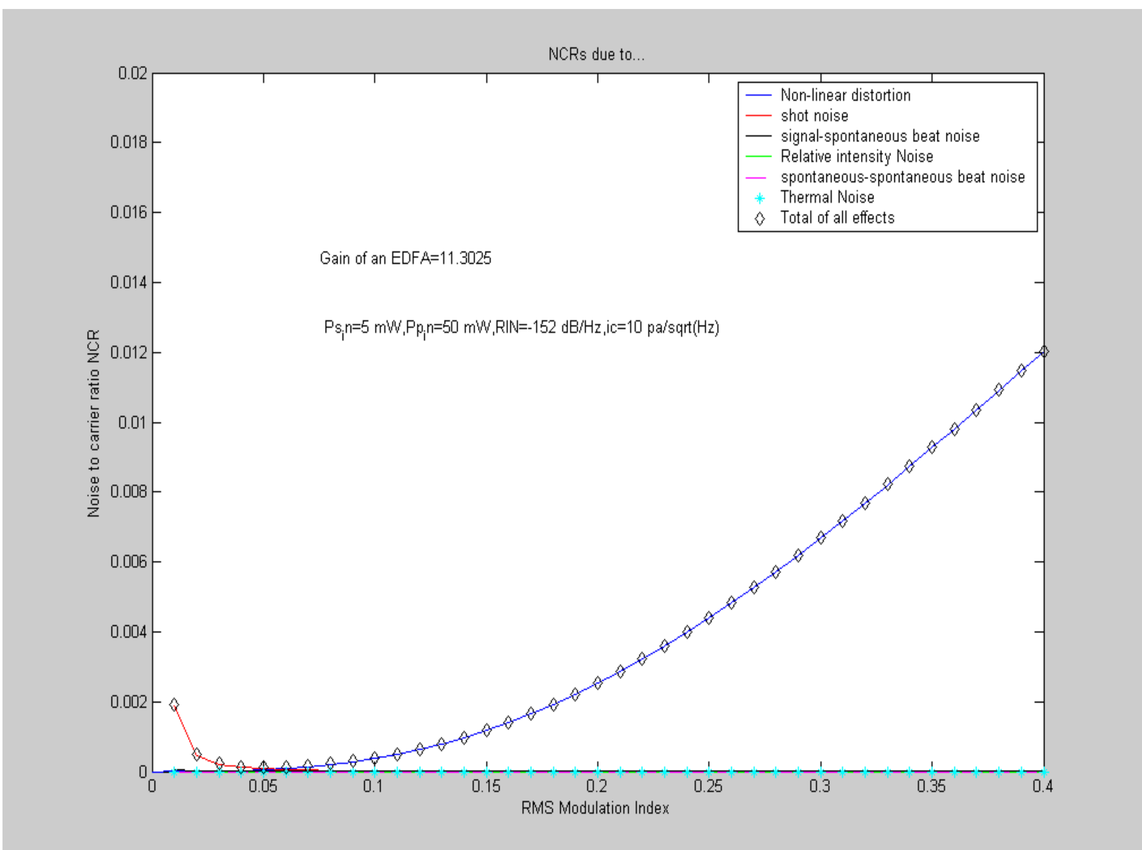


Fig. 3.1 Individual Noise to Carrier Ratios with respect to rms modulation index for AM-VSB channels.

Similar plots were obtained for other values of input signal power, as mentioned in Table 3.1; the analysis can be proceeded as:

NCR_{total} almost coincides with $CNLD^{-1}$ for higher values of rms modulation index and NCR_{total} coincides with $(NCR_{shot} + NCR_{sig-sp} + NCR_{sp-sp} + NCR_{RIN} + NCR_{thermal})$ for lower values of rms modulation index. So, the optimum value for μ comes out to be when NCR_{total} =2 $CNLD^{-1}$ (3.12)

that is when $CNLD^{-1}$=($NCR_{shot} + NCR_{sig-sp} + NCR_{sp-sp} + NCR_{RIN} + NCR_{thermal}$) (3.13)

To summarize, at the operating point, the total noise power and the nonlinear distortion power are equal. Thus, given the target CNR, we can find the rms modulation index from equations (3.7) and (3.12) by making $NCR_{total} = NCR_{target}$. For simulating the Figure 3.1,we assumed the value of post amplification loss L as shot noise=signal spontaneous beat noise + spontaneous-spontaneous beat noise*. This choice of point corresponds to increasing the post amplification loss where shot noise starts to dominate upon which any further increase in the loss can prove detrimental to system performance.* In the case considered, since the target CNR is 48 dB, solution of the above transcendental equation (3.7) and (3.12) yields the value of μ=0.2756.

Now, from Equation (3.10) and (3.11), where L=1/M, the whole post amplification loss is attributed to signal division, employing Equation (3.12) in it yields the relation between number of AM-VSB receivers (M) and the number of AM-VSB channels (N) as

$$M = G * (61996.28) * ((P_s^{in} / N) - 3.39e - 5) \tag{3.14}$$

For different values of input signal power as 1, 3.2, 5, 10 mW, different graphs are obtained where N is plotted from 20 channels onwards. This relationship is plotted for different values of P_s^{in} and shown in Figure 3.2. As signal power increases, more and more number of receivers and number of broadcast channels can be accommodated, but this results in other complications also, as input power cannot be increased freely. The pump power of EDFA can also be increased for more gain and better performance. However, this work is done by fixing the pump power at 50 mW, so as to avoid the change of all parameters simultaneously.

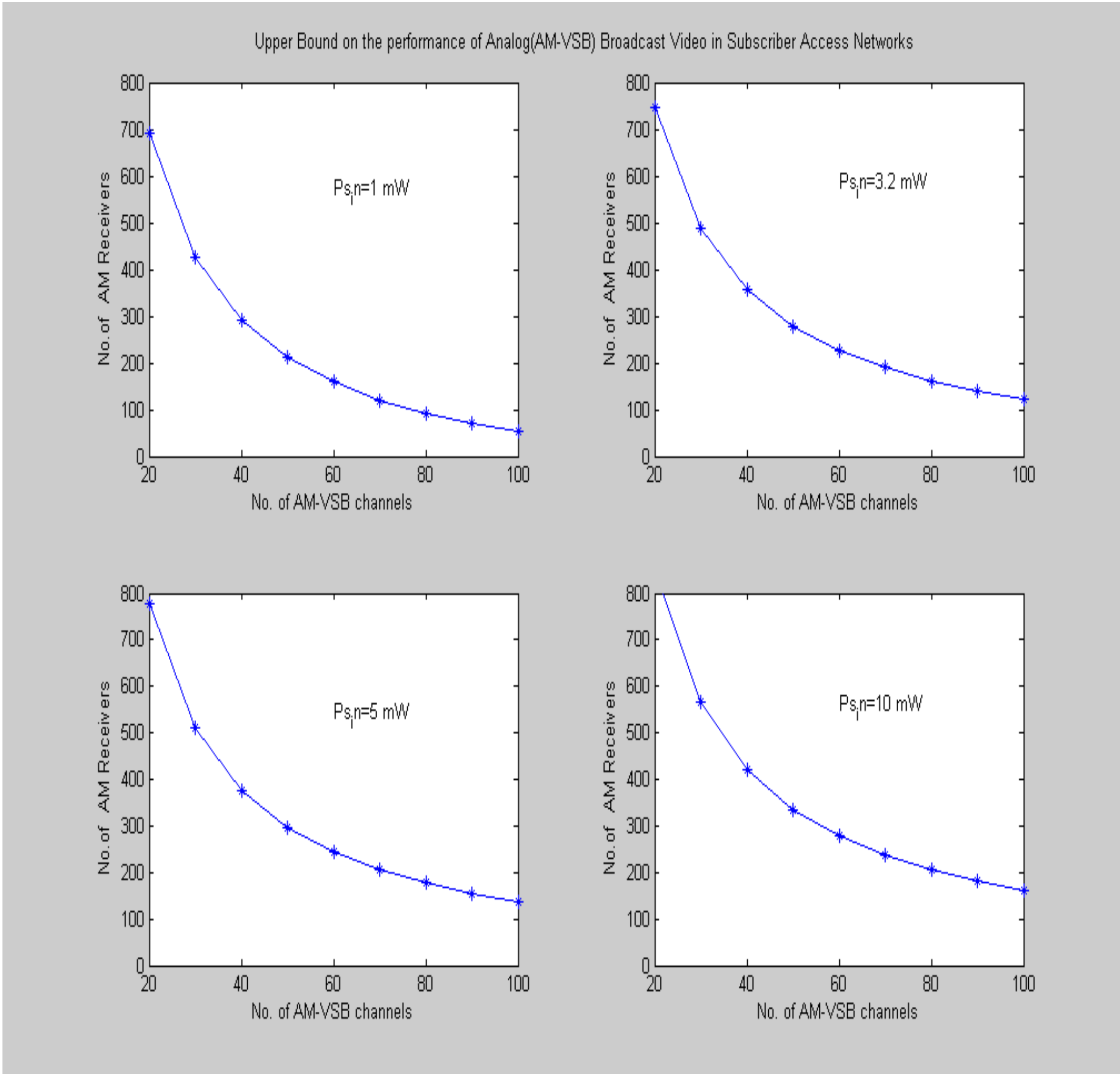


Fig 3.2 Number of subscribers in one branch w.r.t. Number of AM-VSB channels for All Analog Broadcast.

The Subscriber Access Network is for broadband services, so along with AM-VSB broadcast, there will be FM-Broadcast channels also, at a different wavelength as a part of WDM scenario, although FM being economical in terms of power requirement, but scores less in terms of bandwidth efficiency. FM transmission has lesser CNR requirement as 17 dB. Since, AM-VSB requires more power than FM channels, so their power criterion will drive the choice of the number of receivers. For FM-SCM broadcast channels, the relationship is given for the input signal power and the gain of EDFA as a preamplifier, and the same is plotted in Figure 3.3. The impairments considered are shot noise, signal spontaneous beat noise, spontaneous-spontaneous beat noise, thermal noise, Relative Intensity Noise. Nonlinear distortion can be neglected due to its diminutive effect. The expression for $P_{s\ FM}^{in}$ can be expressed as

$$P_{s\ FM}^{in} = \frac{\kappa}{\eta}.h\nu_s.B_e.\left(\frac{1+2\eta n_{sp}.LG}{LG}\right)\left(1+\sqrt{\frac{1+(\sigma_{th}^2/e^2.B_o.B_e)+(2\eta n_{sp}LG)^2}{\kappa(1+2\eta n_{sp}LG)^2}.\frac{B_o}{B_e}}\right)$$

(3.15)

where $\kappa = \left(\left(\frac{m^2}{2.CNR_d}\right) - B_e(RIN)\right)^{-1}$ (3.16)

m is the peak modulation index per channel and taken as 0.1. Figure 3.3 shows the variation of the input signal power with the gain of an EDFA as a preamplifier for some values of M (number of subscribers in one branch taken as 750, 375, 300, and 250 from Figure 3.2 as the AM-VSB power criterion drives the choice of the number of receivers and number of channels). From the plot, it can be inferred that for serving to a particular number of subscribers in one branch, the power required is very less in case of FM broadcast, as is evident.

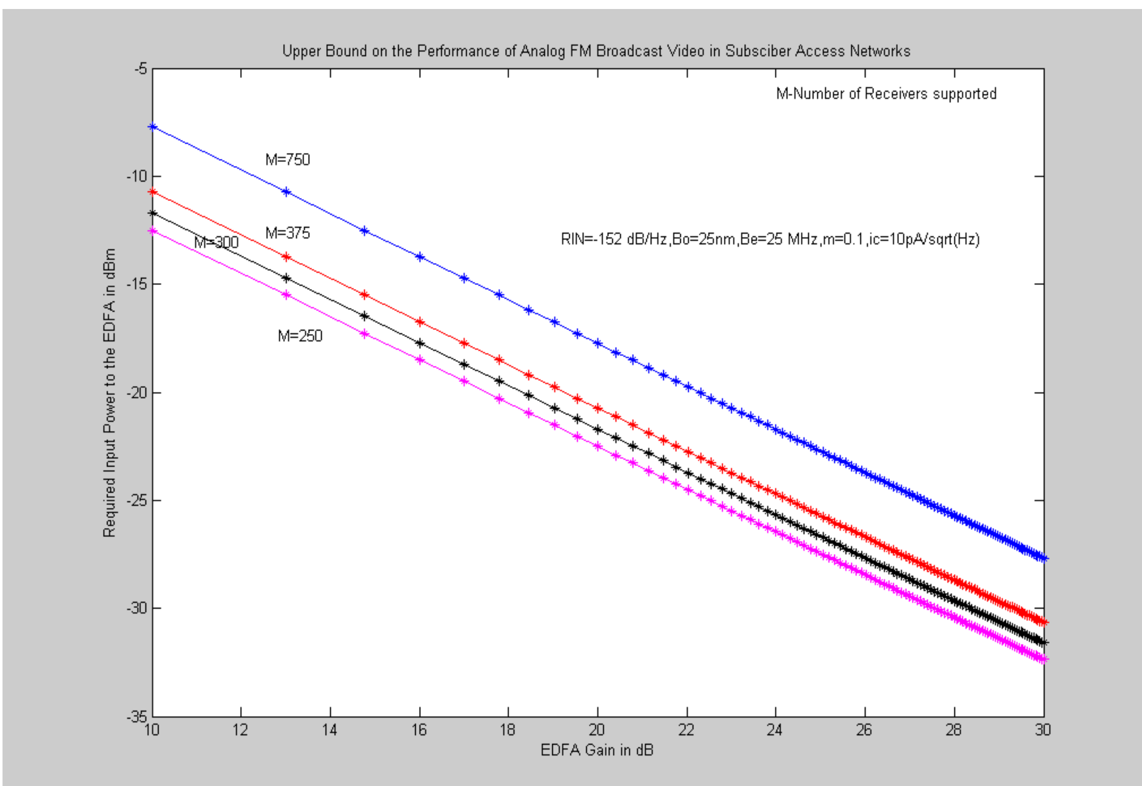


Fig 3.3 Input signal power with respect to gain of an EDFA for FM Broadcast video for different number of subscribers per branch of Subscriber Access Network.

3.2.2 Designing of bus of a Subscriber Access Network:

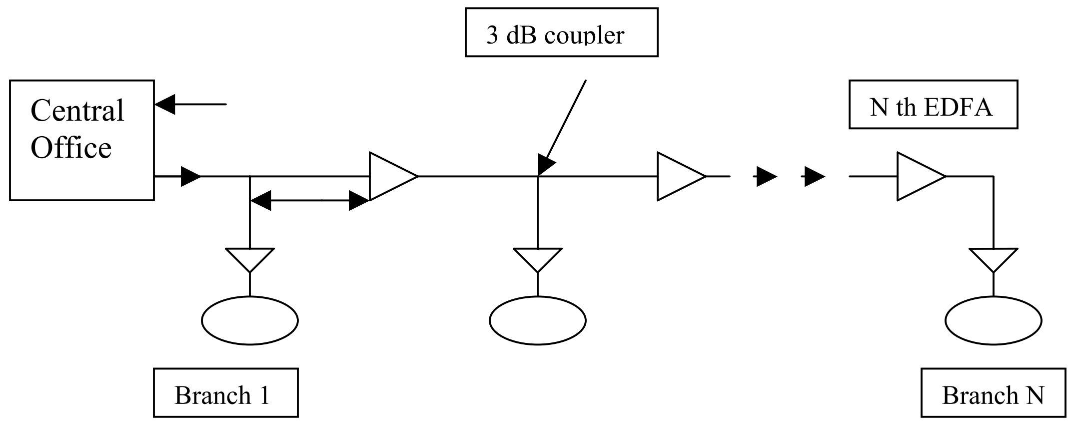


Fig 3.4 Subscriber Access Network considering downstream traffic mode only.

For N EDFAs on the bus, it could support (N+1)M number of users in SAN where M is the number of subscribers in one branch, this many number of users can be supported without optical regeneration. The 3-dB coupler is a wavelength flattened coupler to operate in the WDM scenario. The number of EDFAs supported on the bus depends on the ASE accumulation due to cascade of EDFAs in the main bus. 2-dB of loss is also assumed to account for the attenuation in the optical fiber at the rate of 0.2 dB/Km and splice/connector loss and any other loss (if there are any).

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 3-dB coupler being non-ideal introduces some loss into the splitting, by not splitting into equal halves.

$$\left(P_o\left(\frac{R^N-1}{R-1}\right)\right) \leq \frac{P_{ASE}^{upper\lim it}}{N_{ch}} \qquad \text{where} \qquad (3.17)$$

$$P_o = h\nu_s(G_o-1)B_o\eta$$

R is the loss-gain product. N_{ch} represents the number of WDM channels as we average the ASE power over one channel is averaged where G is the gain of an EDFA as a preamplifier and G_o is the gain of an EDFA as an inline amplifier on the bus. $P_{ASE}^{upper\lim it}$ is calculated keeping in mind the CNR at the receiver end or it can also be calculated as SNR for a particular BER by relation between SNR and BER. The latter method is employed for all digital broadcast to be analyzed in the next section. The SAN is to be used for convergence of services, so the total power must be inclusive of broadcast as well as 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. The limiting factor of the number of EDFAs on the bus is the ASE accumulation to a point that still helps in achieving the desired CNR of 48 dB at the receiver end. However, 50 dB CNR at the ONU level for calculation is employed. $P_{ASE}^{upper\lim it}$ is that value of ASE noise power, beyond which any further increase in ASE noise will make the CNR criterion worse than the one required for good transmission/ reception of video at the remote node. Substituting in the Equation (3.17), the following relation is obtained which gives the relation between the number of EDFAs supported and the number of WDM channels transmitted.

$$N \leq \left[\log_{10}\left(\frac{P_{ASE}^{upper\lim it}.(R-1)}{N_{ch}.P_o} \right) + 1 \right] . \frac{1}{\log_{10} R} \tag{3.18}$$

Since, it is convergence of services concept, only broadcast signals will be present all the time and the rest of switched signals may be there or not according to individual subscribers' requirements. But, since the broadcast power is more than switched services' power by a good margin, the gain of preamplifier does not vary much and will be very much in the tolerable limits. The number of EDFAs supported on the bus can be enhanced by employment of equalization strategies like SNR equalization, power equalization, and gain equalization [12], [13]. However, they take into account that gain varies with wavelength and neglected out ASE saturation. But this work accounts for ASE accumulation, but assumed that variation of gain ($dG/d\lambda$) is very less over the particular range of interest, i.e., 1540 nm – 1570 nm, that can be obtained by doping EDFA with fluoride glass. Equation (3.18) can be used to plot the relation between the number of EDFAs supported and the number of WDM channels, as shown in Figure (3.5). The limitation on analog transmission is reflected in terms of number of WDM channels that it can support. It can be seen that four WDM channels can be transmitted at the most and the number of EDFAs supported is somewhere around seven and decreases as the number of WDM channels increases.

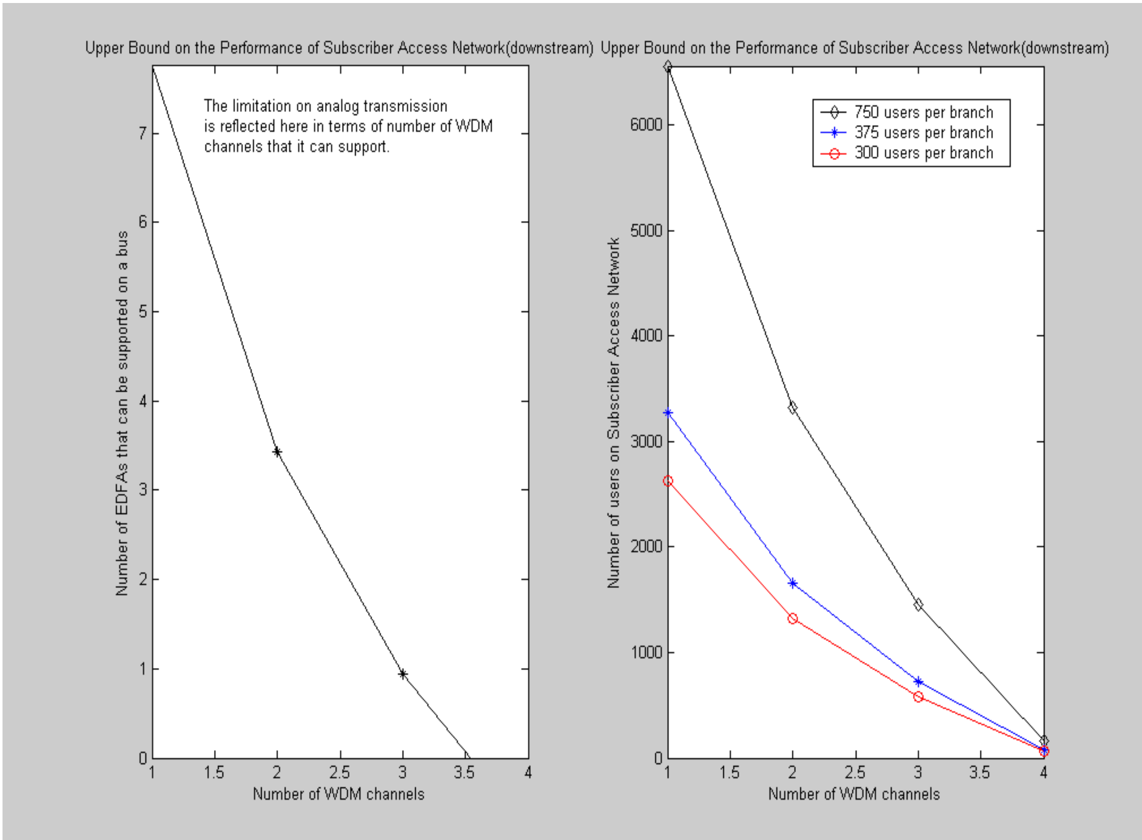


Fig 3.5 Number of EDFAs and number of subscribers in SAN w.r.t. number of WDM channels for analog video broadcast along with switched services.

From the above figure, it can be inferred that as the number of WDM channels increases, the number of subscribers go down, because, increase in the number of WDM channels cause the reduction in EDFAs supported and consequently reduction in the number of subscribers on a subscriber access network in downstream considerations.

The above designing of a SAN can be expressed in an algorithmic fashion that is shown in Figure (3.8) that will help in an optimum design with limited power budget. Thus this concludes the analysis of all analog broadcast along with switched services that has got severe limitations in the number of WDM channels and number of subscribers, thus paving the way for digital trends in communication systems.

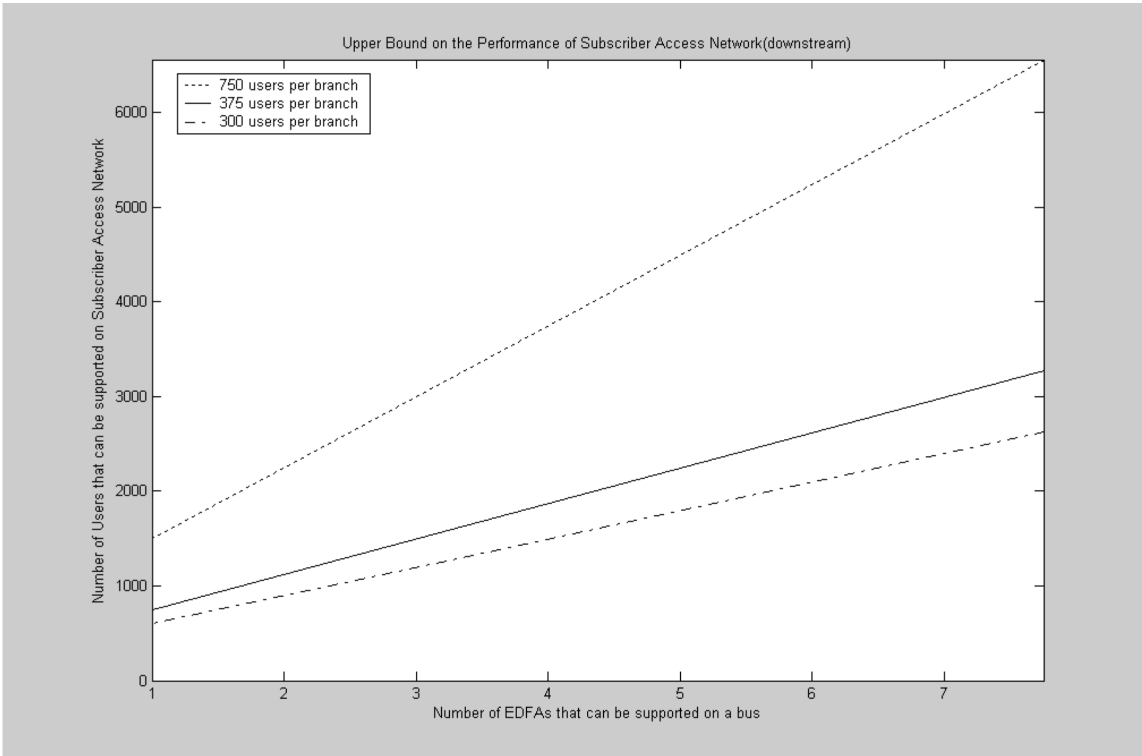


Fig 3.6 Number of users supported on the SAN with the number of EDFAs supported on bus for Analog Video Broadcast along with switched services.

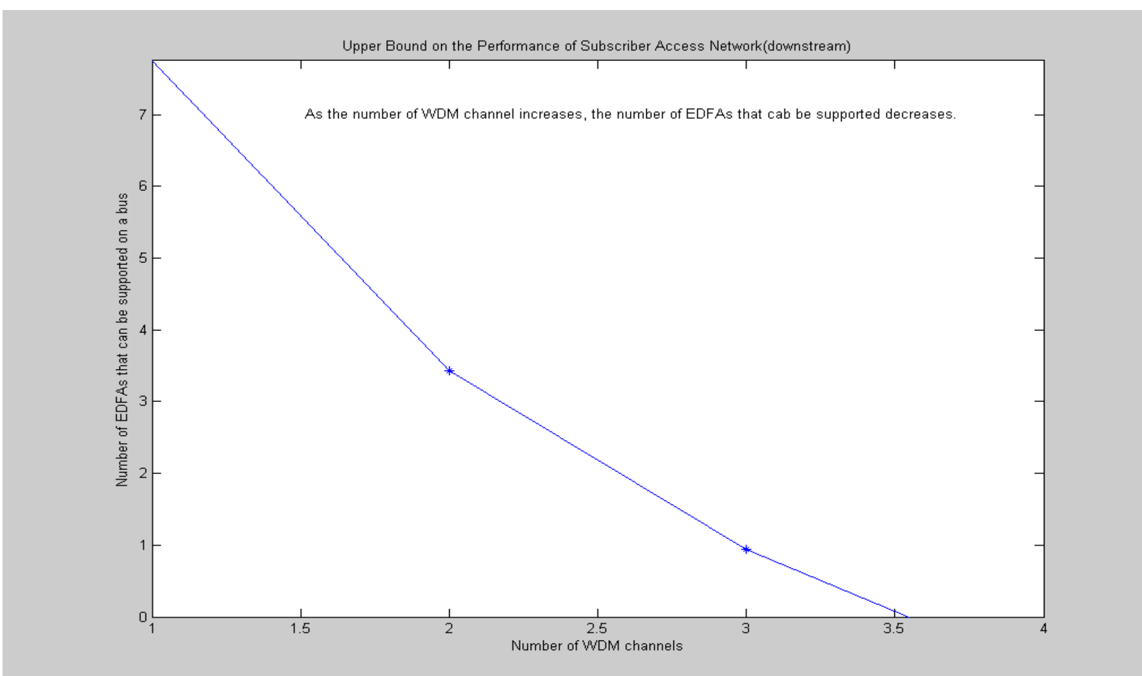


Fig 3.7 Number of EDFAs supported on the bus with respect to the number of WDM channels.

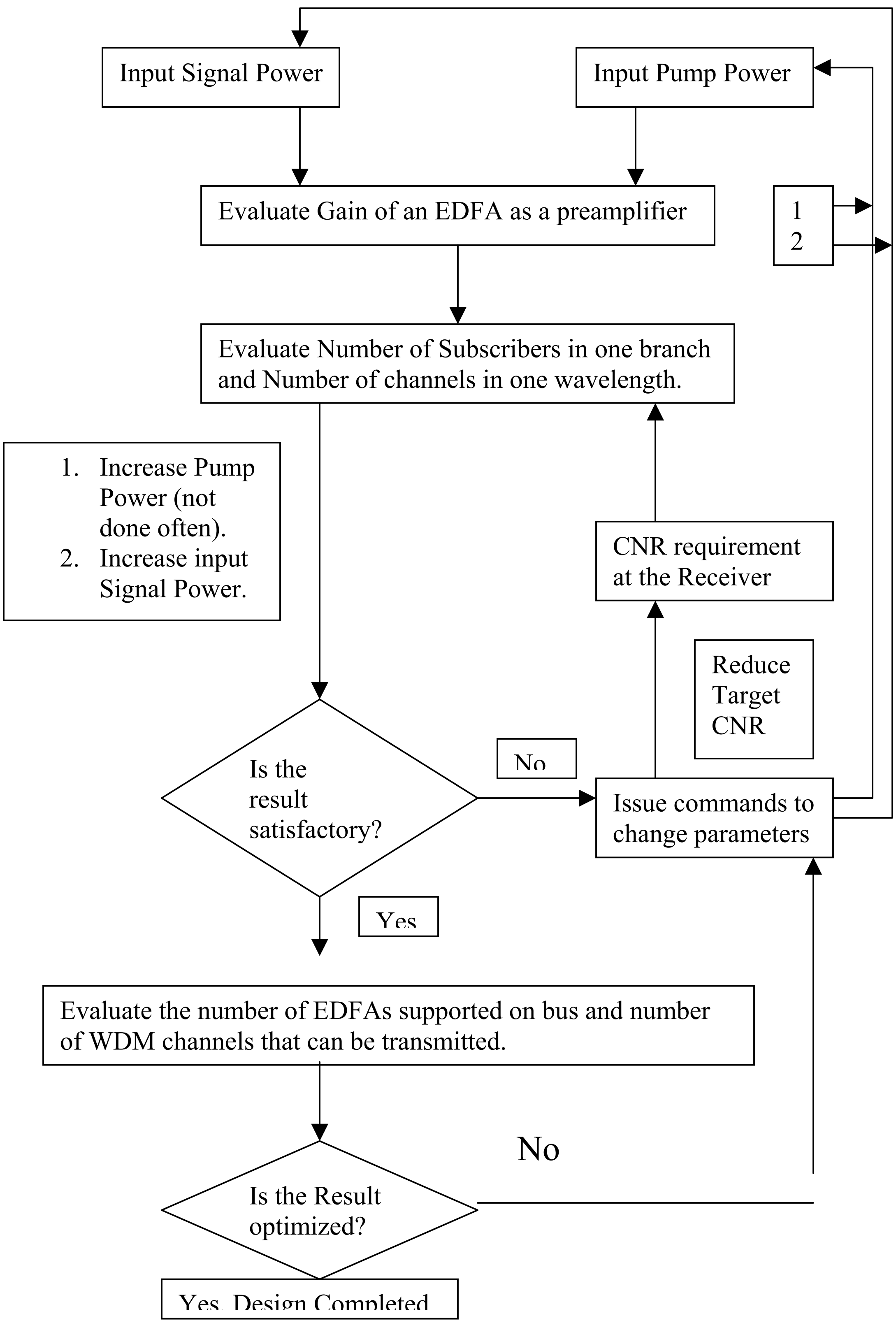


Fig 3.8 Algorithm for the optimum design of SAN for Analog Video Broadcast Services.

3.3 Analysis of All Digital Broadcast (M-QAM/QPSK) with switched services:

For all digital broadcast, since the 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 at high channel count. The nonlinear distortion due to clipping that was assumed earlier in case of all analog broadcast still holds here because the expression was independent of modulation format [14]. It is assumed that all other noise sources are independent of each other. The same sequence of steps has to be followed for the design of SAN, as was done earlier. The results can be discussed according to the figures. The target SNR was calculated according to the achievement of BER of 1e-9 at the receiver end [15],[16].

$$BER = 0.5.\exp(-\alpha.SNR) \tag{3.19}$$

where α =0.25, 0.5, 1 for ASK envelope detection, FSK dual filter detection and CPFSK or DPSK delay demodulation. It can be given in tabular form as in Table 3.2.

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 (3.1)-(3.18), 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 (3.9) shows the number of digital receivers with the number of digital channels mounted on one wavelength for QPSK and M-QAM modulation schemes (Appendix C), where M takes values as 16, 64 and 256.

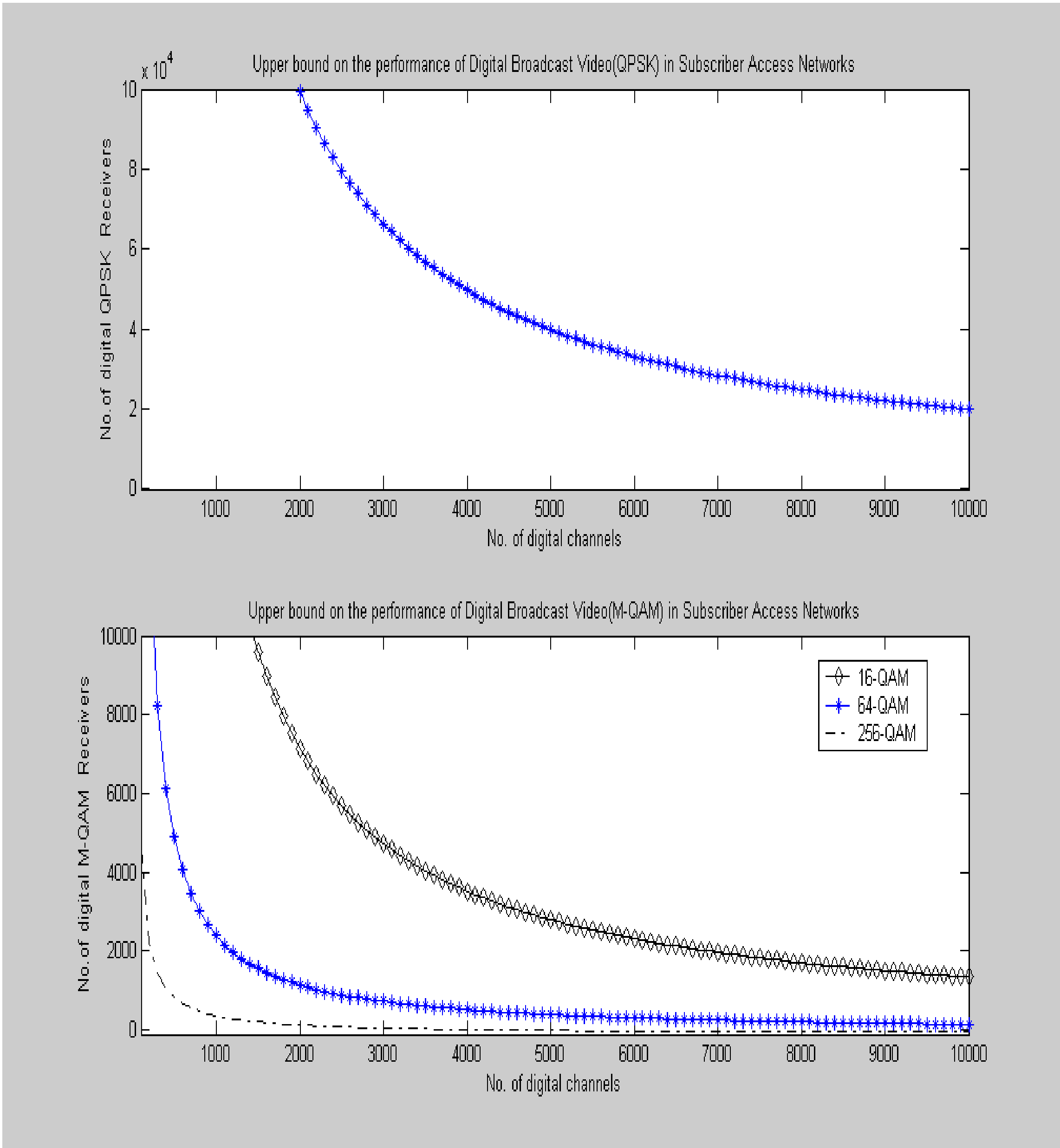


Fig. 3.9 Number of Digital Receivers with number of digitally modulated channels mounted on one wavelength for All Digital Broadcast with switched services.

The whole subscriber access network has been designed for a typical value of 3000 digital channels. From Figure (3.9), it can be inferred that QPSK supports enormous number of users; the number of receivers that can be accommodated reduces as the constellation size increases in M-QAM modulation scheme. It can also be inferred that the performance of 256-QAM is not satisfactory and to make it perform better, Forward Error Correction (FEC) coding schemes [17] have to be employed. Thus, digital broadcast of video is better than all analog broadcast in terms of both number of subscribers as well as the number of channels that can be transmitted. The same method has to be applied for the bus design also. Figure (3.10) gives the relation between the number of subscribers on a SAN with the number of EDFAs that can be supported on a bus in different modulation schemes.

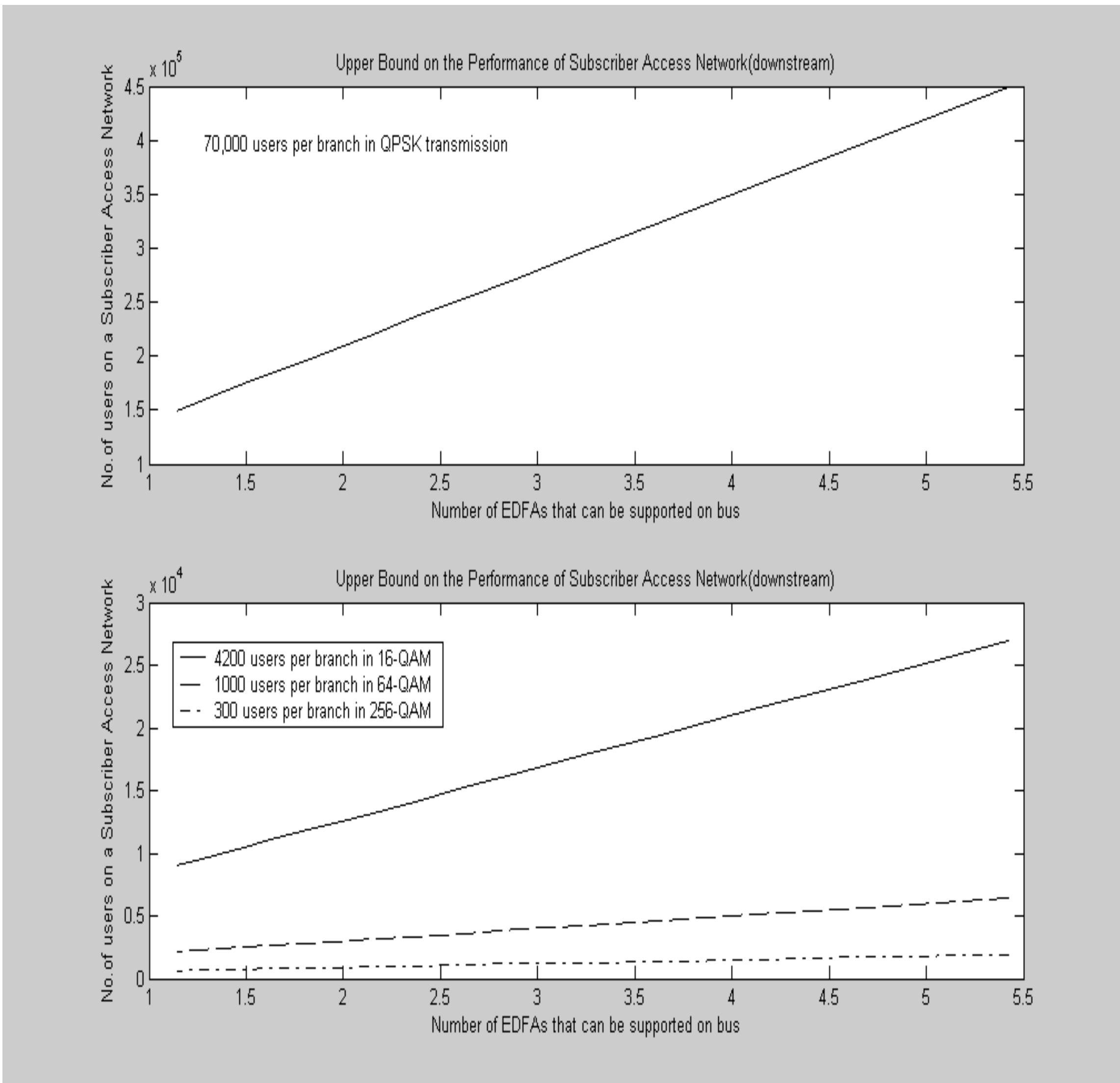


Fig 3.10 Number of Users in a SAN for all Digital Video Broadcast with Switched services.

The number of EDFAs that can be supported in analog broadcast is more by a small number. The reason may be given as, since signal power is reduced, so as ASE power, the limit might have reached earlier. However, there is a phenomenal increase in the number of subscribers with digital video broadcast catering to more than tens of thousand subscribers in a general sense, while analog broadcast services catering to something around five thousand subscribers, inspite of having more number of EDFAs in the bus. However, the main concern is the number of subscribers; in which indeed digital broadcast scores high than the conventional analog video broadcast services. Figure (3.11) gives the plot of the number of subscribers with the number of WDM channels

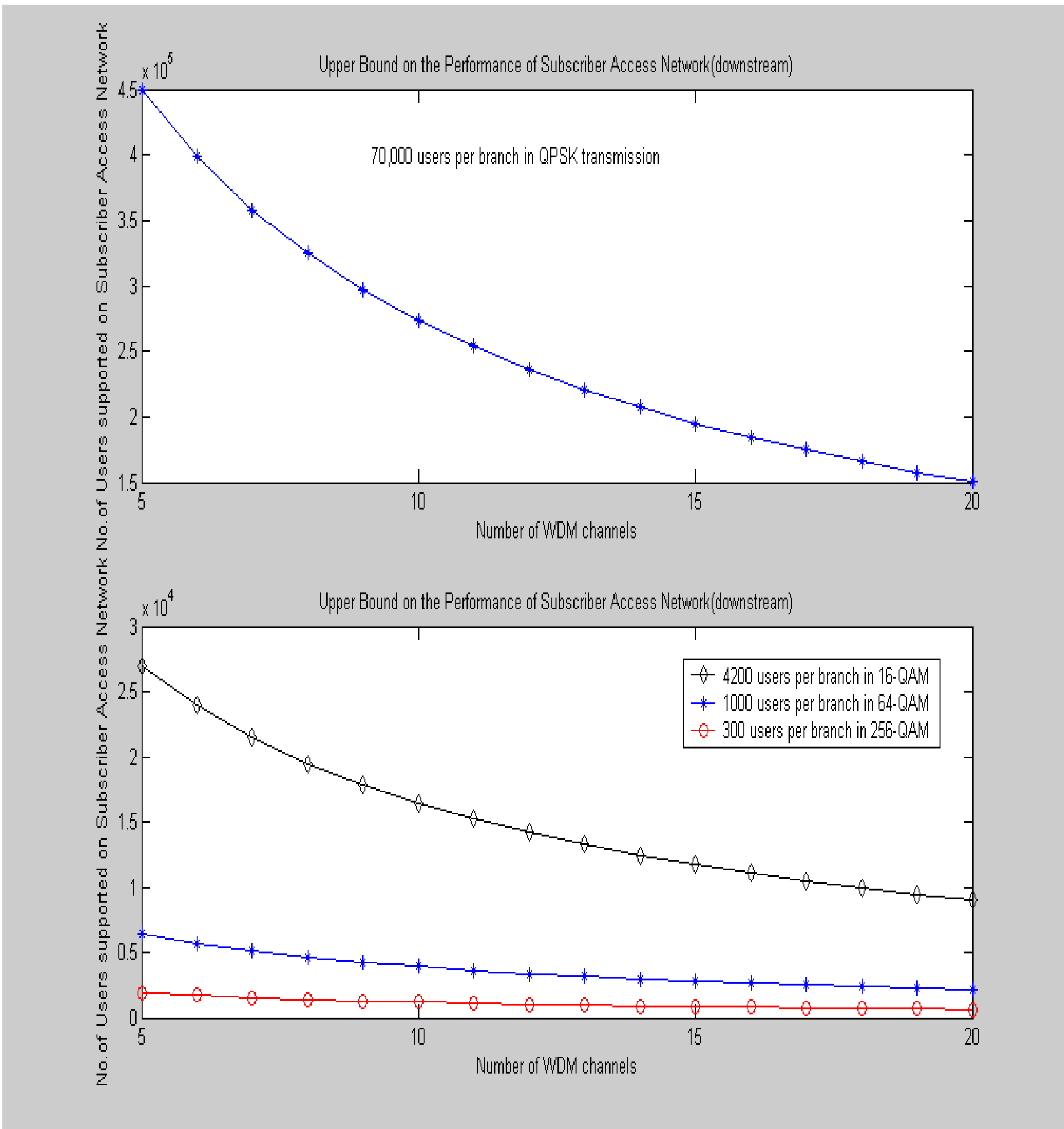


Fig. 3.11 Number of Subscribers in SAN with Number of WDM channels in all Digital video Broadcast along with switched services.

From Figure (3.11), it can be inferred that, upto 20 WDM channels can be transmitted. Again, it can be noticed that QPSK is supporting more number of subscribers and 256-QAM requiring the employment of FEC or precoding for better performance. The key assumption that was carried out is the linearity of gain of an EDFA with the input signal power that can be depicted in Figure (3.12).

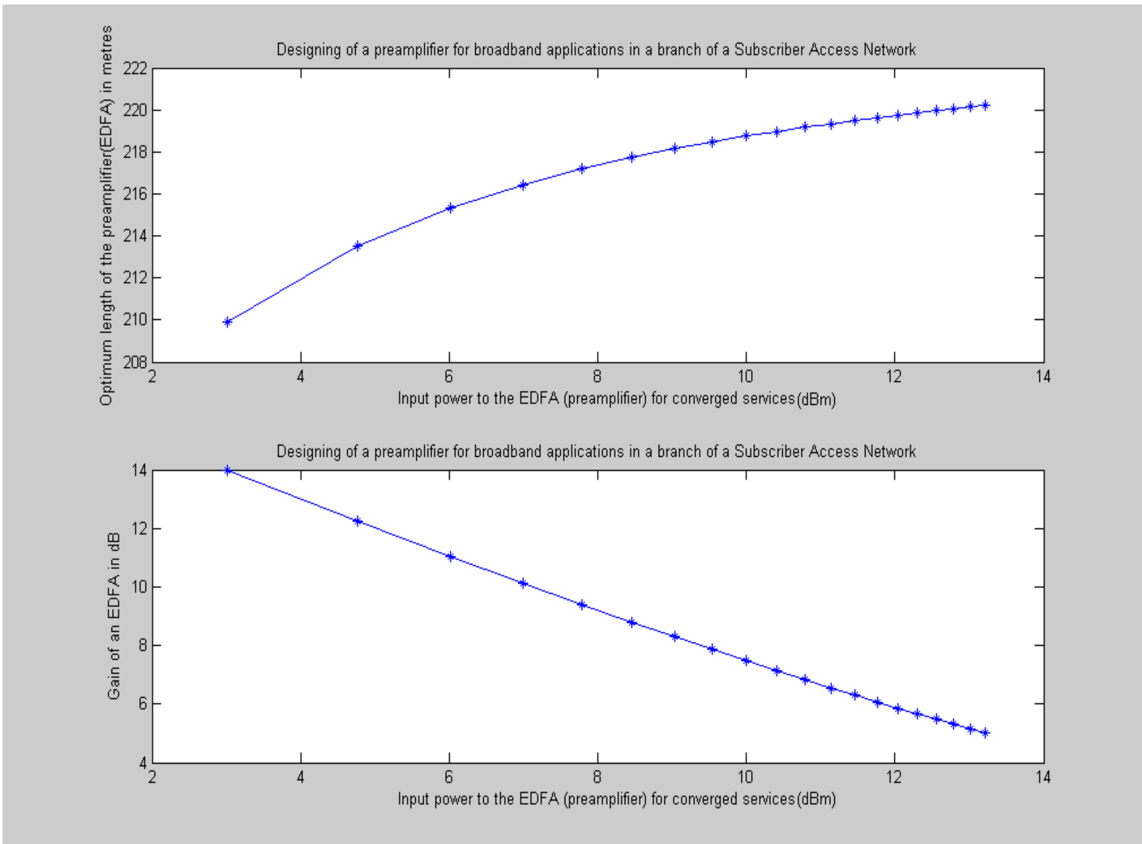


Fig 3.12 Designing of a preamplifier. The linearity of the gain of EDFA with the input signal power over the desired window of interest continues to be key assumption in this work.

The algorithmic approach remains the same what it was for Analog Video Broadcast, except that CNR limitation has to be replaced by the BER limitation at the receiver end. This digital video broadcast may be little bit expensive, in terms of the infrastructure, due to expensive set top boxes, but this technology answers to the ever increasing need for bandwidth, catering to more number of subscribers, thus, it can be vouched as a technology for future. The results were given for the case when optical regeneration is not employed, the employment of which will give a more enhanced performance. This will come into picture once graceful migration to all digital services is accomplished.

3.4 Analysis of Hybrid Multichannel AM-VSB/M-QAM Video Lightwave Transmission systems with switched services:

The motivation behind this part of the work is that multichannel AM-VSB/M-QAM SCM lightwave transmission systems are being deployed by telecom and cable television companies for simultaneous delivery of both multichannel video (broadcast nature) and interactive digital video/data channels (switched nature). 64/256 QAM schemes offer a very high bandwidth efficiency in b/s/Hz and are more robust than analog transmission w.r.t. random noise and nonlinear distortions. The digital set top box, which operates in either 64/256 QAM mode for downstream considerations enables a host of emerging interactive services like Internet access, Video-on-demand, Video streaming, IP telephony, HDTV. Now again, the upper bound on the performance, in terms of the number of users and number of channels will given, along with an algorithmic approach to the design of SAN, i.e., to find the appropriate operating point. The issues in multichannel Hybrid AM-VSB/M-QAM are lot more different from the conventional design issues. 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. The BER of M-QAM is significantly degraded and even a BER floor occurs. This BER degradation is mainly caused by clipping behaviour of laser diode. This clipping noise[18],[19] can be modeled as Gaussian as well as non-Gaussian statistics, however the impulsive and non-Gaussian nature of clipping noise imposes more severe limitations for digital M-QAM signals than the previous Gaussian approximations. M-QAM channels (N_2 in number) are located in higher frequency than AM-VSB channels (N_1 in number) under the Gaussian approximation of the multichannel input to the laser, it is shown that the output of the laser is the sum of a signal term related to laser input and a noise term arising from the clipping. This is the clipping noise and in the case of a rare clipping, the clipping noise can be modeled as a Poisson impulse train with pulse duration following Rayleigh distribution and shape following a parabolic arc and, the mean pulse duration is much smaller than the symbol duration of M-QAM. Utilizing the model, it can be shown that the asymptotic distribution of clipping noise combined with the Gaussian noise in the system approaches to the first order approximation, a generalized Gaussian distributed model which is a sum of Gaussian distributed part with the probability of no clipping occurrence and a non-Gaussian part with a probability of clipping occurrence. With a non-Gaussian statistics for the clipping noise, the analytic expression for the uncoded BER of M-QAM signal in a hybrid multichannel AM-VSB/M-QAM is[20], [21]:

$$P_e = \frac{1-\left(\frac{1}{\sqrt{M}}\right)}{\log_2 \sqrt{M}}.\left\{\gamma\left[erfc\left(\frac{\Delta_1}{\sqrt{2}}\right)+2.25\gamma.\frac{\phi_3(\Delta_2)}{(2+\gamma G)^2}+5.25\gamma^2.\frac{\phi_5(\Delta_3)}{(3+\gamma G)^3}\right]+(1-\gamma).erfc\sqrt{\frac{1.5\Gamma_g}{(M-1)}}\right\}$$

$$where;\Delta_i = \sqrt{\frac{3\Gamma_g}{\left((M-1)(1+i\gamma^{-1}G^{-1}\right)}}$$

$$i = 1,2,3$$

$$\Gamma_g = P_{av}/(\sigma_g^2 R_s)$$

$$\phi_k(z) = H_k(z).\frac{\exp(-z^2)}{2\sqrt{2\pi}} \tag{3.20}$$

The last term indicates the effect of Gaussian noise alone while the rest of the terms indicate the effect of both Gaussian and clipping noises. Bandwidth of 64/256 QAM signal is 6 MHz. $H_k(z)$ are Hermite polynomials (Appendix –E). γ is the clipping index denoting the clipping probability per symbol interval. σ_g^2 is the Gaussian noise variance.

$$P_{av} = \frac{m_q^2.(RGLP_s^{in})^2}{2} \tag{3.21}$$

Gaussian noise refers to the other kinds of additive noise in the fiber due to Laser RIN, shot noise, thermal noise.

$$\sigma_g^2 = i_c^2 + 2e(RGLP_s^{in}) + (RIN)(RGLP_s^{in})^2 + 4R\eta en_{sp}(G-1)L^2GP_s^{in}$$
$$where; L = 1/M \tag{3.22}$$

The first term in Equation (3.22) corresponds to thermal noise followed by Shot Noise, Relative Intensity Noise and Beat Noise respectively. Again, the splitting at the ONU is assumed to be passive, the way it was assumed in the earlier two cases. The clipping noise that was modeled as Poisson statistics, the variance of which can be given as:

$$\sigma_I^2 = (4\tau/3).\pi^{(-3/2)}.\mu^5.\exp(-1/\mu^2).(RGLP_s^{in})^2$$
$$where; \mu^2 = N_1.m_a^2 + N_2.m_q^2 \tag{3.23}$$

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 [24], [25], that can be expressed mathematically as:

$$\tau = erfc(1/\mu).(1/2\gamma.R_s) \tag{3.24}$$

R_s is the symbol rate (Baud Rate) of M-QAM. Equations (3.23) and (3.24) 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. Both channel capacity and Output Modulation Index (OMI) of M-QAM is limited by the presence of clipping noise which is non-Gaussian and impulsive. At the receiver end, best performance for both analog and digital channels is desired, the analysis of which requires some parameters to be fixed as:

- The desired CNR at the receiver end is 48 dB, so at the ONU, this value is kept somewhere around 49.5 dB, as the CNR of 48 dB corresponds to picture judged subjectively excellent as per CATV standards.
- CSO and CTB play a crucial role in the design, they can be modeled collectively as CNLD. CNLD can be monitored individually also, but as such it is taken into effect along with CNR considerations, as the degradation in CNLD will spill into the CNR calculations, resulting in suboptimum performance of SAN. So, this performance degrading impairment has to be taken care of.
- BER has to be better than 1e-9. This work carried out the design of SAN with BER consideration of 1e-10.
- For lower BER, the non-Gaussian modeling of clipping noise requires a much lower OMI for AM for the same BER than does the Gaussian noise model.
- Because of the presence of non-Gaussian clipping noise, only a limited number of channels can be accommodated, if signals of larger constellation size like 64/256-QAM are used.
- Large number of QAM channels can be accommodated if power ratio of M-QAM channels to AM channels is small enough.

- Transmitted signal power must also be high in the Gaussian clipping noise modeling than non-Gaussian model for M-QAM signal case. RF power ratio between AM and M-QAM signal plays a vital role in system design, as higher the ratio is, more the number of M-QAM channels can be accommodated without appreciable change in the BER.

$$CNR_{total}^{-1} = CNR_{shot}^{-1} + CNR_{thermal}^{-1} + CNR_{sig-sp}^{-1} + CNR_{RIN}^{-1} + CNLD^{-1} \qquad (3.25)$$

  Externally Modulated DFB Laser transmitter is used that has a capability to provide higher power as broadband subscriber access networks require higher power budget. Besides this, EM-DFB laser transmitters have a built in mechanisms for linearization and suppression of Stimulated Brillouin Scattering (SBS).

Simulations have been carried out using MATLAB to find out the optimum operating point for the design of SAN, the results of which are discussed below. 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). Figure (3.13) deals with the digression into this argument, so as to make things pretty clear. The following conclusions can be drawn from Figure (3.13):

- The key assumption still holds here, i.e. , Linearity in EDFA gain with the input signal power.
- In the high power case; $GP_s^{in} = P_s^{out}$ is the difference in both. 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.

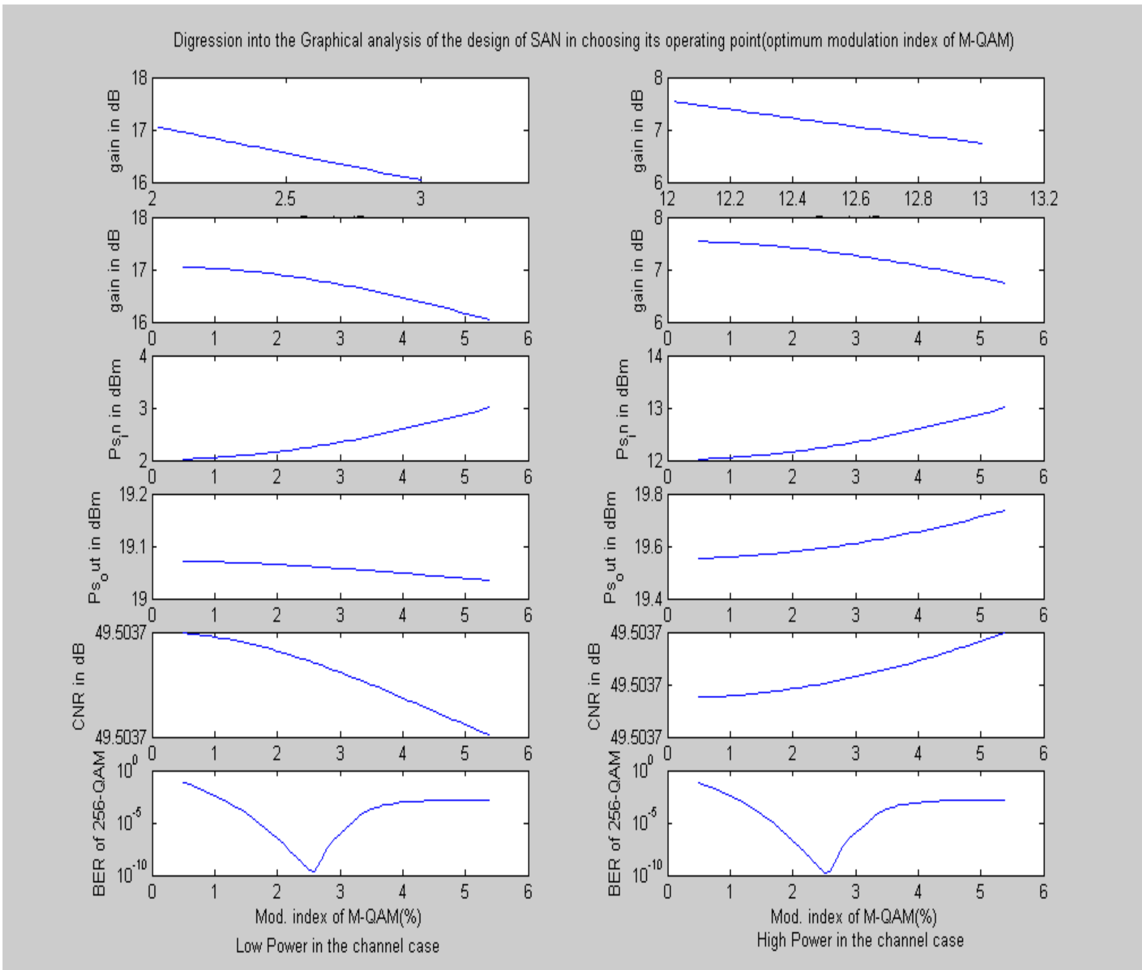


Fig. 3.13 Analysis of two regimes of operation in Hybrid AM-VSB/M-QAM transmission case in SAN to find the optimum operating point.

The designing of a SAN can be carried out in similarly in an algorithmic fashion. Since, the RF power ratio between the QAM and AM signals have a say in the design, this contributes to the analysis of two cases, as when the QAM signals' power is less compared to AM signals' power and secondly, when they have a comparable power. The analysis can be carried out on similar lines. Simulation Results are shown for both the cases. 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. Starting with the former one:

Step 1: There are two approaches to the start of the design.

- 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, because as the RMS modulation index is increased, CNLD ratio will degrade, so that the point of AM modulation index corresponds to the maximum, where CNLD is just satisfied, although anything less than that will have better CNLD. 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. If lesser number of channels is incorporated, then obviously, there is a better performance than the former case.
- Fix the number of AM channels and find AM modulation index accordingly. Once the number is fixed, then optimum modulation index of AM has to 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.

Thus, at the end of Step 1, Number of AM channels, modulation index of AM for desired CNLD has been determined when started by either of the two approaches.

Step 2: The number of subscribers and the number of QAM channels have to be determined for BER< 1e-9 and SNR > 28 dB. Both these criterion determine the number of subscribers that can be accommodated and the number of QAM channels that can be sent. Increasing the number of QAM channels improves the SNR, but degrades the BER. However, increase in the number of subscribers, results in the degraded BER and SNR. So, the number of subscribers and the number of QAM channels have to be chosen in an optimum way, so as to satisfy the BER criterion.

At the end of Step 2, Number of QAM channels and number of subscribers has been fixed for a given Subscriber Access Network.

Step 3: Figure (3.14) depicts the results obtained from previous steps, from which, optimum modulation index of M-QAM has to be found out at the minimum probability of error. BER is fixed at 1e-10 for the design and the rest of the parameters have been found out for the previously mentioned criterion as CNR ≥ 49.5 dB and P_s^{in} ≤ 13 dBm (power constraint being imposed arbitrarily, as power consideration also comes into the picture in the design of SAN.

Step 4: With modulation index of QAM being fixed as in step 3, the branch design of the SAN is done with. The parameters already fixed will be used for the bus design of the SAN. $P_{upper\lim it}^{ASE}$ has to be found out in the similar fashion as was done in the previous case, with passive splitting being assumed at the ONU stage. The method of analysis remains the same, what was carried out in the previous analyses, giving the number of EDFAs supported and consequently, number of subscribers in the network.

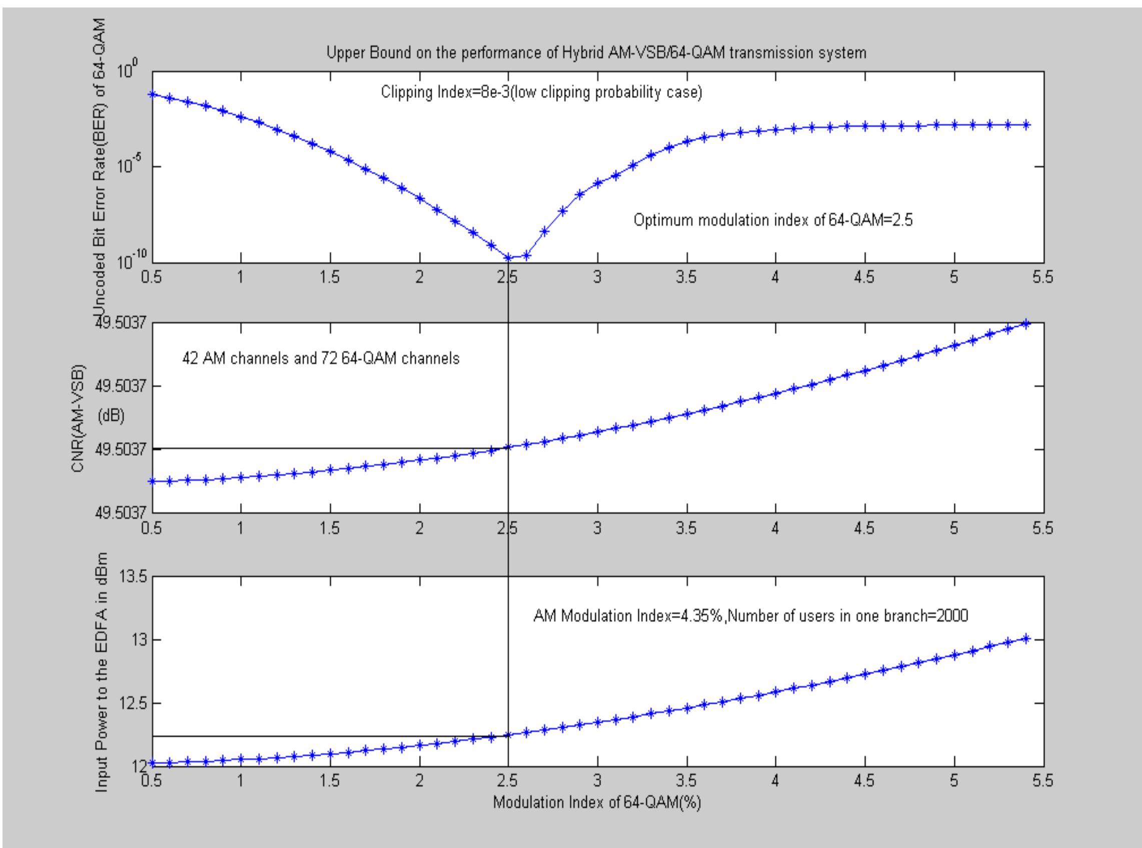


Fig. 3.14 Performance Analysis of AM-VSB/64-QAM in SAN when 64-QAM signal is less as compared to AM-VSB signal power.

From Figure (3.14), 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 8e-3. 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 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 without optical regeneration in a SAN, as depicted in Figure (3.15).

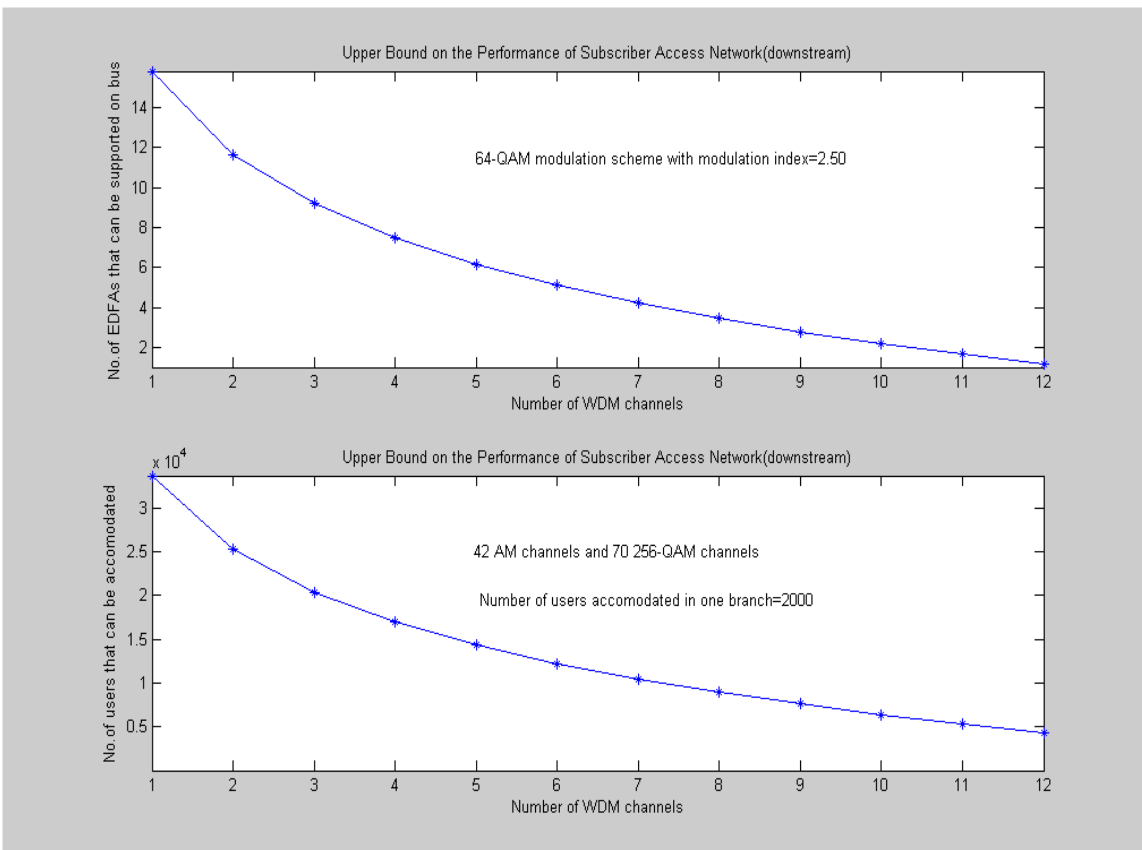


Fig. 3.15 User Base Size and Channel capacity in AM-VSB/64-QAM in SAN when 64-QAM signal is less as compared to AM-VSB signal power.

When higher constellation size, like 256-QAM is considered, either the number of subscribers be kept fixed and the number of QAM channels being found accordingly or vice-versa, as number of QAM channels being fixed and the number of subscribers, being reduced in number, found out. Starting with the former one, when the number of subscribers is kept fixed at 2000 and the steps1-4 repeated, the number of 256-QAM channels being transmitted turned out to be 18, which is far less as compared to 70 QAM channels as in the former case, as shown in Figure (3.16).

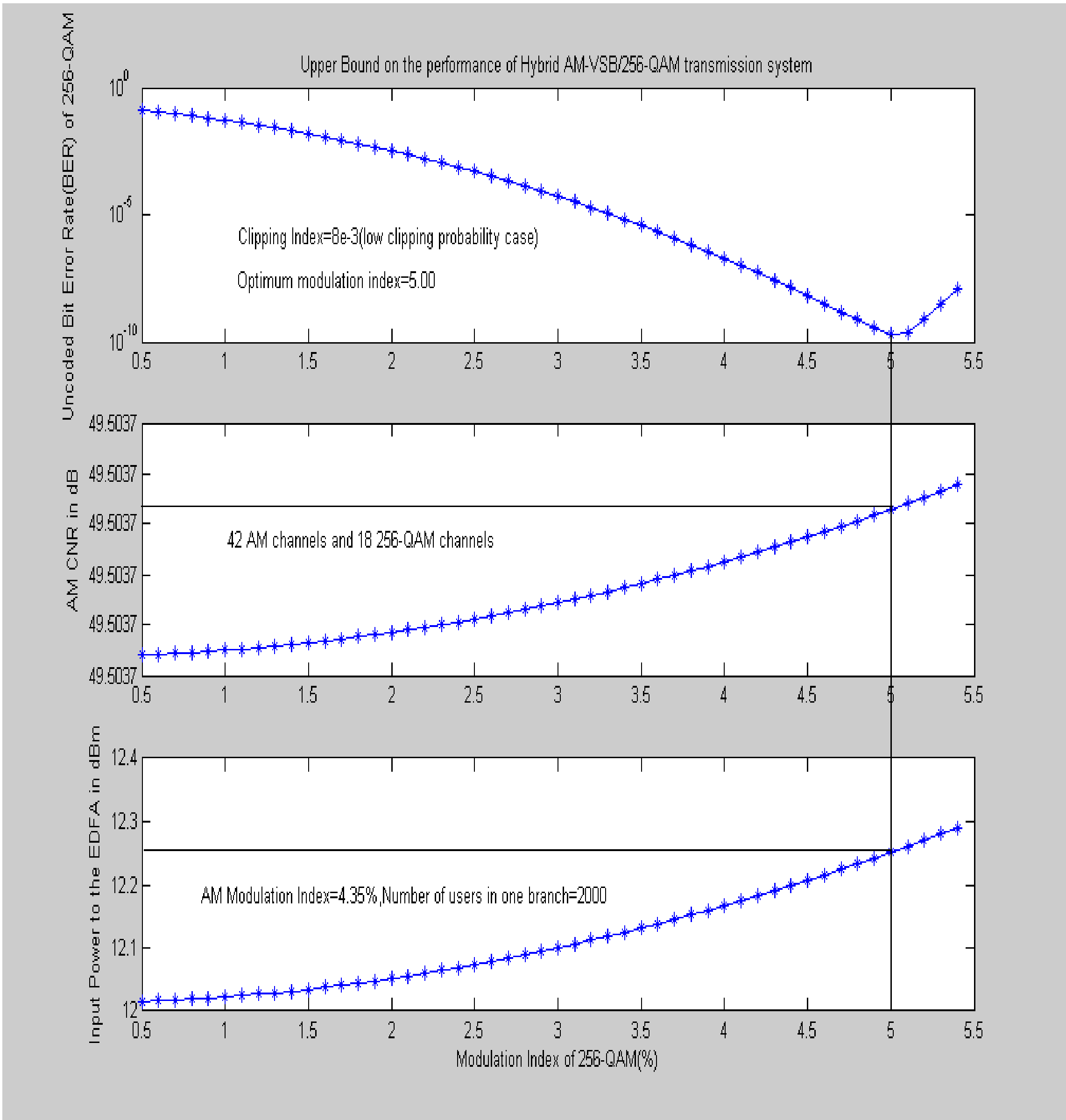


Fig 3.16 Performance Analysis of AM-VSB/256-QAM in SAN when 256-QAM signal is less as compared to AM-VSB signal power when number of subscribers is fixed.

The optimum modulation index has gone up to 5%, implying more power in the QAM channels, resulting in more clipping distortion and hence increased QAM SNR.

However, the number of channels and number of subscribers remain the same, because power budget remains the same with more users to be accommodated being compensated by lesser number of channels, with enhanced QAM OMI per channel. When the latter case is considered, i.e., when the number of 256-QAM channels is fixed at 70, and number of subscribers searched for BER=1e-10, it resulted in 800 subscribers at an optimum modulation index of 2.2 with CNR being 49.5037 dB (as before) and SNR=34.79 dB, with a minute difference in power shown in Figure (3.17).

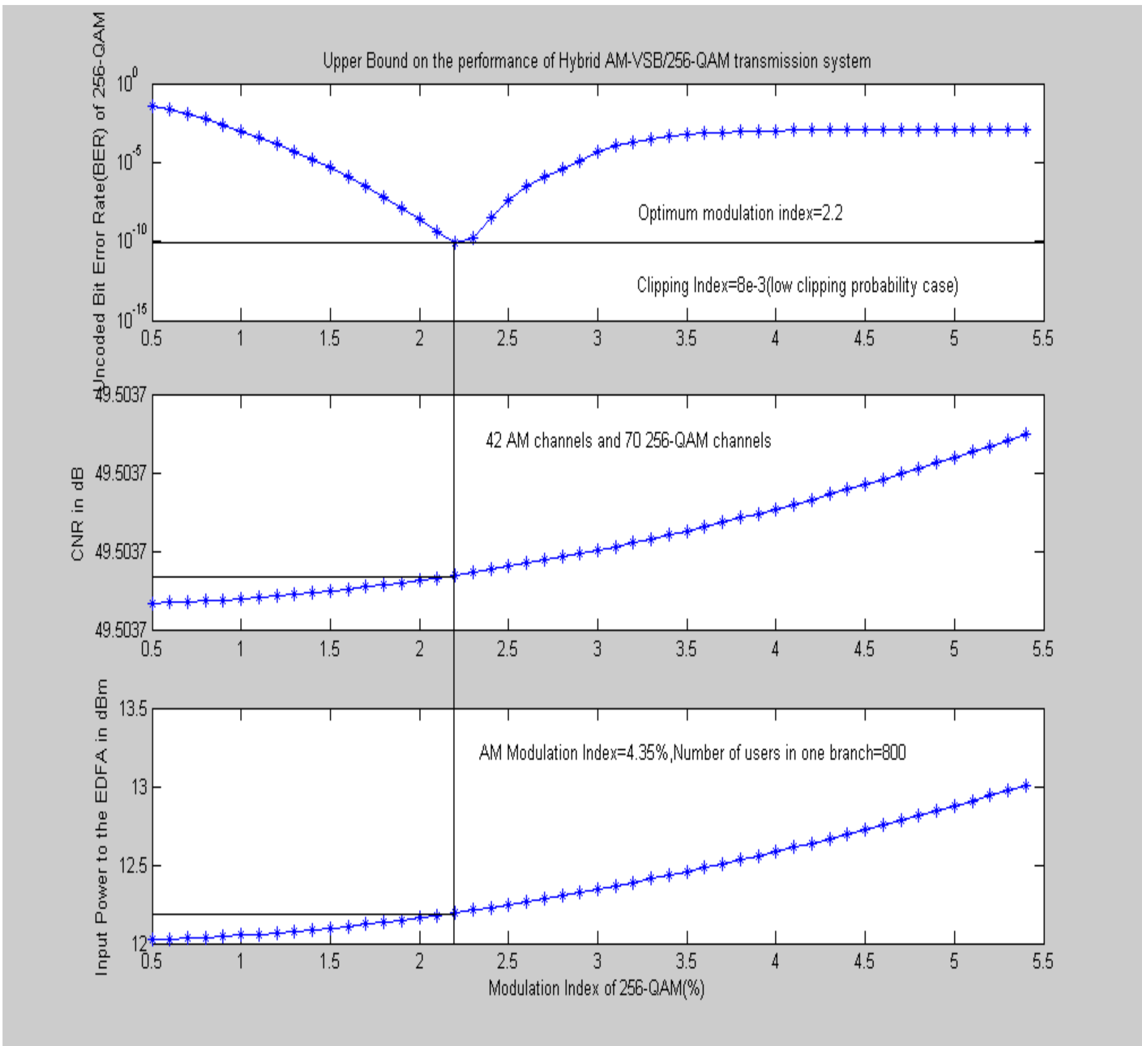


Fig. 3.17 Performance Analysis of AM-VSB/256-QAM in SAN when 256-QAM signal is less as compared to AM-VSB signal power when number of QAM channels is fixed.

There is a drastic reduction in the number of subscribers. So, either way, it can be adopted, as per requirement, going for more number of subscribers or more number of QAM channels.

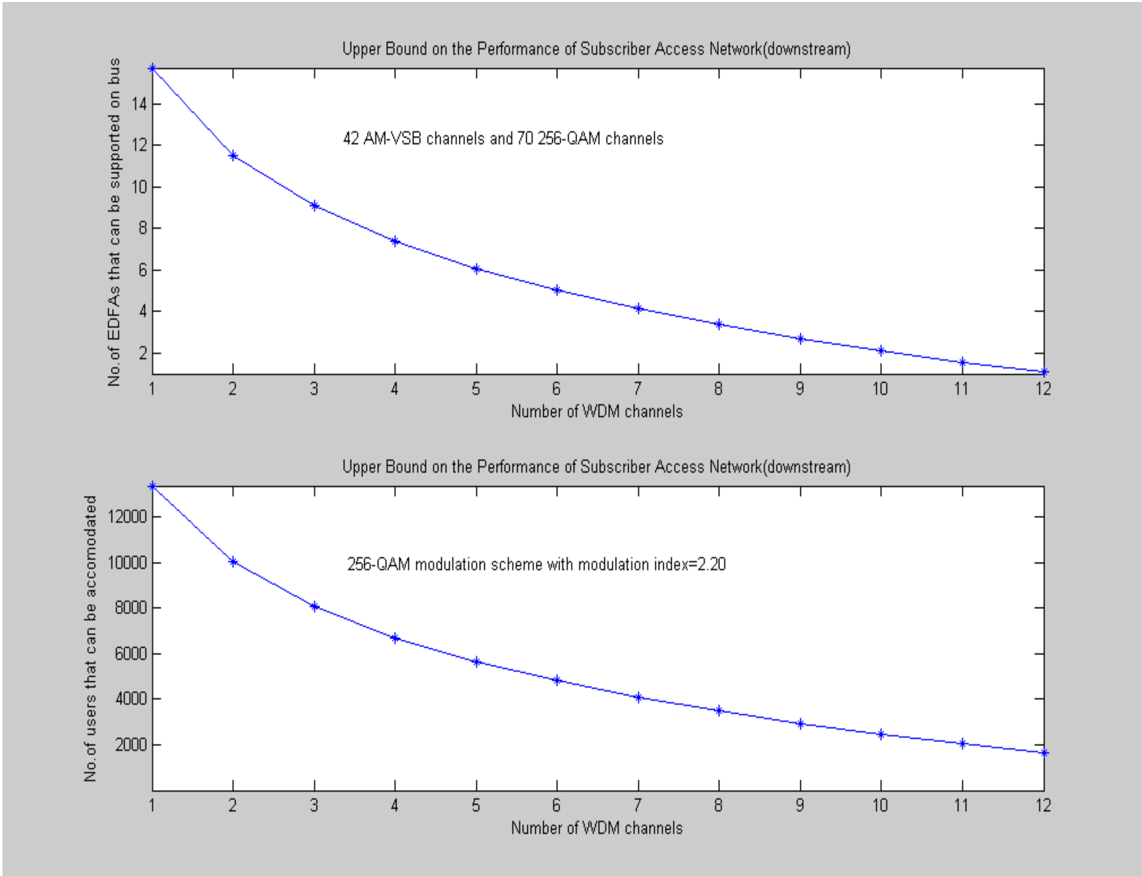


Fig. 3.18 User Base Size and Channel capacity in AM-VSB/256-QAM in SAN when 256-QAM signal is less as compared to AM-VSB signal power.

The reason for this degraded performance in QAM can be owed to reduction in immunity to ISI due to clipping induced impulse train, resulting in QAM states being close together. The modulation index of 256-QAM is also much higher than that of 64-QAM for the same number of subscribers per branch to achieve the same BER of 1e-10. Although, the BER performance can be improved by operating the 256-QAM channels at higher QAM signal levels, the increased QAM channel loading may cause the degradation of AM-channel quality. QAM signal level for the transmission link was found to be higher than that without EDFAs. This is expected considering the added ASE noise from EDFAs [23]. The reason, why only AM-to-QAM interference is considered, is that dominant components of clipping noise comes from the clipping of AM signals, therefore QAM-to-QAM interference shall not be taken into account [22]. The model has neglected the bandlimited effect of clipping noise by assuming the noise to be white. However, the actual noise spectrum is bandlimited and not flat, that makes the way for assumption as any finite bandwidth corrections are small. As the OMI of AM signals increases, the probability of clipping increases and the power ratio of Gaussian noise component to clipping noise component reduces, thus the BER of M-QAM degrades significantly. For higher clipping probability, the employment of FEC becomes imperative, as application of higher power/ higher SNR of M-QAM does not improve BER very much. This work carried out the analysis by assumption of low clipping probability density. As the constellation size increases, BER performance degrades, since higher the size of M-QAM, the more stringent is the SNR required to obtain the same Bit Error Rate. As iterated earlier, the transmission of QAM channels in a hybrid multichannel AM-VSB/M-QAM system has a strong dependence on the RF power ratio between AM and QAM channels, so, the other case when, the QAM channels' power is comparable to AM channels' power will be considered through simulation results shown in Figure (3.19)-(3.24).

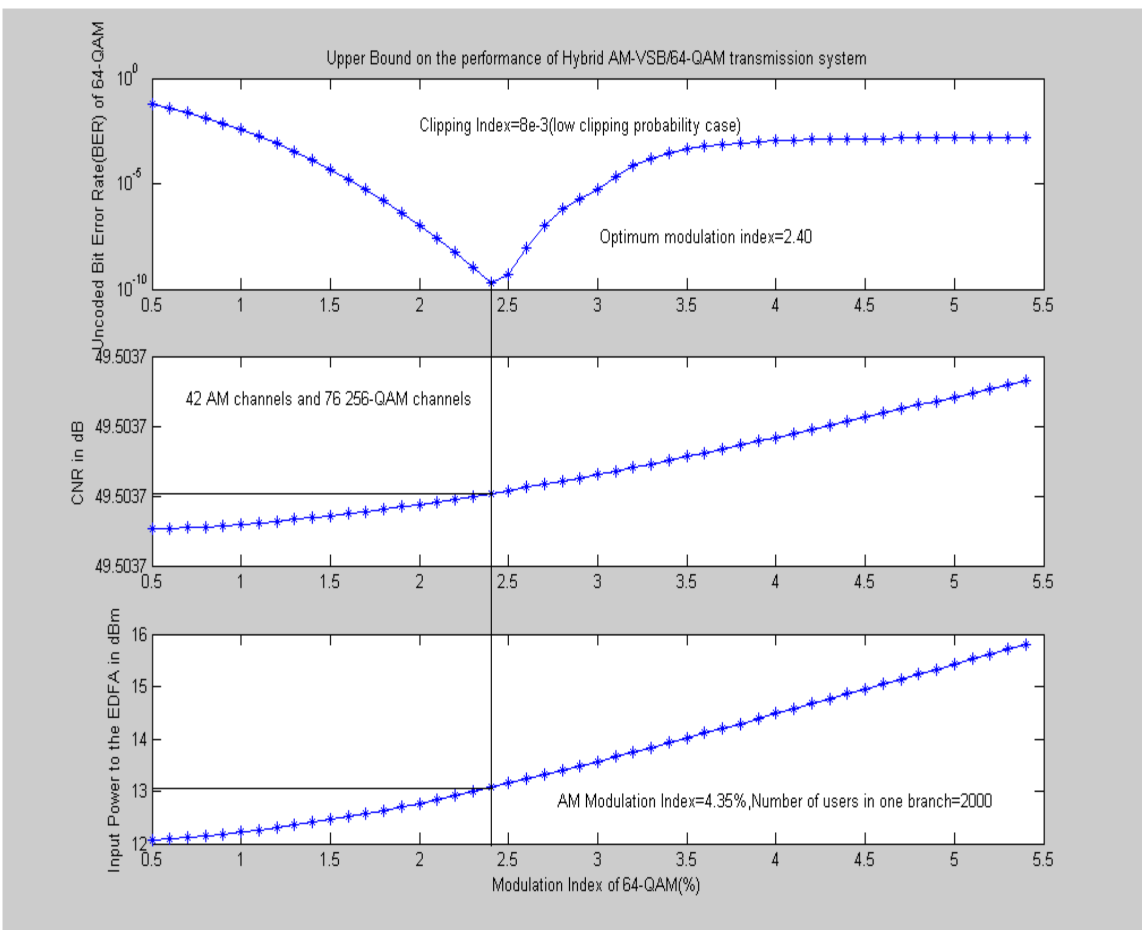


Fig. 3.19 Performance Analysis of AM-VSB/64-QAM in SAN when 64-QAM signal is comparable as compared to AM-VSB signal power.

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, 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 resulted in increment in the number of QAM channels supported to76 in number. Figure (3.20) depicts the user base size and number of WDM channels obtained from the design of the bus network.

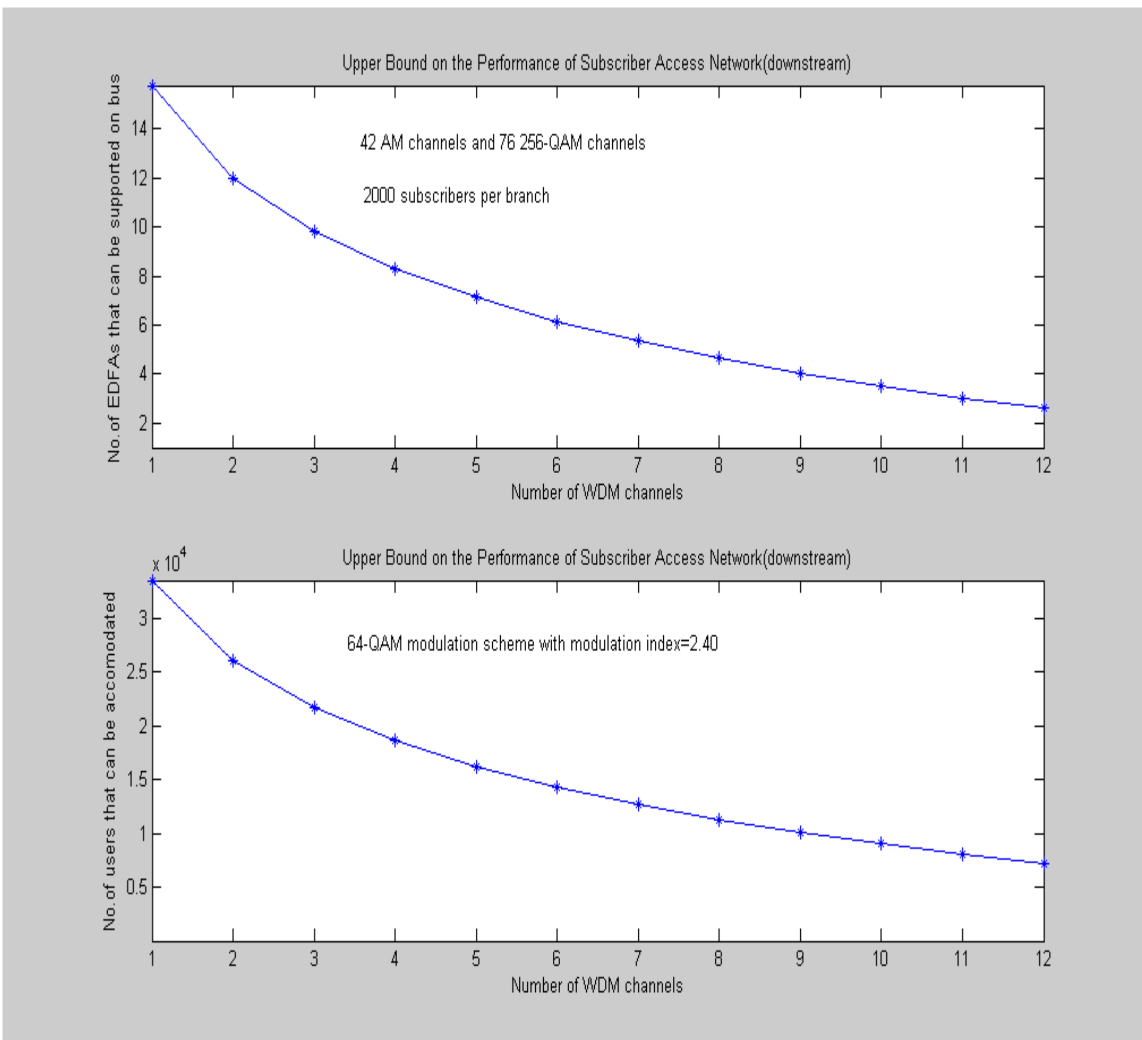


Fig.3.20 User Base Size and Channel capacity in AM-VSB/64-QAM in SAN when 64-QAM signal is comparable as compared to AM-VSB signal power.

When 256-QAM modulation scheme is analyzed, with the subscribers kept fixed as before, and steps followed in a similar fashion as before, the number of QAM channels went down to 18 and optimum modulation index was upto 5, so nothing much difference in the performance except that QAM SNR has gone upto 35.4 dB, with subscribers base kept at 2000. Power has gone above somewhere around 13 dBm owing to enhanced QAM channels' power. However, when the number of QAM channels is fixed at 76 with 42 AM-VSB channels, the number of subscribers went down to 800 with optimum modulation index of 2.10 and power being around 13 dBm as before. The above analysis is shown in Figure (3.21) and Figure (3.22).

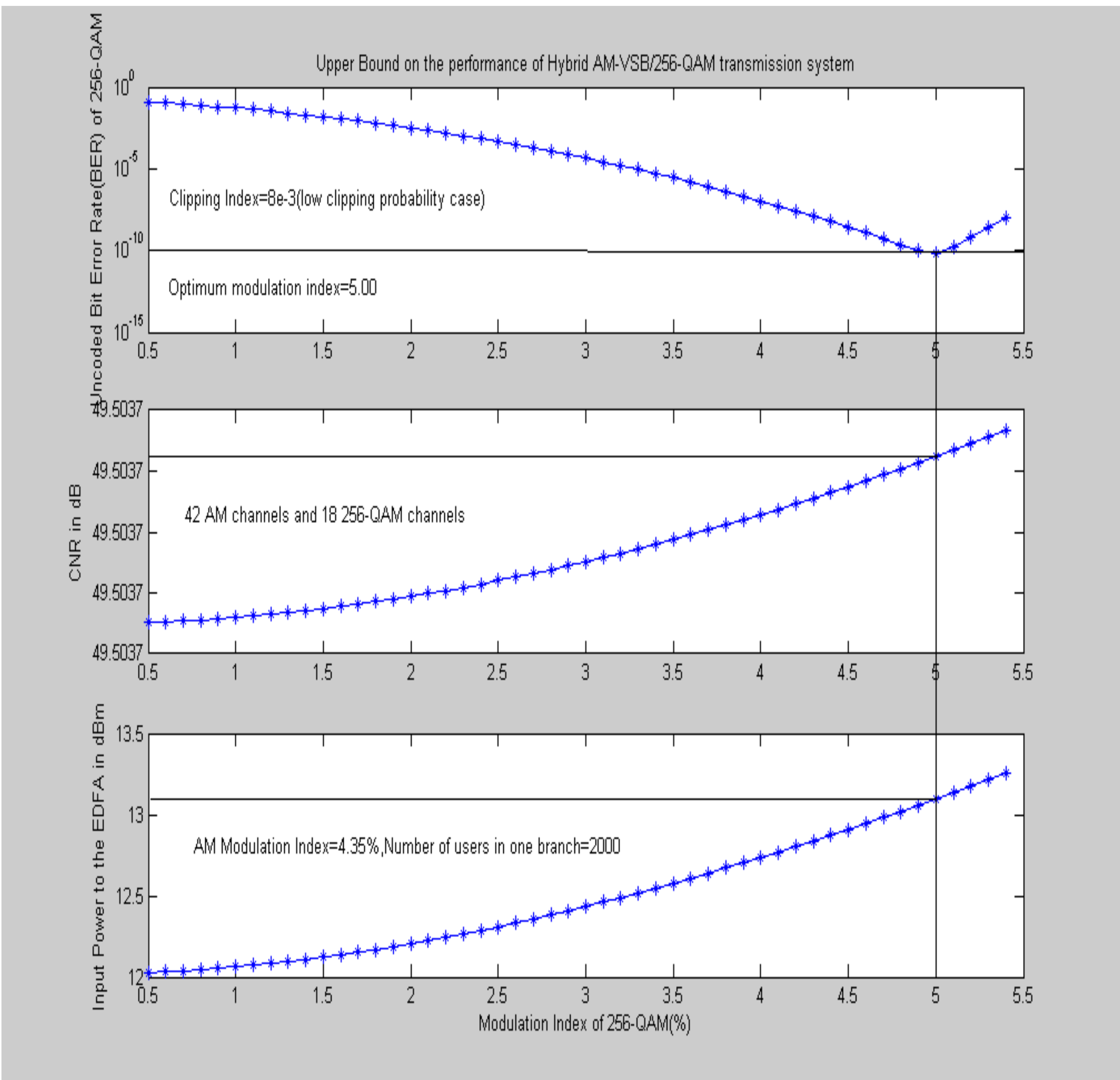


Fig. 3.21 Performance Analysis of AM-VSB/256-QAM in SAN when 256-QAM signal is comparable as compared to AM-VSB signal power when number of subscribers is fixed.

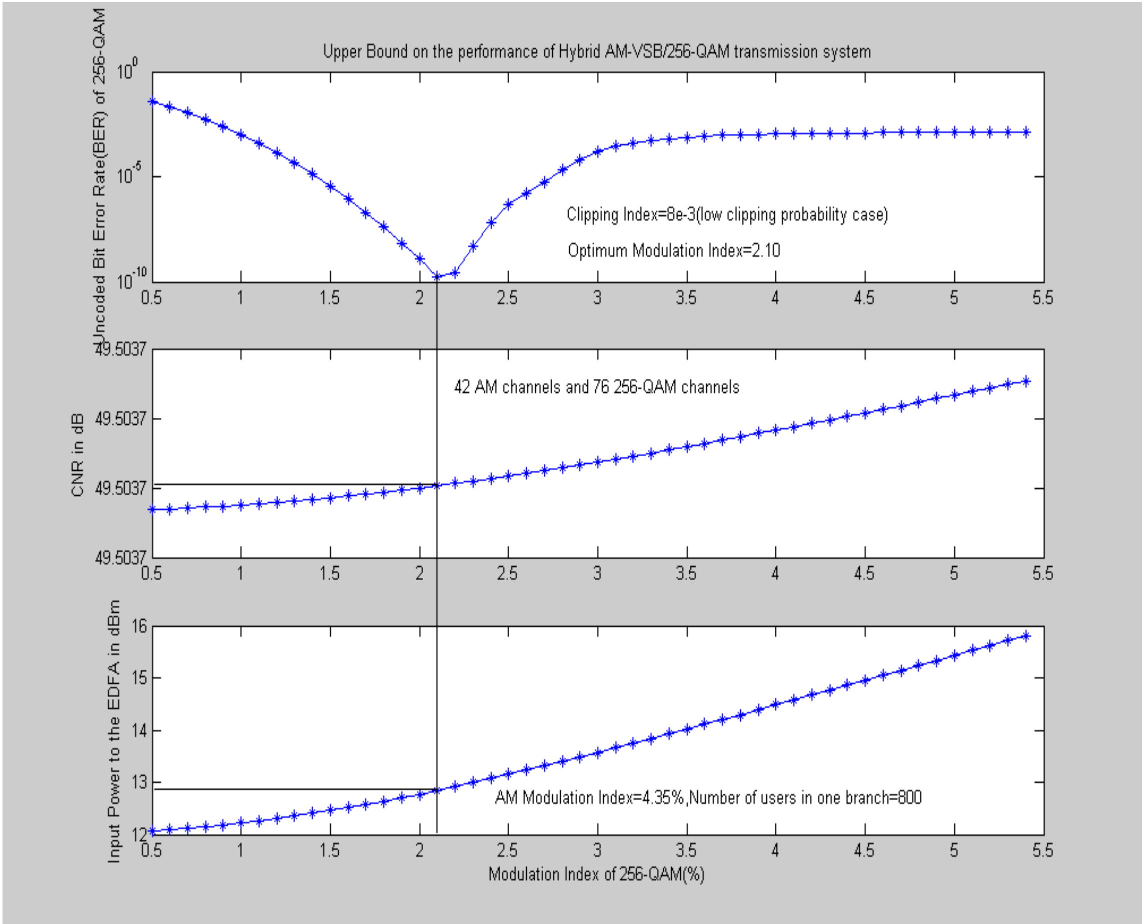


Fig. 3.22 Performance Analysis of AM-VSB/256-QAM in SAN when 256-QAM signal is less as compared to AM-VSB signal power when number of QAM channels is fixed.

The bus designing results remain more or less the same as previous analyses. Although, coded BER is phenomenally better in many orders of magnitude than uncoded BER, still this work did not consider the employment of error control coding, because by the employment of (3,2,1) Reed Solomon code (Appendix D), the throughput goes down resulting in bandwidth efficiency of 66.67% . Such coded system having very high coding gain, can give good performance of SAN in terms of the number of channels, number of subscribers, number of AM-VSB/M-QAM channels. However, error correction schemes do not work well in terms of performance improvement in impulse noise environment. They basically give better performance for bursty errors generated due to nonlinear distortions. A suitable interleaver-deinterleaver combination or frequency offset method can be employed to enhance the burst noise tolerance.

3.5 Consideration of issues pertaining to practical deployment of SAN:

The impairments that arise due to high power regime operation, like nonlinearities, Four Wave Mixing, Stimulated Raman Scattering need to be taken care of. Like SBS mechanism, that usually places an upper limit on the optical power does not show its effect on 1550 nm transmission systems and only occur at 1350 nm systems. However, it can be taken care of by low frequency dithering of optical frequency of laser transmitter by modulating laser bias current. A single tone phase modulation at a frequency above, about twice the maximum frequency (~1.8 GHz) is used to avoid additional distortions. Phase Modulation method is more effective in reducing interferometric noise, but requires relatively high electrical powers to achieve the necessary phase modulation index. Laser frequency dithering has got a superior performance in increase of SBS threshold power and requires only a simple low power laser current modulation. However, this method works for DFB lasers that happens to be our choice of transmitter also. Other impairments like FWM and SRS are not considered in this work. Self Phase Modulation effect occurs at 1550 nm due to interaction between fiber's chromatic dispersion and modulated optical spectrum of the propagating signal in the fiber. At the higher powers being employed in optical fiber, due to enhanced requirements driving the use of optical fiber amplifiers, high level of second and third distortions of DM or EM lasers are generated by the nonlinear refractive index of fiber, $n = n_o + n_2 I$, where n_2 is the nonlinear refractive index, will make the CSO and CTB effect to dominate in such a manner that using DM-DFB laser transmitter; 1550 nm transmission will be limited to few kilometers distance. However, these can be fixed by:

- Using an Externally Modulated Laser transmitter that has a very low frequency chirp and this work vouch for this transmitter only.
- Using a Dispersion Shifted Fiber/ Dispersion Compensating Fiber/ Dispersion Flattened Fiber.
- Magnitude of resultant CSO distortion is determined by the complex interplay of the SPM, fiber length, dispersion, the sign of phase modulation index due to external modulator's laser chirp. The SPM contribution to CSO distortion could be equal, but opposite in sign to the CSO, due to initial phase

modulation. Thus, the total cancellation of CSO distortion at a particular distance can be achieved for fiber optic links around 100 Km; phase modulator due to optical modulator's residual chirp is typically not a problem.

Thus, this chapter dealt with the design of Subscriber Access Network for all analog video broadcast, all digital video broadcast and hybrid of both along with switched services. The analysis was done from the physical layer point of view, with power budget consideration being the cardinal point in the design. Efforts were made to make the whole design optimistic from practical perspective. The objective behind the work was not to suggest the possible scheme of transmission for video broadcast, but to make the design optimum for a given scheme of transmission and to analyze tomorrow's technology so as to assist in graceful migration to next generation lightwave networks for convergence of services.

Chapter 4

Some Insights into practical deployment Considerations

Network design is constrained from transmission impairments resulting from analog nature of processed signals. These are the ones that accumulate along the routed paths, but also due to the wavelength dependency of optical components. The transmission quality of a wavelength connection (lightpath) is the function of the type of allocated optical network elements, and is characterized by the additive nature of impairments. They result in unacceptable SNR values at the optical receiver, i.e., unacceptable bit error rate values at the receiving node. Nonlinearities play a cardinal role in the design of optical networks.

4.1 Holistic picture of transmission impairments:

In a wavelength routed optical network spanning a large geographical area, an optical signal may traverse a number of intermediate nodes and long fiber segments. The progressive loss incurred by the signal in all these nodes and long fiber segments necessitate the use of optical amplifiers at strategic locations in the network. While other optical components like cross connects and optical amplifiers like EDFAs offer transparent switching and loss compensation, respectively, for optical signals may introduce significant transmission impairments e.g.,

- Crosstalk generation when two or more optical signals copropogate through the same cross connects.
- Generation of amplified spontaneous emission noise in EDFAs while providing signal amplification.
- Nonlinearities that crop up due to power constraints.

The crosstalk and ASE noise generated at every node copropogate with the signal over the assigned lightpath; and all of them undergo variable gains at variable wavelengths because of the non-flat gain spectra of EDFAs. However, this factor has been dealt with the assumption of flat gain spectra over the desired window of transmission. In general, the signal degrades in quality as it traverses through switches and fiber segments while propagating through its assigned lightpath towards its destination, and the signal to noise ratio continues to decrease. When the signal finally arrives at the destination, the crosstalk and ASE noise that have accumulated along with the signal may result in significant degradation of the SNR, which might in turn increase the receiver bit error rate beyond its acceptable value. In order to examine the reliability of physical layer, one needs to capture all the physical layer limitations together and evaluate the achievable BER for a given lightpath. This chapter therefore dwells into the introduction of nonlinearities [26], the modeling or solution of which can be seen as an extension of the work.

4.2 Prominent Nonlinear Interactions:

Stimulated Raman Scattering (SRS), an interaction between light and vibrations of silica molecules, causes frequency conversion of light and results in excess attenuation of short wavelength channels in wavelength-multiplexed systems. Stimulated Brillouin Scattering (SBS), an interaction between light and sound waves in the fiber, causes frequency conversion of reversal of propagation of light. Cross Phase Modulation (XPM), is an interaction, via the nonlinear refractive index, between the intensity of one lightwave and optical phases of other light waves. Four Photon Mixing (FPM) is analogous to third order intermodulation distortion whereby two or more optical waves at different wavelengths mix to produce new optical waves at other wavelengths. Each of these nonlinearities will affect specific lightwave systems in different ways. However, in general, SRS, SBS, FPM will deplete certain optical waves and, by means of frequency conversion, will generate interfering signals for other channels. These will degrade both direct detection and heterodyne systems. XPM on the other hand affects only the phase of signals, as a result of which only angle modulated systems are affected by it. Of all the nonlinearities, FPM is the most sensitive to the system parameters. Not only does it depend on fiber length and core area but it also depends on channel separation and fiber dispersion.

Most nonlinear optical interactions involving two optical waves propagating in a medium can be characterized by

$$P_1(L) = P_1(0).\exp(gP_2L / A) \tag{4.1}$$

where $P_1(0)$ and $P_1(L)$ are power of one wave entering and exiting, respectively, a medium of length L. This amplified wave is also called as probe wave.

4.3 AM/OFDM is better than AM/M-QAM for hybrid transmission:

M-QAM signals fare well for hybrid multichannel subcarrier multiplexed voice, video and data transmission owing to better spectral efficiency and noise immunity over their analog counterparts. However, the upper bound on their performance is put by the clipping noise effect induced in such SCM environments. Orthogonal Frequency Division Multiplexing (OFDM) is a new player in this field that is considered to be equally feasible for digital data transmission due to its inherent immunity against impulse noise and multipath effects. OFDM involves multiplexing of low data rate subchannels, each of them being independently modulated with conventional QAM symbols.

OFDM provides a significant improvement over M-QAM signals in terms of bit error rate, channel capacity, optical modulation depth range in the lightwave SCM environment where clipping impulse noise and Gaussian noise are present resulting in less interference effects on the nominal AM channels than the M-QAM signals under the same operating conditions. An OFDM signal consists of a multiple of independently modulated QAM subchannels that are orthogonal in frequency and narrow band, and can be demodulated with a bank of narrowly spaced matched filters. In practice, the modulation and demodulation of an OFDM signal can be effectively carried out through Fast Fourier Transforms (FFTs). Because of this concurrent transmission of many narrow band carriers in OFDM, the symbol duration may be much larger than that of the conventional single carrier M-QAM signal. This gives an inherent advantage for OFDM to deal with any short time domain interferences like impulse noise, whereas many symbols may be corrupted due to impulse noise in M-QAM signals' case; while in OFDM, smaller number may only get affected resulting in better signal quality. *The reason why OFDM is relatively immune to impulse noise effect is that it uses the narrowband multicarrier modulation and spreads the duration across the channels, so as to stretch out the duration of impulse noise and make it behave like a Gaussian noise to the system.*

The modelling of clipping noise as Gaussian follows the same analysis as was done in the last chapter. The analysis of AM/OFDM is shown and simulations of them can be carried out in a similar fashion as before. This work gives a bird's eye view of this recent alternative digital modulation technique that is widely used in wireless spread spectrum communications.

The clipping noise is modeled as an impulse train following Poisson characteristics and exhibiting shot noise effect after matched filter demodulation. For an OFDM with M-QAM modulated subchannels, the bit error rate can be given as [22], [23]:

$$P_e = \frac{1-\frac{1}{\sqrt{M}}}{\log_2 M}\left\{(erfc(\frac{\Delta}{\sqrt{2}})-\frac{5}{2\gamma})(\frac{1}{1+G})^2\phi_3(\Delta)-\frac{1}{\gamma^2}(\frac{1}{1+G})^3\left[\frac{35}{3}\phi_5(\Delta)+\frac{25}{16}\phi_7(\Delta)\right]+...\right\} \tag{4.2}$$

γ is the clipping index denoting the probability of clipping per OFDM symbol interval. G is the variance ratio of Gaussian noise to clipping noise, SNR being the total signal to noise ratio.

$$\Delta = \sqrt{\frac{3.SNR}{(M-1)}}$$

$$\phi_k(x) = \frac{d^k}{dx^k}\left(\exp(-\tfrac{x^2}{2}).\frac{1}{\sqrt{2\pi}}\right). \tag{4.3}$$

$$SNR = 0.5.m_e^2(\rho P_o)^2\left[i_n^2 + 2q\rho P_o + RIN.(\rho P_o)^2 + \sigma_c^2\right]^{-1} B^{-1}$$

where B is the OFDM signal bandwidth, m_e is the effective modulation index per OFDM signal, P_o is the received optical signal power, i_n^2 is the receiver thermal current. The variance of clipping noise is given as:

$$\sigma_c^2 = 4\bar{\tau}(\pi)^{(-3/2)}\mu^5.\exp(-1/\mu^2).\frac{(\rho P_o)^2}{3}$$

$$\bar{\tau}\_is\_the\_mean\_duration\_of\_clipping\_impulses$$

$$\bar{\tau} = erfc(\tfrac{1}{\mu}).\frac{T_s}{2\gamma} \tag{4.4}$$

$$\mu^2 = \frac{(N_{am}.m_a^2 + N_{ofdm}.m_e^2)}{2}$$

As $\gamma \to \infty$, the OFDM probability of error approaches the Gaussian model. The value of γ can be expressed as:

$$\gamma = T_s \sqrt{\frac{\mu_{am}^2 (f_{ab}^3 - f_{aa}^3) + \mu_{ofdm}^2 (f_{ob}^3 - f_{oa}^3)}{3\left[\mu_{am}^2 (f_{ab} - f_{aa}) + \mu_{ofdm}^2 (f_{ob} - f_{oa})\right]}} .\exp\left(\frac{-1}{2\mu^2}\right) \tag{4.5}$$

where $T_s = N_{FFT} / B$ with N_{FFT} being the number of OFDM subchannels or FFT size. With N_{FFT} being large, γ will be large and Gaussian approximation prevails. The AM and OFDM channels have the flat spectrum over the band assumed.

The signal is corrupted by both the Gaussian noise and non-Gaussian modeled clipping noise in both QAM and OFDM cases. However, for QAM, the probability density function for the sum of two noise behaves approximately as the Gaussian one in the lower amplitude region and approaches the clipping one with the increasing amplitude, while for OFDM, the sum probability density function is almost the same as Gaussian one for a fairly wide range.

The performance is a function of the number of OFDM subchannels or FFT size. The OFDM performance degrades when the FFT size is small. So, to have a better performance, it is desired to have a larger FFT size, provided the larger size does not increase the accuracy requirement for the carrier recovery of the OFDM demodulation. The OFDM signals also produce less effect on the performance of AM channels than QAM signals, since they can operate at smaller signal power or OMD for a required BER. *The reason why OFDM is more immune to nonlinear effects is that an OFDM signal operates at higher peak to average ratio than an M-QAM signal, due to its large number of subchannels with random amplitude and phase.*

4.4 Crosstalk Analysis:

Crosstalk [29], [30], [Bib 4] mainly arises from the interactions between the subcarriers on the one wavelength and the optical carrier on other wavelength. In a dispersive fiber, crosstalk can be attributed to cross phase modulation, Stimulated Raman Scattering combined with group velocity dispersion. Crosstalks induced by SRS and XPM add in electrical domain and can interfere constructively and destructively. FWM efficiency decreases very quickly with increasing dispersion; the FWM crosstalk in these SCM-WDM systems is negligible. XPM affects only the phase of the signal, and in the absence of dispersion, does not affect IM-DD systems. However, in the presence of dispersion, the phase modulation is converted to intensity modulation leading to crosstalk. SRS contributes to crosstalk through Raman gain modulation and depletion. SRS induced crosstalk dominates at low modulation frequency and large wavelength separation, and XPM induced crosstalk dominates at high modulation frequency and small wavelength separation. If the pump wavelength is shorter than the probe wavelength, the SRS and XPM induced crosstalks will add in electrical amplitude, and if the pump wavelength is longer than the probe wavelength, they cancel.

The phase and magnitude relations of crosstalks are made use in two counter measures. In parallel transmission technique, the advantage of phase dependence on dispersion and pump/probe relationship to achieve cancellation is accrued. By transmitting the same set of signals over two equal length fibers, the signals can be added and crosstalk can be cancelled simultaneously at the receiver. In the optical carrier suppression technique, the magnitude dependence of crosstalk on the transmitted carrier power is taken advantage of. By reducing the carrier power through carrier suppression technique, crosstalk can be reduced while signal remains constant. The phase dithering for SBS suppression can be removed when the optical carrier is increased to increase the received CNR. Both the crosstalk counter measures can achieve wideband crosstalk suppression and cancellation. The advantage of parallel transmission technique is that crosstalk can be cancelled, theoretically, to the first order, regardless of the magnitude of the crosstalk; however, the drawbacks lie in system complexity, equal fiber requirement and the need for reverse dispersion fiber. The advantage of optical carrier suppression technique lies in its simplicity and the removal of SBS suppression frequency/phase dithering. The level of crosstalk can be reduced significantly over all frequencies and the shape of the crosstalk spectrum will remain the same. The above details are just the subjective analysis and more details can be found in standard literatures for bibliophiles.

4.5 Dispersion Effects:

Dispersion [3] is the name given to any effect wherein different components of the transmitted signal travel at different velocities in the fiber, arriving at different times at the receiver. A single pulse launched into a fiber arrives smeared at the other end. This smearing causes intersymbol interference that results in power penalties, thus putting an upper limit on the length of a link owing to accumulated dispersion.

Use of single mode fiber (where the fiber core is of the order of the operating wavelength) can get rid of modal dispersion, leaving only chromatic dispersion to be taken care of, when polarization mode dispersion is not taken into account. The capacity of an optical communication system is measured in terms of bit rate-distance product. An idea of the transmission impairments imposed by dispersion can be obtained by assuming that the pulse spreading due to dispersion should be less than a fraction ε of the bit period. The bit rate-distance product can be obtained assuming the fiber chromatic dispersion to be D at the operating wavelength, B to be bit rate, $\Delta\lambda$ being the spectral width as

$$BL(\Delta\lambda)|D| < \varepsilon \qquad (4.6)$$

The spectral width of transmitted signal depends on the type of source and whether it is directly modulated or externally modulated. EM-DFB lasers used in this work has got a fairly less value of spectral width that helps in alleviation of effects of dispersion. As the modulation current and thus optical power varies, it is accompanied by the changes in carrier density within the laser cavity, which in turn, changes the refractive index of the cavity, causing frequency variations in the output. Decreasing the extinction ratio can reduce chirping. The spectral width can also be increased owing to back-reflections from splices, connectors, and other elements in the optical path. Thus dispersion management plays a cardinal role in the design of WDM transmission systems. Dispersion can be very well compensated using dispersion compensated fibers or by the external modulated DFB lasers.

4.6 Laser Phase Noise:

The laser phase noise [31] acts as an independent noise contribution that adds to the influence of local oscillator shot noise and thermal receiver noise in the case of heterodyne detection and to the influence of ASE noise and thermal receiver noise in the case of a preamplifier noise.

$$S(t) = \exp(j\omega t + j\phi(t)); \qquad 0 \le t \le T \qquad (4.6)$$

The above equation applies in the heterodyne case by letting the stochastic process $\phi(t)$ to be caused by laser phase noise from the local oscillator as well as from the transmitter laser. In the preamplifier case, the stochastic process is due to the laser phase noise of the transmitter assuming that preamplifier does not affect the laser phase noise.

The modelling of laser phase noise can be carried out using Taylor Expansion Method, in which a signal sample at time τ at the output of the bandpass filter, given by the convolution of the signal time response and of the bandpass filter as

$$S_o(\tau) = \int_0^{\tau} h'(\tau - t).\exp\big(j(\omega t + \phi(t))\big).dt \tag{4.7}$$

The phase term can be expanded using Taylor's series and introduction of suitable normalization of phase noise influence can be carried out. The normalization makes use of the fact that the phase drift over a time interval is a Brownian process, i.e., a zero mean Gaussian process with variance given by diffusion parameter $D\tau$. The continuous wave optical laser power spectrum can be considered to be Lorentzian with a 3-dB linewidth of

$$\Delta\nu \equiv \Delta\nu_{tr} \equiv \frac{D}{2\pi} \tag{4.8}$$

This finite linewidth of laser output becomes a source of noise in digital optical communication systems. The parameter of interest is the 3 dB linewidth of the laser measured with respect to the bit rate. The 3 dB linewidth for typical single mode DFB semiconductor lasers ranges between the few MHz and the order of 100 MHz. The laser linewidth in the preamplifier case is entirely due to laser transmitter whereas in heterodyne case, it is the sum of the linewidth of the transmitter and the local oscillator laser. The considerations about the laser phase noise influence are of importance for systems operating at low bit rates in the order of 100 Mbps or lower. However, the future lightwave networks have to be operated with robust systems that allow the use of cheapest lasers with large linewidths in excess of the bit rate, i.e., the systems should be able to tolerate large amounts of phase noise. DPSK and DM-DPSK systems are highly sensitive to phase noise and that, such systems require linewidths below the order of 0.5%-1% of the bit rate, making them not so preferable candidates for consumer types of applications. The details regarding the modelling and mathematical analysis of the laser phase noise are available in standard literatures, the details of which can be sought as an extension to this work.

4.7 How the impairments could be taken care of and insight into future digital system implementations.

The power criterion is decided so as to avoid the nonlinearities resulting from the higher optical power in the optical fiber. For low bit rate systems, of the order of 1 Gbps, laser phase noise can be a significant impairment, whereas for higher bit rates, like the one that is employed in this work, 10 Gbps, it is expected not to be significant. The use of digital modulation formats is expected to be of prime importance because this allows a highly flexible and signal transparent high capacity network implementation. The ASK, dual filter FSK, limiter discriminator FSK, discriminator FSK and PolSK systems tolerate significant amounts of laser phase noise whereas CPFSK, DM-DPSK and DPSK systems have slightly better sensitivity without any influence of phase noise and somewhat poorer phase noise tolerance. The use of EM-DFB lasers result in reduced chirping. Dispersion shifted fibers are used to take care of the dispersion menace. Soliton based ASK systems can be used that takes advantage of the Kerr effect [26] in the optical fiber that is utilized (for short optical pulses transmitted at power levels of a few milli Watt power) to counteract the fiber dispersion and to maintain the optical pulse shape. The analysis of laser phase noise is subject to the different types of filters like integrator filter, raised cosine filter, and the choice of modulation scheme; the inclusion of this impairment is taken as per the choice of the system.

Chapter 5

Conclusion and Scope for Future Work

The work dealt with the design of Subscriber Access Networks that are expected to play a vital role in the future lightwave systems supporting convergence of voice, video and data traffic. Dealing the whole issue from the physical layer point of view, first detection schemes were studied and sensitivity for different schemes were compared. The choice of detection scheme is a subjective issue that depends on the requirement of the system, however in general; the direct detection scheme is better in terms of simplicity and performance. Subcarrier Multiplexing scheme along with Wavelength Division Multiplexing is a good option for providing convergence of services on home TV network. The choice of architecture is the cardinal part of any network design. The architectural considerations should be done keeping in view the need of subscriber number and power budget requirements.

The future convergence of services will be a mixture of broadcast and switched services. With digital modulation techniques already penetrated deep into the communication sector owing to its numerous advantages, this work accounted 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 and QPSK transmission schemes. The employment of doped fiber amplifiers has revolutionalised the All Optical Networks. This work has assumed the linear model for EDFA, thus giving the upper bound on the performance considerations.

With individual results and algorithmic approach for the network design being already explained along with relevant figures, this chapter mainly deals with the gist of results. This work does not try to suggest the modulation scheme, stating any particular scheme to be used in all CATV networks. Since, these issues are highly subjective to practical considerations like ease of deployment, cost effectiveness and availability of required infrastructure for the same from operators point of view; this work 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 for triple play of voice, video and data using the ‘Data in a Rainbow’ concept.

With the analog broadcast scheme being AM-VSB along with switched services, there is a serious limitation in terms of the number of WDM channels accommodated and the number of subscribers in a SAN. Analog transmission requires more power and considerably gives diminished performance. But, being already into cable networks very much in the last few years, the need for better performance is paving the way for digital transmission, with many entertainment channels going completely digital. Digital broadcast gives much better performance in terms of subcarriers per wavelength and in terms of number of WDM channels that can be supported. Digital broadcast is certainly the technology for future with supporting tens of thousands of subscribers without going for optical regeneration, that will certainly be helpful in future with many communication companies trying to get the big share of this market.

However, no change can be observed overnight and the graceful migration is sought from all analog broadcast to all digital broadcast. So, the current systems have to be designed that can support both as a form of hybrid services. This work tried to optimize the performance for hybrid fiber optic video transmission by finding the appropriate operating point for 64-QAM and 256-QAM. It can be found from the results that clipping distortion that was modeled as non-Gaussian statistics proved to be the significant impairment in the hybrid transmission case. The number of WDM channels that can be accommodated and the number of subscribers that can be set in a SAN were found in a similar fashion. However, the comparision cannot be made between the three cases considered because of the absence of the common benchmark in terms of power; and this work is not intended to do that also.

Several practical considerations were taken care of, like, nonlinearities, dispersion, laser phase noise. Also, the advantages of AM/OFDM than AM/M-QAM were touched upon. OFDM scores over M-QAM in terms of more number of channels and less interference of AM channels on digital channels, the performance measure of OFDM being dependent on the number of its subchannels or FFT size. Dispersion can be taken care of by the employment of dispersion compensated fiber; chirping can be effectively reduced by the use of externally modulated laser diodes like DFB lasers. The network design accounted for 0.2-dB/Km loss in optical fibers as well as losses arising from splices and connectors, as a result of which the network is limited in terms of distance also. However, the distance is good enough to accommodate a large number of subscribers in a pretty large geographical area.

Every work gives an idea for others to follow giving new dimensions to explore further, and that's how things move ahead. Like all, this work also explores other problems for research. The upstream and downstream traffic can be considered to be over one fiber and analysis can be made for it. The design of SAN can be carried out using other modulation schemes. OFDM analysis can be carried out further by simulations that can open a whole new area in itself. Designing of a SAN has been carried out with many assumptions like linear gain model of EDFA, no corrections from finite bandwidth of optical filters, absence of polarizer at the detector end. So, the designing of a SAN can be carried out by relaxing some or all of the assumptions that will yield an accurate performance, unlike an upper bound as in this work.

Architecture wise, there can be lot of extensions that can be sought. Using multilevel topologies, by the cascade of amplifiers, the number of users can be enhanced to any extent. This work gave the analysis for one such architecture, thus giving the way to analyze others in a similar fashion. The work can be extended to other layers of OSI reference model.

Thus, the work gives an upper bound in the performance of Subscriber Access Networks that gives results for designing future lightwave networks supporting convergence of services, catering to the ever increasing demand of bandwidth and need for enhanced services, like triple play of voice, video and data.

Appendix A:

Comparision of SCM/WDM with WDM:

Driving a transmitter laser diode with the spectral sum of many information streams, and at the receiver end to recreate the entire spectrum at the photodetector output for further processing is called Subcarrier Multiplexing. With WDM being at the helm of today's optical communication technologies, the combination of them gives manifold advantages.

- This approach is cost effective reducing the unit cost of bandwidth owing to enhanced number of users that can be accommodated in a subscriber access network.
- Tighter channel spacing can be achieved because the stability of RF tuning is much greater than that of laser tuning, and because the RF conversions can be derived from the quartz crystals.
- The tuning speed of RF local oscillator circuits can be much faster than today's commercially available tunable optical filters, thus proving to be a better player for fast packet switching. The normal way of providing RF tuning is to use a voltage controlled oscillator whose tuning speeds are in tens of microseconds, but submicrosecond tuning can be achieved by switching between two oscillators.
- It is easier at microwave frequencies than at optical frequencies to use modulation formats that achieve more than one bit per baud, such as QPSK.
- The large number of channels can be supported, and, in the case of a network, an interesting approach to packet switching is opened up. Although large number of channels can be achieved either with many wavelengths and few subcarriers per wavelengths, or with the converse, considerably more photonic amplification is required in the latter approach, due to the need to reduce the modulation index to avoid excessive clipping.

However, the disadvantages of this approach lie in the finite dynamic range of laser diodes and photodetectors and requirement to equip each receiver with frequency and wavelength tunability, that places certain limits on how the network can be laid out topologically.

Appendix B:

Rate and Propagation Equations in EDFA:

This appendix deals with the rate and propagation equations characterizing an EDFA operating in C band and pumped at 1480 nm. The simulation of EDFA requires the simultaneous solution of rate equations, which define the transition between energy levels, and the propagation equations, which characterize signal, pump and ASE power variations along the active fiber. The performance of absorbing injected pump light and then emitting it as a signal light by stimulation are known as absorption cross section and emission cross section or in a different way as loss and gain coefficients, respectively. In erbium, the absorption is higher at 1480 nm whereas the emission is higher at 1535 nm. The signal and pump powers along the fiber vary due to absorption, spontaneous emission and stimulated emission processes. The amplifier is modeled as a three level system having population densities in the ground level (1), metastable level (2) and pump level (3). The consideration of Excited State Absorption (ESA) demands the inclusion of fourth level in the model. The rate equations describing the effects of pump P_p, signal P_s and ASE P_a power on these populations are

$$\frac{dN_1(z,t)}{dt} = \left[-\frac{-\sigma_{sa}\Gamma_s}{h\nu_s A}(P_s + P_a^+ + P_a^-) + \frac{\sigma_{pa}\Gamma_p}{h\nu_p A}(P_p^+ + P_p^-) \right] N_1$$
$$+ \left[\frac{\sigma_{se}\Gamma_s}{h\nu_s A}(P_s + P_a^+ + P_a^-) + A_{21} \right] N_2 \qquad \text{(B.1)}$$
$$+ \frac{\sigma_{pe2}\Gamma_p}{h\nu_s A}(P_p^+ + P_p^-) N_2 + \frac{\sigma_{pe}\Gamma_p}{h\nu_p A}(P_p^+ + P_p^-) N_3$$

$$\frac{dN_2(z,t)}{dt} = \left[\frac{\sigma_{sa}\Gamma_s}{h\nu_s A}(P_s + P_a^+ + P_a^-) \right] N_1$$
$$- \left[\frac{\sigma_{se}\Gamma_s}{h\nu_s A}(P_s + P_a^+ + P_a^-) + A_{21} \right] N_2 \qquad \text{(B.2)}$$
$$- \frac{\sigma_{pe2}\Gamma_p}{h\nu_s A}(P_p^+ + P_p^-) N_2 + A_{32} N_3$$

And by conservation, $N_3 = N_t - N_1 - N_2$, where N_1, N_2, N_3 are the population densities of the ground level, metastable level, and pump level, respectively, and N_t is the total Er^{3+} density. The superscript + designates pump and ASE copropagating together with the signal, and – when they counterpropagate to the signal. The absorption (a) and emission (e) cross-sections of the pump (p) and signal (s) are $\sigma_{s,p;a,e,e2}$. With pumping into the metastable level (wavelength of the pump in the range of 1450-1500 nm), the amplifier behaves as the two level system and $\sigma_{pe2} = \sigma_{pe}$. Other parameters are the fiber core area (A), the signal to core overlap (Γ_s) and the pump to core overlap (Γ_p). The assumption carried out is that no other effects of the radial distribution of ions or the optical mode are included, since the erbium ions are confined to the region of the optical mode's peak intensity and $\Gamma_{s,p}$ are small. The non-radiative transition rate from level 3 to 2 is A_{32} and the radiative transition rate from level 2 to level 1 is A_{21}. The propagation equations describing the spatial development of pump, signal and ASE in the fiber are

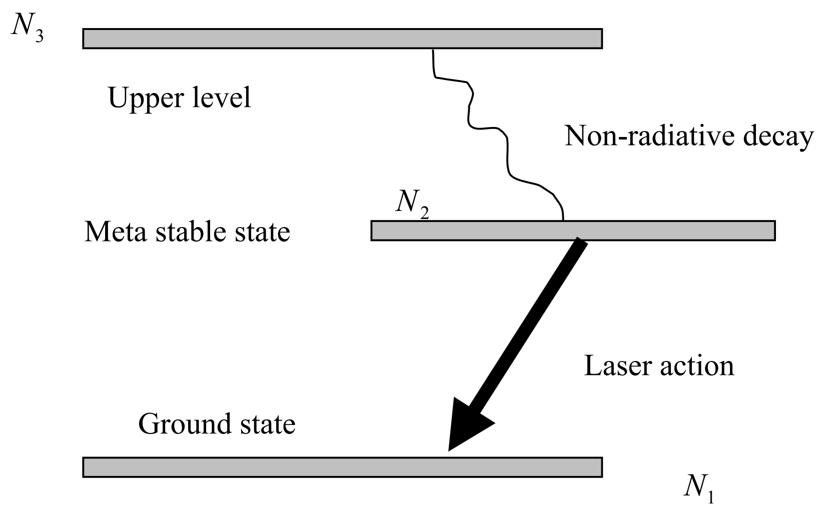
$$\begin{aligned}
\frac{dP_p^{+}(z,t)}{dz} &= \mp P_p^{\pm}\Gamma_p(\sigma_{pa}N_1 - \sigma_{pe2}N_2 - \sigma_{pe}N_3) \mp \alpha_p P_p^{\pm} \\
\frac{dP_s(z,t)}{dz} &= P_s\Gamma_s(\sigma_{se}N_2 - \sigma_{sa}N_1) - \alpha_s P_s \qquad \text{(B.3)} \\
\frac{dP_a^{\pm}(z,t)}{dz} &= \pm P_a^{\pm}\Gamma_s(\sigma_{se}N_2 - \sigma_{sa}N_1) \pm 2\sigma_{se}N_2\Gamma_s h\nu_s\Delta\nu \mp \alpha_s P_a^{\pm}
\end{aligned}$$

The second term in the last equation is ASE power produced in the amplifier per unit length within the amplifier homogeneous bandwidth $\Delta\nu$ for both polarization states. The loss terms $\alpha_{s,p}$ represents internal loss of the amplifier, which is particularly important in the case of the distributed optical amplifier whose length is equal to the span length and the loss terms are the usual signal and pump attenuation in the transmission fiber. The above sets of equations are simultaneously solved for a given condition $dN_1/dt = 0$, to yield output ASE power and the amplified signal with amplifier saturation. The amplifier gain is calculated as $G = P_s(l)/P_s(0)$ and the spontaneous emission noise factors in the forward and backward directions are defined as

$$n_{sp}^{+} = \frac{P_a^{+}(l)}{2h\nu_s\Delta\nu(G-1)} \qquad \text{(B.4)}$$

$$n_{sp}^{-} = \frac{P_a^{-}(0)}{2h\nu_s\Delta\nu(G-1)} \qquad \text{(B.5)}$$

The evolution of signal and pump is calculated numerically and simplifications of them yield the amplifier noise figure as $F = 2n_{sp}$. The noise figure increases with the increasing ASE power and decreases with the increasing gain. The decrement in EDFA gain with increasing input signal power can be owed to easier saturation of the EDFA at higher signal powers for a constant pump power. The pump power rapidly attenuates with fiber length due to erbium absorption and background loss of silica fiber. The ASE power increases with the increasing fiber length due to the gain provided inside EDFA and reaches to larger values for high pumping powers. The parameters can be simulated using any mathematical tool like MATLAB or MATHCAD. The pump power applied to EDFA sharply reduces due to absorption in the erbium doped fiber; in addition, gain and noise figure is strongly dependent on the fiber length, pumping power, signal input power and erbium ion density. When the EDFA is supplied with sufficient pump power, EDFA could be shown to operate in saturation regimes leading to maximum gain and minimum noise figure. The physics behind the amplification in EDFA can be found in many literatures related to optical physics [16]. Other models can be utilized for the same, all of them varying in complexity, by making some valid assumptions so as to carry out the mathematical analysis in a simplified fashion.

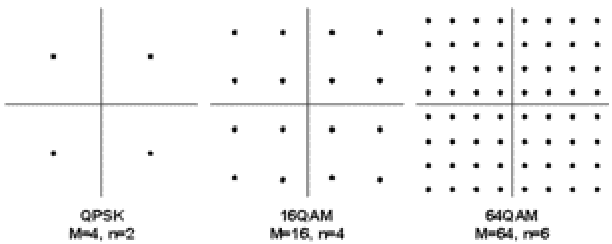


The above figure depicts the lasing action in the EDFA. The absorption and emission parameters are wavelength dependent, thus making the gain terms in the EDFA also to be wavelength dependent. Thus, stimulated emission along with spontaneous emission forms the vital mechanisms for light amplification in EDFAs.

Appendix C:

M-QAM modulation schemes: An introduction.

The transmission of data in digital form is known to give inherent advantages over analog form pertaining to various known reasons. The better bandwidth efficiency can be obtained by adopting M-QAM modulation schemes. These modulation methods could be applied either to the modulation of single carrier with a high data rate signal or to modulation of large number of carriers with low data rate signals. Spectral efficiency results not only from the fundamental spectral information "density" in bit/s/Hz of the modulation system within any given channel, but is also influenced very much by the spectrum re-use characteristics of a particular digital system. M-QAM modulation scheme is a combination of AM+ PSK; the constellation size increases with the values of M as 16, 64, and 256.

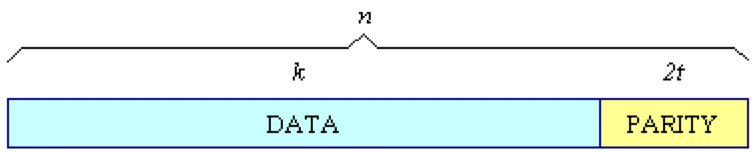


Grouping more bits into a symbol increases the size of a constellation (transmit power), for the same minimum distance between the points. However, the transmission bandwidth decreases since the baud rate is less than the bit rate. The mathematical analysis regarding the calculation of Probability of bit error and other decoding issues can be found in literatures related to digital communication [6], [Bib6]. The intersymbol distance in M-QAM is less than the intersymbol distance in the corresponding M-ary PSK. This modulation scheme results in high bandwidth efficiency. With many points in the constellation pattern, even a small amount of noise in the detected amplitude and phase can result in an error, and potentially, many corrupted bits. To reduce the chance of an error, standards for the higher speed modems do error correction by adding extra bits to each sample, the schemes are known as Trellis Coded Modulation (TCM). Turbo Coding schemes are also employed for efficient channel coding, the details of which can be found in research papers in transactions and journals.

Appendix D:

Error Correcting Codes: Reed Solomon Code

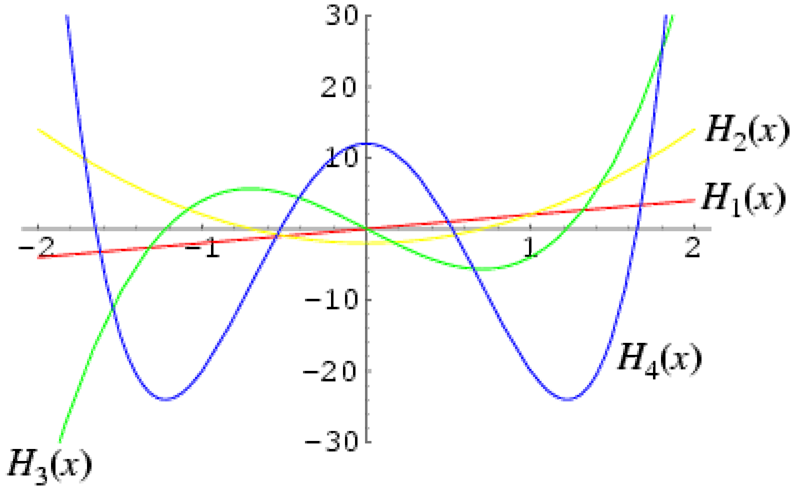
Coding is useful in the sense that it increases the rate at which information may be transmitted over a channel while maintaining a fixed error rate. Alternatively, coding reduces the information bit error rate while maintaining a fixed transmission rate. It allows, in principle, upto the Shannon limit to design a communication system in which both information bit rate and error rate are independently and arbitrarily specified subject to a constraint on bandwidth. The price paid, to attain the Shannon limit, is increased hardware complexity, both at the transmitter and receiver end. Thus the employment of coding will allow transmitting at channel capacity and with an error rating which may be made as small as desired. One measure of efficiency of code is precisely the extent to which it approaches the Shannon limit. Block codes and Convolution codes are generally employed for channel coding.



Reed Solomon codes are block-based error correcting codes that are used to correct mainly burst errors. Reed Solomon codes are a subset of BCH codes and are linear block codes specified as RS (n, k) with s-bit symbols. The encoder takes k data symbols of s bits each and adds redundant bits to form an n bit codeword. There are (n-k) parity symbols of s bits each. A Reed Solomon decoder can correct upto t symbols that contains errors in a codeword, where 2t = (n-k). RS codes may be shortened by making the number of data symbols zero at the encoder, not transmitting them, and then reinserting them at the decoder. The advantage of using RS codes is that the probability of an error remaining in the decoded data is usually much lower than the probability of error if RS code is not used. This is often described as coding gain. The amount of processing power required to encode and decode Reed Solomon codes is related to the number of parity symbols per codeword. A large value of t means that large number of errors can be corrected, but requires more computational power than a small value of t. RS codes are more suitable for correction of bursty errors, occurring due to fading channels where the level of received signal power waxes and wanes with time.

Appendix E:

Hermite Polynomials



The Hermite polynomials $H_n(x)$ are set of orthogonal polynomials over the domain $(-\infty,\infty)$ with weighting function of $\exp(-x^2)$, illustrated above for $x \in [0,1]$ and n=1, 2, 3, 4. The Hermite polynomial $H_n(z)$ can be defined by the contour integral where the contour encloses the origin and is traversed in the counter clockwise direction.

$$H_n(z) = \frac{n!}{2\pi i}\oint e^{-t^2+2tz} t^{-n-1} dt \tag{E.1}$$

The first few Hermite polynomials are

$$\begin{aligned}
H_0(x) &= 1 \\
H_1(x) &= 2x \\
H_2(x) &= 4x^2 - 2 \\
H_3(x) &= 8x^3 - 12x \\
H_4(x) &= 16x^4 - 48x^2 + 12 \\
H_5(x) &= 32x^5 - 160x^3 + 120x \\
H_6(x) &= 64x^6 - 480x^4 + 720x^2 - 120
\end{aligned} \tag{E.2}$$

The values $H_n(0)$ are called Hermite numbers. Like other polynomials, Hermite polynomials are the result of sequence called Sheffer sequence with the generating function, the details of which can be found in literatures related to orthogonal polynomials, under the area of special functions in the domain of Calculus and Analysis (http://mathworld.wolfram.com/HermitePolynomial.html).

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