CHAPTER 2

LITERATURE REVIEW

2.1 REVIEW FOR LINK POWER ESTIMATION OF VARIOUS PON ARCHITECTURE

A review of the work carried out in link power estimation for DBA / DWA scheme of various PON architecture systems is given below in general. Also some of the major literature reviews for the link power estimation of various PON towards the research are pointed out in every chapter. ITU-T has created several standards for optical access systems. Several customers share the optical fiber and OLT; PON can offer economical services by reducing subscriber (or customer) cost. For these reasons, a PON system is considered to be eminently suitable for the future optical access system (Expression of Interest for GPON FTTH Systems 2005).

2.1.1 1.25 Gbps EPON

In LAN to WAN, the Fiber cost, local loop deregulation and high speed internet demand are the major needs and still require to upgradation of fiber based IP architecture for full service access networks (FSAN). In late 1980s the asymmetric digital subscriber line (ADSL) had been developed to access high speed transmissions and continued its operations for triple play services (Ingrid Van de Voorde and Gert Van der Plas 1997). But it suffered with limited bandwidth transmissions through metallic cables. Synchronous optical network (SONET) based ATM PON is a type of low cost EPONs
developed in 1990 and its format was accepted in 1995 by ITU-T standard G.983 to deliver triple play services for FSAN (Nam Jae-Hyun et al 1998). The transmission was considered with fixed 53 bytes of ATM cell size, maximum speed supported 622 Mbps both downstream and upstream.

Owing to ATM PONs inadequate bandwidth, more expenses and complexity in an operation, EPON was developed in 2000 by Ethernet in the First Mile (EFM) study group (Glen Kramer and Biswanth Mukherjee 2000). The EFM had concentrated the FTTX applications and offered triple play services with higher bandwidths and low cost. In 2001, the Broadband PON (BPON) standard was recognized with recommendations G.983.4 were additionally operate upstream transmission from 155 Mbps to 622 Mbps for DBA (IEEE 802.3 Ethernet in First Mile Study Group 2001). At the same time in 2003, recommendations G.983.1 recognized additionally to BPON standard to process downstream transmission up to 1.25Gbps (Tsutomu Tatsuta et al 2003). A survey analyzed and EPON novel method using ring topology developed in 2004 for the upstream transmission up to 1Gbps for DBA scheme (Michel McGarry et al 2004, ASM Delowar Hossain et al 2005).

The wavelength ranges used for upstream and downstream transmission are 1310 nm and 1490 nm respectively. IEEE 802.3 working group has started to extend the EPON access rate from 1 Gbps to 10 Gbps recently (Glen Kramer 2006). The power budget and path penalty have been calculated to 1 Gbps EPON which is 21 dBm and 1.5 dBm for the launched and received power -2.2 dBm and -23.2 dBm respectively using wavelength range 1480nm - 1500nm. Similarly the 10Gbps EPON has expected the power budget and path penalty of 30 dBm and 1 dBm for the minimum transmitted optical power 4 dBm and received power -26.1 dBm. So, it is ascertained that the link power budget and path penalty requirements depend on the maximum
receiver sensitivity (Frank Chang and Vitesse 2007). Also higher design complexity have been identified using Ethernet frame burst mode compared with non-frame burst mode in the EPON downstream link (Wen-Kang Jia and Yaw-Chung Chen 2008). So, an EPON complete study has been carried out to access 1 Gbps DBA scheme for the High Definition Television (HDTV) video demand and other broad band service applications (Hussain Sattar and Fernando Xavier 2008). Based on the EPON performance for DBA scheme, the link power estimation is a very essential one while upgrading the bandwidth capacity.

2.1.2 10 Gbps Gigabit PON (GPON)

BPON transmission capacity has been expanded its transmission speed in upstream transmission. But the difficulties occurred in upstream transmission bit rate above 622 Mbps due to the problem of synchronization as in physical layer of BPON. Alternatively, high speed PON specification for higher gigabit transmission with variable length packets called Gigabit EPON or GPON had begun in 2001. The standardization work was divided into three parts, i.e. G-PON service requirements (GSR), G-PON physical medium dependent (G-PMD) layer and G-PON transmission convergence layer (GTC) (Hadjiantonis Sherif et al 2004). A comparative relationship of GPON with EPON the standardization of the EPON by IEEE 802.3; its transmission speed supports 1 Gbps in both directions and transmits Ethernet frames without alteration. Sometimes it is also called as Gigabit Ethernet PON (GEPON). It was developed by ITU-T G.984 in 2003 and supports 2.5 Gbps in both directions, but it has not yet reached the deployment stage. In June 2004, the IEEE ratified EPON as the IEEE802.3ah standard. GPON offers three Layer 2 networks: ATM for voice, Ethernet for data, and proprietary encapsulation for voice, whereas EPON employs a single Layer 2 network that uses IP to carry data, voice, and video. It suggested that there are some
distinct differences between EPON and GPON at Layer 2. The EPON channel link capacity and utilization need more number of segments in their system than GPON, but its transceiver cost to carry the VoIP is nearly 70 percentage lesser than the GPON system. So, the major differences between GPON and EPON come in utilization of the link capacity, reach, per-subscriber costs, and management (Sami Lallukka and Pertti Raatikainen 2005).

In the link power budget, the GIANT project in 2005, a burst mode packet transmission using PMD layer approach for upstream optical link has been experimented for the 1.25 Gbps GPON. The analysis was carried out using SMF link distance 20 km, 1x 32 splitter at RN. The bandwidth was shared for 32 ONUs with P2MP and TDMA technique. The results were found out for the power leveling mechanism by setting the APD gain 6. The sensitivity obtained was -31.6 dBm with a dynamic range of 21.9dB, extinction ratio with and without fiber for the distance 15km were 14 to 17 dB and 11 to 14 dB and bit-error rate (BER) was $10^{-10}$ (Verhulst et al 2005).

A 10 Gbps GEPON burst mode receiver has carried out in 2007 with system budget 26dB, -0.5dB and 0.6 dB as a power penalty, the optical budget measured for both downstream and upstream respectively with 20km SMF link and 1xN star coupler at RN (Junichi Nakagawa 2007). The minimum and maximum path loss for the loss budget of GPON system has been calculated for 1490 - 1500nm range with 13dB and 28dB. Also, the power budget has been calculated for the worst case scenario and obtained required minimum power penalties were 25.5dB and 2.5dB for 1.25 Gbps GPON using wavelength 1550nm, 32 ONUs and SMF distance 20km (Ivica Cale and Aida Salihovic 2007).

In this way, an attempt made for another GPON budget extension for 2.5 Gbps GPON using Erbium Doped Fiber Amplifier (EDFA) has been
analysed. The various parameters assumed for EDFA are the noise factor less than 4.5, maximum gain 35-40dB with the SMF distance 20 km also to reach for 32 ONUs. The extended optical budget was obtained upto 38.4dB and 36dB as required by minimum and maximum level in budget (Genay et al 2007). The 2.5 Gbps GPON was extended up to 135 km to support 2560 ONUs with 64 split. The every split was considered by a split of 1x8 followed by 1x8 at RN using 40λ amplified dense WDM system for metro functions. The network design has been considered to reduce cost and total split loss by 32 (Davey et al 2006). Similarly for the metro network applications, a long reach 10Gbps GPON symmetrical network was developed for 1024 users at a distance of 100 km length using two Nx16 and one Nx4 splitter in cascade with optical amplifiers to meet out the optical power budget. The analytical modeling was performed with OptSim simulation package and aimed to achieve the system performance values for Q-factor and BER are 16 dB and $10^{-10}$. The optimized study has been carried out for receiver downstream filter bandwidth with respect to various noise powers in the range of -160 dBm to -110 dBm. Also the Optical Signal-to-Noise Ratio (OSNR) is increased with the given high input power from OLT in downstream path (Darren Shea and John Mitchell 2007).

The Ericsson’s suggested that GPON has been possible to extend the long reach 60 km and increase the splitting ratio using power splitter and optical amplifiers or new components for NGA networks. Also outlined to extend the 2.5 Gbps GPON to change into 10Gbps even upto 640 Gbps with separate overlay of G.984.5 wavelength using TDM PON along with four WDM multiplexers and it is called XGEPON. But the XGPON system requires higher in cost, power, speed optical transceiver and more complexity (Elmar Trojer et al 2008).
2.1.3 10Gbps Time Division Multiplexing PON (TDM PON)

In 1989, the Multiple Access Customer Network (MACNET) system was introduced by an Australian access network. It had been described that the subscriber loop applications to access 2 Mbps per user end by the Singe Mode Fiber (SMF) distance of 2.1 km using TDM PON. It was shared with the bandwidth in the process 10 log N dB and equally distributed in 12dB signal strength using synchronous multiplexing techniques transmission for 16 end users with 1x16 optical fiber couplers at the RN. The multi-longitudinal mode laser sourced the wavelength range from 1060 to 1400 nm and receiver side the p-i-n-FET received the information. The received optical power and total loss for downstream was -28 dBm and 25 dB for launched optical power -3dBm. Similarly in the upstream side -40 dBm and 29 dB for the launched optical power was -11 dBm. The assumed crosstalk penalty was 0.5 dB at 10dB signal-to-crosstalk ratio and calculated receiver sensitivity was greater than 15.4 dB (Ian McGregor et al 1989).

In 1995, Cell-Based TDMA system was a new approach introduced for APONs. It has been suggested that the selection of a phase confirmed by 70% eye closure waveform has enough within the open part of the eye for jitter from the bit and byte synchronization analysis. (Stephen Topliss et al 1995). In the last half decade, tree topology and MAC protocol had been developed in the first generation access networks. Presently TDM-PON supports the line rate up to 1Gbps and maximum link reach of 20 km or more. These capabilities support the high-speed broadband access to care the needs of current residential end-users. The cost maintenance is controlled in TDM PON by sharing a light source among ONUs using power splitters at RN. At the same time, TDM PON still suffers in major issue of synchronization of packet transmission which is a major drawback and with some types of MAC protocol complications. The entire architecture upgradation for TDM PON is required for any change in line rate and frame format of the MAC protocol (Fu-Tai An and Kyeong Soo Kim 2004).
In 2006, a tree topology based TDM PON architecture was proposed with a 1xN Splitter and N 2x2 coupler at RN were used for decentralized DBA among ONUs. The intention of the proposed decentralized DBA scheme was to obtain better synchronization among ONUs and satisfy the issue of MAC layer, i.e. free from collisions of packets during upstream transmission. The performance was evaluated by decentralized algorithm with respect to IPACT and static EPONs. The measure was verified for the average end-to-end delay between OLT and ONU distances of 20 km and 30 km using OPNET™. It suggests that a stable approach has been proposed and supported for cost effective and higher speed operation of TDM PON (Sungkuen Lee et al 2006). The TDM PON was possible to change its topology from star to ring with feeder network set up. The changes are used to propose next generation PON using DFB laser to produce the wavelength of 1490nm as optical source at the OLT (Ki-Man Choi et al 2007). In 2007, a TDM PON model was proposed to provide next generation guaranteed higher bandwidth 1.25 Gbps for 32 end user and access bandwidth (40Mbps per end user) with negligible crosstalk (avoided synchronization mismatching) using DFB laser source with the wavelength of 1480nm to 1500nm range at OLT during downstream. The transmission has been carried out for a length of 20km with a splitting ratio of 32. The measured optical signal power for downstream was in the range of -60dBm to -10dBm and for upstream -80dBm to -20dBm with reference to obtained optical spectrum (Junichi Nakagawa 2007). Also another novel approach has been proposed using TDM PON standard overlaid with different WDM channels with single-fiber-ring-tree topology at a distance 20km for the resilience if the fiber is cut.

In the proposed network architecture TDM/TDMA protocols of GPON have been extended to deliver 1Gbps to 2.5 Gbps by increasing the RN in the order of $2^N$ (N=2, 4, 8 and 16). The maximum bandwidth distribution has been extended upto 2048 users with 32.25Mbps as average bandwidth per
user when the splitting ratio \((k)\) arrives 64. In every RN, all the wavelengths were routed with optical interleaver, and the power budget was optimized within the range \(-40\text{dB} \text{ to } -10\text{dB}\) for 16 RNs and used 50/50 power coupler in RN for resilience purpose. It suggests that the power loss and BER decrease were mainly due to more RN passes and not affected the receiver sensitivity by keeping the OSNR range higher than 26 dB and 34 dB for downstream and upstream respectively (Carlos Bock et al 2007).

2.1.4 10Gbps Wavelength/Dense Wavelength Division Multiplexing PON (WDM/dense WDM PON)

WDM PON offers better solution for increasing high capacity of high speed optical networks. The IP based WDM network and its access network architecture support for IPv4, IPv6, and interoperability WiMax based internet access concepts design (Biswaht Mukherjee 2000). Many passive optical components including Arrayed Waveguide Gratings (AWG) are consuming power in signal paths during multiplexing / demultiplexing process of WDM PON (Fu-Tai An and Kyeong Soo Kim 2004). In 2005, the modulation of Fabry Perot-Laser Diode (FP-LD) was demonstrated experimentally and studies the usage of low cost WDM device. The proposed spectrum sliced Broadband Light Source (BLS) and it’s wavelength-locked by mutual injection technique of FP-LD which performed well to reduce the Relative Intensity Noise (RIN). The investigation describes the importance of RIN, symmetric and asymmetric bias requirement for FP-LD lasing condition.

Also low RIN was obtained by setting asymmetric bias condition while transmitting 3 channels which carried out the transmission individually from 155Mbps Pseudo Random Bit Sequence (PRBS) data to 20km distance through fiber. The received signal power was obtained in the range of \(-39\text{ dBm} \text{ to } -42\text{ dBm}\) almost for all three channels (Ki-Man Choi et al 2005). Also
In 2005, the same group researchers demonstrated another experiment for 12 channels of denseWDM PON with 50GHz channel spacing (0.4nm) based on wavelength-locked FP-LD. In the experiment again it was chosen and transmitted 155Mbps both downstream and upstream bidirectionally over 20 km through SMF. Also two cyclic AWG have been chosen and placed in both OLT and RN. In the proposed method it was possible to accommodate 80 channels with C-band range 1548.1 to 1553.3nm for upstream and L-band range 1581.1 to 1585.8nm for downstream transmission using EDFA. The investigation reported that there was no dispersion penalty while checking the crosstalk among 12 channels in the dense WDM PON transmission. But the power penalty upto 4dB and detuning has been required while decreasing the mode spacing 0.6 to 0.4 nm. Also, detuning was accepted for the range increase for 0.08 to 0.26nm when using the FP-LD reflectivity was 1%. The analysis was made for transmission length up to 30 km including 10 km distribution fiber distance. The measured receiver sensitivity and output optical signal power range -37.5 to -36 dBm was achieved BER $10^{-10}$ (Sang-Mook Lee et al 2005).

In 2006, bidirectional Long reach PON has been demonstrated for 10Gbps both downstream and upstream transmission using wavelength 1550.4nm and 1548.0nm respectively for a distance of 120 km through Non-Zero Dispersion Fiber (NZDF), dense WDM channels spacing and Raman Amplifier. An optical Band Pass Filter (BPF) was used to remove the Amplified Spontaneous Emission (ASE) in the receiver side. The link power budget has been calculated for the splitting ratio 1/8. Various losses were assumed as 6dB, 9dB, 1.5dB and 4dB for dense WDM channels, split loss, splice loss and transmission loss for the distance 10 to 20 km respectively. The obtained result 40dB OSNR was shown as an excess value and limited the transmission penalties in 0.8dB (Rasmus Kjaer et al 2006). Also in 2006, BSIK Freeband Broadband Photonic Project (BSIK-FBPP) has modeled a
flexible design for dense WDM PON with cost effective control and management scheme. The cost effective investigation is considered by configurable control plane and protection management of better performance in the node components design flexibility. In this scheme a node component passive splitter has replaced and introduced Lambda-Router which equally performs like Reconfigurable Optical Add-Drop Multiplexer (ROADM) in dense WDM PON networks. It is suggested that the BSIK-FBPP design of a dense WDM PON provides better protection for the optical plane and cost effective scheme control the components design in hardware and software (Rajeev Roy et al 2006).

In 2007, the long reach 64 channel dense WDM PON was demonstrated and equally considered 64 channels for downstream (L-band) and upstream transmission(C-band) using 50GHz channel spacing with FP-LD. It has been proposed to have an access to a maximum of 155Mbps PRBS sequence with a length of $2^{31}-1$ up to 70km reach through SMF, guaranteed 100Mbps per channel in metro network for the satellite and HDTV applications.
The obtained link budget is nearly 32dB and the link loss occurred for two AWG is 10dB, and insertion loss due to other device is 3dB. Finally 13dB is considered as total loss without fiber between transmitter and receiver. The link loss has occurred due to backscattered BLS. It is suggested that the possibility of colour free operation using Reflective Semiconductor Optical Amplifier (RSOA) in place of FP-LD was to minimize the utilization of high current and device cost (Sang-Mook Lee et al 2007).

An investigation was made for colour free optical source in WDM PON. The effect of back reflection penalty has been reduced by increasing the line width of the seed light. In this experiment, the Distributed Feedback Laser Diode (DFB-LD) coherent light source was used as a seed
light at OLT. FP-LD was used as a modulator at ONU and optical coupler at RN with EDFA. The Rayleigh backscattering was also considered in this back reflection analysis. The obtained result for 1.25Gbps transmission describes the Quality factor (Q-factor) which is lesser for narrow line width 19.1dB than the widest line width 21.1dB.

The investigated results describe the higher back reflections which depend on reflectivity of RSOA. The link budget has been calculated for effects of seed light line width with maximum fiber loss 12.5dB and obtained guaranteed Q-factor of 16.9dB. Also the fiber dispersion limits the seed light line width while changing the channel spacing from 100 GHz to 200GHz. Finally, the optimized line width for optical signal or seed light was obtained in the range of 7 to 30 GHz (Jung-Hyung Moon et al 2007).

In 2008, the high Data-Rate WDM PON (DRWDM-PON) using Direct Modulated Lasers (DML), Fabry-Perot Etalon (FPE) with FSR of 100GHz per channel (0.8nm) and RSOA has developed a scheme with 10Gbps and 1.25 Gbps for downstream and upstream transmission respectively. AWG has been used for demultiplexing the downstream channels and the total link distance is considered at 25 km. The eye opened and received power arrived in the range of -21 to -15 dBm and -26 to -22dBm for downstream and upstream respectively (Shu-Chuan Lin et al 2008).

In 2008, with the support of IT research and development program of MIC/IITA, Republic of Korea, for the growth of Korean Telecommunication (KT) standard, a group of researchers demonstrated the cost effective transmission to upgrade 10Gbps to 40Gbps using dense WDM PON infrastructure and optimized the 10Gbps line rate over SMF by the obtained Q-factor value. The transmission link has been considered with 40 channels. In these 40 channels, 20 channels were linked for 10 Gbps line rate
using Non-Return-to-Zero (NRZ) format and another 20 channels were linked for 42.8 Gbps line rate using Carrier-Suppressed Return-to-Zero (CS-RZ) format.

All multiplexed signals were transported through Standard SMF (SSMF) distance of 511 km in the KT network with the support of eight span of link located in every 80 km. The obtained results were for dispersion and power in the range of -400 to 1000 ps/km and 5dB to reach the distance of 640 km using 1500nm wavelength range. The Q-factor obtained for 10Gbps transmission is 17 to 19dB with forward error correction (FEC) limit for BER $10^{-11}$ and a margin of 5.4dB and for 42.8Gbps transmission is 14 to 16dB with super-FEC limit for BER $10^{-15}$ and a margin of 5.2dB (Sang Soo Lee et al 2008).

TDM PON is not possible for the future 10 Gbps transmission since it is limited with two major factors by the power budget analysis. One is occurrence of severe insertion loss or splitting loss using 1x N splitter ratio and the second is long reach or link length distance between OLT and ONU with power budget. The above limitations were overcome by WDM PON and every channel is assigned individually to every ONU support to offer 10Gbps in near future. WDM PON also has more scalability and possible to make splitting ratio even up to 1x1000 and above. The long reach is more than 1000 km to route the multiplexed signal. Hence, it is referred and made suitable for DWA scheme (Klaus Grobe and Jorg-Peter Elbers 2008). MAC protocol issue is not a major issue in WDM PON since it supports packet transmission for both synchronous and asynchronous transmission. Similarly both line rates and frame rates are independent during the packet transmission (Fu-Tai An and Kyeong Soo Kim 2004, David Gutierrez et al 2005).
2.1.5 10 Gbps dense WDM/TDM PON or Hybrid PON (HPON)

Finally in this section the literature concerned with HPON performance with the arrival of certain novel ideas which were compared with TDM PON and WDM PON as given in the previous sections have been proposed and demonstrated. In 1998, the WDM/TDM PON has been operated with four fixed DFB lasers sourced the Continuous Wave (CW) 1550nm range wavelength for WDM PON and one Acousto-Optical Tunable Filter (AOTF) for TDM PON optical sources with EDFA. In the experiment, better line rate 51.84 Mbps was transported and obtained receiver sensitivities BER $10^{-9}$ and $-30.0$, $-29.5$, $-30.6$ and $-31.0$dBm for all four WDM PON channels, whereas the BER from the receiver sensitivity for TDM PON was $10^{-11}$. The estimated value of power penalty for AOTF was 0.17dB (Chang-Joon Chae and Nam-Hyun Oh 1998).

In 2001, dense WDM/TDM multiplexing techniques have been considered for interferometric fiber optic sensor applications using Optical ADM (OADM) and found out the crosstalk level range between $-47$dB and $-76$dB. The power budget has been determined by receiving a peak pulse power $-25.8$dBm which arrived from the single reflector in the array (Geoffrey Cranch and Philip Nash 2001). In 2002, an investigation was made to analyze the amplitude noise and timing jitter of pulse for slicing coherent Supercontinuum (SC) spectrum. The investigation has been made for data regeneration or data recovery in the TDM/ WDM system and its applications. The SC has been optimized the amplitude and jitter level for data regeneration by obtaining Q-factor values with normalized fiber length (Taccheo and Ennser 2002).
In 2004, the Stanford University aCCESS (SUCCESS) or hybrid WDM/TDM PON architecture with ring-star topology was proposed with Photonic Networking Research Lab (PNRL) researchers. The focus of the SUCCESS PON was to upgrade the DWA / DBA and the migration of TDM PON to dense WDM PON with advanced WDM techniques for the FTTH applications. The above new novel approach was attempted during 2004 by the PNRL researchers for the PON network and called it as Hybrid WDM / TDM-PON, or SUCCESS-HPON. This architecture is meant for the smooth migration from TDM PON to dense WDM PON. Again the PNRL research team has analyzed various scheduling algorithms including batch scheduling algorithms using OMNET++ testbed and measured the end-to-end delay, throughput and average packet delay for both downstream and upstream transmission for 10Gbps line rate (Varga 2003, Fu-Tai An et al 2004).

In 2005 many group of researchers including PNRL group proposed many demonstrations for hybrid WDM/TDM PON for the line rate 2.5Gbps to 10Gbps with SMF distance 30km and above. This section outlines three major proposals which were given by three different group researchers in the year 2005. One group of researchers analyzed the unicast and multicast data using free spectral range (FSR) periodicity of two cascaded AWG in hybrid WDM/TDM PON for the line rate 2.5Gbps. It was suggested that the topology was having the features of security, suitability of tunable laser and fixed laser for unicast and multicast respectively (Carlos Bock and Josep Prat 2005).

The second group of researchers identified and proposed a novelty of SUCCESS PON, to operate the DWA scheme. Also it has been suggested as a powerful architecture for NGA optical network in terms of cost, scalability and performance (Yu-Li Hsueh et al 2005). Finally, another novel architecture has been presented in 2005, a centralized light source and DBA
scheme using AWG FSR for WDM/TDM PON. It focused the importance of space division multiplexing (SDM) support for hybrid WDM/TDM, tunable laser source and photo detector in receiver for DBA scheme and finally transmission made with 2.5 Gbps for the SMF distance of 30 km using the wavelength range 1500nm (Carlos Bock, Josep Prat and Stuart Walker 2005).

In 2006, an experiment dealing with numerical approach was made for 10Gbps hybrid dense WDM-TDM PON to the maximum long reach of 115 km for 1088 users (17 PON x 64 split) and an accessed mean data rate of 155Mbps has been analyzed. The investigated result was almost satisfied by obtained OSNR range -20 to 30dB with respect to Rayleigh Back Scattering (RBS) for hybrid dense WDM/TDM PON (MacHale et al 2006).

In 2007, the proposed lower cost maintenance self protection scheme describes the usage of optical components AWG, WDM coupler and optical splitter at OLT, RN and ONUs of hybrid WDM/TDM PON. The study has been made for 16 ONUs and found out the power budget 23 dB for downstream and 11.2 dB for upstream respectively (Jiajia Chan and Lena Wosinka 2007). Also in 2007, a few among the WDM/TDM research groups analyzed the QoS for reservation based DBA scheme by properly designing the size of ONUs time slot, GATE message transmission time and dynamic control of ONUs service weight for fairness. Another group proposed an innovative concept on Optical Burst Switching (OBS) for metro-network application using hybrid WDM/TDM PON and pointed out the usage of Reflective ONU (R-ONU), tunable laser at OLT and AWG at the outside plant which was a good choice for upstream transmission to reduce the cost. (Seung Jin Lee et al 2007).

In addition, a scheme has been proposed in 2007 for HDTV/Gigabit/CATV applications with bidirectional hybrid dense WDM
PON. In this architecture four Vertical-Cavity Surface Emitting Lasers (VCSEL) and DFB laser were operated with 1550nm wavelength range to carry the bit rate 1.25Gbps in bidirectional for the SMF distance 40km with Ethernet link, and finally supported 129 and 77 channels for HDTV and CATV respectively. The obtained results have proven the better BER $10^{-9}$ received optical power within the range -28 to -26.2dBm and controlled the power penalty improvements without using the AWG component in the hybrid dense WDM / TDM PON system (Hai-Han Lu et al 2007).

In 2008, the literature viewed the importance of RSOA which has taken a device and considered it for following two major applications of hybrid WDM/TDM PON.

1. The RSOA has taken care of remotely pumped EDFA for 1.25Gbps upstream transmission controlled 32-WDM channels and 16-TDM splits at SMF distance of 25 km and distributed maximum of 512 ONUs. The results obtained without and with RSOA were better and occurred value for BER is $10^{-9}$ and sufficient gain 15dB for upstream signal with CW seed light power in the range of 0 to -14dBm (Jung Mi Oh et al 2008).

2. The RSOA was used in burst mode operation for hybrid WDM / TDMA PON and is proposed as a low cost PON. The demonstration describes the achievement to transport 1.25Gbps with SMF distance 50km and is distributed the bandwidth to 1024 users. The obtained result gives the RSOA differential power gain changed to a maximum of 2dB and supports 20 to 22dB as maximum power budget. Also
comparative performance was made with GPON class B+ type power budget between 13 to 28dB (Belfqih et al 2008).

Extended hybrid PON architecture which has been proposed in 2008, shared the wavelength similar to GPON using colourless ONT. It supports 128 users with four 1x32 PONs over a SMF distance of 60km and shared 40Gbps in downstream transmission using Course WDM (CWDM) and Medium-Dense WDM (MDWDM) filters. The obtained results were compared with GPON module over the distance transmission of 80km and given better result improvement in BER $10^{-15}$ and received signal power in the range of -29 to -28dBm (Martin Bouda et al 2008).

In the following section an analytical traffic model for PON access system has been proposed innovatively from the literature review to identify the limitations of MAC layer issues of PON access system. The traffic model analyzes the MAC and network layer performance and measures the waiting time in queue, time-slot assignment accuracy, tuning latency and utilization at the peak traffic or burst mode transmission. This traffic model investigation supports the fiber based 10 Gbps and above high bit rate packet or frame transmission of PON access system. Similarly, the physical layer performance of PON and its various parameters of Optical Signal Power (OSP), Optical Noise Power (ONP), OSNR, gain and fiber distance are also measured in the following main chapters.

The Figures 2.1 and 2.2 explain the specialized Poisson queuing situations and its model with uniform packet distribution in service among all the ONUs and OLT for both the downstream and upstream processes.
2.2 TRAFFIC MODEL

2.2.1 Specialized Poisson Queuing model for PON Access System
(Packet or Frame - steady state transmission model for Burst Mode Operation)

Figure 2.1 PON packet queuing system for downstream process

Figure 2.2 PON packet Queuing system for Upstream Process

The packet arrival rate at the PON system is ‘λ’ ONUs per unit time. The packets are received from the ONUs and distributed with uniform speed like parallel in service i.e., without delay using different wavelengths
called the WDM-PON and with different delays using different time slots called the TDM-PON. If all the parallel services are identical, then the service rate for any service is ‘µ’ ONUs per unit time. Ultimately the numbers of ONUs accessing the information in the PON system is defined by those ONUs which are in service and those ONUs which are in queue. The traffic model of PON access system using specialized Poisson queues have been explained in Figures 2.1, 2.2 and 2.3 and following expressions (2.1) - (2.10) are used for the PON queuing system in traffic model (Hamedy Taha 2002)

The characteristics of queuing situation as per the following format

\[(A_p / D_p / ONU_{pp}): (Q_d / e / f)\]  \hspace{1cm} (2.1)

where,

- \(A_p\) - Packets arrival distribution
- \(D_p\) - packet departure (transmission time) distribution
- \(ONU_{pp}\) - number of parallel packet transmission from RN to \(ONU_n (n = 1, 2, 3... \infty)\)
- \(Q_d\) - Queue discipline
- \(M_p\) - maximum number (finite or infinite) allowed in the system (in queue plus and in transmission)
- \(S_{OLT}\) - size of the OLT (finite or Infinite)

The Packet queue discipline can be formed by Markovian modulated Poisson process as for WDM-PON Model is

\[(M/D/m): (GD/m/\infty)\]
\[(M/D/64):(GD/64/\infty)\]  \hspace{1cm} (2.2)
The Packet queue discipline can be formed by Markovian modulated Poisson process as for TDM-PON Model is

\[(M/DD/m): (GD/m/\infty)\]
\[(M/DD/1024):(GD/1024/\infty)\]  \hspace{1cm} (2.3)

where,

- **M** - Markovian (or) Poisson arrivals or departures distribution (or equivalently exponential inter-arrival or transmission time distribution)
- **m** - Number of customers (64 in WDM PON and 1024 in TDM PON) on the entire system
- **D** - Constant (deterministic) time
- **DD** - different/constant time slot
- **GD** - General discipline of packet queue (any queue model like FIFO, LILO, LIFO etc.,)

**Steady-state measurement of performance**

The most common measure used in PON system as per queuing model in a queuing situation could be represented by information arrival rate \(\lambda\) relationship, which is shown in Figure 2.3 as a concept diagram.

![Figure 2.3 Relation between \(\lambda\), \(\lambda_{lost}\) and \(\lambda_{eff}\)](image-url)
Rs - Expected number of ONUs in PON system.
Rq - Expected number of ONUs in packet queue
Ws - Expected packet waiting time in PON system.
Wq - Expected packet waiting time in queue.
\( \text{ONU}_{pp} \) - Expected number of ONUs in the busy (or) burst mode operation

It should be remembered that, any PON system includes both packet queue and packet in transmission time facility. Therefore, the steady state probabilities \( P_n \) of ‘n’ ONUs in the PON system can be used to determine the Rq and Rs values by using the relations,

\[
R_s = \sum_{n=1}^{\infty} nP_n \quad (2.4)
\]

\[
R_q = \sum_{n=\text{ONU}_{pp}+1}^{\infty} \left( n - \text{ONU}_{pp} \right)P_n \quad (2.5)
\]

The relation between the \( R_s \) and \( W_s \) and also between \( W_q \) and \( R_q \) is known as Little’s formula and can be given by the simple relations

\[
R_s = \lambda_{\text{eff}} W_s \quad (2.6 \text{ a})
\]

\[
R_q = \lambda_{\text{eff}} W_q \quad (2.6 \text{ b})
\]

The above relations 2.6(a) and 2.6(b) are valid under general conditions. Parameter \( \lambda_{\text{eff}} \) is the effective packet arrival rate of the system. In this way, the direct relation between the \( W_q \) and \( W_s \) can be determined using the relation
Expected packet waiting time in system = Expected waiting time of packet in queue + expected packet service time i.e.,

\[ W_s = W_q + \frac{1}{\mu} \]  \hspace{1cm} (2.7)

From the above relation it is possible to relate the \( R_s \) and \( R_q \) by simple multiplication of \( \lambda_{\text{eff}} \) on both sides, obtain

\[ R_s = R_q + \frac{\lambda_{\text{eff}}}{\mu} \] \hspace{1cm} (2.8)

By definition the difference between the average numbers of ONU s (\( R_s \)) and the average number of packet queues (\( R_q \)) must equal the average number of busy or Bursty mode

\[ \overline{\text{ONU}}_{\text{pp}} = R_s - R_q = \frac{\lambda_{\text{eff}}}{\mu} \] \hspace{1cm} (2.9)

It follows the facility utilization which could be given as,

\[
\text{Utilization} = \frac{\overline{\text{ONU}}_{\text{pp}}}{\overline{\text{ONU}}_{\text{pp}}} = \text{Bursty mode / Non – Bursty mode performance}
\]

(2.10)

A PON traffic analysis is given with an example in the Appendix 1.
2.3 MOTIVATION, PROBLEM FORMULATION AND DEFINITION

2.3.1 Motivation

In the previous section of this chapter, from the literature review, the status of various PONs link power estimation, power budget requirements in physical layer, various algorithms in MAC and network layer which contributed nearly past two decades for NGA networks were almost investigated.

The Table 2.1 gives the detailed basic comparison of various PONs types through characterwise among WDM/ denseWDM-PON and TDM PON (Fu-Tai An and Kyeong Soo Kim 2004, Giuseppe Talli and Paul Townsend 2006, Elmar Trojer et al 2008, Klaus Grobe and Jorg-Peter Elbers 2008). EPON is economical when compared with other types of PONs. But it has limitations in higher bandwidth transmission. WDM PON has more advantages in view of QoS which provides even 10 Gbps per channel than TDM PON types, but its cost is high. Based on the PONs characteristics from the Table 2.1, every PON architecture is having its own advantages, disadvantages, issues and problems towards the QoS, cost and simplicity. Ultimately, the link power estimation or budget demands the optical power required for the ‘optical path’ to transport the high bit rate of information from transmitter to receiver i.e. measured signal power at source to channel and received signal power at channel to receiver. So the thesis has been motivated to analyze the suitable PON architecture and its link power estimation / budget to provide to access 10 Gbps and above as average bandwidth per user at low cost. The 10 Gbps bidirectional transmission to be developed both burst and non-burst mode operation for NGA networks not only in Metropolitan Area Network (MAN) and Wide Area Network (WAN) but also in rural LAN.
## Table 2.1 Different PONs types and its characteristics

<table>
<thead>
<tr>
<th>Characteristics of PON</th>
<th>TDM PON</th>
<th>WDM/ dense WDM PON</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BPON</td>
<td>EPON</td>
</tr>
<tr>
<td>Standard</td>
<td>ITU-TG.983</td>
<td>IEEE 802.3 ah</td>
</tr>
<tr>
<td>Framing and Protocol</td>
<td>ATM</td>
<td>Ethernet</td>
</tr>
<tr>
<td>Maximum bandwidth access (Mbps)</td>
<td>622 down 155 up</td>
<td>1.25 down 1.25 up</td>
</tr>
<tr>
<td>Number of Users per PON and split-ratio</td>
<td>1:32</td>
<td>1:16</td>
</tr>
<tr>
<td>Average bandwidth per user</td>
<td>20 Mbps</td>
<td>60 Mbps</td>
</tr>
<tr>
<td>Span (km)</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Video</td>
<td>RF</td>
<td>RF / IP</td>
</tr>
<tr>
<td>Max. Budget (dB)</td>
<td>15/22</td>
<td>15/20</td>
</tr>
<tr>
<td>Estimated Cost</td>
<td>Low</td>
<td>Lowest</td>
</tr>
</tbody>
</table>
2.3.2 Problem formulation and definition

All the above specification details, literature review and PON traffic mathematical model have been investigated in the previous sections to access 10Gbps in future with standard PON architecture. Even though many proposed methods and analysis were carried out with optical amplifiers, generally the link power estimation of any PON system architecture design performance in traffic is to be satisfied for receiver sensitivity and system degradation (Cooper et al 1992, Govind Agarwal 1997, David Cunningham and Piers Dawe 2002, Lisa Peng and Robert Carlisle 2002, Lee Sorin and Byong Yoon Kim 2006). It is an issue and compensating the Power Penalty Requirements (PPR) or link power budget, as well as better receiver sensitivity or ONU performance during downstream and upstream high bit rate transmission. In this way a problem is formulated for link power estimation to any PON architecture which can meet out and full fill its power penalty during DBA / DWA. Based on above needs, it is essential to select optimal optical pulse for assigning more number of channels with less channel spacing which needs to be suited for high bandwidth transmission through fiber by operating with best tunable source, RN and receiver components. Every pulse is responsible to carry a maximum bandwidth and it is to be allocated properly to access every user node from OLT to ONUs with negligible fiber pulse dispersion, non-linear effects and optical power distribution complexity bidirectionally from the RN (Marcuse and Lin 1981, Dilwali and Soundra Pandian 1992, Zhou et al 2000, Cheng-Chung Chien and Ilya Lyubomirsky 2007). In order to get loss free optical power or negligible optical pulse power penalty from OLT to ONUs, optical pulses are controlled with 3R techniques which are Re amplification, Re timing and Re shaping.

The PPR and power budget improvements are necessary for LAN to any type of long haul PON access system. The PON system itself is very
less to view as an ideal or optical pulse power loss free system both in non
burst and burst mode transmission (Frank Effenberger et al 2007). So, in this
research work, it is interested to investigate the importance of downstream
link power budget for types of TDM and WDM PON, since downstream
bandwidth (downloading) required ratio has more demand in end user side
than upstream bandwidth (uploading) for IP, HDTV and satellite link based
applications in practice. Also the PPR for various PONs have been analyzed
and compared in the following chapter of this research work. The above
discussion motivated to define the problem as follows (Frank Effenberger

The novel link power budget estimation problem in PON is defined
as the occurrence due to the RN power splitting loss complexity, routing the
wavelength in undirected optical path, not receiving optimal optical and
electrical pulse power to every ONU unknown location, while transmitting
high bit rate from OLT through unoptimized fiber medium link length and
hence the need for power penalty

2.4 RESEARCH METHODOLOGY

2.4.1 Optimization techniques for Power Penalty Requirements
(PPR)

Based on the problem formulation and definition, estimating the
PPR for various PONs, the research method of analyzing the PPR uses two
optimization techniques which are as follows (Optisystem 2006)

(a) Single-Parameter-Single-Result Optimization (SPO) technique
which is to measure the PPR value for single parameter
performance.
(b) Multi-Parameter-Multi-Result Optimization (MPO) technique which is to measure the PPR value with two or more parameters performance.

Both techniques are having some advantages to find the PPR for PON which are as follows:

- Optimize the optical amplifiers parameters and obtain the gain.
- To measure the effective value of Q-factor and minimum BER (Min.BER) by optimizing the fiber length of the link.
- To estimate system margin and noise figure.

The SPO optimization deals with the main operation set up within a span of fiber link length using optical amplifiers in PON architecture. In this research work, the SPO optimization technique is only used to find the stated problem of PPR for all PONs type with the arrived optical link power performance results like gain, noise figure, fiber length and received optical signal power and so on.

2.5 GENERIC PLATFORM FOR THE WORK

2.5.1 Various links in PON Architecture

The schematic diagram for bidirectional link of DBA/ DWA in PON architecture is shown in Figure 2.4. Feeder network and distribution networks are establishing a link between OLT to RN and RN to ONU. In the proposed 10 Gbps PON architecture, Source-Fiber Coupling Power (SFCP) is shown as feeder network and Fiber- Receivers Coupling Powers (FRCP) via RN as distribution networks. Inter coupling process between the links are very
important for the analysis of the link power budget estimation. In this research work, the simulation has considered for various losses occurred in between the fiber links and other various segments. Various links available for the PON network have been described in relation to this research work and their losses are also considered for the power budget analysis.

(i) OLT-Fiber link

The first link is establishing a link between the OLT and the fiber. The OLT is powered by FPF and AOTF are the tunable laser/tunable filter for transmitting tunable wavelengths or multi optical pulses for the wavelength range of 1550nm. DFB laser and other CW lasers are also used as seed light laser source. The AM and Mach Zehnder Interferometer (MZI) are used as optical modulator. The NRZ format signal is considered as the encoded signal in the analysis. The OLT may also be sourced by other laser sources and modulators. The prime losses occurred in this section of the link is the connector loss ($l_{con}$) (Biswanth Mukherjee 2005, Th. Pfeiffer et al 2005) which is mostly in the OLT side.

Figure 2.4 Schematic diagram for bidirectional link of DBA / DWA in PON
(ii) Fiber–RN link

Single mode fiber or multi mode fibers have been used for connection between the OLT and RN. Losses were due to high bit transmission for long distances using MMF and other losses due to various dispersions mechanism and bandwidth distance product. The important losses occurred in this links are dispersion loss ($l_{\text{disp}}$) and bandwidth-distance loss ($l_{\text{bd}}$). The fiber coupled with 1xN power splitter in the RN and splitter stage the splitting ratio 0.1 to 0.5 have been considered for link budget analysis (Dhillon and Chris DiMinico 2002, Kim and Chen 2004, Chan and Chen 2006, Huan Song and Biswanth Mukharjee 2006, Davey et al 2006).

(iii) RN – ONU’s link

The final stage of PONs consists of various end user nodes which are connected in symmetric distance among all ONU’s with fiber link. Normally, the receiver unit consists of PIN or APD photo detectors with an operating wavelength of 1310nm for CWDM and 1550nm for WDM/DWDM respectively (Glen Kramer et al 2000, Kyeong Soo Kim et al 2005, Sawsan Al Zahr and Maurice Gagnaire 2006). The power and bandwidth losses are identified and redistributed again to ONU’s from RN by the feedback set up (Glen Kramer et al 2001, Sherif et al 2004). In this analysis, APD has been used to receive the optical signal at wavelength range of 1550 nm for all ONU’s.

(iv) Bidirectional link

PONs which are considered as information, pulse and packet (bit or byte) transmission between physical and network layer of from OLT to ONU’s as downstream or downlink and from ONU’s to OLT as upstream or uplink.
From an architectural point of view, every PONs nodes is operating as transceiver. (David Gutierrez et al 2005). So for many link powers budget designs have suffered to stand long term and aimed to do good services to various PONs like TDM PON, WDM PON, HPON and long reach (LR PON). All these PONs provide 10 Gbps over 100 km up to 1000-way multistage split with lower cost fiber by minimizing components of ONUs, splitting losses and lack of bandwidth sharing while accessing in bursty traffic (Optical Broadband Working Group 2006, Biswanth Mukherjee 2005). Practical implementation requires complete study and analysis of link budget estimation. In this link budget analysis, cost trade off and the point of customer feasibility for link power budget design of 10 Gbps DBA scheme using PON architecture with a data handling capacity from 1Gbps to 10 Gbps are focused.

In the link power budget analysis for the 10Gbps PON architecture, three major issues were considered. The first needs more efficient wavelength selective passive device at OLT, RN and ONUs i.e., upgradation of physical layer performance using tunable mechanism. The second one needs faster or modified scheduling algorithm, routing and wavelength assignment algorithm for higher bandwidth allocation dynamically i.e., to achieve or improve high throughput especially at burst mode receiver operations to improve the network layer performance, and adaptively processing interleaving/de-interleaving time of packet transmission without any collision. Finally with minimum number of device how packet transmission time was effectively utilized by maximum throughput taken to achieve cost trade off and best QoS availing high bandwidth at lowest cost for the end user needs or customer satisfaction. (Sherif et al 2004, David Gutierrez et al 2005)
2.5.2 Flowchart Approach for 10 Gbps PON Link Power Estimation (LPE)

In the proposed link budget estimation, the third window wavelength region near 1550nm range has been taken for the lowest fiber loss occurring for bit rate $R \leq 10$Gbs. CW laser source bit rate-distance product (RL) can use laser source with SI – SM fiber to achieve RL for 1550nm in 10Gps (Franz and Jain 2000, Glen Kramer et al 2001) and also has chosen the 1550nm range for downstream and 1300nm link for upstream link power in burst mode traffic which has been modeled in a flowchart is shown in Figure 2.5. The flowchart gives an idea to estimate the link power budget with power margin ($P_m$) and ‘m’ is the number of decibels which are greater than or equal to 4dB as per maximum link length calculation and power budget (Franz and Jain 2000, Chan and Chen 2006). In this research work the flowchart is considered not only a novel model to estimate the link power for one PON but also it helps to estimate the link power for all PON types.

It is concluded in this chapter, the advances in PON devices and accessing technology offer higher bandwidth capacity, but researchers have recognized that many problems need to be addressed before these various PONs are implemented on a large scale. Currently, many researchers including Stanford University are working on building a hybrid PON system. The literature on the design requirement of link power estimation for standard 10 Gbps PON was discussed. The main focus of the study is on OLT, RN and receivers of various PON, since it is the most promising architecture in terms of scalability with the DBA/DWA and number of ONUs. The difficulties involved in the design of high performance PON have been described.
Figure 2.5 Flow chart for modeling the link power budget design for 10 Gbps PON
After formulating the problem of link power estimation as power budget requirements problem in the optical path, various PONs developments were introduced. The NGA network of PONs will still be to develop simpler and more efficient broad band access networks.

2.5.3 Overview of the thesis work

The detailed overview of the thesis work is shown in Figure 2.6 for the 10 Gbps link power estimation with various innovative in the proposed PONs using SPO optimization technique.
Figure 2.6 An Overview of the thesis work