CHAPTER 1

INTRODUCTION

1.1. INTRODUCTION

Internet access is the means by which individual computers, mobile devices and networks are connected to the Internet, which enables users to access Internet services such as email, World Wide Web and peer-to-peer networks. Internet Service Providers (ISP) offer users the access to the internet and related services by employing a range of technologies. The available technologies range from telephone lines, cables, to Wireless Fidelity (WiFi) and fiber optics, and could be classified into traditional wired and wireless access techniques. Wired techniques include Multilink dial-up, Integrated services for digital network, Leased lines, Digital Subscriber Link (DSL), Fiber to the Home, ATM and Frame Relay. Wireless techniques include WiFi, Wireless ISP, Worldwide interoperability for Microwave Access (WiMAX), Satellite broadband and Mobile broadband. These technologies come with a wide range of data rates.

With the emergence of bandwidth-intensive applications such as Voice over IP (VoIP), IPTV, and Audio / Video streaming, broadband access is becoming increasingly important for the Internet and these require high data rates which are best offered by fixed fiber links. The core transport network’s transmission capacity has tremendously increased with the advances in photonic technologies and worldwide deployment of optical fibers, and the fiber optical transmission technology has reached 10 Tb/s in a single fiber. The backhaul networks must be robust in order to provide high
speeds, and to utilize these high data rates the system should have sufficient provisions. Among the different network access solutions available, Passive Optical Network (PON) emerges as the most assuring cost-effective and high-performance solution. Among the different PON techniques, Ethernet PON (EPON) is a cheap solution due to the facts that 95% of already existing local networks use Ethernet based communication, overlapping of Ethernet equipment with fiber infrastructure is feasible and is void of maintenance cost. Additionally, EPON offers extremely high bandwidth in addition to possessing reliability and network availability. EPONs interoperability with Ethernet network is eased by the fact that the transmission data is encapsulated in Ethernet frames, which makes it easy to carry IP packets. EPON is ratified by the Institute of Electrical and Electronics Engineers (IEEE) 802.3ah Task Force. Multipoint Control Protocol (MPCP) which arbitrates channel access among central office and subscribers in EPON is also developed by this Task Force. However, they are still very costly for deployment to each home, and provide little flexibility and no mobility; whereas wireless solutions support mobility and have low deployment costs.

To offer bandwidth intensive application services to mobile end-users, the wireless broadband plays an important role. Broadband wireless access networks like Global System for Mobile communications (GSM), WiFi, WiMAX and Long Term Evolution (LTE) provide high-capacity bandwidth links, coverage and Quality of Service (QoS) support. When many users share the bandwidth, it limits the bandwidth available to each user, and this is why the wireless networks generally suffer from a limited wireless spectrum. This necessitates the development of an efficient “last-mile” access network that provides high bandwidth with QoS support, mobility and cost-effective access.
Integrating both wireless and optical access network technologies is essential in the evolution of a new generation wired-wireless access to combine mobility with high speeds, which would see the integration of the latest advances in optics and electronics. One major challenge associated with the integration process is the proper selection of a Dynamic Bandwidth Allocation (DBA) algorithm since DBA is solely responsible for effective allocation of resources in the system. The wireless technologies focused in this work are WiMAX and LTE. EPON is chosen for the optical part of the network.

1.2. PON

PON technology is one of the best solutions for last mile access used by FTTx, with FTTx relating to Fiber To The Home, Fiber To The Building, and Fiber To The Curb. It is a Point to MultiPoint (P2MP) network topology implemented with passive optical splitters, and optical fibers. Active devices exist only in the central office and at user premises, and there is no active component between the central office and the user premises. A single-mode optical fiber runs from the central office and ends at the user premises with a 1:N passive optical power splitter. Subscribers are connected to each output port of the passive splitter with individual single-mode fibers. The transmission distance for PONs is limited to 20 km. The fibers and passive components between the central office and users premises are commonly called an optical distribution network. The number of users supported by a PON can be anywhere from 2 to 128, depending on the power budget, but typically, 16, 32, or 64.

PON technology broadcasts downstream signals to all users sharing the fiber, and upstream signals are combined using Time Division Multiple Access (TDMA) protocol. At the central office, an Optical Line Terminal (OLT) broadcasts downstream data to each user. The downstream data and
video packets contain the destination’s Media Access Control (MAC) address, and the users select the data packet intended to them based on the MAC address. 1490-nm wavelength is used for downstream data, and 1550-nm wavelength is used for video. At the user end, an Optical Network Unit (ONU) transmits upstream data at 1310-nm wavelength. To avoid collision in upstream transmission, a multiple access protocol is used to assign time slots to each user and the users transmit only in the particular timeslots assigned to them. PON network topologies are flexible and include tree, tree-and-branch, star, and bus topologies. Tree is the widely used topology with OLT connected to the trunk of the tree and ONUs connected at the branches of the tree as shown in Figure 1.1 (Kazovsky et al 2011) (Lam 2007).

![Figure 1.1 PON topology](image)

1.2.1. Network Elements

A PON is a shared network, in that the OLT sends a single stream of downstream traffic which is seen by all ONUs. Each ONU only reads the content of those packets that are addressed to it. Encryption is
used to prevent eavesdropping on downstream traffic. For the sake of conceptual clarity, the entities and terminologies involved in the process are introduced:

OLT is the network-end Data Terminal Equipment (DTE) for an optical access network and is the master entity in a P2MP network with regard to the MPCP protocol. OLT provides the interface between a PON and a service provider's core network, and typically resides at the service provider’s facility. ONU is the subscriber-end DTE to an optical access network and is a slave entity in a P2MP network with regard to the MPCP protocol. The ONUs are typically located at the subscriber premises which terminate the PON and provide the service interfaces to the user. In an access network, transmission away from the subscriber end of the link is called upstream access. The OLT (master) issues grants to the ONUs (slaves) by means of GATE messages. With the help of grants, the ONUs have the permission to transmit at a specific time for a specific duration. The OLT is connected to ONU via 1:N passive splitter or cascade of splitters. The downstream data from the OLT to ONU are transmitted by means of broadcasting, and the ONUs recognize their data by using Logical Link Identifier (LLID) established during registration phase. All ONUs in an EPON system share upstream bandwidth by TDMA and the signal transmitted by an ONU will only reach the OLT, but not the other ONUs.

ONU transmissions are arbitrated by OLT by assigning timeslots to every ONU. The ONU defers its transmission until its timeslot arrival to avoid data collision and to increase the efficiency of the network. The OLT also takes care of calculating Round Trip Time (RTT) to each ONU since ONUs reside at varying distances from the OLT making the transmission delay from each ONU a unique one.
The Optical splitter couples the upstream data from the ONU into one and forwards it to the OLT. It also distributes the downstream data to all ONU.

1.2.2. PON Technologies

The transmission modes for downstream (that is, from OLT to ONU) and upstream (that is, from ONU to OLT) are different in PON due to its topology. The OLT broadcasts optical signal to all the ONU in continuous mode for the downstream transmission, and thus the downstream channel always has optical data signal. Contrarily, the ONU cannot transmit optical data signal in continuous mode in the upstream channel. Use of continuous mode would result in all of the signals transmitted from the ONU converging into one fiber by the power splitter, and overlapping. Burst mode transmission is adopted for upstream channel to solve this problem. The ONU transmits optical packet only when it is allocated a time slot, and all ONU share the upstream channel in the Time Division Multiplexing (TDM) mode (ITU-T G.983.1 2005).

Amplitude difference between the received packets in the OLT is realized by the fact that the distance between the OLT and ONU are not uniform. Since the ONU are not synchronized to transmit optical packet in the same phase, and the distance between OLT and given ONU are random, there is a phase difference between the burst mode optical packets received by the OLT. Burst mode clock and data recovery need to be employed to compensate the phase variation in short time. Amplitude variation is compensated by employing burst mode amplifier. Burst mode transmission requires the transmitter to work in burst mode as well, since a burst mode transmitter is able to turn on and off in short time.

In continuous mode optical communication link, the above three kinds of circuitries are quite different.
1.2.3. PON Variants

The PON technology variants available today are:

- Time Division Multiple-based PON (TDM-PON),
- Wavelength Division Multiplexing-based PON (WDM-PON) and
- Long Reach Optical Access Networks (LROAN).

Further, TDM-PON variants are:

- ATM PON (APON) / Broadband PON (BPON),
- Ethernet PON (EPON) /10Gbps EPON (10GEPON) and
- 1Gbps PON (GPON)

TDM-PON usually implements TDMA technology on uplink and downlink transmission to achieve bandwidth sharing. A passive power splitter is used as the remote terminal and the signals of the OLT which will be allocated to each ONU have to go through the passive optical splitter. Signals of all ONUs are multiplexed in the time domain and the ONUs recognize data meant to it through the address labels embedded in the signal.

WDM-PON uses WDM technology in its system, and the passive optical splitter will allocate signals to each ONU by identifying a variety of optical wavelengths from the OLT. The multiple wavelengths of a WDM-PON can be used to separate ONUs into several virtual PONs co-existing on the same physical infrastructure. Alternatively the wavelengths can be used collectively through statistical multiplexing to provide efficient wavelength utilization and lower delays experienced by the ONUs. There is no common standard for WDM-PON or any unanimously agreed upon definition of the term. By some definitions, WDM-PON is a dedicated wavelength for each ONU. WDM-PON has better privacy and better scalability because each
ONU only receives its own wavelength. The high cost of WDM-PON initial set-up is due to high cost of the WDM components. Another challenge to be handled in WDM-PON is temperature control, because wavelengths tend to drift with environmental temperatures.

The concept of the Long-Reach Optical Access Network (LROAN) is to replace the optical/electrical/optical conversion that takes place at the local exchange with a continuous optical path that extends from the customer to the core of the network. Payne & Davey (2002) showed that significant cost savings could be made by reducing the electronic equipment and real-estate required at the local exchange or wire center. A proof of concept demonstrator showed that it is possible to serve 1024 users at 10Gbit/s with 100 km reach (Shea & Mitchell 2007). This technology has sometimes been termed Long-Reach PON, however, many argue that the term PON is no longer applicable as, in most instances, only the distribution remains passive.

1.2.3.1. APON/BPON

APON /BPON integrate the ATM data link layer and physical layer and considered as the best PON technology when first developed. APON transmits continuous ATM cell streams. Each cell is of 56 bytes long with 53 data bytes and 3 overhead bytes. The overhead bytes are for:

- Time protection - to prevent damages to signal from small phase shift,
- Prefix-for synchronization,
- Delimiter- to identify beginning of micro-slots and for synchronization.

For the downlink direction, APON applies a broadcasting TDM. Each ONU will receive all cells, and is able to extract its own cells from the appropriate time gap according to the targeted address of cells. For the uplink direction APON transmits ATM cells in burst mode. For the purpose of conflict free
and effective uplink access, and in order to ensure that all uplink signals for each ONU will fully arrive at OLT, TDMA is used as the uplink access control technology. Therefore, APON has to measure the transmissions for each ONU and coordinate signaling based on the time delay. BPON strengthens a part of APON standards.

1.2.3.2. GPON

APON and EPON both have fixed encapsulation formats: ATM encapsulation for APON and Ethernet encapsulation format for EPON. GPON does not have a fixed encapsulation format and applies GPON Encapsulation Method based on the original format of user signals (ITU-T G.984.3 2004) (ITU-T G.987.3 2010). Because of its special encapsulation format, GPON can keep high efficiency when it transmits multi service data, including voice, Ethernet, ATM, leased lines and other service data. The efficiency can reach above 90%. Meanwhile, GPON retains many features of G.983 which are not directly related to PON protocol, such as Operation, administration and maintenance and DBA. There are a variety of GPON transmission methods such as Synchronous Optical Network (SONET) / Synchronous Digital Hierarchy defined in ITU-T G.709 (ITU-T G.709 2012).

1.2.3.3. EPON

Ethernet almost dominates the network market with its simplicity, practically low cost, and nearly 40 years of development, and is the best carrier for IP data packets. EPON is compatible with the existing Ethernet protocol. Given the market advantages of Ethernet, the compatibility of EPON with Ethernet is one of the most significant advantages of EPON. 802.3ah working team is the force behind EPON which works for EPON’s simpler access to the network, and transmit Ethernet frames with minor changes compared to the existing IEEE 802.3 protocol.
For the downlink direction, the OLT applies TDM and transmits optical data packets to multiple ONUs in the form of IEEE 802.3 frame encapsulation. Each data packet carries a unique identity to identify the destination of ONUs. For the uplink direction, each ONU combines all its data to be transmitted and EPON uses TDMA technology to prevent packet collision with specific timeslots assigned for each ONU. The transmission distance can be up to 20km. When combined with the Ethernet protocol, such a network is referred to as EPON (Kramer 2005). The main advantages of EPON include:

- Harmonious integration with Ethernet.
- 20km transmission distance - solves the problem of distance bottlenecks of copper wire, cable and hence supports remote user access.
- Low operation and maintenance cost - only optical fiber, optical splitter and passive optical devices between OLT and ONU - no power supply, no spacious occupation, no in-person maintenance.
- Low construction cost - fiber prices continue to decline lowering cost of optoelectronic devices.
- Supports variety of IP-based network services.
- High bandwidth (1G / 10G).
- High reliability - optical fiber and passive optical devices effectively avoids electromagnetic interference and lightning to ensure high quality of transmission.
- Uniform Standards.

1.2.3.4. 10G-EPON

10GEPON and 1GEPON protocols differ in the physical layer and data link layer. Comparing the EPON hierarchical model defined by IEEE
802.3ah and the 10GEPON hierarchical model expanded by IEEE 802.3av, there are no significant changes above the data link layer. The 10G EPON hierarchical model is compatible with the coexistence of 10G and 1G. However, in order to avoid too many changes in the MAC layer, the physical layer is redefined a little. The Physical Medium Attachment sub-layer and the Physical Media Dependent sub-layer are quite different. The Forward Error Correction (FEC) function in EPON is optional but in 10G EPON protocol, FEC is a necessary feature.

As the rate of uplink and downlink has greatly changed from 1Gbits/s to 10Gbits/s, the operating frequency of 10G EPON has also changed. The MAC layer, Reconciliation sub-layer and Physical Code sub-layer defined in the protocol have changed correspondingly. The MAC sub-layer expands the MPCP layer based on the MPCP defined by the previous IEEE 802.3ah. Two bytes are added to the discovery gate frame sent by theOLT to identify whether the OLT has the ability to support 10G and 1G uplink, and to determine if the current discovery window is 10G or 1G. Two bytes are also added into the corresponding registration request frame sent by each ONU to identify whether the ONU has the ability to support 10G and 1G uplink, and to determine if the current registration request sent by the ONU is for 10G or 1Guplink. In this way, 10G EPON and EPON are compatible with each other. This compatibility can facilitate upgrade of the existing EPON devices (Hood & Trojer 2012).

1.2.4. EPON Transmission

The upstream and downstream transmission channels should be appropriately separated in EPON system to increase the transmission efficiency. Space division multiplexing with two separate optical fibers and passive couplers, one for upstream transmission and the other for downstream
transmission is a simple solution. But, a more cost-effective solution is to use a single coupler and a single fiber for both directions with one wavelength for upstream transmission and another for downstream transmission. Typically, a 1550 nm wavelength is used for downstream transmission and a 1310nm wavelength is used for upstream transmission.

Multiple ONUs transmit data packets to the OLT through a common passive combiner and share the same optical fiber from the combiner to the OLT in the upstream direction. Directional property of the passive combiner ensures that data packets from an ONU can only reach the OLT but not the other ONUs. Since the ONUs are not able to easily detect a collision that may occur at the OLT, conventional contention-based multiple access is difficult to implement. Although the OLT is able to detect a collision and inform the ONUs by sending a collision message, the transmission efficiency would be largely reduced because of considerable propagation delay between the OLT and the ONUs. To address this problem, optical looping-back technique is used, where a portion of the upstream signal power transmitted by each ONU is looped back to the other ONUs. If two or more ONUs transmit data simultaneously, collisions will be detected at each ONU and all data transmissions will be stopped immediately. The OLT will receive the data packets transmitted by each ONU and will discard those packets with collisions. However, to implement the optical Carrier Sense Multiple Access / Collision Detection (CSMA/CD) protocol, each ONU has to use an additional receiver operating at the upstream wavelength and a carrier sensing circuit, which would largely increase the network cost. On the other hand, contention-based multiple access is unable to provide guaranteed bandwidth to each ONU and thus is difficult to support any form of QoS. For these reasons, contention-based multiple access is currently not a preferred solution to the upstream multiple access.
Another possible solution is to use WDM technology and allow each ONU to operate at a different wavelength, thus avoiding interference with the transmissions of the other ONUs. It requires either a tunable receiver or a receiver array at the OLT to receive the data transmitted in multiple channels. In particular, it also requires each ONU to use a fixed transmitter operating at a different wavelength, which would result in an inventory problem. Although the inventory problem can be solved by using tunable transmitters, such devices are costly, making the solution not cost-effective.

Given the above details, TDM on a single wavelength is more attractive for upstream transmission in an EPON system. With TDM, each ONU is allocated a timeslot or transmission window for data transmission by the OLT. Each timeslot is capable of carrying several Ethernet packets. Packets received from one or more users are buffered in an ONU until the timeslot for that ONU arrives. Upon the arrival of its timeslot, the ONU will send out its buffered packets at the full transmission rate of the upstream channel. Accordingly, TDM avoids data collisions from different ONUs. Moreover, it requires only a single wavelength for all ONU transmissions and a single transceiver at the OLT, which is highly cost-effective. The OLT is responsible for allocating upstream bandwidth to the ONUs. Because the optical distribution network is shared, ONU upstream transmissions could collide if they were transmitted at random times. ONUs can lie at varying distances from the OLT, meaning that the transmission delay from each ONU is unique. The OLT measures delay and set a register in each ONU via physical layer operations and maintenance messages, to equalize its delay with respect to all of the other ONUs in the PON. Once the delay of all ONUs has been set, the OLT transmits so-called grants to the individual ONUs. A grant is permission to use a defined interval of time for upstream transmission. The grant map is dynamically re-calculated every few milliseconds. The map allocates bandwidth to all ONUs, such that each ONU
receives timely bandwidth for its service needs. Some services like Plain Old Telephone Service (POTS) require essentially constant upstream bandwidth, and the OLT may provide a fixed bandwidth allocation to each such service that has been provisioned. DS1 and some classes of data service may also require constant upstream bit rate. But much data traffic, such as browsing web sites, is burst and highly variable.

The Up-stream transmission necessitates the implementation of controlled upstream access and time schedule for ONU transmission to avoid collision. Hence an efficient, fair and QoS provisioning allocation of upstream bandwidth is necessary and becomes the focal point of EPON research. The bandwidth scheduler must be efficient and computationally simple enough to support all traffic flows with different QoS requirements and allocate fair bandwidth to users.

1.3. BANDWIDTH MANAGEMENT

Resource management is the critical issue in most of the systems and EPON is no exception to that with the resource to be managed being bandwidth. As described in the earlier sections, TDM is employed in EPON systems for upstream data transmission. The upstream wavelength is been shared by all the user entities in the system and hence bandwidth management between the entities become critical for efficiently utilizing the upstream bandwidth. Bandwidth management usually involves:

- Negotiation and
- Allocation

1.3.1. Negotiation

Each ONU reports to OLT about its bandwidth requirement for the current cycle. The OLT after receiving report message from all ONUs,
decides the amount of bandwidth to be allocated to each ONU based on the bandwidth allocation policy it follows. The OLT then sends its bandwidth allocation decision to each ONU. Bandwidth negotiation includes all the information exchange that happens for the above process. To support the bandwidth negotiation process, IEEE 802.3ah defines the REPORT and GATE messages in the MPCP between the OLT and ONUs. Each ONU generates REPORT message to reports its data queue length to the OLT. The OLT processes the received REPORT message of all ONUs and then allocates bandwidth in terms of timeslot for each ONU based on the queue status and bandwidth allocation policy it follows, and delivers its bandwidth allocation decision to each ONU by using the GATE message.

REPORT message could be sent to OLT in two ways:

- By dedicating a defined timeslot in the upstream channel.
- By piggybacking in the data transmission timeslot.

Dedicated timeslot involves laser on/off twice for one upstream transmission for each ONU, whereas Piggybacking reduces laser on/off times into one per transmission for each ONU, and thus reduces the physical-layer power overhead and the inter frame guard.

1.3.2. Allocation

Bandwidth allocation in terms of timeslot by OLT to each ONU is based on the following:

- Bandwidth request from the ONU,
- Bandwidth allocation policy and
- Service Level Agreement (SLA)
In line with the above, there are many bandwidth allocation algorithms proposed in the literature and could be broadly classified into two categories:

- Static Bandwidth Allocation (SBA)
- Dynamic Bandwidth Allocation (DBA)

SBA allocates fixed timeslots to each ONU and is simple to implement since it does not involve bandwidth negotiation. However, due to the burst nature of the network traffic, some timeslots end up being overflowed even under very light load causing the packets to be delayed for several timeslots, while other timeslots are not fully used even under very heavy load, leading to the bandwidth being underutilized. This property of static allocation makes it less desirable.

For better utilization of the bandwidth, variable timeslots must be dynamically allocated to the ONU by the OLT based on the bandwidth request by the ONU for the particular cycle. DBA is complex to implement since the dynamic allocation could be based on a number of factors pertaining to the environment (Haran & Sheffer 2008). Polling is one of the widely used mechanisms wherein, the OLT dynamically allocates bandwidth for each ONU and arbitrates the transmission of multiple ONUs, which increases the bandwidth utilization significantly and improves the network performance.

1.3.3. MPCP

Dynamic bandwidth allocation and arbitration of the transmission of multiple ONUs is facilitated by the MPCP protocol. MPCP is a signaling protocol that resides at the MAC control layer and operates in two modes:

- Normal mode and
- Auto-discovery mode.
To allocate bandwidth to each ONU, MPCP in normal mode operation utilizes two control messages: GATE and REPORT. ONU uses REPORT message to report its instantaneous bandwidth requirement condition to the OLT. OLT allocates a transmission window to an ONU by using GATE message. In the auto-discovery mode, the protocol discovers an ONU, registers a newly connected ONU, and collects information such as round trip delay and MAC address of that ONU, by utilizing three control messages: REGISTER, REGISTER_REQUEST, and REGISTER_ACK.

In normal mode, a request is sent to the OLT to transmit a GATE message to a particular ONU. On receiving such a request, OLT timestamps the GATE message with its local time and then sends it to the ONU. The GATE message along with the 4-byte timestamp typically contains a granted start time and a granted transmission window. The timestamp is used to calculate the round-trip time between the OLT and the ONU. ONU on receiving the GATE message extracts the timestamp from it and programs its local register with the values contained in the GATE message. Meanwhile, it also updates its local clock to that of the timestamp value in order to maintain synchronization with the OLT. At the granted start time, the ONU will start to transmit data for up to the granted window size. The amount of data transmitted depends on the granted window size and the data queue length in the ONU. If a packet cannot be transmitted in the current window, it will be deferred to the next window, since no packet fragmentation is allowed during the transmission. A data packet from the ONU transmitted in the allocated transmission window includes REPORT message for the next cycle by way of piggybacking. The REPORT message is generated and time stamped at the MAC layer and then gets transmitted to the OLT. REPORT message is transmitted either automatically or on demand either at the start or at the end of a window. REPORT message typically contains the bandwidth demand of an ONU based on the data queue length of that ONU. OLT on receiving the
REPORT message from the ONU passes it to the MAC layer for bandwidth allocation and recalculation of the round-trip delay of that ONU (IEEE 802.3ah Ethernet in the First Mile Task Force 2004). A flow of GATE (G) messages and REPORT (R) messages for upstream transmission of three ONUs is illustrated in Figure 1.2.

![Figure 1.2 A flow of GATE-G and REPORT-R messages](image)

MPCP is highly flexible and vendor friendly by not restricting the process with any particular bandwidth allocation and transmission scheduling algorithm, but allows them to be vendor-specific. This allows the vendor to design and customize the bandwidth allocation, dictated by the environment and their customer needs. But in customizing the polling protocol, several problems must be considered to make the allocation process an efficient one (Zheng & Mouftah 2005b), which are:
• Maximum bandwidth limit,
• Channel utilization,
• Packet scheduling and
• SLA.

1.3.4. Maximum Bandwidth Limitation

Typical operation of a polling protocol is cycle-based, wherein each ONU is polled once during each polling cycle, and is allocated a transmission window based on its bandwidth demand. If an ONU is allowed to transmit all its buffered data for the current cycle in one transmission, then ONUs with high traffic load will monopolize the entire upstream bandwidth and the data transmission of ONUs with low traffic load will get deferred to the next available window which is unfair to the low traffic load ONUs. Hence, the OLT should limit the maximum transmission bandwidth of each ONU. The maximum window size can either be variable based on instantaneous network conditions or fixed based on some criterion, such as SLA. The maximum window size determines the maximum polling cycle and has a great impact on network performance. A longer maximum polling cycle will result in larger delay for all packets under high traffic load, including the high-priority packets. Whereas, a shorter maximum polling cycle will result in more bandwidth being wasted by inter-frame gaps and guard times. The limit on the maximum bandwidth that can be allocated to each ONU in each polling cycle is enforced by the maximum window size which is also the maximum guaranteed bandwidth available to each ONU. ONUs are allocated only their requested bandwidth and hence if any ONU requests less bandwidth, it will be allocated a smaller window size, making the polling cycle shorter and thus increasing the actual bandwidth available to all other ONUs. Only when all other ONUs use all their available bandwidth will an ONU be limited to its guaranteed bandwidth.
1.3.5. **Polling Strategies**

Each ONU is polled every cycle and all ONUs are polled for a cycle. Different strategies based on which the ONUs could be polled are:

- Poll-and-stop,
- Interleaved and
- Interleaved with stop

Poll-and-stop polling is a simple strategy, wherein the OLT sends a GATE message to an ONU and then waits till the data and REPORT message from that ONU is received before sending GATE message to the next ONU as described in Figure 1.3. Obviously, a lot of upstream channel bandwidth is wasted by this scheme which in turn would largely reduce channel utilization and increase packet delay.

![Figure 1.3 Poll-and-stop polling policy](image-url)
Interleaved polling is a more efficient strategy compared to poll-and-stop strategy (Kramer et al. 2002a), wherein the OLT does not wait but services the next ONU even before the current polled ONU sends data and REPORT message back for its received GATE message. This process is described in Figure 1.4. The fact that the upstream channel and downstream channel are independent and the information about each ONU is maintained by the OLT in a polling table, including the bandwidth demand of each ONU and the round-trip time to each ONU, makes the interleaved policy a feasible one. The interleaved polling protocol significantly improves the network performance in terms of channel utilization and average packet delay. However, the OLT allocates bandwidth to the ONUs based on only the already received bandwidth demands of each ONU and is unable to take into account the bandwidth demands of all ONUs and make a more intelligent decision on bandwidth allocation.

![Figure 1.4 Interleaved polling policy](image)

Interleaved polling with stop, a variation to the interleaved polling effectively overcomes this shortcoming. Similar to the interleaved polling,
here also the OLT sends a GATE message to the next ONU before the arrival of transmission and REPORT message(s) from the previous polled ONU(s), but within a single cycle. The efficiency is introduced by making the OLT to wait until the transmissions and REPORT messages from all ONUs in a cycle are received before starting the next polling cycle. Thus the OLT makes a more intelligent decision by performing bandwidth allocation based on the bandwidth demands of all ONUs and not a single ONU at the end of each polling cycle. However, this introduces another shortcoming of reduced upstream channel utilization because the upstream channel is not utilized from the time the last polled ONU in the previous cycle completes its transmission to the time the first polled ONU in the next cycle starts its transmission. Interleaved-polling-with-stop protocol is described in Figure 1.5.

![Interleaved Polling with Stop Policy](image-url)

**Figure 1.5 Interleaved polling with stop policy**
1.3.6. Transmission Scheduling

When scheduling transmissions of multiple ONUs, data collisions must be avoided to ensure efficient transmission and the polling protocol should handle it (Zheng & Mouftah 2005b). Since scheduling is based on the granted window size and the round-trip time to each ONU and the OLT knows the granted window size and the round-trip time to the last polled ONU, it can calculate the transmission start time and window size for the next ONU and effectively avoid data collisions. A minimum gap or guard time is usually required between the transmissions of different ONUs to allow the OLT to prepare for receiving the transmissions. Scheduling the transmission order of different ONUs also has a great impact on network performance and could be effectively handled by the OLT by performing a scheduling algorithm to determine the order of the transmissions one cycle ahead. Round-robin is the most widely-used scheduling algorithm which uses the indexing order of the ONUs in the polling table to schedule the transmission of different ONUs, and has been adopted by many polling protocols being simple to implement. However, this algorithm may not be able to provide the best performance in terms of packet delay and data loss since it does not take into account the instantaneous traffic conditions at each ONU. Hence, an adaptive scheduling algorithm that dynamically schedules the order of different ONU transmissions based on the instantaneous traffic conditions at each ONU is highly desirable to improve network performance. Below are some scheduling policies for an adaptive scheduling algorithm (Zheng & Mouftah 2005a):

- Longest queue first (LQF): schedule the ONU transmissions in a descending order of the instantaneous queue length of each ONU.
- Earliest packet first (EPF): schedule the ONU transmissions in an ascending order of the arrival time of the first packet queuing in each ONU.
1.3.7. QoS Provisioning

Triple-play services are to be delivered by an EPON system, which includes data, voice and video. Hence EPON system should not only deliver Best Effort (BE) data traffic, but also real-time data traffic that have strict bandwidth, packet delay, and delay jitter requirements. To support this and to meet the service requirements of different end users, differentiated QoS provisioning should be enforced in EPON system and could be achieved by:

- Priority Queuing
- ONU Scheduling

1.3.7.1. Priority Queuing

The network traffic is classified into a set of classes based on their QoS requirements. Each class has a priority level and a priority queue is maintained at each ONU for each class. This method of classifying traffic is called Priority queuing and is an effective way to realize differentiated QoS in EPON systems. Priority queuing could be well understood with the illustration in Figure 1.6, in which three priority queues are maintained by an ONU. ONU on receiving the network data packets from end users classifies them based on the IP header’s Type of Service (ToS) field and then forwards them to the corresponding priority queue.

![Figure 1.6 Priority Queuing](image-url)
When a packet with lower-priority arrives at the ONU and the buffer for the queue meant for that packet happens to be full, then the packet will be discarded. On the other hand, when a packet with higher-priority finds the buffer for its queue to be full, a preemption of lower-priority packet happens and the higher-priority packet gets into the queue for transmission. This results in high packet loss and even resource starvation for lower-priority packets. This problem could be addressed by the ONU introducing traffic policing to control the amount of higher-priority traffic from each end user.

1.3.7.2. ONU Scheduling

There are two aspects of QoS provisioning in ONU scheduling as illustrated in Figure 1.7:

- Inter-ONU scheduling: for arbitrating the transmissions of different ONUs.
- Intra-ONU scheduling: for arbitrating the transmissions of different priority queues in each ONU.

The above scheduling could be realized either in OLT only or both OLT and ONU. OLT handles the arbitration of the upstream transmissions when it does both the inter-ONU scheduling and intra-ONU scheduling. For the OLT to allocate bandwidth to ONU’s each traffic class independently, the ONU must report the status of its individual priority queues to the OLT. MPCP supports the provision of reporting the status of up to eight priority queues by each ONU (Assi et al 2003). The OLT can then generate multiple grants, each for a specific traffic class, to be sent to the ONU using a single GATE message.
Figure 1.7 Intra-ONU and Inter-ONU scheduling
In the other strategy, the OLT performs inter-ONU scheduling and each ONU performs intra-ONU scheduling. Each ONU requests the OLT to allocate a cumulative bandwidth based on its data queue length of all priorities and the OLT only allocates the requested bandwidth to each ONU. Each ONU then divides the allocated bandwidth among different classes of services based on their QoS requirements and schedules the transmission of different priority queues within the allocated bandwidth.

Intra-ONU scheduling involves two types of scheduling paradigms:

- Strict priority scheduling and
- Non-strict priority scheduling.

In strict priority scheduling, only when all higher-priority queues are empty then a lower-priority queue is scheduled. Obviously, infinite packet delay and high packet loss will be experienced by low-priority traffic. Non-strict priority scheduling ensures fairness by transmitting all the packets reported for the timeslot and transmits the newly arriving packets not reported for scheduling in the current timeslot if it can accommodate more packets based on their priority. Priority for reported packets is not considered for transmission and only if more packets could be accommodated in the current timeslot, then higher-priority packets are privileged for transmission first. This ensures all traffic classes get transmitted in the allocated timeslot as reported to the OLT while their priorities are maintained.

1.3.8. Dynamic Bandwidth Allocation

Bandwidth allocation could be of two types:

- Static
- Dynamic
SBA algorithm was proposed during the early stages of EPON that allocates fixed transmission time slot to every active ONU by the OLT. SBA is void of request generation and processing overhead and is suitable for time-sensitive or Constant Bit Rate (CBR) services like POTS, digital signal 1 which require constant upstream bandwidth, and the OLT may provide a fixed bandwidth allocation to each such service. But much network data traffic such as browsing is burst, self-similar and highly variable due to the fact that each ONU may serve one or more users with varying bandwidth request for which SBA fails miserably, and hence DBA algorithms took the favorable position.

In DBA, the required bandwidth can be dynamically calculated by the OLT by observing the traffic from the ONU. Also the ONU in its report message states its requirement for the current cycle. As the performance of EPON is by large dependent on the chosen bandwidth allocation algorithm, it is critical to choose the best allocation algorithm. DBA algorithms allocate bandwidth dynamically based on a number of parameters that matter to a service provider for satisfying the end user needs. Hence, DBA algorithms have been the focus of research among the research community. A good DBA algorithm should have the following features:

- Maximum bandwidth utilization,
- Minimum packet delay,
- QoS support and
- Fairness.

1.3.8.1. Bandwidth Utilization

Bandwidth utilization is a well-known but not well-accounted statistic. Static bandwidth allocation is a simple and fair algorithm but do not
consider real time requirements and has very low bandwidth utilization. Light load ONUs underutilize the bandwidth allocated to it, but heavy load ONUs do not get enough bandwidth. Dynamic bandwidth allocation scheme improves bandwidth utilization rate with a reasonable maximum transmission window size and also supports fairness among ONUs. Bandwidth utilization rate of each DBA algorithm differs based on the allocation policy it follows. Some DBA algorithms (Kramer et al 2002a) (Kramer et al 2002b) have lower bandwidth utilization rates and (Zhu & Ma 2008) (Bhatia & Bartos 2007) are attempts to improve (Kramer et al 2002a) to have a better a bandwidth utilization rate.

1.3.8.2. Packet Delay

EPON supports triple-play services of data, voice and video and hence is required to ensure packet delay since these services are sensitive to packet delay. Service providers tend to satisfy customer needs and a customer request might include any or all of the triple-play services. In this regard, the service providers opt to provide integrated service access and the EPON system design should consider this (Aurzada et al 2008).

1.3.8.3. Guaranteeing QoS

In the next generation network, guaranteed QoS will be the primary focus (Zhang et al 2009) (Kani et al 2009) which is an important indicator in evaluating DBA algorithms. EPON system must support multiple services each with different requirements; voice services are sensitive to delay and jitter but do not consume much bandwidth, video services consume more bandwidth but can tolerate some delay and jitter (Park et al 2005). Allocating bandwidth for different services ensuring appropriate QoS becomes the primary consideration aspect in DBA algorithm designing (Yang et al 2009). Supporting multimedia services will require a transmit window with constant
size irrespective of the priority of the data to be sent, and then other service flow need to be considered. Each DBA algorithm has its advantages and disadvantages and users and operators must select suitable DBA algorithms according to their own requirements.

1.3.8.4. The Problem of Fairness

Nace & Pioro (2008) defines fairness in bandwidth allocation to be of twofold:

- Fairness among ONU's and
- Fairness of the data queues within ONU.

Bandwidth utilization and fairness are two factors that conflict each other and a good balance must be found to not allow overruling of one over the other. Statistical bandwidth multiplexing addresses the fairness issue by introducing a weight based DBA scheme but ignores the instantaneous requirement of each ONU (Bai et al 2005), thus having absolute fairness, but have low efficiency, and waste much bandwidth. A number of strategies are followed for improving the fairness of queues in the ONU. Maximum transmission window concept ensures fairness among ONU's while satisfying the instantaneous requirement of each ONU. In this scheme, each ONU is provided the required transmission window, but the window size may not exceed the maximum transmission window size. Priority scheduling supports QoS for multimedia services wherein higher priority packets would be transmitted before any of the lower priority packets. This results in lower priority services packets getting delayed within multi transmission cycles, or discarded. Non-strict priority scheduling scheme provides improvement over strict priority scheduling.
1.4. **MPCP PROTOCOL OVERVIEW**

Multi-point MAC Control defines the MAC control operation for optical P2MP networks and deals with the mechanism and control protocols required to reconcile the P2MP topology into the Ethernet framework. MPCP operates by defining a Multi-point MAC Control sublayer as an extension of the MAC Control sublayer. The architectural positioning of the Multi-point MAC Control sublayer is between the MAC and the MAC Control client as illustrated in Figure 1.8. The Multi-point MAC Control sublayer takes the place of the MAC Control sublayer to extend it to support multiple clients and additional MAC control functionality (IEEE 802.3ah Ethernet in the First Mile Task Force 2004).

![Diagram of MPCP message communication process](image)

**Figure 1.8 MPCP message communication process**

The Multi-point MAC Control functional block comprises the following functions:
• Discovery Processing: Discovers an ONU and registers a newly connected ONU.
• Report Processing: Generation and collection of REPORT messages for informing the OLT about the ONU’s bandwidth requirement.
• Gate Processing: Generation and collection of GATE messages for arbitrating the transmission of multiple ONUs.

The Multi-point MAC Control sublayer is flexible enough to support new functions, and MPCP, the management protocol for P2MP specifies a control mechanism between the OLT and ONUs and uses MPCP Protocol Data Unit (MPCPDU) for the process. To accomplish P2MP control function at the MAC control layer, MPCP uses five control messages: REGISTER, REGISTER_REQ, REGISTER_ACK, REPORT and GATE control messages, described in Figure 1.9.

![Figure 1.9 MPCP Control Messages](image)

To automatically discover the newly connected and offline ONUs and to allocate an identifier to uniquely identify them, auto
discovery mechanism is used. OLT periodically broadcasts a discovery GATE message which includes the discovery window start time and duration. Unregistered ONUs on receiving them transmit a REGISTER_REQ message using a random offset into the discovery window. OLT, on receiving a valid request message, registers the ONU, allocates and assigns a LLID for the ONU binding MAC to it and performs ranging computation. OLT then transmits a REGISTER message to ONU containing the LLID details followed by a standard GATE message allowing ONU to transmit a REGISTER_ACK. The registration process is complete on receipt of REGISTER_ACK message by OLT and ONU goes into normal transmission mode waiting for grants.

In order to handle failure states and to keep the watchdog timer in the OLT from expiring leading to deregistration of the ONU, PONs does the following:

- GATE message is periodically sent by OLT to ONUs, even when no request for bandwidth is made.
- On receipt of the corresponding REPORT message from the ONU, OLT resets its watchdog timer.

Upstream traffic in EPON follows TDMA with each ONU transmitting with proper delay and guard time between timeslots to avoid overlap. In order for the ONU to transmit at the correct time, the delay between ONU transmission and OLT reception need to be known and it should be noted that upstream delay is not equal to downstream delay. Accurate knowledge of the delay results in smaller guard time which increases the efficiency of the system. When ONU receives a packet from OLT, it sets its clock according to the OLT's timestamp and when the OLT
receives a response packet it computes the RTT and informs the ONU of the value, which is used to compute transmit delay and OLT amends all grants with RTT before sending to ONUs.

The OLT controls an ONU’s transmission by the assigning of grants via GATE message. At the OLT MAC layer, MPCP supports time slot allocation for multiple ONUs. A single GATE message could include up to four grants and the number of grants is set to zero if it is to be used as an MPCP keep alive from OLT to the ONU. The transmitting window of an ONU is indicated by the start time and length fields. An ONU will begin transmission when its local time counter matches start time value indicated in the GATE message. An ONU will conclude its transmission with sufficient margin to ensure that the laser is turned off before the grant length interval elapses. ONU updates OLT with its bandwidth requirement via REPORT messages which has several functionalities:

1. Time stamp in each REPORT message is used for RTT calculation.
2. ONUs indicate the upstream bandwidth needs they request.
3. They are also used as keep-alive from ONU to OLT. ONUs periodically issue REPORT messages to maintain link health at the OLT. In addition, the OLT may specifically request a REPORT message.

1.4.1. Discovery Processing

Access to the PON for newly connected or off-line ONUs is provided by the discovery process and is handled by the OLT. Off-line ONU’s are given the opportunity to make themselves known to the OLT through the discovery windows which the OLT generates periodically. The periodicity of these windows is implementer-specific. The OLT broadcasts a discovery gate message with the starting time and length of the discovery
window, and the off-line ONUs on receiving this message, wait for the period to begin and then transmit a REGISTER_REQ message to the OLT. The REGISTER_REQ message includes the ONU’s MAC address and number of maximum pending grants and is shorter than the length of the discovery time window. Multiple ONUs can use the same discovery window to access the PON simultaneously, and hence transmission overlap can occur which is reduced by using a contention algorithm by all ONUs. Each ONU waits for a random amount of time and then transmits the REGISTER_REQ message. It should be noted that multiple valid REGISTER_REQ messages can be received by the OLT during a single discovery time period. On receiving a valid REGISTER_REQ message, the OLT registers the ONU, allocates and assigns a new port identity (LLID), and maps the ONU’s MAC to the LLID.

The OLT then transmits a REGISTER message to the newly discovered ONU. The REGISTER message includes the ONU’s LLID, the OLT’s required synchronization time and the maximum number of pending grants of the ONU is echoed by the OLT. The OLT then transmits a standard GATE message allowing the ONU to respond with a REGISTER_ACK. The discovery process for an ONU is complete on receiving the REGISTER_ACK. The ONU is now registered and normal message traffic can begin. Figure 1.10 describes the process.

Situations may arise wherein the OLT might require the ONU to go through the discovery sequence again and reregister. Also, there may be situations where an ONU might desire to deregister by going through the discovery sequence. The REGISTER message from the OLT includes a Reregister or Deregister bit which will force the receiving ONU into reregistering. The REGISTER_REQ message from the ONU contains the Deregister bit to signify deregistration of the ONU.
OLT

\textbf{GATE}^1 \{ DA=MAC \text{ Control}, SA=OLT \text{ MAC address}, content=Grant+Sync Time \}

\textbf{REGISTER\_REQ}^1 \{ DA=MAC \text{ Control}, SA=OUNU MAC address, content=Pending grants \}

\textbf{REGISTER}^1 \{ DA=OUNU MAC address, SA=OLT MAC address, content=LLID+Sync Time+echo of pending grants \}

\textbf{GATE}^2 \{ DA=MAC \text{ Control}, SA=OLT MAC address, content=Grant \}

\textbf{REGISTER\_ACK}^2 \{ DA=MAC \text{ Control}, SA=OUNU MAC address, content=echo of LLID + echo of Sync Time \}

ONU

\text{Random delay}

\text{Grand start} \rightarrow

\text{Discovery handshake completed}

\textsuperscript{1} Messages sent on broadcast channel

\textsuperscript{2} Messages sent on unicast channel

\textbf{Figure 1.10 Discovery handshake message exchange}
1.4.2. Report Processing

The Report Processing functional block deals with the generation and termination of REPORT messages in the network. Reports are generated by higher layers and passed to the MAC Control sublayer by the MAC Control clients. A watchdog timer is maintained in the OLT that expires when failure to receive at least one MPCPDU frame within the watchdog interval happens. This leads to deregistration of the ONU. Hence, reports are generated periodically even when there is no request for bandwidth and for proper operation of this mechanism the OLT grants the ONU periodically. Also, status reports are used to signal bandwidth needs as well as for arming the OLT watchdog timer.

1.4.3. Gate Processing

A key concept pervasive in Multi-point MAC Control is the ability to arbitrate transmissions of multiple ONUs. The OLT controls an ONU’s transmission by the assigning of grants and the GATE message for an ONU includes the start time and length of the transmitting window. An ONU begins transmission when its localTime counter matches the start time value indicated in the GATE message and concludes its transmission with sufficient margin to ensure that the laser is turned off before the grant length interval has elapsed. The OLT might issue multiple grants to each ONU, but not more than the maximal supported grants as advertised by the ONU during registration. In order to maintain the watchdog timer at the ONU, grants are periodically generated and for this purpose, empty GATE messages may be issued periodically. When registered, the ONU ignores all gate messages where the discovery flag is set.
1.4.4. MPCPDU Structure and Encoding

MPCPDUs are basic IEEE 802.3 frames. The MPCPDU structure is illustrated in Figure 1.11, and is further defined in the following definitions:

<table>
<thead>
<tr>
<th>Octets</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Destination Address</td>
<td>6</td>
</tr>
<tr>
<td>Source Address</td>
<td>6</td>
</tr>
<tr>
<td>Length / Type = 88-08</td>
<td>2</td>
</tr>
<tr>
<td>Opcode</td>
<td>2</td>
</tr>
<tr>
<td>Timestamp</td>
<td>4</td>
</tr>
<tr>
<td>Data / Reserved / Pad</td>
<td>40</td>
</tr>
<tr>
<td>FCS</td>
<td>4</td>
</tr>
</tbody>
</table>

**Figure 1.11 Generic MPCPDU**

- **Destination Address**: The MAC Control Multicast address or the individual MAC address associated with the port to which the MPCPDU is destined.
- **Source Address**: The individual MAC address associated with the port through which the MPCPDU is transmitted.
- **Length/Type**: Identifies the packet type of the MPCPDU being transmitted.
- **Opcode**: Identifies the specific MPCPDU being encapsulated.
- **Timestamp**: Contains the localTime at the time of transmission of the MPCPDUs. This field is 32 bits long, and counts 16 bit transmissions. The timestamp counts time in 16 bit time granularity.
• Data/Reserved/PAD: These 40 octets are used for the payload of the MPCPDUs. When not used they would be filled with zeros on transmission, and be ignored on reception.

• FCS: Frame Check Sequence typically generated by the underlying MAC.

The LLID is generated based on the MAC instance used to generate the specific MPCPDU.

1.4.4.1. GATE Description

GATE message is used by OLT to grant transmission windows to ONU's for both discovery messages and normal transmission and up to four grants can be included in a single GATE message. When the GATE message is used as MPCP keep alive the number of grants is set to zero.

The GATE MPCPDU, illustrated in Figure 1.12 is an instantiation of the Generic MPCPDU, and is further defined using the following definitions:

• Opcode: 00-02 is the opcode for GATE MPCPDU.

• Flags: An 8 bit flag register that holds the Number of grants field, Discovery flag and Force Report flag, defined in Table 1.1. The number of grants field, a value between 0 and 4 contains the number of grants, composed of valid Length, Start Time pairs in this MPCPDU. When number of grants is 0, the sole purpose is conveying of timestamp to ONU. The Discovery flag field indicates that the GATE message is for discovery process and includes a single grant. The Force Report flag fields inform the ONU to respond with a REPORT message for each of the grant in the GATE message in its transmission window.
<table>
<thead>
<tr>
<th>Octets</th>
<th></th>
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</thead>
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<tr>
<td>Destination Address</td>
<td>6</td>
</tr>
<tr>
<td>Source Address</td>
<td>6</td>
</tr>
<tr>
<td>Length / Type = 88-08</td>
<td>2</td>
</tr>
<tr>
<td>Opcode = 00-02</td>
<td>2</td>
</tr>
<tr>
<td>Timestamp</td>
<td>4</td>
</tr>
<tr>
<td>Number of grants / flags</td>
<td>1</td>
</tr>
<tr>
<td>Grant #1 Start time</td>
<td>0 / 4</td>
</tr>
<tr>
<td>Grant #1 Length</td>
<td>0 / 2</td>
</tr>
<tr>
<td>Grant #2 Start time</td>
<td>0 / 4</td>
</tr>
<tr>
<td>Grant #2 Length</td>
<td>0 / 2</td>
</tr>
<tr>
<td>Grant #3 Start time</td>
<td>0 / 4</td>
</tr>
<tr>
<td>Grant #3 Length</td>
<td>0 / 2</td>
</tr>
<tr>
<td>Grant #4 Start time</td>
<td>0 / 4</td>
</tr>
<tr>
<td>Grant #4 Length</td>
<td>0 / 2</td>
</tr>
<tr>
<td>Sync Time</td>
<td>0 / 2</td>
</tr>
<tr>
<td>Pad / Reserved</td>
<td>13 - 39</td>
</tr>
<tr>
<td>FCS</td>
<td>4</td>
</tr>
</tbody>
</table>

**Figure 1.12 GATE MPCPDU**
Table 1.1 GATE MPCPDU Number of grants / Flags Fields

<table>
<thead>
<tr>
<th>Bit</th>
<th>Flag Field</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2</td>
<td>Number of grants</td>
<td>0 – 4</td>
</tr>
<tr>
<td>3</td>
<td>Discovery</td>
<td>0 – Normal GATE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 – Discovery GATE</td>
</tr>
<tr>
<td>4</td>
<td>Force Report Grant 1</td>
<td>0 – No action required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 – A REPORT frame should be issued at the corresponding transmission opportunity indicated in Grant 1</td>
</tr>
<tr>
<td>5</td>
<td>Force Report Grant 2</td>
<td>0 – No action required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 – A REPORT frame should be issued at the corresponding transmission opportunity indicated in Grant 2</td>
</tr>
<tr>
<td>6</td>
<td>Force Report Grant 3</td>
<td>0 – No action required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 – A REPORT frame should be issued at the corresponding transmission opportunity indicated in Grant 3</td>
</tr>
<tr>
<td>7</td>
<td>Force Report Grant 4</td>
<td>0 – No action required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 – A REPORT frame should be issued at the corresponding transmission opportunity indicated in Grant 4</td>
</tr>
</tbody>
</table>

- Grant #n Length: A 16 bit unsigned field denoting the length of the grant counted in 16 bit time increments and includes the laserOnTime, syncTime, and laserOffTime as well. A GATE message could have 4 such grants in it.
- Grant #n Start Time: A 32 bit unsigned field denoting the Start time of the grant which is compared to the local clock to enforce correlation between the start of the grants. The condition Grant #n Start Time
<Grant #n+1 Start Time is satisfied for consecutive grants within the same GATE MPCPDU.

- Sync Time: A 16 bit unsigned value counted in 16 bit time increments signifying the required synchronization time of the OLT receiver. During the synchronization time the ONU transmits only IDLE code-pairs. This field is present only when the gate is a discovery gate, as signaled by the Discovery flag and is not present otherwise.

- Pad/Reserved: An empty field transmitted as zeros, and ignored on reception. The size of this field depends on the used Grant #n Length/Start Time entry-pairs, and varies in length from 13 - 39 accordingly.

The GATE MPCPDU when used for providing transmission window for an active ONU is marked with a unicast LLID. When the GATE is used for discovery purpose and is mapped to all ONUs, it is marked with the broadcast LLID.

1.4.4.2. REPORT Description

REPORT messages have several functionalities:

- Time stamp in each REPORT message is used for round trip (RTT) calculation.
- ONU's indicate the upstream bandwidth needs they request per 802.1Q priority queue using REPORT messages.
- REPORT messages are also used as keep-alive from ONU to OLT and ONU's issue REPORT messages periodically in order to maintain link health at the OLT. In addition, the OLT may specifically request a REPORT message from an ONU.
The REPORT MPCPDU, illustrated in Figure 1.13 is an instantiation of the Generic MPCPDU, and is further defined using the following definitions:

- **Opcode**: The opcode for the REPORT MPCPDU is 00-03.

<table>
<thead>
<tr>
<th>Octets</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Destination Address</td>
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<tr>
<td>Source Address</td>
<td>6</td>
</tr>
<tr>
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<td>2</td>
</tr>
<tr>
<td>Opcode = 00-03</td>
<td>2</td>
</tr>
<tr>
<td>Timestamp</td>
<td>4</td>
</tr>
<tr>
<td>Number of queue sets</td>
<td>1</td>
</tr>
<tr>
<td>Report bitmap</td>
<td>1</td>
</tr>
<tr>
<td>Queue #0 Report</td>
<td>0 / 2</td>
</tr>
<tr>
<td>Queue #1 Report</td>
<td>0 / 2</td>
</tr>
<tr>
<td>Queue #2 Report</td>
<td>0 / 2</td>
</tr>
<tr>
<td>Queue #3 Report</td>
<td>0 / 2</td>
</tr>
<tr>
<td>Queue #4 Report</td>
<td>0 / 2</td>
</tr>
<tr>
<td>Queue #5 Report</td>
<td>0 / 2</td>
</tr>
<tr>
<td>Queue #6 Report</td>
<td>0 / 2</td>
</tr>
<tr>
<td>Queue #7 Report</td>
<td>0 / 2</td>
</tr>
<tr>
<td>Pad / Reserved</td>
<td>0 - 39</td>
</tr>
<tr>
<td>FCS</td>
<td>4</td>
</tr>
</tbody>
</table>

**Figure 1.13 REPORT MPCPDU**
- Number of Queue Sets: This field specifies the number of requests defined by the Report bitmap, Queue #n entry-pair in the REPORT message.
- Report bitmap: 8 bit flag register that indicates which queues are represented in this REPORT MPCPDU. Table 1.2 defines the field.
- Queue #n Report: An unsigned 16 bit integer represents the length of queue# n at the time of REPORT message generation. The length of queue# n represents the transmission request in units of time quanta. This field is present only when the corresponding flag in the Report bitmap is set.

**Table 1.2 REPORT MPCPDU Report bitmap fields**

<table>
<thead>
<tr>
<th>Bit</th>
<th>Flag Field</th>
<th>Values</th>
</tr>
</thead>
</table>
| 0   | Queue 0    | 0 – Queue 0 report is not present  
|     |            | 1 – Queue 0 report is present    |
| 1   | Queue 1    | 0 – Queue 1 report is not present  
|     |            | 1 – Queue 1 report is present    |
| 2   | Queue 2    | 0 – Queue 2 report is not present  
|     |            | 1 – Queue 2 report is present    |
| 3   | Queue 3    | 0 – Queue 3 report is not present  
|     |            | 1 – Queue 3 report is present    |
| 4   | Queue 4    | 0 – Queue 4 report is not present  
|     |            | 1 – Queue 4 report is present    |
| 5   | Queue 5    | 0 – Queue 5 report is not present  
|     |            | 1 – Queue 5 report is present    |
| 6   | Queue 6    | 0 – Queue 6 report is not present  
|     |            | 1 – Queue 6 report is present    |
| 7   | Queue 7    | 0 – Queue 7 report is not present  
|     |            | 1 – Queue 7 report is present    |
- Pad/Reserved: An empty field transmitted as zeros, and ignored on reception. The size of this field depends on the used Queue Report entries, and accordingly varies in length from 0 to 39.

The REPORT MPCPDU is generated by an active ONU destined to the OLT, and as such marked with a unicast LLID.

1.4.4.3. REGISTER_REQ Description

The REGISTER_REQ MPCPDU is generated for an undiscovered ONU, and as such marked with a broadcast LLID.

The REGISTER_REQ MPCPDU, illustrated in Figure 1.14 is an instantiation of the Generic MPCPDU and is further defined using the following definitions:

<table>
<thead>
<tr>
<th>Octets</th>
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<tbody>
<tr>
<td>Destination Address</td>
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<tr>
<td>Length / Type = 88-08</td>
<td>2</td>
</tr>
<tr>
<td>Opcode = 00-04</td>
<td>2</td>
</tr>
<tr>
<td>Timestamp</td>
<td>4</td>
</tr>
<tr>
<td>Flags</td>
<td>1</td>
</tr>
<tr>
<td>Pending grants</td>
<td>1</td>
</tr>
<tr>
<td>Pad / Reserved</td>
<td>38</td>
</tr>
<tr>
<td>FCS</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 1.14 REGISTER_REQ MPCPDU
• Opcode: The opcode for the REGISTER_REQ MPCPDU is 00-04.
• Flags: 8 bit flag register that indicates special requirements for the registration as described in the Table 1.3.
• Pending grants: An unsigned 8 bit value signifying the maximum number of grants that the ONU can buffer. The OLT should not grant the ONU more than this maximum number of Pending grants.
• Pad/Reserved: An empty field transmitted as zeros, and ignored on reception.

**Table 1.3 REGISTER_REQ MPCPDU Flags fields**

<table>
<thead>
<tr>
<th>Value</th>
<th>Indication</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Reserved</td>
<td>Ignored on reception</td>
</tr>
<tr>
<td>1</td>
<td>Register</td>
<td>Registration attempt for ONU</td>
</tr>
<tr>
<td>2</td>
<td>Reserved</td>
<td>Ignored on reception</td>
</tr>
<tr>
<td>3</td>
<td>Deregister</td>
<td>This is a request to deregister the ONU. Subsequently, the MAC is deallocated and the LLID may be reused.</td>
</tr>
<tr>
<td>4 - 255</td>
<td>Reserved</td>
<td>Ignored on reception</td>
</tr>
</tbody>
</table>

**1.4.4.4. REGISTER Description**

The REGISTER MPCPDU is generated by the OLT to an ONU and as such marked with the unicast LLID. The REGISTER MPCPDU, illustrated in Figure 1.15 is an instantiation of the Generic MPCPDU, and is further defined using the following definitions:

• Destination Address: MAC address of the discovered ONU.
• Opcode: The opcode for the REGISTER MPCPDU is 00-05.
- Assigned Port: This field holds a 16 bit unsigned value reflecting the LLID of the port assigned following registration.
- Flags: An 8 bit flag register that indicates special requirements for the registration as defined in Table 1.4.

<table>
<thead>
<tr>
<th>Octets</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Destination Address</td>
<td>6</td>
</tr>
<tr>
<td>Source Address</td>
<td>6</td>
</tr>
<tr>
<td>Length / Type = 88-08</td>
<td>2</td>
</tr>
<tr>
<td>Opcode = 00-05</td>
<td>2</td>
</tr>
<tr>
<td>Timestamp</td>
<td>4</td>
</tr>
<tr>
<td>Assigned port</td>
<td>2</td>
</tr>
<tr>
<td>Flags</td>
<td>1</td>
</tr>
<tr>
<td>Sync Time</td>
<td>2</td>
</tr>
<tr>
<td>Echoed pending grants</td>
<td>1</td>
</tr>
<tr>
<td>Pad / Reserved</td>
<td>34</td>
</tr>
<tr>
<td>FCS</td>
<td>4</td>
</tr>
</tbody>
</table>

**Figure 1.15 REGISTER MPCPDU**

- Sync Time: A 16 bit unsigned value counted in 16 bit time increments signifying the required synchronization time of the OLT receiver. During the synchronization time the ONU transmits only IDLE code-pairs.
- Echoed pending grants: An unsigned 8 bit value signifying the maximum number of grants that the ONU can buffer. The OLT should not grant the ONU more than this maximum number of Pending grants.
- Pad/Reserved: An empty field transmitted as zeros, and ignored on reception.
Table 1.4 REGISTER MPCPDU Flags field

<table>
<thead>
<tr>
<th>Value</th>
<th>Indication</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Reserved</td>
<td>Ignored on reception</td>
</tr>
<tr>
<td>1</td>
<td>Reregister</td>
<td>The ONU is explicitly asked to re-register</td>
</tr>
<tr>
<td>2</td>
<td>Deregister</td>
<td>This is a request to deallocate the port and free the LLID. Subsequently, the MAC is deallocated.</td>
</tr>
<tr>
<td>3</td>
<td>Ack</td>
<td>The requested registration is successful.</td>
</tr>
<tr>
<td>4</td>
<td>Nack</td>
<td>The requested registration attempt is denied by the higher-layer-entity.</td>
</tr>
<tr>
<td>5 - 255</td>
<td>Reserved</td>
<td>Ignored on reception</td>
</tr>
</tbody>
</table>

1.4.4.5. REGISTER_ACK Description

The REGISTER_ACK MPCPDU is generated by an active ONU, and as such marked with a unicast LLID.

The REGISTER_ACK MPCPDU, illustrated in Figure 1.16 is an instantiation of the Generic MPCPDU, and is further defined using the following definitions:

- Opcode: The opcode for the REGISTER_ACK MPCPDU is 00-06.
- Flags: An 8 bit flag register that indicates special requirements for the registration as defined in Table 1.5.
- Echoed assigned port: This field holds a 16 bit unsigned value reflecting the LLID of the port assigned following registration.
- Echoed Sync Time: This is an unsigned 16 bit value echoing the required synchronization time of the OLT receiver as previously advertised.
- Pad/Reserved: An empty field transmitted as zeros, and ignored on reception.

<table>
<thead>
<tr>
<th>Octets</th>
<th>Destination Address</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Source Address</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Length / Type = 88-08</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Opcode = 00-06</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Timestamp</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Echoed assigned port</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Echoed Sync Time</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Pad / Reserved</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>FCS</td>
<td>4</td>
</tr>
</tbody>
</table>

**Figure 1.16 REGISTER_ACK MPCPDU**

**Table 1.5 REGISTER_ACK MPCPDU Flags fields**

<table>
<thead>
<tr>
<th>Value</th>
<th>Indication</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Nack</td>
<td>The requested registration attempt is denied by the higher-layer-entity.</td>
</tr>
<tr>
<td>1</td>
<td>Ack</td>
<td>The registration process is successfully acknowledged.</td>
</tr>
<tr>
<td>2 - 255</td>
<td>Reserved</td>
<td>Ignored on reception.</td>
</tr>
</tbody>
</table>
1.5. WIRELESS ACCESS TECHNOLOGIES

1.5.1. WiMAX

WiMAX is a wireless communications standard and refers to the interoperable implementations of the IEEE 802.16 family of wireless-networks standards ratified by the WiMAX Forum (WiMAX Forum 2001), which was formed in June 2001 to promote conformity and interoperability of the standard. The forum describes WiMAX as "a standards-based technology enabling the delivery of last mile wireless broadband access as an alternative to cable and DSL". WiMAX provides a robust, reliable, and cost-effective means to deliver broadband services in metropolitan and rural areas. The most outstanding advantage of broadband wireless access is its low cost for installation and maintenance compared with traditional wire or fiber network access, especially for those areas that are too remote or difficult to reach. Networks could be created in a short time by deploying a small number of Base Stations (BSs) on buildings or poles to create high-capacity wireless access systems. WiMAX can provide at-home or mobile Internet access and given the relatively low costs associated with the deployment of a WiMAX network, it is now economically viable to provide last-mile broadband Internet access in remote locations. A typical WiMAX network is shown in Figure 1.17. WiMAX is a replacement candidate for cellular phone technologies such as GSM and Code Division Multiple Access (CDMA), or can be used as an overlay to increase capacity. WiMAX has more substantial backhaul bandwidth requirements than legacy cellular applications. WiMAX directly supports the technologies that make triple-play service offerings such as QoS and Multicasting possible, which are inherent to the WiMAX standard.
**Figure 1.17 WiMAX Network**

The key features of WiMAX are:

- Range - 50km radius from BS.
- Speed - 70 megabits per second.
- Spectral efficiency - 3.7 (bit/s)/Hertz. The effective spectral efficiency comes through multiple reuse and smart network deployment topologies resulting from combining Scalable Orthogonal Frequency Division Multiple Access - SOFDM with smart antenna technologies.
- Line-of-sight not necessary between user and BS.
- Frequency bands - 2 to 11 GHz (licensed) and 10 to 66 GHz (unlicensed bands).
- No global licensed spectrum, however the WiMAX Forum has published three licensed spectrum profiles: 2.3 GHz, 2.5 GHz and 3.5 GHz, in an effort to drive standardization and decrease cost.
1.5.1.1. Architecture

WiMAX Forum defines how a WiMAX network connects with an IP based core network. Nevertheless the WiMAX BS provides seamless integration capabilities with other types of architectures as with packet switched Mobile Networks. The WiMAX forum proposal defines a number of components, plus some of the interconnections or reference points between these, labeled R1 to R5 and R8, illustrated in Figure 1.18:

- SS/MS: the Subscriber Station/Mobile Station
- ASN: the Access Service Network
- BS: Base station, part of the ASN
- ASN-GW: the ASN Gateway, part of the ASN
- CSN: the Connectivity Service Network
- HA: Home Agent, part of the CSN
- AAA: Authentication, Authorization and Accounting Server, part of the CSN
- NAP: a Network Access Provider
- NSP: a Network Service Provider

The advantage of WiMAX architecture is that it can be designed into various hardware configurations rather than fixed configurations and flexible enough to allow remote/mobile stations of varying scale and functionality and BSs of varying size - e.g. femto, pico, and mini BS as well as macros.
1.5.1.2. Media Access Control

The WiMAX MAC uses a scheduling algorithm to schedule the subscriber device. Once scheduled, the subscriber device is allocated an access slot by the BS. The time slot can expand and contract, but remains assigned to the subscriber station, which means that other subscribers cannot use it. In addition to being stable under overload and over-subscription, the scheduling algorithm can also be more bandwidth efficient. The scheduling algorithm also allows the BS to control QoS parameters by balancing the time-slot assignments among the application needs of the subscriber device.
1.5.1.3. Inherent Limitations

WiMAX can operate at higher bitrates or over longer distances but not both, similar to other wireless technologies. Lower bitrate results for operations at the maximum range of 50 km, since bit error rate increases when range increases. Conversely, reducing the range to less than 1 km allows a device to operate at higher bitrates. As such, WiMAX cannot deliver 70 Mbit/s over 50 kilometers.

Available bandwidth is shared between all the users in a sector, similar to other wireless technologies. When there are many active users in a single sector, the performance naturally deteriorates. A minimum guaranteed throughput for each subscriber can be ensured with adequate capacity planning and the use of WiMAX's QoS (Nair et al 2004).

1.5.2. LTE

LTE developed by the 3rd Generation Partnership Project (3GPP) is a standard for wireless communication of high-speed data for mobile phones and data terminals and aims to provide improved backhauling. LTE is an evolution of the GSM/Universal Mobile Telecommunications System (UMTS) standards with the goal to increase the capacity and speed of wireless data networks using new digital signal processing techniques and modulations (Mcqueen 2009). LTE also aims to redesign and simplify the network architecture to be an all-IP network to take advantage of upper layer protocols such as QOS and also it significantly reduces transfer latency compared to the 3G architecture. The LTE wireless interface is incompatible with 2G and 3G networks, and hence must be operated on a separate wireless spectrum. LTE is the latest step in moving forward from the cellular 3G services and the main objectives for LTE include: improved peak data rates with reduced
latency, improved spectral efficiency, reduced cost for the operator, improved system capacity and coverage, scalable bandwidth, all-IP network, and support a multitude of user types (Dahlman et al 2008) (Astely et al 2009).

1.5.2.1. Specification

The main features defined in LTE specification are:

- Peak downlink rates up to 300 Mbit/s and uplink rates up to 75 Mbit/s. All terminals will be able to process 20 MHz bandwidth.
- A transfer latency of less than 5 ms, lower latencies for handover and connection setup time.
- Improved support for mobility, exemplified by support for terminals moving at up to 350 km/h or 500 km/h depending on the frequency band.
- Orthogonal Frequency Division Multiple Access (OFDMA) for the downlink, Single Carrier – FDMA for the uplink to conserve power.
- Support for both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) communication systems as well as half-duplex FDD with the same radio access technology.
- Support for all frequency bands currently used by IMT systems by ITU-R. Each country follows a different band and as a result, phones from one country may not work in other countries. Users will need a multi-band capable phone for roaming internationally.
- Increased spectrum flexibility: 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz wide cells are standardized.
- Support for cell sizes with radius from tens of meters up to 100 km.
- Supports at least 200 active data clients in every 5 MHz cell.
- Simplified architecture: The network side of Evolved UMTS Terrestrial Radio Access Network (EUTRAN) is composed only of eNode Bs and this result in lower operating costs.
- Support for inter-operation and co-existence with legacy standards.
- Packet switched radio interface.
- Support for Multicast-Broadcast Single Frequency Network.

1.5.2.2. Architecture

LTE network, as shown in Figure 1.19 includes two parts:
- a radio access network part - EUTRAN, and
- a core network part - Evolved Packet Core (EPC).

EPC

```
MME
S-GW / P-GW
```

```
MME
S-GW / P-GW
```

```
eNB
```

```
eNB
```

```
eNB
```

```
eNB
```

```
eNB
```

S_1

X_2

E-UTRAN

eNB: E-UTRAN NodeB
MME: Mobility Management Entity
S-GW: Serving Gateway
P-GW: PDN Gateway

Figure 1.19 LTE Architecture
LTE networks are intended to bridge the functional data exchange gap between very high data rate fixed wireless local area networks and very high mobility cellular networks (3GPP 1998). Functions like modulation and header compression are taken care by the access network part, and the core network part handles functions like seamless handovers, charging and mobility management. EUTRAN uses shared packet switching links to support all services achieving better spectral efficiency, and thereby increasing the total systems capacity. With the exploitation of packet switching technology, services are better integrated among wireless and wired technologies. EPC covers the packet switched domain and divides user data flows into control and data planes. Each plane has its own defined specific node, including a generic gateway which connects the LTE network with the rest of the network. EPC is being comprised by four different functional entities as shown in the Figure 1.20:

- Mobility Management Entity (MME) - The control plane functions between the subscriber and the session management are managed by this entity.

- Serving Gateway - The connection point between EPC and EUTRAN, and serves as routing node for other 3GPP technologies as well.

- Packet Data Network (PDN) Gateway –Terminating point for sessions towards the internet.

- Policy and Charging Rules Function (PCRF) - Manages charging subscribers and IP multimedia configuration for each subscriber.
Figure 1.20 EPC Network Entities

The LTE physical layer is based on Orthogonal Frequency Division Multiplexing (OFDM) scheme to meet the targets of high data rate and improved spectral efficiency. The spectral resources are allocated/used as a combination of both time (in terms of slot) and frequency units (in terms of subcarrier). Multiple Input and Multiple Output (MIMO) options with 2 or 4 Antennas is supported. Multi-user MIMO is supported in both uplink and downlink. The modulation schemes supported in the downlink and uplink are Quadrature phase-shift keying – QPSK, 16 and 64 Quadrature amplitude modulation.
1.5.2.3. Frame Structure

LTE frame is divided into subframes and there are two frame structures defined for LTE system, one for TDD and other for FDD schemes, driven by their requirements:

- Type 1 for FDD mode systems
- Type 2 for TDD mode systems

Each type 1 frame as detailed in Figure 1.21 is of 10ms and is divided into 20 individual slots. 2 such slots make up a subframe, and hence there are 10 subframes within a LTE frame.

![Figure 1.21 Type 1 LTE Frame Structure](image)

Each type 2 frame is of 10ms, and comprises two half frames of length 5ms. Five subframes each of length 1ms make up a half frame. A Type 2 frame is expanded in Figure 1.22.

LTE frame and subframe structures are designed to be compatible with the existing structures to enable migration from UMTS and High speed packet access–HSPA as well as Time division synchronous CDMA.
1.6. INTEGRATION BETWEEN OPTICAL NETWORKS AND WIRELESS ACCESS TECHNOLOGIES

The weakest link in today’s internet is the performance of the access network, which has gained the attention of lot of researchers. A good amount of research has been carried out to propose solutions to improve the efficiency of specific access technologies.

Copper based networks, mainly DSLs and coaxial cables make most of today’s access network. The high increase of service demand by users is making these networks obsolete and, in most cases, they are being gradually replaced by optical access networks. One of the most promising candidates for the next generation broadband access networks is the integrated architecture of optical and wireless technology (Ali et al 2010). This integration has both the advantage of the optical network’s high bandwidth support and the wireless network’s mobility for subscribers. Such integration also provides the user with access to diverse services with a high degree of
ubiquity, while maintaining high resource utilization efficiency. Particularly, rural area service providers gain economic efficiency where the existing wired infrastructures such as DSL, T-l/E-l networks or fiber deployments are either costly or unreachable. Such integration faces many technical issues which need to be addressed efficiently for ensuring end-to-end and diverse QoS for various service classes. Last decade has witnessed lots of broadband access deployment to both fixed and mobile communication infrastructures that require integration of both wired and wireless technologies (Shen et al 2007) (Vrdoljak et al 2000).

The most deployed solutions for the wired broadband access networks are DSL and modems. Terrain, physical distance and traffic growth are the major problems that these networks face. The problems of these networks vary from supporting subscribers located far from the central office (say, more than 5 km) to limited bandwidth with which to support triple-play services of bandwidth-savvy users.

Of all the available optical access networks, PONs without any active internal devices offer excellent maintainability and robustness. Also, due to their ultra-high bandwidth and low attenuation, PONs are the most attractive option for backhaul networks. Even though they provide high bandwidth in addition to availability and reliability, they are still very costly to deploy to each subscriber premises. Also, they provide little flexibility and no mobility. On the other hand, the ubiquitous nature, QoS support, coverage and the rapid progress in wireless technologies are making wireless communications more promising for access networks. Additionally, they support mobility and also have low deployment costs. The most attractive options are WiMAX (IEEE 802.16 - The IEEE 802.16 Working Group on Broadband Wireless Access Standards 2001) and WiFi (IEEE 802.11 - IEEE 802.11 Wireless Local Area Networks 1997), which are expected to yield
maximum user data rates around 100 Mbps. The popularity of wireless technologies is primarily due to their mobility, scalability, low cost, and ease of deployment. However, they suffer from limited wireless spectrum and when many users share the services they end up having low bandwidth. In the future, convergence of optical and wireless technologies is inevitable in the access segment for quadruple play (voice, data, video, and mobility). However, as the traffic behavior and channel quality of these two technologies are far from each other, seamlessly integrating passive optical networks and wireless mesh networks present a very challenging task that demands further investigation (Kazovsky et al 2011). A major challenge in such a process is the selection of the right bandwidth allocation algorithm since it is exclusively responsible for the allocation of resources in the system. Also, in such converged scenarios an effective QoS mapping mechanism would be required between optical and wireless queues in order to avoid performance degradation of both types of users (Ekstrom 2009).

1.7. OBJECTIVE OF THE THESIS

Ensuring stringent QoS requirements is a critical issue in determining the performance of the network. Added to that, when the network happen to be converged EPON and LTE which is essential for today’s bandwidth-intensive customer needs, it is still more critical. Hence, allocation of resources to the end-points is the crucial process in such a converged network. This work reports a new centralized scheme for allocating time-slots to the end user services in converged EPON and LTE networks. Most of the earlier works enforce QoS based on the request from the ONU s in a cycle and in the process do not maintain fairness between cycles. Fairness among the ONU s is not maintained in serving high priority requests of a heavily loaded network for a longer duration extending for a number of cycles, and the first set of high priority requests in the list always get serviced in all the cycles.
Hence an attempt is made in this research work to maintain fairness among heavily loaded ONU units between cycles along with enforcing QoS. And it is enhanced to support end-to-end QoS by establishing a mapping mechanism between the LTE bearers and EPON queues. Though EPON and LTE represent fixed PON and 4G mobile access technologies in the work, the proposed algorithm is also applicable to other PON and 4G access networks such as GPON and WiMAX.

In the process of realizing the algorithm in commercial switches, it is crucial to implement the algorithm in processor and affirm its compatibility in hardware architecture. This way, the number of clock cycles consumed for the execution of the algorithm could be calculated which is significant, because the number of clock cycles determines the speed of the algorithm. In turn, the speed of the algorithm is the deciding factor to implement the algorithm in a particular network. Real time service assurance of LTE necessitates that the algorithm be tested in a processor before implementing it for commercial practice and hence the same is done using Intel’s IXP 2400 Network Processor.

Most of the proposed DBA algorithms in the literature are centralized, wherein OLT takes the sole responsibility for bandwidth allocation process which determines the amount of bandwidth to be allocated to the reporting ONU units. There are two major advantages in migrating to decentralized DBA algorithm. First, it reduces the DBA processing overhead in the OLT thereby improving the system efficiency. Second, although EPON protocol permits large split ratios (up to 32,768), in practice most PONs deploy a split ratio of 1:32 or smaller. 1G EPON supports 1:16 splitter ratio without FEC and 1:32 splitter ratio with FEC. With 10G EPON and new power budget classes, split ratios of 1:256 or more could be easily supported. When N increases in the 1:N optical splitter used, the overhead due to DBA
operation in the OLT would increase since N describes the number of ONUs supported by a single OLT. Hence decentralization of DBA calculation from OLT to ONUs proves to be the best direction in the effort to improve the system for future. The research community has however put maximum effort in proposing and improving centralized DBA algorithms with different viewpoints and the one in (Andrade et al 2007), which attempts to do it in decentralized way has multiple drawbacks. Garfias et al (2012) extends the work to realize it in 10G EPONs. Hence an attempt is made in this research work to fine tune the decentralized DBA process in a different perspective to maximize bandwidth utilization and minimize packet delay, which are the objectives of a good DBA algorithm. A new framework for EPON is described, wherein, the DBA estimation is shared by the OLT and ONU, thereby reducing the idle time in OLT and improving the bandwidth utilization for EPON-WiMAX convergence. Also, an effective QoS mapping mechanism is devised between the optical and wireless queues in order to avoid performance degradation in the converged network.

WiMAX aims to guarantee real time service and this necessitates that the algorithm be tested in a processor beforehand of implementing it for commercial practice. To realize the same, the work is extended to implement and test the performance of the algorithm in a WiMAX switch.

The objectives of the current research work are:

- To design a Distributed DBA algorithm for EPON-WiMAX convergence network (DDA-EPON) and enhance it to support QoS by providing a mapping mechanism between WiMAX QoS classes and EPON 802.1p priority queues.
- To design a Centralized DBA algorithm for EPON-LTE convergence network (CDA-EPON) and improve it for QoS assurance with a mapping between LTE bearer flows and EPON 802.1p priority queues.
• To analyze the overall network performance of the algorithms for throughput and QoS services like jitter and delay, under heavy load conditions and for applications such as voice and video.

• The algorithms are also tested for hardware compatibility.

1.8. ORGANIZATION OF THE THESIS

The thesis is organized in 7 chapters and an overview of the chapters is given below:

Chapter 1 provides an overview of the PON system, its characteristics, and the variants. Particularly, EPON system and its transmission details are discussed in detail. Also, bandwidth management in EPON is discussed in detail. It also includes an overview of the MPCP protocol used in EPON transmission. An overview of the wireless access technologies WiMAX and LTE which are used in the work is also discussed. Also, the necessity for convergence between wired and wireless networks for future consumer needs is elaborated.

Chapter 2 offers a detailed insight of the existing bandwidth allocation algorithms in EPON as a literature survey. Openings in the area are identified and the framework for the research is originated.

Chapter 3 presents a detailed description of the devised distributed dynamic bandwidth allocation algorithm in EPON-WiMAX networks. The chapter provides a detailed step by step procedure of the algorithm and the processor utilization for executing the same is studied. Also, the performance of the algorithm is studied for throughput, delay, jitter, and various service classes using OPNET simulator and the efficiency of the algorithm is analyzed in comparison with the conventional scheme.
Chapter 4 details the real time performance analysis of the algorithm using network processor. WiMAX aims to guarantee real time service and this necessitates that the algorithm be tested in a processor beforehand of implementing it for commercial practice and hence the same is done using Intel’s IXP 2400 Network Processor. The chapter also discusses the result of the study and compares the performance of the work with the conventional scheme.

Chapter 5 presents the designed framework for the centralized dynamic bandwidth allocation algorithm ensuring QoS for EPON-LTE networks. The chapter describes the process in detail and also the merit of the work is discussed in detail. The algorithm is studied for throughput and other QoS services like delay and jitter. The chapter also advises an enhancement for the work by assuring QoS of the converged networks. The same is achieved by employing a mapping mechanism between the EPON priority queues and the WiMAX QoS classes / LTE bearers. The effectiveness of the mapping mechanism is studied for the networks.

Chapter 6 details the real time performance analysis of the algorithm using Intel’s IXP 2400 network processor. The chapter also discusses the result of the research work done and compares the performance of the work with the conventional scheme.

Chapter 7 provides the summary of conclusion for the research work done and the scope for the future extension of the same.