Long Term Evolution Backhaul over Ethernet Passive Optical Network:

An Analysis Study

by

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ABSTRACT

LTE (Long Term Evolution) represents an emerging technology that will change how service providers backhaul user traffic to their infrastructure over IP networks. To support growing mobile bandwidth demand, an EPON backhaul infrastructure will make possible realtime high bandwidth applications. LTE backhaul planning and deployment scenarios are important factors to network success. In this thesis, we are going to study the effect of LTE backhaul on Optical network, in an attempt to interoperate Fiber and Wireless networks. This project is based on traffic forecast for the LTE networks. Traffic models are studied and gathered from literature to reflect applications accurately. Careful capacity planning of the mobile backhaul is going to bring a better experience for LTE users, in terms of bit rates and latency they can expect, while allowing the network operators to spend their funds effectively.

DEDICATION

To my parents

and all my family

ACKNOWLEDGEMENTS

I would like to take this opportunity to thank my Advisor Dr. Martin Reisslein, for giving me this opportunity to research and for the continuous guidance to maintain the right path towards research. I would like to thank Dr. Yanchao Zhang whose classes were my fundamental building block for research. I would like to express my thanks to Dr. Michael McGarry. I thank my lab mates Yousef Dashti, Anu Mercian, Xing Wie, Po-Yen Chen and all of the others, who provided me with immediate help and support that helped me complete my thesis. I would like to also thank my family and friends, whose constant support and encouragement kept me going till the end.

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Chapter 1

INTRODUCTION

Long Term Evolution (LTE) is considered as the solution for high bandwidth mobile communications. With higher bit rate, larger cell coverage, improved mobility management and a reduced latency. As we move towards an age where Internet forms the sole means of communication, demands for bandwidth, mobility and speed becomes high priority. Bandwidth hungry services such Youtube, Video on Demand (VoD), Gaming Apps etc, have increased number of users traffic.

The backhaul networks used by LTE predecessors need to be replaced due to the flat IP nature of LTE architecture. Traffic profile is different form LTE predecessors, due to delay improvements. As project shows, high bandwidth and low delay constraints will lower the overbooking factor than can be applied to dimension 4G networks. These major demands cannot be satisfied with the previously deployed copper lines such as the DSL Network or Microwave links. Optical fibers is the replacement of obsolete backhaul solutions for it high bandwidth capability and minimum delay. Passive Optical Networks (PON) are the leading Optical solution. PON network are completely supported by optical fibers and certain passive devices such as couplers, splitters etc, which consume very less power.

LTE is currently launched and backhaul planning and scenarios are important factors to network success. Careful capacity planning of the mobile backhaul is going to bring a better experience for LTE users, in terms of bit rates and latency they can expect, while allowing the network operators to spend their funds effectively.

1.1 Thesis Outline

In this thesis, we are going to study the effect of LTE backhaul on Optical network, in an attempt to interoperate Fiber and Wireless networks. This project is based on traffic forecast for the LTE networks. Traffic models are studied and gathered from literature to reflect applications accurately. The importance of this area of research is, although the idea is lucrative, the integration involves a lot of issues of compatibility.

The remainder of this thesis is organized as follows. In Chapter 2, PON standards and Dynamic bandwidth allocation are presented. In Chapter 3, LTE architecture and QoS were discussed. In Chapter 4, we present Fiber Wireless Network architecture and types. Then in chapter 5, we investigates the LTE backhaul traffic forecasts and models. In Chapter 6, the simulation setup and experiment conditions are introduced. In Chapter 7, experiment results and analysis are presented. Finally, we conclude this paper and present future research.

Chapter 2

PASSIVE OPTICAL NETWORK

Fiber to the x (FTTx) is a term that describe the optical fiber architecture in the last mile communication broadband network solution. The x in the generic term is used for different fiber configuration, such as FTTB, FTTH, FTTC, and FTTN. The FTTx architectures vary with the regard of the distance between the optical fiber and the customer or end-users. As the fiber for FTTN (Fiber-to-the-node) is terminated in a cabinet located 300 meters away from the customer premises where as for FTTH (Fiber-to-the-home) the cabinet could be located right inside the home [18].

Passive Optical Networks (PON) have received high preference as the last mile solution because it offers huge amount of bandwidth and can comply with higher QoS standards. Also, PON access network are easy to deploy and maintain since they consist of only splitters, combiners, and couplers in its network [26] and are cost effective in both operation and capital. PON make use of a passive optical splitter/combiner to produce a fiber shared by the different end users. Sharing the fiber and using passive components help in reducing physical deployment and power costs to operate the network. These lower costs drive PON as the optical access networks preferred choice.

PON consist of three main elements, the Optical Line Terminal (OLT) is located at the service providers central office which connect the core network to the access network, the Optical Network Unit (ONU) the network end unite located near the end-users and the optical splitter that splits the optical fiber from the OLT into the multiple ONUs. ONU bear majority of operations in the network such as bandwidth allocation [20] and it functions as the interface between the end user and access network. It consists of a queue buffer that collects data/packets from the user and transmits. PON was easily implemented to the present network structure and can overlaid on the existing topologies as can be seen in Fig 2.1 .

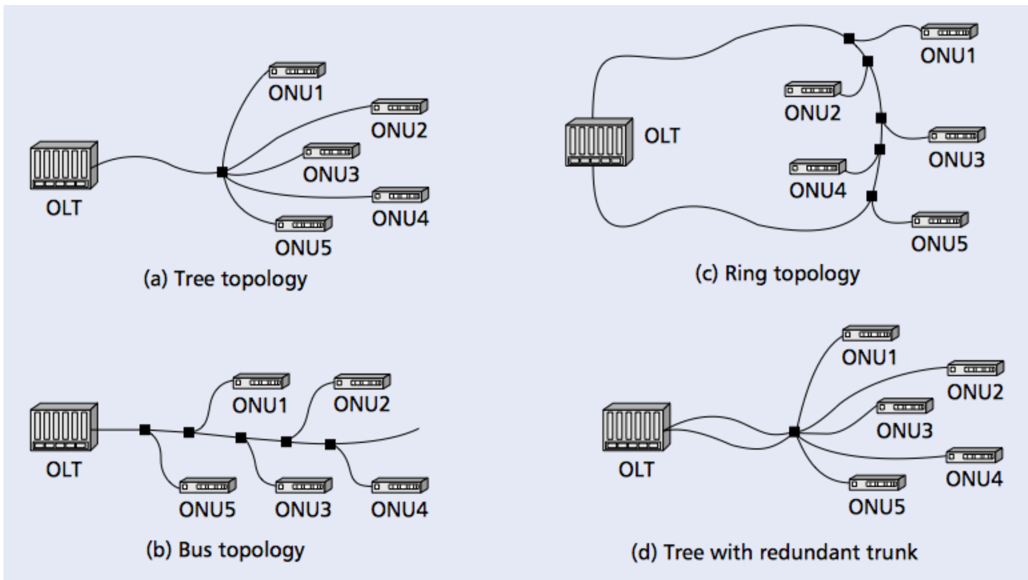


Figure 2.1: PON Topologies [22].

The main standards of Passive Optical Networks (PONs) are categorized based on the used link layer protocol. Asynchronous Transfer Mode PON (APON) employ ATM as its link layer protocol, where Ethernet PON (EPON) uses Ethernet, and a Gigabit PON (GPON) uses the GPON Encapsulation Method (GEM) in addition to ATM to support Ethernet [27] [25]. The standards of APON and GPON are defined by ITU-T G.983.x and ITU-T G.984.x series of recommendations. while IEEE has ratified EPON as IEEE802.3ah Ethernet in the First Mile standard. EPONS are considered to be cost effective since Ethernet devices are present in LANs and thought the worldwide backbone networks and 90% of the data traffic originates and terminates in Ethernet frames.

The ONU upstream multiplexing technique needs to be taken care of when designing PONs network.Wavelength Division Multiplexing (WDM) provides high bandwidth but it is very costly since the OLT must have a transmitter array with one transmitter installed for every ONU. Time Division Multiplexing (TDM) each ONU signal is multiplexed with other ONUs signals in the time domain and only one transmitter needed at the OLT. One of its disadvantages is that is more complicated than WDM where synchronization is needed for the ONUs.

2.1 Ethernet Passive Optical networks

Ethernet Passive Optical networks (EPONs) employ single layer 2 network which makes a use of IP to carry data, video and voice [4]. IEEE has finalized EPON as IEEE802.3ah standard [26]. Typical EPON network, Figure 5, provides connectivity for any IP-based communication. EPONS are considered to be cost effective since Ethernet devices are present in LANs and thought the worldwide backbone networks. EPON can offer services to customers that are scalable from 1.5 Mbps up to 1 Gbps. EPONs have a bandwidth guarantee to provide 1-Gbps service for downstream and upstream bandwidth. The major difference between GPON and EPON in terms of the upstream bandwidth is that EPON uses an extra 250 Mbps for encoding (8B/10B line coding is used) [34].

The downstream traffic from the single point OLT is to multipoint ONUs and it is a transfer and can be compared to a broadband networks. all packets are sent to all the ONUs and a unique ONU ID number will determine the respective ONU as shown in Fig 2 [22]. On the other hand, the upstream traffic which follows the multi to single-point traffic as shown in Fig 3. Since all packets come towards the splitter they could collide if the packets are not multiplexed on the upstream channel. In the upstream channel, EPON works in a burst mode, in which the transmission of the different ONUs are multiplexed through TDM while having guard times [15] where there is no transmission from any ONU between their transmissions. The guard time helps the laser at the OLT to turn off and back on to adjust its power to the ONU that is scheduled to transmit next and also to have the proper alignment for the incoming stream as shown in Figure 2.2 .

The practical limitation of EPON reach is 20 Km and it has no limit on the number of ONUs it can support. The number of ONUs that can be supported by the OLT depends greatly on the used laser diode amplitude. The data transmission has variable packet lengths of up to 1518 bytes which is specified by the IEEE standard. As per Ethernet rule, the incoming data frames can not be fragmented in EPON.

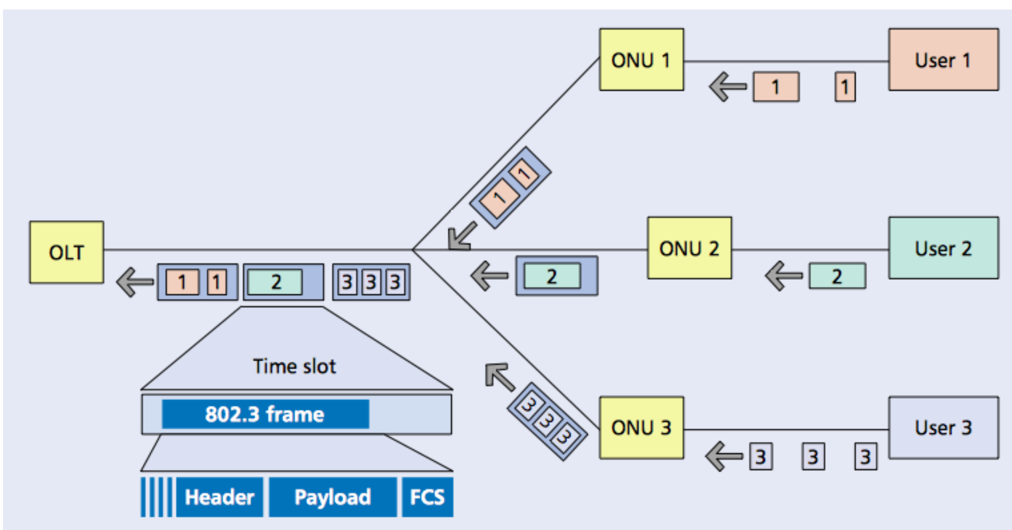


Figure 2.2: EPON Upstream [22].

2.1.1 10G-EPON

10G-EPON was developed in order to provide data rates of 10 Gbps and has become a candidate for the next generation high data rate access systems. IEEE 802.3av task force standardized the 10G-EPON and developed it physical layer specification and management parameters. The 10G-EPON standard provides asymmetric 10 Gbps downstream and 1 Gbps upstream, and also symmetric 10 Gbps downstream and upstream data rates [5]. In order to provide backward compatibility with the existing and widely deployed 1G-EPON, the OLT in a 10G-EPON is equipped with dual rate receivers for receiving data from 1G and 10G-ONUs. Therefore, the MAC protocol of 1G-EPON remains unchanged. In fact, the 10G-EPON MAC-layer control protocol is an extension of MPCP for 1G-EPON that includes enhancements for management of 10G-EPON FEC and inter-burst overhead [34].

2.1.2 MultiPoint Control Protocol

To assist the medium access in EPONs, MultiPoint Control Protocol (MPCP) has been defined in IEEE 802.3ah standard [20] for discovering and registering the ONUs. MPCP consist of five messages; REGISTER REQ, REGISTER, and REGISTER ACK are in charge of for discovering and registering the ONUs. REPORT and GATE messages are responsible for coordinating the medium access as shown in Fig 4. The ONUs will REPORT its aggregated traffic in the queue to the OLT. Upon receiving that the OLT will feed them to a DBA algorithm after that it will issue GATE messages to the ONUs based on the ONUs-ID that include grant size and schedule. The OLT consider the RTT for each ONU in order to utilize the bandwidth more efficiently and it updates the RTT of each ONU by observing the time when the grants are sent and when the data is received [22]. MPCP has two modes of operation, First the auto-discovery mode to find the newly activated ONUs, to learn their RTT and MAC addresses. The OLT and ONUs both implement the discovery process and initiate it periodically, which is driven by the discovery agent. Auto-discovery employs four MPCP messages: GATE, REGISTER_REQ, REGISTER and REGISTER_ACK. The bandwidth assignment mode maintains the connection between OLT and ONUs where it provide periodic granting for each ONU and it employs GATE and REPORT messages [22].

2.2 Dynamic Bandwidth Allocation

Bandwidth Allocation is key performance factor of any access network and it draws exhaustive research attention. Static Bandwidth Allocation (SBA) was the initial methods of bandwidth allocation and it allocated a static bandwidth to each ONU no matter what its traffic demands [4]. SBA didnt consider the bursty nature of the network which led to bandwidth inefficiency. Also, network traffic is increasing with the introduction of services like video streaming, online gaming etc. and SBA has not been able to provide for the huge demand. As a result, the need for Dynamic bandwidth allocation(DBA) has gained a lot of appeal [30]. Dynamic bandwidth allocation react to the ONUs instantaneous changes and allocate to meet this demand. Standard polling was the first type of DBA and it lost it edge since it had long delays due to it long wait time. As a result, Interleaved Polling with Adaptive Cycle Time(IPACT) was introduced [22]. IPACT increases the throughput and reduced the delay significantly since the ONUs wait time have been reduced. IPACT presume that the OLT has the round-trip time(RTT) for each ONU connection[22] and they vary depending on the distance between the ONU and the OLT. Also, The REPORT message informed the OLT with ONU bandwidth requirement which allow the OLT to send the GRANT message to the next ONU before the data from the current ONU is received [35], As shown in Fig 2.3 .

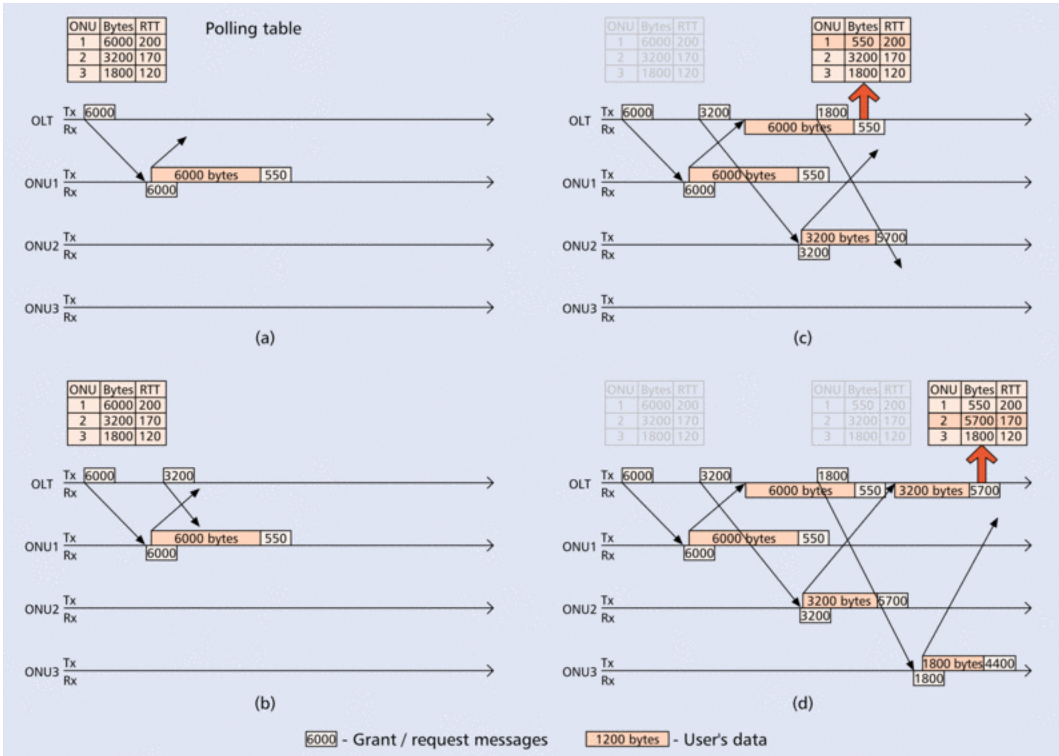


Figure 2.3: DBA Technique: IPACT [22].

In the research of DBA, we classify DBA mechanisms with three factors:

- Grant scheduling framework: which is characterized by the type of event initiating a bandwidth allocation.
- Grant sizing: determines after DBA processing the size of the transmission window assigned to an ONU;
- Grant scheduling policy: determines the ordering of scheduled transmission windows.

2.2.1 Grant Scheduling Framework

The grant scheduling framework dictate the response of the OLT to REPORT message. After it make the access decisions for the OLT it send GATE messages to the ONUs. We can distinguish the scheduling frameworks according to the event that triggers the create a grant [24] [17].

Offline

Offline was the first introduced DBA scheme. All the ONUs are polled together with their granted transmission window but they offline scheme will wait for receiving all of REPORTs from all the ONUs to trigger them.The offline scheme helps the OLT make intelligent allocation schemes.

The advantage of offline scheduling is that it allow the OLT to make informed decisions about each ONUs grant size. Using the knowledge of all ONUs packet queue sizes it can intelligently allocate bandwidth to ONUs. For example, the ONU that have a larger queue size may be granted a large window slot while the lightly loaded ONU grant small window slot. Also, some grant sizing method can only be applied when OLT has all the Report messages. The offline scheme has disadvantage of allowing an idle period for OLT between the last grant size message and the data arrival from the first ONU.

Online

The online DBA was first introduced by the term IPACT [22]. In the online scheme, the OLT schedule an ONU as soon as it receives the REPORT from that ONU. As a result, the requested window size is granted as requested exactly because different allocation algorithms cannot be implemented in the OLT. Online scheme doesnt suffer from the OLT idle time problem because pooling of different ONUs in a cycle is overlapped with other polling cycles. However, when OLT making bandwidth allocations, it only has the knowledge of the reporting ONU, thus advanced scheduling policies that needs more information from other ONUs cannot applied under this framework.

2.2.2 Grant Sizing Schemes

The grant sizing scheme control the size of window size that allocated for each ONU. This scheme is the most important as it effect the throughput directly. The important terms in grant sizing to be noted from are: G(i,j) which is the transmission window size granted to ONUi in granting cycle j; G_{max} is the maximum grant size that any ONU can be assigned, this will determine the bandwidth provided in the fiber network; R(i,j) is the requested window size by the ONU i in the granting cycle j via REPORT. The different grant sizing schemes are:

Fixed

In this technique, the granted transmission window for any ONU, is fixed by the OLT. This grant sizing scheme simplifies the DBA computation process. But as a disadvantage, it will grant the maximum window size even if the ONU requests a very small Window size, which the excess bandwidth will be wasted.

Gated

In this method, the transmission window size is equal to the requested window size in the REPORT. The gated scheme has an advantage over the fixed scheme,that in case of small Request size, the OLT will keep the remaining bandwidth. Although, it suffers if the ONU requests a large window size, which will result in that ONU will occupy the entire bandwidth. Resulting in preventing the other ONUs from their fair share of bandwidth.

Limited

Limited grant sizing scheme was designed having the flaws of Fixed and Gated in mind. This scheme grants the requested window size in all cases if it less or equal to the maximum allowed Grant size G_{max} , if it exceeds that maximum, it will be limited to G_{max}. The advantage of this method that it prevents any ONU from monopolizing the bandwidth.

Excess

The excess grant sizing scheme is an advance DBA method to utilize the available bandwidth[31]. Excess bandwidth allocation cover the fairness for each ONU in the network. The excess bandwidth is based on sharing the bandwidth from each lightly-loaded ONU in each cycle and hand it out to the heavily-loaded ONUs. This required to categorize ONUs as either lightly-loaded or heavily-loaded based on the ONU traffic. The threshold for classification is set as the maximum grant transmission window size G_{max} [28].

2.2.3 Scheduling Policies

The ONUs are scheduled mostly offline, the ONUs can be scheduled in an orderly manner in a granting cycle based on different logical flows. In offline case all the REPORTs are received at the OLT before scheduling them. If the ONUs are arranged, we can observe some change in throughput. This scheme is possible for cases when the REPORTs are collected, therefore, this scheme is not necessary for online/IPACT schemes where only one ONU is scheduled at any time.In our analysis, we do not compare different scheduling policies, but we utilize the most optimized scheme.

Chapter 3

LONG TERM EVOLUTION

Long Term Evolution (LTE) is a project of 3rd Generation Partnership Project (3GPP) group, initially proposed in 2004 at 3GPP conference. The LTE standard is officially known as 3GPP Release 8. LTE is a leap from the 3rd generation (3G) capacity and speed of mobile networks. LTE is designed based on full Internet Protocol (IP) network architecture. LTE aimed to achieve high data rates with improved spectrum efficiency and less latency with low cost for operators[9].

LTE proposed Evolved Universal Terrestrial Radio Access Network (E-UTRAN) as its new access network architecture. E-UTRAN is a simple and flat architecture that consists of only one node which allow it to achieve the requirements of less latency, cost and processing time. Orthogonal Frequency Division Multiple Access (OFDMA) is the downlink access technology used in LTE. LTE uses Single Carrier Frequency Division Multiple Access (SC-FDMA) for uplink access. LTE can operate in different frequency bands and also utilize Multiple Input Multiple Output (MIMO) antennas to achieve higher capacity, coverage and data rates which wasn't possible using the single antenna system[9].

3.1 Network architecture

3GPP group begin two programs to research Next Generation Network (NGN) [1]. The LTE program worked on the radio and air interface (Evolved UMTS Terrestrial Radio Access Network). The Service Architecture Evolution (SAE) program explored the evolution of packet core network (the Evolved Packet Core)shown in Fig 3.1 . Despite the fact that LTE is the key term for the whole system the term Evolved

Packet System (EPS) is used in 3GPP documents refer to the system which consists of E-UTRAN, Evolved Packet Core (EPC) and the user terminals [2].

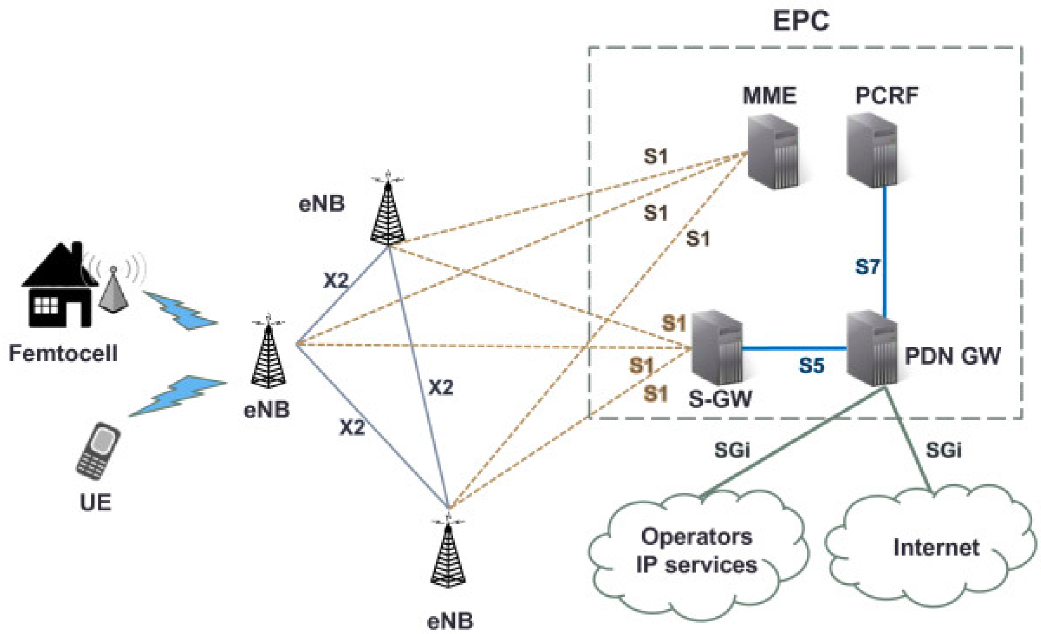


Figure 3.1: LTE E-UTRAN and EPC Architecture [1].

3.1.1 E-UTRAN

The LTE radio access network consists of several Evolved Node B (eNodeB). eNodeB are LTE radio base station that control all radio related functions. It inherits functionalities of the 3G NodeB and the Radio Network Controller (RNC). The eNodeB is also responsible for header compression, ciphering, reliable delivery of packets, admission control and radio resource management (RRM)[1]. eNodeBs are interconnected using the X2 interface. The main purpose of this interface is to facilitate seamless user mobility by reducing data loss during handover. The S1 interface is used to connect the eNodeBs to the EPC[8].

3.1.2 Evolved Packet Core

The EPC is designed to have only packet switch core [1]. The EPC has different interfaces for data and control providing flexibility to the network operators. its responsible for the overall control of the UE and establishment of the bearers. The EPC consists of the following primary functional elements:

The Policy Control and Charging Rules Function (PCRF): in charge of policy control decision making and controlling the flow. It provides the QoS class identifier (QCI) and bit rates.

The Home Subscriber Server (HSS): database server containing user subscription information such as the EPS QoS profile and roaming restrictions. Also, HSS records the identity of the MME to which the user is currently attached too and It can integrate the authentication center (AUC) that generates the user authentication and security keys.

The Packet Data Network Gateway (P-GW): is responsible for IP address allocation for the UE and QoS enforcement. The P-GW enforce the QoS for guaranteed bit rate (GBR) bearers.

ServingGateway (S-GW): it transfers all user traffic and acts as local mobility anchor for the data bearers at handoff. It also buffers the downlink data while the MME initiates paging of the UE to establish the bearers.

The Mobility Management Entity(MME): control the signaling between the UE and the EPC using the Non Access Stratum (NAS) protocols. It functionalities include the selection of P-GW AND S-GW.

LTE differentiate it traffic flows into logical pipes named bearer services. Every bearer service has a set level of QoS parameters decided by it type. VoIP require higher level of QoS than web browsing in term of delay, while web browsing the requires a lower packet loss rate. EPS bearer are characterized by the following set of QoS attributes[3]:

Minimum guaranteed bit rate (GBR): sustaining a minimum bit rate based on the policy set by the operator. if resources are available higher bit rates may be allowed. This type of service can be used with application such as VOIP, Video Streaming.

Non-GBR: there are no guaranteed bit rate and non permanently allocated resources. This type of service can be used with application such as web browsing or FTP transfer.

QCI	RESOURCE TYPE	PRIORITY	PACKET DELAY BUDGET (MS)	PACKET ERROR LOSS RATE	EXAMPLE SERVICES
1	GBR	2	100	10^{-2}	Conversational voice
2	GBR	4	150	10^{-3}	Conversational video (live streaming)
3	GBR	5	300	10^{-6}	Non-conversational video (buffered streaming)
4	GBR	3	50	10^{-3}	Real-time gaming
5	Non-GBR	1	100	10^{-6}	IMS signaling
6	Non-GBR	7	100	10^{-3}	Voice, video (live streaming), interactive gaming
7	Non-GBR	6	300	10^{-6}	Video (buffered streaming)
8	Non-GBR	8	300	10^{-6}	TCP-based (for example, WWW, e-mail), chat, FTP, p2p file sharing, progressive video and others
9	Non-GBR	9	300	10^{-6}	

Figure 3.2: LTE Standardized QCI [3].

In the access network, it is the responsibility of the eNodeB to ensure the necessary QoS for a bearer over the radio interface. Each bearer has an associated QoS Class Identifier (QCI), and an Allocation and Priority. Each QCI is characterized by priority, packet delay budget and acceptable packet loss rate. The QCI label for a bearer determines how it is handled in the eNodeB. there are 9 QCIs that have been standardized as shown in Figure 3.2 .

Chapter 4

FIBER WIRELESS NETWORKS

FiWi is merging wireless networks and optical networks together by exploiting the advantages of using each one of them. Optical networks are deployed to benefit from its offered high bandwidth and long distance reach which could be extended up to 100 KM. The main advantage of deploying wireless networks is communication mobility to the end-users in a local area which does not consider high bandwidth. Optical networks and wireless networks are used as an access network [33]. Each technology addresses different issues and challenges, where each technology cannot resolve all the issues in the access point. As an example, the optical networks offer a high bandwidth but have a high deployment cost as there should be a dedicated infrastructure at the user's house or business unit. On the other hand, the wireless access network offers a mobile connection with cheap deployment [32]. A solution to most of these challenges could be reached by combing these two networks. This hybrid architecture can offer a reliable connection to mobile and fixed users with a high bandwidth.

4.1 FiWi Architecture

New architectures were adopted to enable optimized integration between wireless networks and optical fiber networks. In this section, we present various state-of-the-art FiWi network architectures that were adopted and described in [11]:

4.1.1 Independent Architecture

In this architecture, each customer is allocated an Optical Network unit (ONU); therefore each customer connection is independent of another customer. This type of architecture may lead to high cost of implementation but provides excellent bandwidth facility for the end user. The interface use standard Ethernet Interface and operates independent of each other.

4.1.2 Hybrid Architecture

In this architecture, an attempt to combine the ONU and the base station of wireless network. In that, integration happens not only at the software level but also at the hardware level. This technique will guarantee more coordination between the software and hardware module. All the dynamic bandwidth allocation schemes will be handled by the ONU-BS, this will help reduce the elaborate routing protocols and allocation schemes deployed in ONU and BS.

4.1.3 Unified Connection-Oriented Architecture

This architecture is similar to the Hybrid Architecture, but with the difference that the data carried is a Wireless MAC protocol data unit (PDUs) which has multiple encapsulated Ethernet frames. The bandwidth is granted using connection-oriented rather than EPONs queue-oriented bandwidth allocation.

4.1.4 Microwave-over-Fiber Architecture

In this technique, the wireless signal is modulated on a carrier frequency and multiplexed together with the baseband EPON signal onto a common optical frequency at the combined ONU-BS (EPON node and wireless base station). The OLT will access the traffic from the ONU and macro-BS from the wireless units. This architecture is vastly deployed because the combining cost is the initial expenditure and with efficient bandwidth allocation schemes and routing protocols, the combined unit can be maintained.

4.2 Types of FiWi Network

4.2.1 Radio over Fiber

RF signals that are sent over the wireless networks and modulate an optical carrier in the Central Office (CO) are being propagated over an fiber link to Remote Antenna Units (RAUs) and are then transmitted to clients through the air [12]. Radio over Fiber (RoF) systems are mainly for distribution of signals in distributed base stations systems and it have a low implementation and maintenance costs. The RoF FiWi network provides higher bandwidth, immunity to radio frequency interface, reduced power-consumption, and low attenuation of the signal [21].

The main problem with RoF is the Medium Access Protocol (MAC) layer, the timeout increased in the wireless MAC because of the optical distribution networks. As a result, reducing the throughput of the FiWi networks[13]. Due to WiMAX centralized polling and scheduling RoF fiber propagation delay has lees effect on the network, So WiMAX is a perfect RoF enabling technology [[11].On the other hand, RoF creates a possible bottleneck at the CO which put the whole network in fear of disconnection if any failure occurs at the CO.

Protocols & Algorithms for bandwidth allocation such as switching, modulation and other RF functions are performed at a CO and the allocation can be done dynamically. Therefore, bandwidth can be allocated to peak areas whenever required. Also, RoF offers operational flexibility, depending on microwave generation technique. The application of fiber-wireless is to change the physical layer of the TCP/IP stack; this requires changes in the higher layers for compatibility. The extension of fiber links to wireless networks can have detrimental effects to the MAC layer. Therefore certain protocols and algorithms at the MAC are discussed to elaborate on these challenges [21]:

- Integrated channel assignment and bandwidth allocation: Bandwidth efficiency can be affected by the integration of optical and wireless networks. Therefore, powerful load balancing and reconfiguration techniques are used in FiWi Networks, where bandwidth allocation in fiber networks and spectrum allocation of wireless medium are done dynamically allocated to obtain better service to hotspot BSs (base station) and APs (Access Point).

- Integrated path selection: with respect to path or base station selection for the mobile user, FiWi networks are at an advantage as because of the logical topological arrangements of FiWi Networks in backhaul networks, the mobile users especially the high speed customers may have less handoff or can even be avoided.

- Optical burst assembly and wireless frame aggregation: In Wireless networks, 802.11n high throughput next generation, use two frame aggregation schemes such as A-MPDU (Aggregate- MAC protocol data units) and A-MSDU (Aggregate-MAC service data units), this can be used separately or together. Although EPON does not support frame aggregation, FiWi gives the opportunity of using the advantage of frame aggregation in a two-level EPON/WLAN network.

- Flow and Congestion Control: The differences in bandwidth between the optical and wireless interfaces bring about certain issues. Traffic transition between optical networks to wireless network can cause congestion and exceed the buffer capacity and cause overflows and packet re-transmission thus leading to poor QoS performance such high delay. Therefore efficient congestion control schemes at the interface to improve throughput.

4.2.2 Radio and Fiber

Radio and Fiber (R&F) Networks are different from RoF Networks in the sense that in the former case, we try to integrate optical and wireless networks in the physical layer itself, so that we can overcome the issues in optical-wireless interface. Therefore, R&F Networks are generally deployed as a two level architecture [4, 22]. Also R&F use different MAC protocols for the two parts of the networks, and access control for clients are done differently and gives ways to avoid the extra propagation delays that degrade the performance. The disadvantage of this architecture is length of the fiber deployed, but it compensates that feature by providing resiliency such that packets can be served even if connectivity with optical segment is lost [21].

Considering an example of EPON and WiMAX utilizing the advantageous points of dynamic bandwidth allocation by utilizing different means of centralized polling and scheduling schemes. The issues that arise from the convergence of the schemes can be discussed further [23]. The EPON DBAs concentrate on QoS-aware schemes and the Wireless spread spectrum concentrate more on the Class-of-Service (CoS) schemes. By combination of both the schemes, network throughput, delay and bandwidth utilization have reported to perform much better. The integrated rate controller (IRC) plays the major role in integrating. It has the following elements, BS controller, traffic class mapping unit, central processing unit (CPU), and traffic shaper. IRC optimizes the uplink and downlink schedulers. The above mentioned setup provides triple-play services (voice, video and data) [29].

Routing techniques are important for the second level of R&F architectures; it determines the efficiency of the wireless deployment. The general routing techniques used in wireless networks can be deployed here as well. The general routing techniques are: Minimum-hop routing algorithm (MHRA), shortest-path routing algorithm (SPRA), predictive-throughput routing algorithm (PTRA), delay-aware routing algorithm (DARA), and risk- and-delay aware routing algorithm (RADAR) [36]. RADAR is generally used for best performance of delay, throughput and load-balancing under high and low loads and also provides risk awareness [23].

Chapter 5

LTE BACKHAUL

LTE provides remarkably higher data rates for users at a lower cost for the service providers. LTE end user can download at rates in excess of 100Mbps [2] which raises concerns in the operator side on how to backhaul that increasing amount of data. Also, what is the bandwidth requirement to backhaul a base station supporting hundreds of users.

In this chapter we consider the LTE eNodeB total traffic during the busy hours and in the quiet times. This provides us with figures for the total backhaul traffic per eNodeB needed in the last mile of network, shown in Figure 5.1[1].

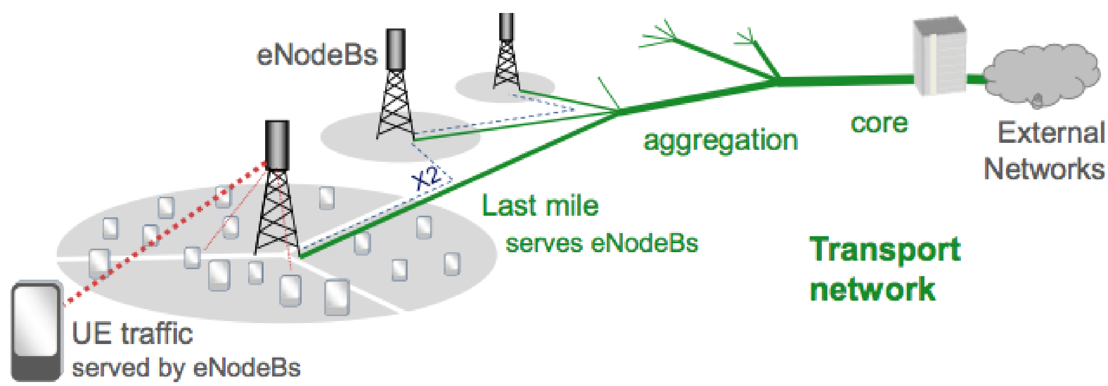


Figure 5.1: LTE Backhaul [7].

There is a variation in cell throughput during busy hour and quiet times in the network. There are many UE being served by each cell during busy hour as shown in Figure 5.2. The so the cell average spectral efficiency will reduce since the cell is serving a large number of users with different radio link qualities. On the other hand, there may only be one UE served by the cell during quite time. The cell spectrum efficiency will be based on that UE. One UE with a good link has the entire cells spectrum to itself. This is the condition which represents the cell peak data rate, as seen in Figure 5.3 .

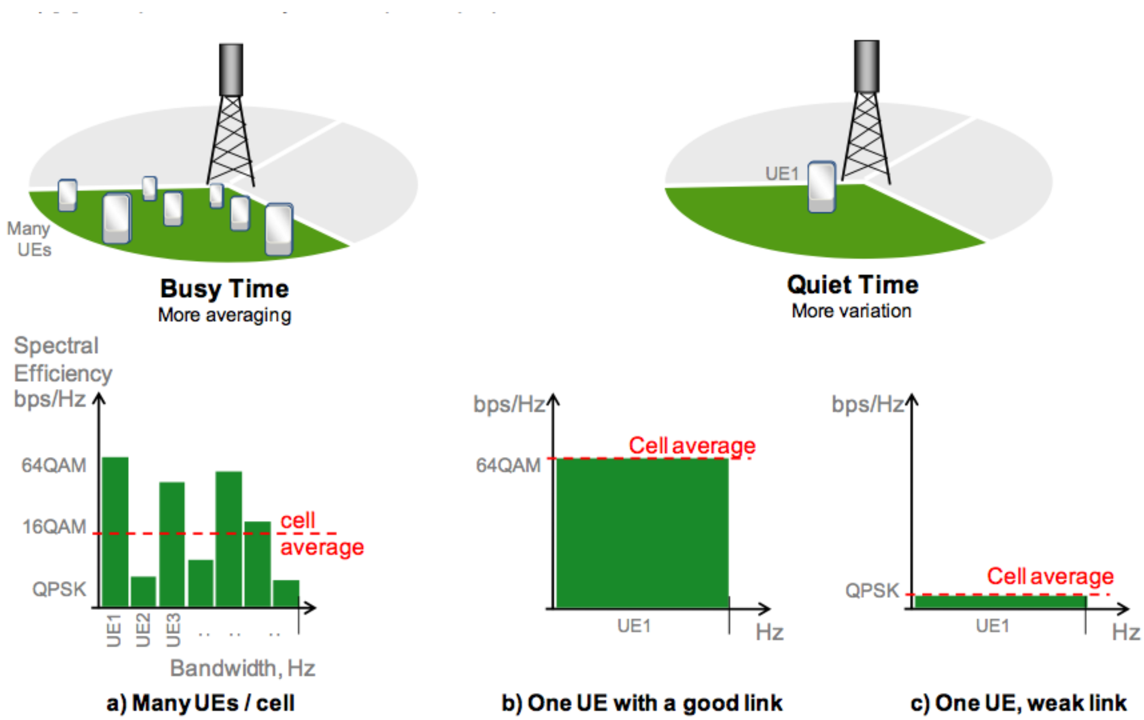


Figure 5.2: LTE busy and quiet times [7] .

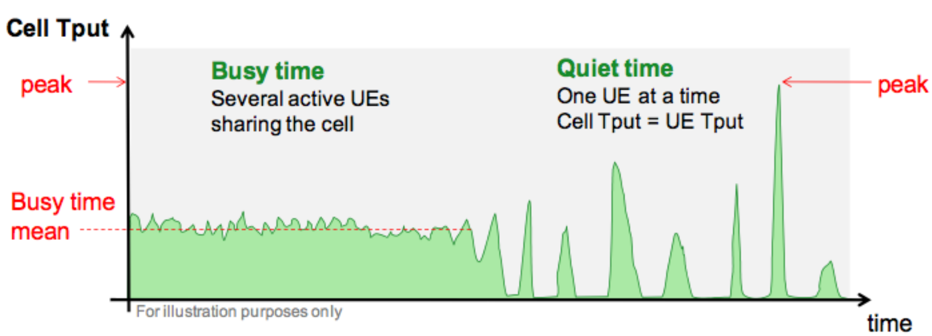


Figure 5.3: LTE busy and quiet times Throughput [7].

LTE backhaul traffic characteristics are different from past circuit mobile networks. Where the number of voice calls at that time determined the backhaul traffic. During busy hour there are more calls which generate more backhaul traffic. Where in data services, the network strive to serve users faster by giving higher data rates. As we have seen in Figure 5.2 and 5.3, the cell can be fully utilized while only serving one user [7][8].

5.1 Backhaul Traffic Estimation

Peak cell throughputs are most applicable to last mile of the transport network. Where the busy hour mean is the dominant factor for backhaul traffic towards the core as the traffic of many cells are aggregated together. Next Generation Mobile Networks (NGMN) Alliance developed a model for estimating backhaul traffic levels in LTE eNodeBs [7] [6]. Also, the provided guidance to how to understand the results and how it can be adapted to suit other conditions.

LTE network simulations revealed the characteristics of cell throughput. As many users during the busy hour are connected to the cell causing an averaging effect, and cell throughput is characterized by the cell average spectral efficiency. On the other hand, it is during quiet times that the peak throughputs take place. Figure 5.4 and 5.5 shows NGMN backhaul traffic estimations for a variety of downlink and uplink configurations [7]. The peak cell throughput is based on the 95%-ile user throughput under light network loads.

5.1.1 Backhaul Traffic Model

To simulate the LTE traffic dynamics, we need more parameters to understand the quiet time behavior. Peng et.al [14] defined the busy time to be typically between 9 AM - 7 PM while the Quiet time is between 12 AM - 6 AM. They have observed

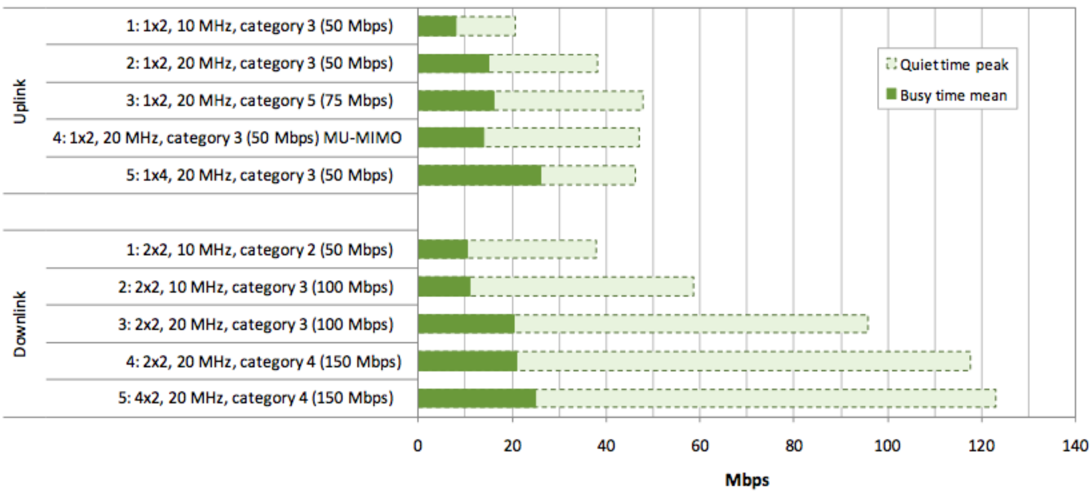


Figure 5.4: Mean and Peak User Plane Traffic [7].

All values in Mbps		Single Cell		Single base station		X2 Overhead		Total U-plane + Transport overhead: No IPsec		IPsec	
Scenario		Mean	Peak	Tri-cell Tput		overhead 4%		overhead 10%		overhead 25%	
		(as load-> infinity)	(95%ile @ low load)	busy time mean	peak (95%ile)	busy time mean	peak	busy time mean	peak (95%ile)	busy time mean	peak (95%ile)
DL	1: 2x2, 10 MHz, cat2 (50 Mbps)	10.5	37.8	31.5	37.8	1.3	0	36.0	41.6	41.0	47.3
DL	2: 2x2, 10 MHz, cat3 (100 Mbps)	11.0	58.5	33.0	58.5	1.3	0	37.8	64.4	42.9	73.2
DL	3: 2x2, 20 MHz, cat3 (100 Mbps)	20.5	95.7	61.5	95.7	2.5	0	70.4	105.3	80.0	119.6
DL	4: 2x2, 20 MHz, cat4 (150 Mbps)	21.0	117.7	63.0	117.7	2.5	0	72.1	129.5	81.9	147.1
DL	5: 4x2, 20 MHz, cat4 (150 Mbps)	25.0	123.1	75.0	123.1	3.0	0	85.8	135.4	97.5	153.9
UL	1: 1x2, 10 MHz, cat3 (50 Mbps)	8.0	20.8	24.0	20.8	1.0	0	27.5	22.8	31.2	26.0
UL	2: 1x2, 20 MHz, cat3 (50 Mbps)	15.0	38.2	45.0	38.2	1.8	0	51.5	42.0	58.5	47.7
UL	3: 1x2, 20 MHz, cat5 (75 Mbps)	16.0	47.8	48.0	47.8	1.9	0	54.9	52.5	62.4	59.7
UL	4: 1x2, 20 MHz, cat3 (50 Mbps)*	14.0	46.9	42.0	46.9	1.7	0	48.0	51.6	54.6	58.6
UL	5: 1x4, 20 MHz, cat3 (50 Mbps)	26.0	46.2	78.0	46.2	3.1	0	89.2	50.8	101.4	57.8

Figure 5.5: Mean and Peak User Traffic [7].

that the busy to quiet traffic load ratio is larger than 4. From their results, we have observed that the Quiet time mean is around 20-25% of the Busy time mean [14].While,the busy time throughput varies little about its mean due to the averaging effect of the many UEs using the network. Since we have the Peak and Mean of the LTE traffic we can use a Poisson traffic generator to simulate the network.

Chapter 6

SIMULATION SETUP

OMNeT++ is an open source event simulation platform is used in this study[37]. It is an existing network simulation and analysis tool that is simple to apply and adapt. OMNeT++ simulation library is written in C++ and easy to extend to any variety of specific needs. The thesis simulations were conducted in OMNeT++ 4.2.2 using INETMANET 2.0 modules. we simulate a network with 8 ONU as shown in Fig 61.

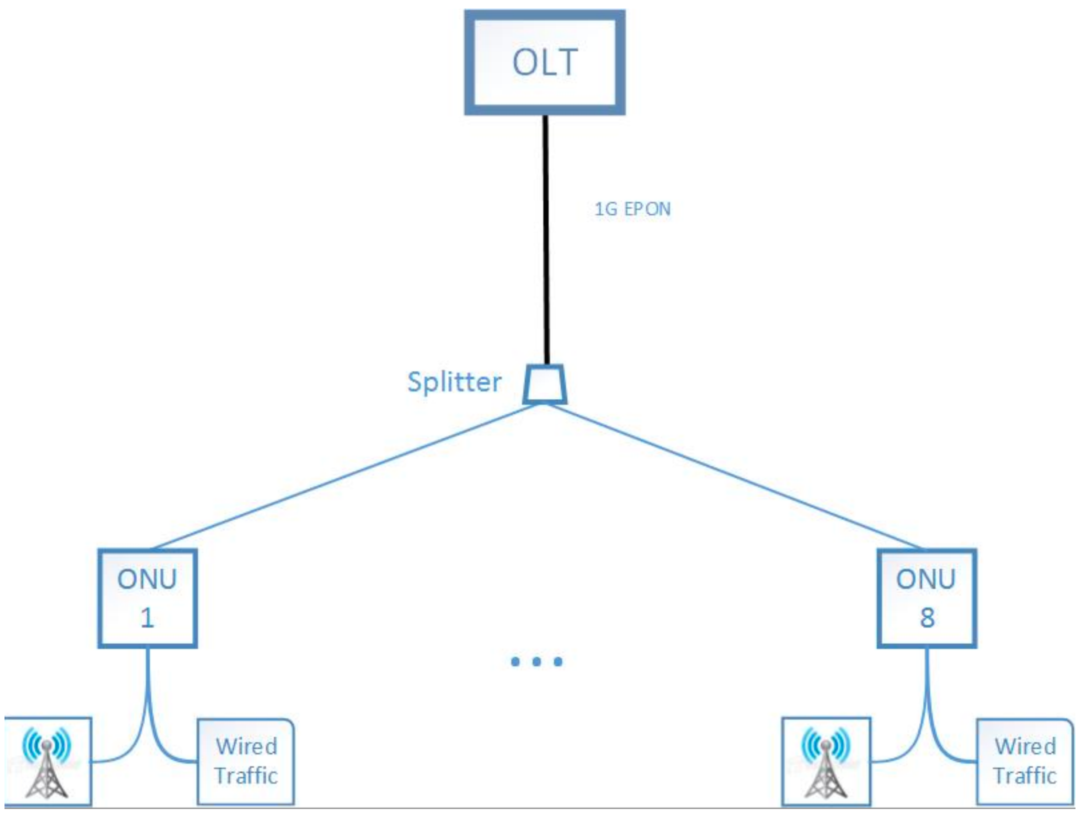


Figure 6.1: Simulation Setup.

The simulator configuration that was adopted for running the simulations for experiments are:

- EPON channel capacity, C =1Gbps.
- Number of ONUs =8.
- Distances between ONU and OLT are uniformly distributed in the range of [15,20] Km.
- Each ONU has an LTE eNodeB connected to it with Uplink Busy Time mean of 48 Mbps.
- LTE Uplink Quiet Time has a peak of 47.8 Mbps and a mean of 12 Mbps.

The EPON DBAs used in this study are combinations of different scheduling framework and grant sizing methods listed below:

- (Online, Gated)
- (Offline, Limited)
- (Online, Limited)
- (Offline, Excess)

We use the quad mode for modeling payload sizes at the UDP level for Wired traffic [16], which includes the following sizes shown in Table 6.1 .

Also, For the LTE eNodeB we use a different Packet size Model obtained from [10] [19] which includes the following sizes as shown in Table 6.2 .

The UDP level payload includes the UDP header of 8 bytes, the IP header of 20 bytes, and MAC level header of 18 bytes at the Ethernet layer. We consider

Table 6.1: Quad Mode Packet Size Model

Payload size	Probability
64 bytes	60%
300 bytes	4%
580 bytes	11%
1518 bytes	25%

Table 6.2: LTE Packet Size Model

Type	Payload size	Probability
VOIP	78 bytes	40%
Data	1518 bytes	60%

independent Poisson packet generation processes having the same mean packet generation rate for each node. All simulation are run until the 95 % statistical confidence intervals of the performance measures are less than 5% of the sample means.

Chapter 7

RESULTS

In this chapter, we cover the experiments we conducted to analyze LTE backhaul and it impact on the optical network. The experiment set-up is as mentioned in the previous chapter. The aim of any network is maximize the throughput and limit the delay. To analyze the performance of the network importance is given for parameters that affect the Quality of Service (QoS). The parameters that determine QoS are generally, average packet delay, resources fairness, throughput and bandwidth utilization. In this thesis, we have considered the average packet delay as our primary analysis parameter.

7.1 Busy time traffic analysis

We use self-similar traffic as it depicts internet traffic to compare the different DBA and their effect on packet average delay. Experiment analysis and observations are done on the following experiment set-up.

- 8 ONU
- SR-PON: (15-20)KM
- Each ONU has an LTE eNodeB + Wired Traffic
- PON Traffic: 10Mbps To 65Mbps , for each ONU
- LTE Traffic: mean= 48Mbps, for each ONU

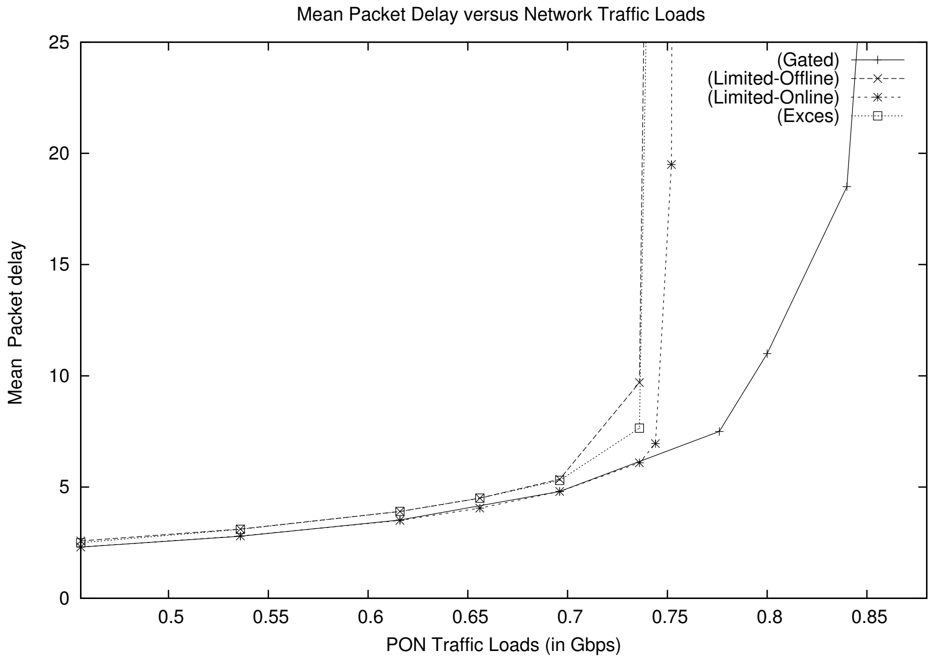
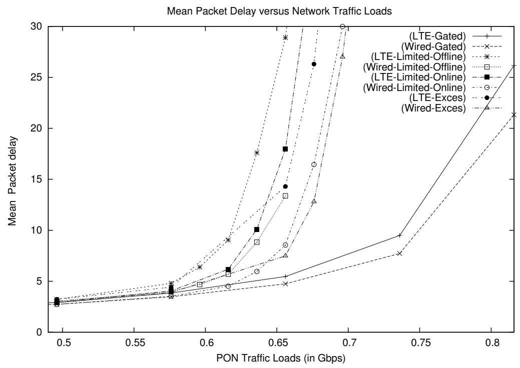


Figure 7.1: Delay Analysis during LTE Busy Time

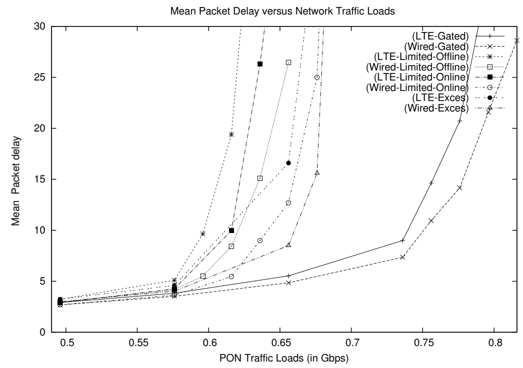
As can be seen from Figure 7.1, the average delay is slowly increasing since the load is fixed. LTE and Wired traffic have the same mean delay. Before the network reaches 75% of it capacity the mean delay is less than 20 ms for all DBA grant sizing schemes. Online scheduling frameworks(Gated and Limited-online) have a lower mean delay when compered to the offline frameworks. Although,the (online,gated) gives the best delay performance of all the DBAs it suffers from resources allocation fairness. Further analysis will be done in future work regarding applying LTE EPS bearer to maintain QoS in the optical backhaul.

7.2 Quiet time traffic analysis

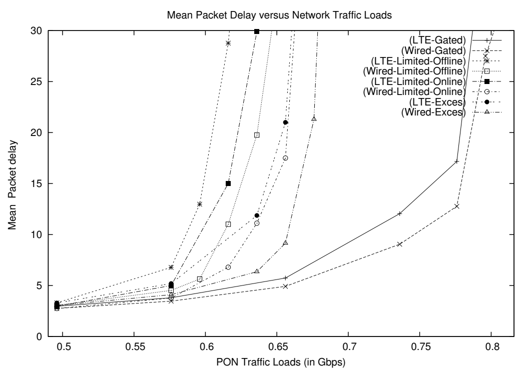
We use self-similar traffic as it depicts internet traffic to compare the different DBA and their effect on packet average delay. Experiment analysis and observations are done on the following experiment set-up.



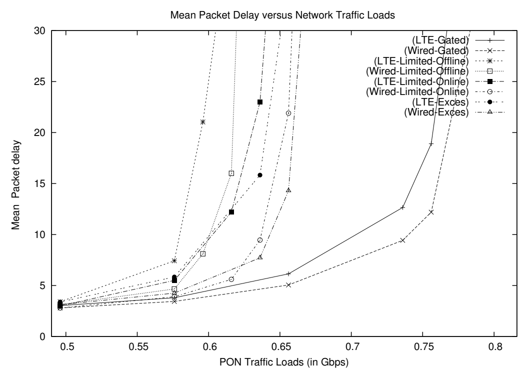
a) LTE Traffic With Sleep Duration= 1 Sec



b) LTE Traffic With Sleep Duration= 3 Sec



c) LTE Traffic With Sleep Duration= 5 Sec



d)LTE Traffic With Sleep Duration= 10 Sec

Figure 7.2: Delay Analysis During LTE Quiet Time

- 8 ONU
- SR-PON: (15-20)KM
- Each ONU has an LTE eNodeB + Wired Traffic
- PON Traffic: 50Mbps To 90Mbps , for each ONU
- LTE Traffic: mean= 12Mbps and Peak=47.8Mbps, for each ONU

The overall network delay will be heavily affected by the LTE traffic,as seen in Figure 7.2 . Wired traffic has an overall lower delay compered to LTE traffic since

LTE traffic is only present 25% of the time. The LTE quiet time performance varies with the change of the burst duration, as the burst duration becomes longer it will add more delay to the network.

7.2.1 Impact of DBA

Online, Gated: In this scheme, the Gated method grants the ONU what it requested which result in delay curves being exponential as seen in Figure 7.2. This is beneficial for heavily-loaded ONU traffic which dominates the network with increasing overall traffic load. However, this will increases the delay of the entire network. This scheme gives the best delay performance of any DBA scheme but it suffers from bandwidth allocation fairness which effect the LTE QoS.

Offline, Limited: As seen in Figure 7.2, this scheme works in favor of lightly-loaded ONUs compared to (online, gated). Since it fix the cycle time ensures every ONU transmit frequently and do not have to wait until the heavily-loaded transmits their entire queues. As the load increases, the queue builds up and results in buffer overflow. The load point where buffer overflows occur mark the stability limit and we observe that the average delays grow very high near and beyond the stability limit.

Online, Limited: follows the same performance trend as of the (offline, limited), while performing slightly better. This is because the offline framework waits for all the REPORTs from the ONUs before sending the GRANT messages. This delay difference is small because only 8 ONUs are considered. As the number of ONUs increases, this delay value would also increase. For LTE traffic, (online, limited) is also better than (offline, limited) because of the reduced waiting time for the REPORTs at the OLT. The trend that can be observed is that online scheduling framework is better than offline framework for traffic in general.

Offline, Excess: For Excess method the average delay is the same as for (offline, limited). This is because, all ONUs are underloaded at low loads and do not require the excess feature. Also, as the load increase, the delay of (offline, excess) is lower than both of the (offline, limited) and (online,limited), and it has a higher stability limit. The reason that (online,limited) is outperforms (offline, excess) only in lightly loaded network is due to that take longer to send the excess grants. Thus, the traffic is queued longer at the ONUs before receiving the grant for the next cycle.

Chapter 8

FUTURE WORK

In this thesis, we are going to study the effect of LTE backhaul on Optical network, in an attempt to interoperate Fiber and Wireless networks. This project is based on traffic forecast for the LTE networks. In this section, we will briefly discuss the issues that were faced in our results and are basis of the future work.

Bandwidth and Resource allocation is an important area of research for any network. Developing scheduling policies for LTE to help maintain QoS over the PON backhaul. Especially, algorithm that translate the LTE EPS bearer to the ONU.

The introduction of LTE small and femto cells is expected to be a cellular paradigm shift. The key to successful operation of small cell networks will be the sharing of already installed high capacity fiber backhaul infrastructures. A promising avenue of future investigation is to develop a similar notational framework and conduct comprehensive performance evaluations for small and femto cells using current backhaul solutions.

Chapter 9

CONCLUSION

In this thesis, we have detailed the Passive Optical Networks and Dynamic bandwidth allocation because it the gateway to provide high bandwidth low latency LTE backhaul. LTE traffic forecast a models have been covered and the challenges have been discussed, thus providing an overview of the research field. From detailed analysis, it can be said that LTE-PON Networks can definitely be the future of broadband access networks from its features,they require a lot more enhancements in techniques both in the physical layer and the MAC layer.

We have examined the combined effects of LTE backhaul and wired traffic on EPON and how it effect it performance. We have studied the LTE modes and developed the simulation scenarios .The performance of the PON DBAs for the uplink transmission is studied in terms of the average delay and stability. From our result, the (online,gated) dynamic bandwidth allocation (DBA) outperform the rest of DBAs at the expense of resources fairness. In the Busy time case, the online scheduling framework performance was better and had a higher stability limit compered to offline frameworks.In the case of quiet time, the offline DBA with excess bandwidth distribution emerged as the second most efficient after the (online,gated).

Developing scheduling policies for LTE to help maintain QoS over the PON backhaul. Also, The introduction of small and femto cells is expected to be a cellular paradigm shift, which raises new research challenges. Furthermore, key to the cost-effective deployment and operation of small cell networks will be the sharing of already installed high capacity fiber backhaul infrastructures.

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