Performance Analysis of xPON Network for Different Queuing Models

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ABSTRACT

Passive optical network (PON) is a point to multipoint, bidirectional, high rate optical network for data communication. Different standards of PONs are being implemented, first of all PON was ATM PON (APON) which evolved in Broadband PON (BPON). The two major types are Ethernet PON (EPON) and Gigabit passive optical network (GPON). PON with these different standards is called xPON. To have an efficient performance for the last two standards of PON, some important issues will considered. In our work we will integrate a network with different queuing models such M/M/1 and M/M/m model. After analyzing IPACT as a DBA scheme for this integrated network, we modulate cycle time, traffic load, throughput, utilization and overall delay mathematically for single OLT and multi-OLT EPON system, and average delay and throughput for single OLT GPON system. A comparison of average delay and throughput between EPON and GPON is introduced with the same number of ONUs. The results show that the proposed multi-OLT EPON system can supports existing bandwidth allocation schemes with better performance than the single-OLT EPON. Cycle delay and average delay is decreased with multi-OLT system than in single OLT system, while throughput of multi-OLT system is higher than throughput of single OLT system. Splitting ratio and throughput in GPON is much higher than in EPON.

Keywords—Passive optical network (PON); Interleaved Polling with Adaptive Cycle Time (IPACT); Dynamic Bandwidth Allocation (DBA); Queuing models; Optical line terminal (OLT); Optical node user (ONU)

1. INTRODUCTION

With the advancement in the communication systems, there is a need for large bandwidth to send more data at higher speed. Optical communication technology gives the solution by developing the optical networks [3]. There are several PON standards can be summarized in Table 1. Passive optical network is a point- to - multipoint fiber optical network with no active components in the optical distribution networks (ODNs) therefor it is called "passive". This greatly reduces the costs and complexity of the deployment and maintenance of the network [4]. PONs are intended to solve the access network's bandwidth bottleneck by offering a cost-effective, flexible, and high bandwidth solution.

Table.1 XPON standards

Technology	standard	Wavelength (up/down)	Speed	Reach
APON	ITU-T G. 983	1550/1310 1490/1310	155Mbps-622Mbps	20km
BPON	ITU-T G.983	1550/1310 1490/1310	155Mbps-622Mbps	20km
GPON	ITU-T G. 984	1490/1310	1.25Gbps up 2.25Gbps down	20-60km
EPON	IEEE/EFM 802.3ah	1490/1310	1Gbps	10-20km

Dynamic Bandwidth Allocation (DBA) algorithms, based on the TDMA (Time Division Multiple Access) protocol, are the best choice, as they dynamically distribute the available bandwidth depending on the current demand of ONUs [2]. These algorithms implement a status report mechanism to efficiently allocate the bandwidth, where control messages are necessary to establish the communication between the OLT and ONUs. The algorithms used by OLT for bandwidth allocation can be static bandwidth allocation (SBA) or dynamic bandwidth allocation (DBA). Since SBA distributes fixed bandwidth to each ONU, resulting in waste of bandwidth.

DBA is widely researched and employed in practical systems for flexible bandwidth allocation and high transmission efficiency [6]. To support dynamic bandwidth allocation (DBA), Kramer and Mukherjee [2] have proposed an OLT-based interleaved polling system similar to hub-polling system. In [7], the authors analyze and derive an expression for the mean packet delay for the gated service with one ONU but could not extend for multiple ONUs accurately. In [4], Lannoo et al. have made significant progress toward a formal delay analysis for an EPON with dynamic bandwidth allocation using gated service. They have derived a Markov chain model for the cycle length in a multi-ONU EPON with reporting at the end of the upstream transmission. By numerically solving the system of equations corresponding to the

Markov chain model, they obtain the mean cycle length, which is then used to approximate the mean delay. In [5] Aurzada et al. analyze the mean packet delay in an Ethernet passive optical network (EPON) with gated service. Markov chain based approach requiring the numerical solution of a system of equations for reporting at the beginning of an upstream transmission to approximate the mean packet delay in an EPON with multiple ONUs.

In this paper, we present a thorough analysis of IPACT, which focuses on modeling cycle times and network delay analytically by using Queuing theory for analysis. Little's theorem used to find the expression for the traffic intensity. We provide an analytical framework for obtaining cycle time and average network delay in an enhanced version.

The rest of this paper is structured as follows section II will illustrate PON architecture. Section II illustrates the DBA algorithm and in section IV, we present the analytical model of EPON and GPON with single OLT. In section V, we introduce the Analytical model of EPON with multi-OLT PON. Section VI shows the Numerical results and discussion. Conclusion is presented in section VII.

2. PON ARCHITECTURE

PONs networks are usually based on a tree topology between the Optical Line Terminal (OLT) and the Optical Network Units (ONUs). Figure.1 illustrates the component of a PON deployment. The OLT is located at the local exchange and connects the access to the metro backbone. The ONU can reside at the curb [fiber to the curb (FTTC)] or at the end user location [fiber to the home or building and (FTTH or FTTB respectively)].

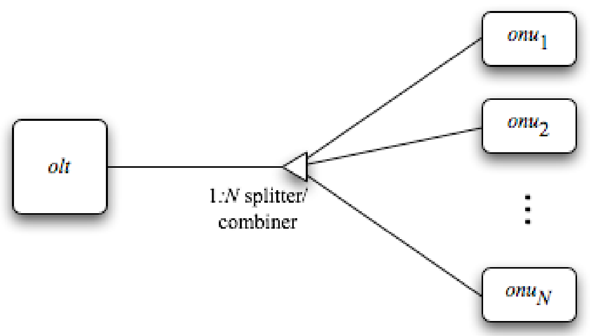

Figure1. Typical PON Architecture

All communication within a PON is mediated by the OLT. In the downstream direction, the OLT broadcasts the messages to all ONUs, but only the designated ONU will deliver the received traffic to its end users. On the other hand, in the upstream direction, PONs has a multipoint to point topology and all ONUs share the same transmission channel. Therefore, in order to avoid collisions among data from different ONUs, a Medium Access Control (MAC) mechanism is needed in the upstream direction. To make every ONU send data normally at the specified timeslot, the PON system must be synchronous and all ONUs must follow uniform clock requirements. To achieve synchronization, the physical distance of every ONU to the OLT must be calculated first. The ranging principle is to test the OLT-to-ONU delay parameter and then perform delay compensation according to the maximum logical distance and the round to trip time of every ONU. PON system uses AES128 encryption for line security control. The key exchange is initiated by the OLT by sending a key exchange request. The ONU responds by generating and sending the key to the OLT. The key is sent three times repeatedly, when OLT receives a new key, it starts the key switchover. The OLT notifies ONU by sending a command containing the frame number of the new key. This command will be sent for three times, and then ONU will switch over the check key on proper data frames.

3.DYNAMIC BANDWIDTH ALLOCATION

Dynamic bandwidth allocation is an algorithm used to distribute bandwidth among users fairly and according to their requirements. Interleaved polling with adaptive cycle time is a DBA scheme, in which the OLT Polls the ONUs individually and issues grants to them in a round-robin fashion. The OLT keeps a polling table containing the number of bytes waiting in each ONU's buffer and the round-trip time (RTT) to each ONU. The OLT then sends a GATE message to an ONU to grant a transmission window allowing it to immediately send a certain amount of bytes. The transmission time of a GATE message is determined by taking the RTT to the concerned ONU and the transmission window of the previous ONU into account, so that packets from different ONUs do not overlap in time [2]. In fact, transmission windows are only separated by a guard time, which provides protection for RTT fluctuations. At the end of a transmission window, an ONU reports its queue size(s) to the OLT by transmitting a REPORT message. The OLT uses this next granted transmission window information to update its polling table and to determine the next granted transmission window.

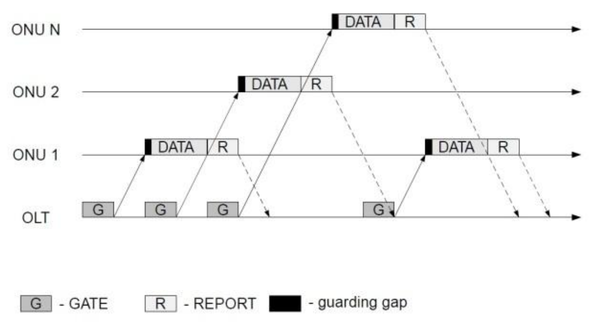

Figure2. IPACT polling scheme [2]

4. ANALYTICAL MODEL WITH SINGLE OLT

Traffic load ,cycle time, average delay, throughput and utilization of EPON, then average delay and throughput of both upstream and downstream GPON will be analyze with single OLT PON system.

4.1 Epon

To analyze traffic load, we denote *C* denotes the upstream transmission speed (in bit/sec) of the EPON. The N ONUs are d km distance from the OLT. The ONUs offer a fixed traffic load over time ρi , i =1, . . . , N. Furthermore, the ith ONU receives traffic from its users following a Poisson process with rate λi packets/sec. Also, each packet requires a fixed amount of service time [10] $[X] = \frac{1}{\mu}$ computed as:

$$E[X] = \frac{1}{\mu} = \lambda i. \frac{8B}{C} \text{ secs} \quad (1)$$

Where *B* refers to the packet size and *C* denotes the line rate. For *B* =1518 bytes and *C* = 1 Gbps, the service time required is $E[X]$ =12.14μs per packet. Hence, the ith ONU offers ρi , i = 1, . . . , N traffic load as:

$$\rho i = \frac{\lambda i}{\mu}$$

(2)

The total offered load ρT , that is, the sum of all individual traffic loads ρi must be smaller than unity [10]:

$$\rho T = \sum_{i=1}^{N} \rho i < 1$$

L is the expected value of N and

$$L = \frac{\rho}{1-\rho}$$

(3)

for M/M/1 model

Sub (1) in (2) we will get:

$$\rho i = \lambda i . \frac{8B}{C}$$

(4)

Sub (4) in (3) to get:

$$L = \frac{\left(\frac{8B\lambda}{C}\right)}{1-\left(\frac{8B\lambda}{C}\right)}$$

$$L = \frac{8B\lambda}{8-8B\lambda}$$

$$L = \frac{8B}{\left(\frac{C}{\lambda}\right)-8B} \quad (5)$$

Cycle length is measured as the time elapsed between two GATE messages sent to the same ONU. The longer the cycle, the longer stations have to wait for their turn and the longer packets have to be buffered. On average, if the order in which ONUs transmit their data is random, the waiting time is equal to half of the cycle length. The length of the polling cycle is adaptive and the minimum and maximum length of the cycle is not dependent on the bandwidth allocation algorithm deployed in the network. The functionality of this approach is briefly outlined by the following steps:

1. The total number of bytes *Qtotal* in all queues is calculated based on latest reports received.
2. The cycle time τ is calculated from (6) where *CL* is the link rate.

$$\tau(n) = \frac{Qtotal}{CL} \quad (6)$$

3. It must be ensured that time $\tau(n)$ satisfy that $\tau_{min} \leq \tau(n) \leq \tau_{max}$ where τ_{min} and τ_{max} are the minimum and maximum length of the cycle. The minimum cycle time must be such that enough time is provided to process all REPORT messages that arrived during the last polling cycle and that GATE messages have enough time to arrive at all ONUs [12].

Let N be the number of ONUs that share the same channel with rate *C* bits per second and let all ONUs send packets of length *B*. The times between packets arrival to the same ONU are independent of each other and have exponential distribution with mean λ in packets per second. Hence, they create a Poisson process. To simplify the analysis let assume that the length of a single transmission window is equal to the length of the packet. The 1 Gbits/s bandwidth has to be shared amongst the *N* ONUs. This would mean that, if all ONUs have the same service level agreement, in a first approximation the bandwidth per ONU is equal to 1/*N* Gbits/s. However, one must take several sources of overhead into consideration that cause the available bandwidth to be lower: the guard time Tguard, the time consumed by REPORT messages, and the Ethernet overhead [3]. Thus, in any cycle an ONU can send only one packet. Based on this assumption, the length of the cycle is calculated as follow:

$$Tcycle = N. \frac{B}{CL} + N. Tguad \quad (7)$$

Where B is the packet size (in bits), and CL is the bit rate (1Gbps). From analysis of the TDMA scheme it can be noted that there are four main factors contributing to the total delay of a packet in the system:

- The packet transmission time, which is equal to $\frac{B}{C\,L}$

- The waiting delay, which is the time that ONU spends waiting for its turn to send data. On average the waiting delay is equal to $\frac{Tcycle}{2}$.
- The queuing delay equal to the time a packet spends in a buffer.

To calculate the queuing delay the model of the TDMA network was considered where every ONU was modeled as an independent and separate *M*/*D*/1 queue where λ is the mean arrival rate. The average queuing delay in the TDMA system is given by (8) [9]:

$$W=\frac{\rho}{2(1-\rho)}.X \quad (8)$$

Where x is average service time, it can be calculated as:

$$X=\frac{NB}{CL} \quad (9)$$

- Round-Trip Time (RTT) which is equal to $\frac{d}{s}$, where d is the distance from the OLT (10km) and S is the speed at which signals travel on the transmission medium (approx.= 2×10^5 km/s). RTT is equal to 100µs. The average delay in the system can be presented as a sum of the transmission, waiting and queuing delay and RTT and can be calculated as follow:

$$T=\frac{B}{CL}+\frac{1}{2}(N.\frac{B}{CL}+N.Tguard)+\frac{\rho}{2(1-\rho)}\frac{NB}{CL}+RTT \quad (10)$$

Throughput denotes the output rate in bit per seconds, and is computed simply by using:

$$\sum_{k=1}^{n}\frac{Wk}{2Tk} \quad (11)$$

Where W is the waiting window and T is the average delay.

Let T is timeslot size and R is a random variable representing unused remainder, then the maximum utilization achieved by an ONU is [12]

$$U=\frac{T-E(R)}{T} \quad (12)$$

4.2 B-GPON

Let δ denote the frame duration of 125 μs of the GPON. A packet generated at an ONU has to wait on average $\delta/2$ for the beginning of the next frame. This next frame has duration (transmission delay) of δ and takes *RTT* to propagate to the OLT. Then, the packet is put into a general queue for the upstream channel. In terms of the mean packet delay, this channel can be modeled as an M/G/1 queue with corresponding delay $(\frac{N.L}{CL}.\frac{\rho}{2(1-\rho)})$ finally, the packet experiences the transmission delay $\frac{L}{CT}$ and propagation delay RTT.

Over all, the mean delay for the TDM upstream channel is [13]

$$D=5\frac{\delta}{2}+(\frac{N.L}{C\,L}.\frac{\rho}{2(1-\rho)})+\frac{L}{CT}+3RTT \quad (13)$$

The TDM downstream channel is analyzed analogously giving:

$$D=\frac{\delta}{2}+(\frac{N.L}{CL}.\frac{\rho}{2(1-\rho)})+\frac{L}{CT}+RTT$$
(14)

5. ANALYTICAL MODEL WITH MULTI-OLT PON

In this section we introduce an access optical network architecture consisting of two OLTs and N ONUs as a single PON network with a tree topology as shown in Figure 3.

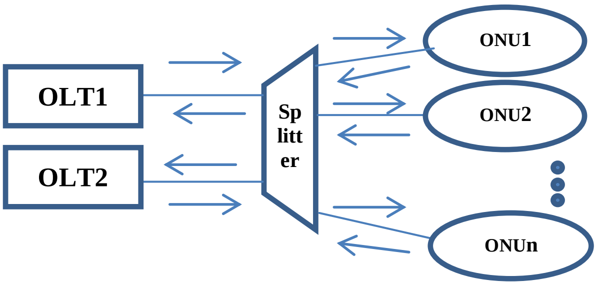

Figure3. Multi-OLT PON

OLT1 is used to support FTTH and the second one is used to support FTTc. All transmissions in the proposed multi-OLT PON are performed between two OLTs in the root side and four ONUs in the leaf side of the tree topology. In downstream transmission, the two OLTs will use the same polling table to start a transmission of the grant messages to all ONUs through the optical splitter and only the concern ONU will receive the packet according to its destination address. Upstream traffic uses TDMA, under control on the OLT located at the CO, which assigns variable time length slots to each ONU for synchronized transmission of its data bursts. In the multi-OLT PON, no guard time is required, because data of every two successive ONUs will be received by two different OLTs. So there is no possibility of data overlapping due to fluctuation of laser on/off timing and RTT. After receiving data from a particular ONU, Every OLT gets enough time before receiving data from the next ONU. This way, packet delay of the network and computational complexity of OLTs can be decreased while bandwidth utilization will be increased [14].

The following formula represents the cycle time for the multi-OLT PON system

$$Tcycle=\frac{NL}{CT} \quad (15)$$

Where N is the number of ONU, B is the packet size, and CT is the link capacity. So, the average delay will be

$$T=\frac{B}{CT}+\frac{NB}{2CT}+\frac{\rho}{2(1-\rho)}\frac{NB}{CL}+RTT \quad (16)$$

Transmission time and propagation delay of the data depend on the data transmission speed of the PON and physical distance between OLTs and ONUs. Usually this distance not equal but the data transmission speed is a constant for TDMA PON.

6. NUMERICAL RESULTS

The results and discussions included the comparison of cycle time (Tcycle), average delay, throughput and utilization of EPON network in case of single OLT and multi-OLT system. Figure 4 shows that cycle time is increased as the number of ONUs increased in both cases single OLT system and multi-OLT system, but cycle time in multi-OLT system is shorter than cycle time in single OLT system with about 55 µsec.

We can say the same observation on fig.5. The average delay of multi-OLT system is shorter about 200 µ sec than the average delay of single OLT system. This is presents a better DBA utilization in the terms of cycle time and average delay, since the multi-OLT PON system can avoid the problem of some bandwidth wastage due to the guard time.

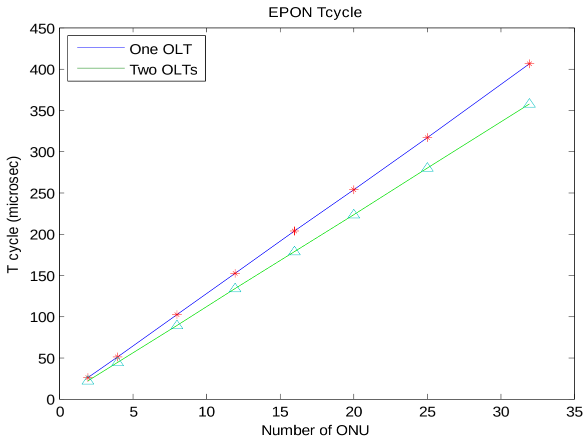

Figure 4. EPON Cycle time

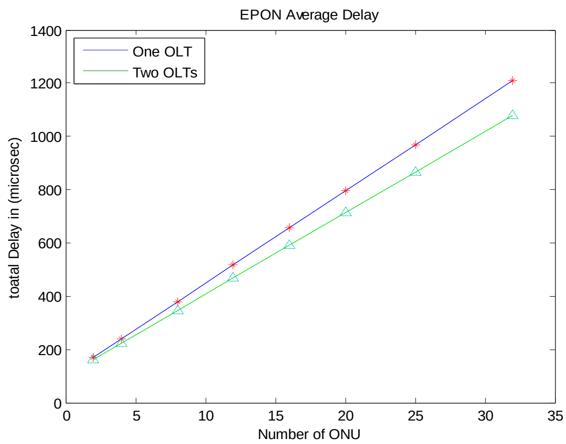

Figure5. EPON Average delay

For the first part of the graph in Figure 6, the average delay increases very slowly; this is the domain determined by the ONU's traffic and by the traffic of the ONUs that are polled right before that ONU. In this domain, the average delay is still very close to its minimum value. For higher traffic loads, the aggregate traffic load becomes the determining factor and the packet delay increases quickly.

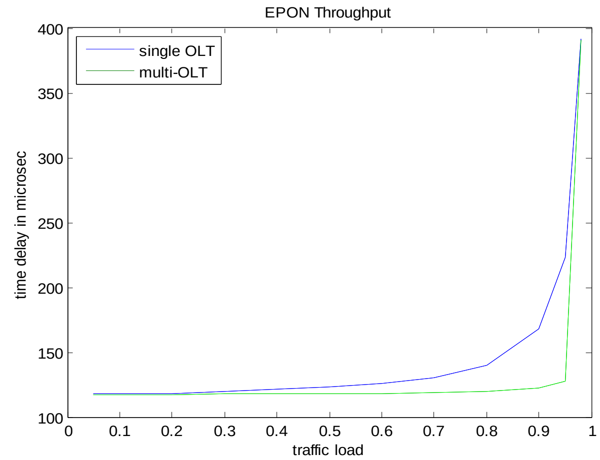

Figure 6. EPON Throughput

The average delay of multi-OLT system is less than the average delay of single OLT system.

Utilization as a function of timeslot size is calculated (according to Equation 12) and it behaves as the plot in Figure 7. Obviously, increasing the timeslot size should result in increased utilization. Where the range for packet sizes is A $\leq size \leq B$. In Ethernet A = 64 bytes, B = 1518 bytes. We assume that we always have packets waiting, i.e., load is heavy.

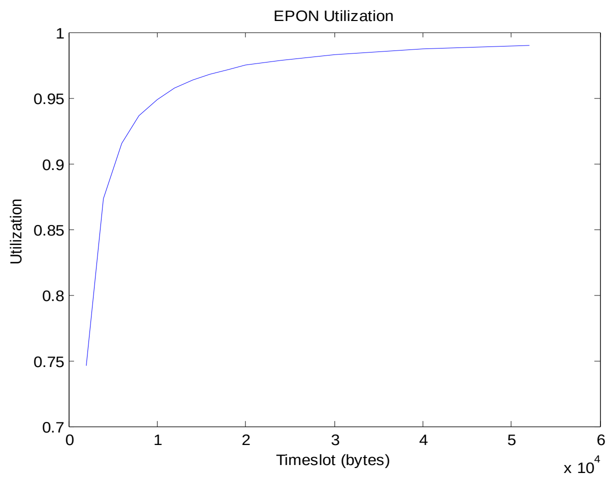

Figure7. EPON Utilization

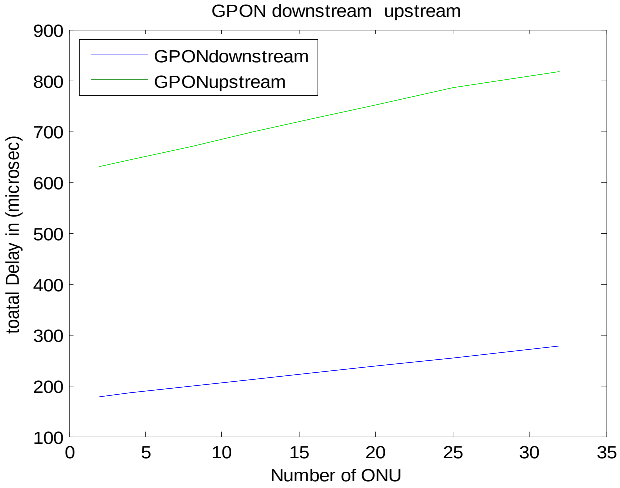

Figure8. GPON downstream and upstream delay

Figure 8 compares the GPON mean delay (D) on the downstream and upstream TDM channels. The delay of upstream channel is higher than the delay of downstream channel because upstream transmissions are delayed by downstream transmissions. In downstream the link capacity is 2.25Gbps and 1.25Gbps in upstream, packet size is 1518 byte [13] and the ONU located at 20 km from the OLT. The difference in delay of both cases with the same number of ONUs is about 400 µsec.

Throughput in the GPON downstream channel with shorter delay than in the GPON upstream channel also with about 400 µsec, and they are behave in the same way as shown in the Figure 9.

In EPON average delay increases linearly and sharply as the number of ONUs increase, while in GPON the increasing happened gradually and in small amount as clear in Figure 10. From this result we can deduce that GPON could serve a larger number of ONUs than those can be served by EPON without affecting very much on the average delay.

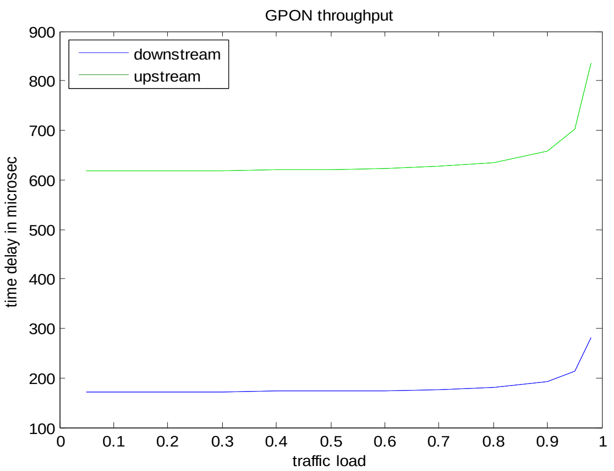

Figure 9. GPON throughput

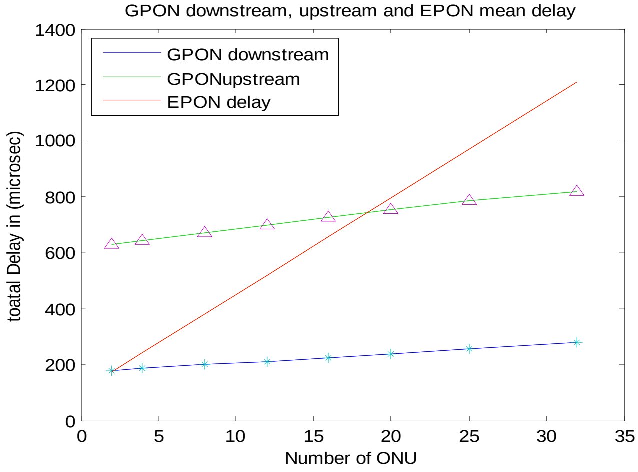

Figure 10. EPON-GPON Delays

Figure 11 shows the throughput of EPON and GPON with the same number of ONUs. They are both in the minimum delay with the light traffic, but delay increases with the heavy traffic.

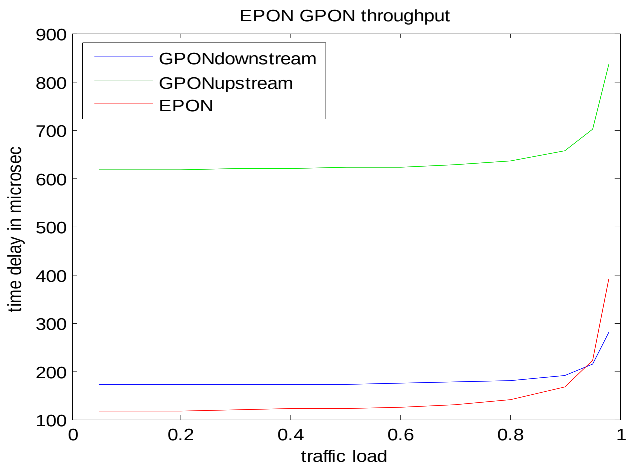

Figure11. EPON AND GPON throughput

7. CONCLUSIONS

We have introduce an analysis of the cycle time, queuing analysis of mean delay, throughput and utilization in an single OLT PON in an Ethernet passive optical network (EPON) and Gigabit passive optical network (GPON). Also a multi-OLT PON is proposed for FTTH and FTTc. From the results it found that the cycle time is reduced about 40-50µces as well as the average delay due to the avoidance of guard time. A multi-OLT PON can accommodate 10% more traffic load than the single OLT PON, this is because the load is distributed among more ONUs resulting shorter cycles and smaller grants and thus less queuing at the ONUs. Also, mean delay and throughput in GPON are investigated in downstream and upstream channels. A comparison between EPON and GPON in terms of mean delay and throughput had been illustrated. EPON achieves significantly lower delays than GPON at small to medium traffic load. This EPON advantage is due to its underlying variable-length polling cycle compared to the fixed length framing structure of the GPON. But GPON can serve very larger number of ONUs could be 128 ONUs, than EPON do, may be only 16 ONUs without very much delay increasing.

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