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Standard-Compliant QoS Provisioning Scheme for LTE/EPON Integrated Networks

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Abstract

Passive Optical Network has been recognized as a solution for next generation mobile backhaul network. Such a network allows service providers to reduce costs by using already deployed fiber-to-the-x (FTTx) systems while simultaneously supporting increasing demands for mobile broadband Internet access. In this article, we describe a QoS provisioning scheme for LTE/EPON integrated networks. With this approach, the Radio Resource Management functions of an integrated device, known as ONU-eNB, can take advantage of the information available from the LTE and EPON networks to improve performance. Furthermore, as an example, we show how the implementation of the proposed approach can improve network utilization and users' quality of service in an integrated network even under the variation of the available bandwidth in the mobile backhaul network.

Keywords

Long Term Evolution, Ethernet Passive Optical Network, Mobile backhaul, Quality of service, Resource management, Scheduling algorithm.

I. INTRODUCTION

Increasing demands for mobile broadband have motivated mobile operators to deploy the Long Term Evolution (LTE) technology. LTE has been touted as a cutting-edge mobile communication technology offering high data rate, better coverage and improved subscriber experience with respect to previous cellular networks. This growth in demand will dramatically increase the number of base stations. For instance, by 2020, the NTT DOCOMO network will grow far beyond the 80.000 base stations currently deployed [1]. Moreover, the LTE base station, also known as evolved NodeB (eNB), can offer peak downlink rates of 100 Mbps in LTE and 1Gbps in LTE-Advanced as well as a half of these values in the uplink direction, thus injecting a large amount of traffic into the mobile backhaul (MBH) network. The cost of the future MBH will be large, but can be reduced by using already deployed network infrastructure such as fiber-to-the-x (FTTx) systems based on Passive Optical Networks (PONs) [2]. Moreover, it is expected that the use of PON technology for mobile backhaul networks will generate a market opportunity on the scale of billions of dollars [3].

Fiber-to-the-home (FTTH) access network based on PONs is the access network technology deployed in several countries [4]. As of June 2011, there were more than 112.6 million FTTx subscribers around the world, and the global FTTx market has continued to grow [5]. In addition, Ethernet Passive Optical Network (EPON) and Gigabit Passive Optical Network (GPON) are the two major standards for Time Division Multiplexing PON (TDM-PON), being EPON the dominant FTTH technology in the market due to its simplicity and cost of deployment, especially in Asia [5]. Given the wide deployment of TDM-PONs and that it will continue to dominate deployment in the near future [6], an attractive solution is to use TDM-PONs as backhaul networks for mobile LTE networks. In this scenario, an LTE base station is a subscriber of the TDM-PON. The network considered in this paper is an integrated network, called LTE/EPON, in which the ONU and the eNB are integrated in a single device, called ONU-eNB.

In LTE/EPON networks, the bandwidth given to an ONU-eNB varies, since the ONU-eNB competes for bandwidth with other ONUs. As a consequence, the bandwidth given to the ONU-eNB in a bandwidth granting cycle may be lower than that needed to support the mobile users in the LTE network. Therefore, the support of QoS requirements of mobile users can be jeopardized. Moreover, the provisioning of Quality of Service (QoS) requirements in such integrated network needs to consider the QoS provisioning in both networks. In addition, any solution to an integrated network should not assume changes in the standards of these technologies.

This paper introduces a novel QoS management scheme for LTE/EPON networks which includes a QoS mapping scheme for the ONU-eNB and a mechanism for priority assignment to users' requests that can be employed by existing schedulers to cope with bandwidth variations in an EPON backhaul. This scheme is independent of both intra-ONU and inter-ONU schedulers. Moreover, it is compliant with both EPON and LTE standards. Numerical examples derived via simulation illustrate the benefits of using the proposed scheme to cope with variations in the available bandwidth.

The rest of the paper is organized as follows. Section II briefly reviews the main QoS provisioning and resource allocation concepts in LTE and EPON networks. Section III describes the integration of these two technologies. Section IV introduces the proposed standard-compliant QoS management scheme for LTE/EPON integrated networks. Section V details the simulation model and the scenarios used and describes the results derived. Section VI describes related work. Finally, Section VII concludes the paper.

II. QUALITY OF SERVICE IN LTE AND EPON NETWORKS

QoS provisioning and resource allocation in EPON and LTE mobile networks differ considerably and the mechanisms involved must be well understood to promote the integration of these two networks. This section reviews the relevant concepts.

A. Long Term Evolution

In LTE networks, flows are mapped onto one of two types of bearers, either Guaranteed Bit Rate (GBR) or non-GBR (nGBR), with the difference between them being a question of support to QoS requirements of the carried flows. A QoS Class Identifier (QCI) is associated with each bearer to determine how that bearer should be served. The QCI is especially related to the following parameters: bearer type, priority level and Packet Delay Budget (PDB). GBR bearers provide guaranteed data rates to the carried flows while non-GBR bearers have no such guarantee. The PDB provides a delay bound with a confidence level of 98% and the priority level indicates the priority of the bearer. In addition to the QCI, each bearer can have other QoS parameters such as the Guaranteed Bit Rate (GBR) which gives the minimum bit rate that should be sustained to the GBR bearers.

The Radio Resource Management (RRM) block of the eNB performs two major tasks: Radio Admission Control (RAC) which decides on the admission of new connections, and Packet Scheduling (PS) which distributes radio resources among User Equipment (UEs). The PS used in this paper is composed of two stages: time-domain (TD) and frequency-domain (FD), each

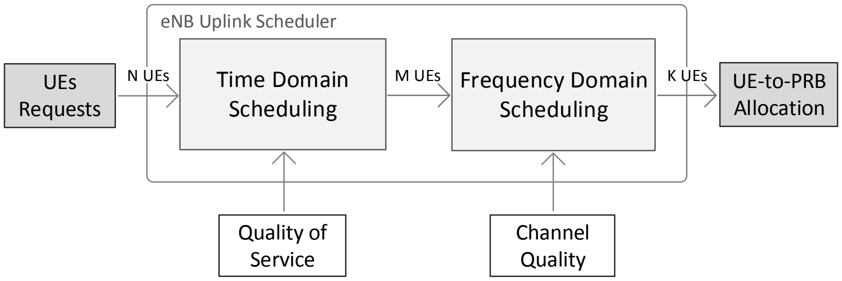


Figure 1: Uplink packet scheduling overview in LTE

with its own scheduling algorithms. In the uplink direction, the TD scheduler selects a group of UE requests based on their QoS requirements to be scheduled for the next transmission time interval (TTI). The selected group is passed to the FD scheduler which determines the Physical Resource Blocks (the smallest allocable part of the spectrum) which should be assigned to users, given their transmission channel quality. Figure 1 illustrates the uplink packet scheduler used here.

Any UE uses two signaling messages, Scheduling Requests (SRs) and Buffer Status Reports (BSRs), to request resources from the eNB for uplink transmission. The SR message informs the eNB that the UE has an unspecified amount of data to send, and the BSR message allows the UE to inform the eNB about the amount of buffered data to be sent and their priority. Based on the QoS requirements of each bearer as well as on the BSR messages received by the eNB, the TD uplink scheduler prioritizes requests to be scheduled for the upcoming TTI. When a scheduled packet arrives at the eNB, it is tunneled using the GPRS Tunneling Protocol User Plane (GTP-u) protocol, and sent over the S1 interface to the mobile core network [7].

B. *Ethernet Passive Optical Networks*

A Passive Optical Network is composed of an Optical Line Terminal (OLT) as well as various ONUs and splitters. The Ethernet Passive Optical Network at 1Gbps was specified in the IEEE 802.3ah standard [8]. The upstream channel is shared among ONUs using Time-Division Multiplexing (TDM) with a Dynamic Bandwidth Allocation (DBA) algorithm, also known as inter-ONU scheduler, that distributes the bandwidth in the upstream direction to the ONUs. The

IEEE 802.3ah standard also defines a signaling protocol for requesting and granting bandwidth, the Multi-Point Control Protocol (MPCP), which can be jointly used with any DBA algorithm. The MPCP defines several messages, among them the Report and Gate messages. The former are used by the ONUs to inform the OLT about the buffered bytes in their queues. The latter are sent by the OLT to ONUs to inform the number of bytes granted for the next cycle and the time at which transmission should start.

The IEEE 802.3ah standard did not, however, define any specific DBA algorithm but rather left it to the vendors to implement their own solutions. One DBA algorithm which has been proposed is the Interleaved Pooling with Adaptive Cycle Time (IPACT) protocol [9]. In IPACT, the OLT polls the ONUs and grants time slots to them in a round-robin fashion. For every round of the bandwidth granting cycle, the OLT decides the amount of bandwidth each ONU will receive. IPACT defines different scheduling policies but the most common is limited scheduling, which grants the minimum between the requested number of bytes and the maximum number of bytes granted per cycle, this depends on the defined maximum cycle length (T_{max}, e.g., 2 ms, 5 ms, 10 ms, etc.). When a Gate message is received by an ONU, an intra-ONU scheduler processes the packets in the ONU queues.

In 2009, the IEEE 802.3av standard was originally proposed to support a 10 Gbit/s EPON (10G-EPON). This standard can operate either symmetrically or asymmetrically. The former allows transmission at 10 Gbps both downstream and upstream direction whereas the latter only allows 1Gbps in upstream direction. Since the MPCP protocol designed for 1 Gbps was maintained for signaling at 10 Gbps the DBA algorithms for 10G-EPON are compatible with those for EPON. Thus, the proposal in this paper is valid for both standards.

Current EPONs can provide QoS within the Differentiated Services (DiffServ) framework which adopts a "class of service" identifier called DiffServ Code Point (DSCP), which is stored in the Internet Protocol (IP) datagram header. Since EPON adopts the IEEE 802.1p standard for traffic prioritization, it can support up to 8 classes of service (CoS), i.e., up to 8 priority queues can be implemented in an ONU. Once the DSCP value have been mapped onto a CoS, incoming packets are classified and sent to one of the ONU queues.

III. THE INTEGRATED LTE/EPON ARCHITECTURE

There are two major approaches to the integration of optical and wireless access technologies; Radio over Fiber (RoF) and Radio and Fiber (R&F) approaches. In RoF, radio signals are directly modulates on the optical carrier. In R&F technology, the integration is done either at layer 2 or layer 3, leading to one of two different architectures [10]. The first, independent architecture, connects the ONU and eNB devices with a common Ethernet interface. The other, hybrid architecture, allows the integration of the software and hardware of both the ONU and the eNB to a single physical box. One of the main advantages of this latter architecture, which is used in this paper, is that resource allocation and scheduling information can be shared by the ONU and eNB, thus improving performance. Figure 2 shows the LTE/EPON integrated network used in this paper.

In such integrated networks, the eNB is a client of the EPON network. The bandwidth granted by the OLT to the ONU-eNB must be distributed among the UE bearers. However, the bandwidth received by the ONU-eNB change potentially at every round of the EPON bandwidth granting cycle. It is thus possible that the ONU-eNB receives less bandwidth than that necessary to support the QoS requirement of the flows carried on the bearers, a variability which must be compensated by an LTE uplink scheduler located in the ONU-eNB so that the QoS requirements can be met.

IV. QOS PROVISIONING IN AN INTEGRATED NETWORK

Figure 3 illustrates the functional modules of the integrated ONU-eNB device which are: ONU-EPON module, eNB-LTE module and ONU-eNB Common Control module. The ONU-EPON and eNB-LTE modules provide, respectively, the functionalities of an ONU and an eNB. An interface, the Common Control module is used for communication between these two modules. The ONU-eNB Common Control module allows the sharing of information about Radio Resources Management functions of the eNB-LTE module and the scheduling functions of the ONU-EPON module. It also performs QoS mapping between the LTE and EPON networks.

When an uplink packet arrives at the eNB, it is reconstructed by the eNB and marked with a DSCP value according to a pre-defined mapping linking QCI values to DSCP values. Then, the packet is encapsulated by using the GTP-u protocol for sending to the mobile core network via an S1 interface. The DSCP value is copied from the inner IP header to the outer one for

QoS provisioning in the backhaul network. Upon arrival at the ONU, a packet classification is performed and the packet joins the ONU queue corresponding to its DSCP value. Each ONU queue follows the First In First Out (FIFO) scheduling policy. When a Gate message is received by the ONU, the intra-ONU EPON scheduler determines which queues will be served and the amount of data that each queue can transmit.

This section shows how QoS can be supported when the bandwidth provided to the eNB in a cycle is not sufficient to provide the required QoS. For that, a QoS mapping scheme and a policy to adjust the priority level of a bearer are introduced. Since there is no need to modify the standardized MPCP signaling protocol to accommodate the ONU-eNB, the deployment of this architecture is facilitated because the ONU-eNB requests bandwidth to the OLT just as any other ONU.

A. *QoS Mapping Scheme*

In order to assure QoS provisioning regardless of the intra-ONU scheduler, all packets are mapped to a single FIFO queue (all-to-one mapping), which is also independent of the EPON

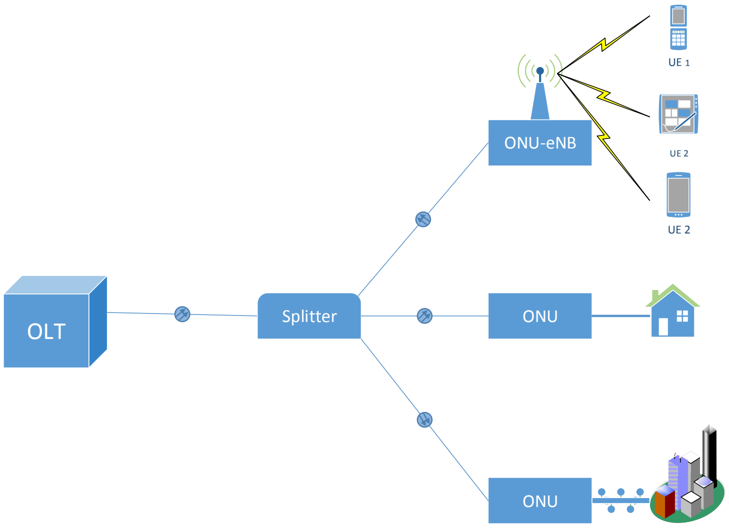


Figure 2: LTE/TDM-EPON integrated network architecture

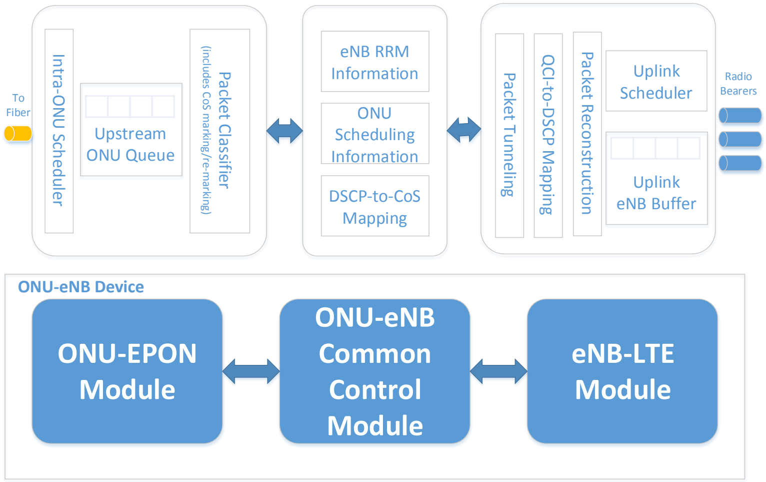


Figure 3: ONU-eNB functional architecture

DBA algorithm adopted. The mapping of all DSCPs to a single CoS means that no restrictions of QoS provisioning in the ONU module of the ONU-eNB device are imposed. This allows the rapid adoption of the proposal in current and future deployments, since no changes are required in the already deployed TDM-based FTTx infrastructure. By leaving the QoS provisioning to the LTE module, the proposed integrated network can capitalize on deployed EPONs. Another advantage of this scheme is that a pre-configured all-to-one DSCP-to-CoS mapping replaces packet classification for every packet in the ONU module, thus avoiding the overhead of packet classification.

Indeed, this scheme allows LTE uplink schedulers to take the backhaul load state into consideration when scheduling users' requests. The ONU queue length can thus be controlled by considering the available capacity of the backhaul network. The next section introduces a simple way for modification of current LTE uplink schedulers, to cope with less bandwidth than the requested to the backhaul network.

B. Use of backhaul information in LTE schedulers

The proposed QoS mapping scheme requires a dynamic prioritization of bearers based on backhaul traffic load but current LTE schedulers do not take into account any backhaul information when scheduling transmission to users. In this section, we provide a simple procedure for modifying existing schedulers so that the current backhaul load can be considered. A compensation factor, $C(k)$, is introduced:

$$C(k) = \frac{Gate(k)}{Report(k-1)} \tag{1}$$

where $Gate(k)$ is the number of bytes granted to a given ONU-eNB by the OLT for the EPON cycle k and $Report(k-1)$ is the number of bytes requested by the ONU-eNB in the EPON cycle $k-1$. When $C(k)$ is equal to 1, the backhaul link is not congested, and the LTE scheduler should operate as usual. When $C(k)$ is less than 1, the EPON link is temporarily congested (i.e., there is a "deficit" of bandwidth) and the priority value of non-GBR bearers must be decreased proportional to this "deficit". The scheduler has to be modified to reduce the amount of low priority traffic scheduled when the backhaul load is high.

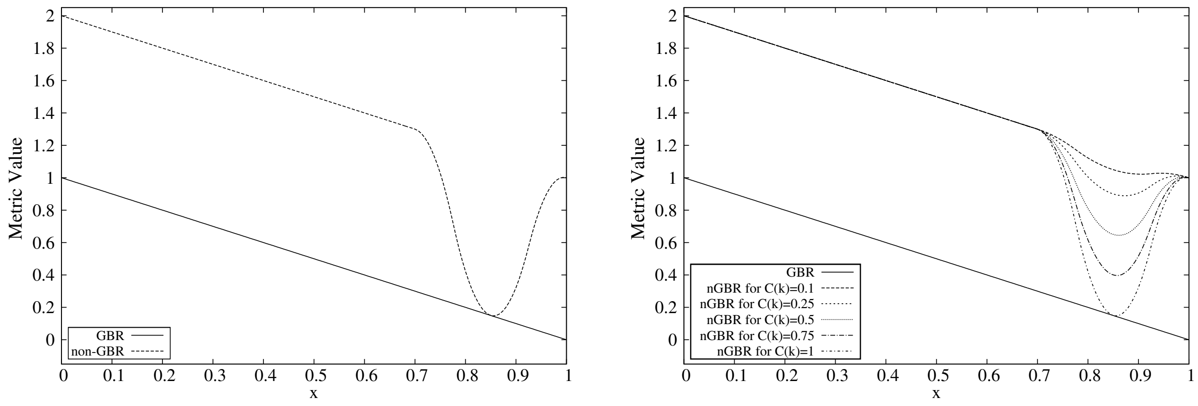
The value of $C(k)$ has to be updated periodically. Data scheduled at a TTI will be receive by the eNB 4 ms later. Since the value of $C(k)$ should consider the most updated information, a recommended lower bound for updating $C(k)$ is 4 ms and the recommended upper bound is the maximum cycle length. (When this value is higher than 4 ms.)

C. *Case Study*

The *Z-Based QoS Scheduler* (ZBQoS) [11] uses a Z-shaped function in its QoS scheduling metric to cope with the dynamic prioritization of bearers. The compensation factor $C(k)$ was introduced into the ZBQoS scheduler so that it could cope with the available bandwidth in the mobile backhaul network, especially when saturated. The ratio x was defined to measure how close the delay is to the packet delay budget; it is defined as follows:

$$x = \frac{HoL_u^i(n)}{PDB^i} \tag{2}$$

where $HoL_u^i(n)$ is the delay of the packet at the head of the line for bearer i of the UE u in the time interval n. PDB^i is the packet delay budget of bearer i, and its value depends on the QCI assigned to that bearer. When x is close to 1, the HoL packet delay for a certain bearer is close to the packet delay budget. This ratio is the input variable to a Z-shaped function, $f_z(x; a, b)$, used in the delay-related metric of non-GBR bearers of the ZBQoS scheduler. Parameters a and b determine the range of x values corresponding to the slope portion of the Z-shaped function.



(a) ZBQoS scheduler [11]

(b) HZBQoS scheduler

Figure 4: Delay-related metric values for GBR and nGBR bearers as a function of the ratio x

Figure 4a shows the ZBQoS delay-related metric values for both GBR and non-GBR bearers as a function of the ratio x (the higher the metric value, the lower the priority).

Applying the proposed scheme leads to a modification of the metric value for non-GBR bearers so that when the backhaul link is saturated, i.e., the $C(k)$ value is less than 1, the priority value of non-GBR bearers decreases. As shown in Fig. 4b, the slope portion of the non-GBR metric value is reduced proportionally and dynamically with the value of the factor $C(k)$, i.e., with the variation in the mobile backhaul network load. We called this modified scheduler, the *Hybrid Z-Based QoS Scheduler* (HZBQoS).

V. PERFORMANCE EVALUATION

To evaluate the performance of the proposed QoS provisioning scheme, a simulator for integrated LTE-EPONs was employed. The LTE module was implemented in the LTE-Sim simulator, version 4.0 [12], which is an event-driven packet level simulator developed in C++ and widely used for simulating MAC functions of E-UTRAN. We implemented the proposed uplink packet scheduler and improved the implementation of the uplink part of the LTE-Sim simulator by introducing the support to QoS for uplink transmissions and dividing the uplink scheduling in time and frequency domains. The EPON module was developed in Java and it implements the IPACT DBA algorithm, jointly with the scheduling disciplines introduced by Kramer *et. al* [9]. In order to simulate an integrated network, we also developed an interface for the LTE and EPON modules and we implemented the GTP-u protocol for the S1 interface between the ONU-eNB and the OLT.

The performance of the proposed scheduler was compared to that of the ZBQoS [11] scheduler, which does not take into account the variation in the bandwidth granted. In order to make a fair comparison, the same frequency-domain uplink scheduler used in the performance evaluation of ZBQoS [11] was employed.

A. *Simulation Model*

The simulated scenario in the EPON is composed of 1 OLT, 31 ONUs and 1 ONU-eNB. The tree topology is used with an optical channel capacity of 1 Gbps. The ONU traffic was simulated using aggregation of ON-OFF pareto sources, with inter-burst generation time exponentially distributed and packet lengths between 64 and 1518 bytes. The LTE network part is composed of a single cell (served by the ONU-eNB device) and several users (varying from 10 to 180, with increments of 10). Users are uniformly distributed, and for every two users transmitting VoIP traffic, and two users transmitting video traffic there is one user transmitting CBR traffic. The UEs move at a speed of 3 Km/h and follow the Random Walk mobility model. VoIP and video traffic are transmitted using GBR bearers and best effort traffic modeled as Constant Bit Rate (CBR) traffic uses non-GBR bearers. When the delay of a packet is greater than the PDB, the packet is dropped. This process is performed at every TTI by the UE at the beginning of the uplink transmission. Information about the delay of the HoL packet of each radio bearer is considered to be available at every TTI in the ONU-eNB. To avoid intra-user scheduling interferences, each UE is assumed to have a single bearer with only one traffic class. Table I contains the traffic models employed in the LTE simulation and their QoS requirements. Table II summarizes the main configuration parameters used in the simulation.

B. *Simulation Results*

The figures presented in this section show mean values, with confidence intervals with 95% confidence level derived on the bases of the independent replication. The duration of each execution was 100 s. Packet loss ratio (PLR), total delay and average throughput per traffic

Table I: Traffic model and QoS requirements (LTE part)

Service	**VoIP**	**Video**	**CBR**
Description	G.729 ON/OFF Model	H.264 Trace-based[a]	1000 Bytes every 8 ms
Bit Rate	8.4 Kbps	242 Kbps	1 Mbps
QCI	1	2	8
PDB	100 ms	150 ms	300 ms
GBR	8.4 Kbps	242 Kbps	N/A
Proportion	2 (40%)	2 (40%)	1 (20%)

[a] We use the trace of the video Foreman; it is available in LTE-Sim [12].

type are used for comparison. All of these metrics are presented as a function of the number of users in the cell (i.e., traffic load in the LTE network).

The aim of these experiments was to assess the ability of the proposed scheme to support the QoS requirements of mobile users under variable load conditions.

We evaluated the performance of the modified scheduler (HZBQoS) and the unmodified scheduler (ZBQoS) using the proposed QoS mapping scheme of the ONU-eNB device. The results are shown for the maximum EPON cycle length of 10 ms under two distinct loads in the backhaul: 0.6 and 0.95. In the *underloaded* scenario (0.6), the ONU mean traffic load is 19 Mbps; in the *heavily loaded* backhaul scenario (0.95) the mean traffic load is 30 Mbps.

Figure 5a shows the PLR of video users. The HZBQoS scheduer is able to provide a low packet loss ratio for all traffic conditions in both the backhaul and the LTE network, which does not happen with the service provided by the ZBQoS scheduler. The packet loss ratio produced by ZBQoS surpasses 1%, and increases with the traffic load, reaching 5% under heavy load. However, the maximum acceptable PLR for video traffic without affecting users' quality of experience is 1% [13]. Moreover, both schedulers produced a no loss service to VoIP traffic (not shown in the paper) as a consequence of its low bandwidth demand and high priority.

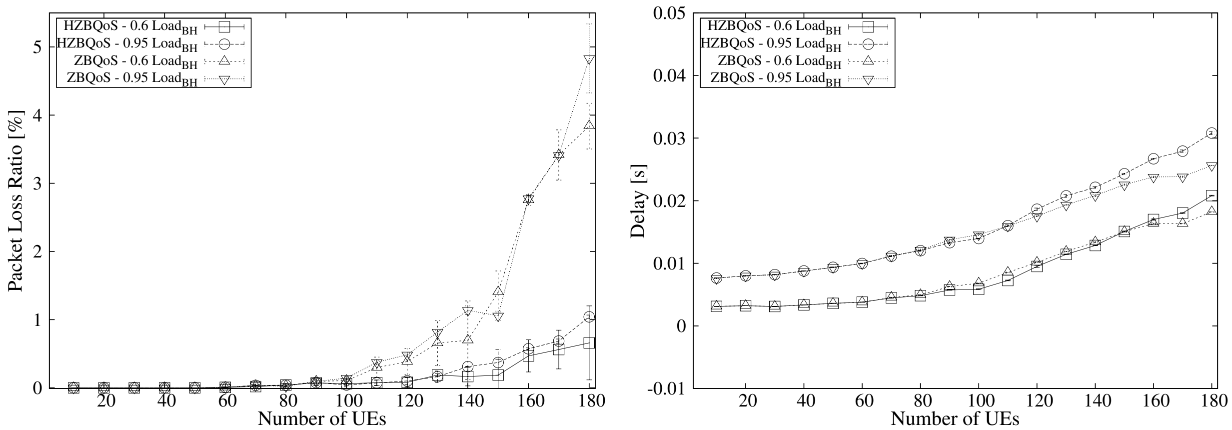
Figure 5b shows the average delay for video traffic. The delay values produced by ZBQoS are slightly shorter than those produced by the HZBQoS scheduler. Although, both schedulers meet the delay requirements for all scenarios, the use of HZBQoS results in fewer packet lost

Table II: Simulation parameters

Parameter	**Value**
System Type	Single Cell
Cell Radius	0.5 Km
Channel Model	Macro-Cell Urban Model
Numbers of UEs in the Cell	10-180
Mobility Model	Random Walk (Speed of 3 km/h)
System Bandwidth	15 MHz
Number of Resource Blocks	75 (BW per RB: 180 KHz)
Carrier Frequency	2 GHz
Frame Structure	FDD
TTI Duration	1 ms
UL Schedulers	TD: ZBQoS FD: PF-FME TD: HZBQoS FD: PF-FME
Max. UEs passed to the FDPS	15
Max. Schedulable UEs per TTI	15
T_{PF}^{TD} and T_{PF}^{FD}	100 ms and 300 ms
Number of ONUs	31
Number of ONU-eNB	1
Optical Speed	1 Gbps
ONU Load	19 Mbps and 30 Mbps
Propagation Delay in Fiber	5 μs/km
Distance between OLT and ONU/ONU-eNB	[10,20] Km
ONU/ONU-eNB RTT	[100,200] μs
ONU/ONU-eNB Buffer Size	10 MB
Maximum Cycle Length	10 ms
OLT Scheduler	IPACT (Limited Policy)
Guard Band	1 μs

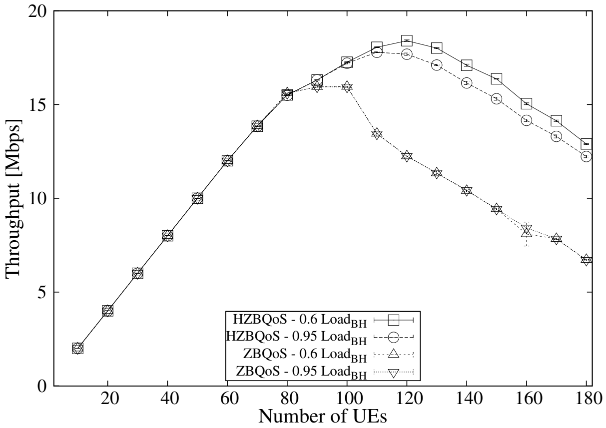
(Figure 5a).

Figure 5c shows the aggregated throughput of CBR users. These throughput decreases as a consequence of the provisioning of the QoS requirements of real-time traffic in overloaded



(a) packet loss ratio for video traffic

(b) average total packet delay for video traffic



(c) aggregated throughput for CBR traffic

Figure 5: Performance evaluation results

scenarios. The HZBQoS scheduler produces higher throughput values for CBR traffic than does the ZBQoS scheduler. Saturation with the ZBQoS scheduler is reached with 90 UEs while with the HZBQoS scheduler this is only reached with 120 UEs. The throughput achieved by ZBQoS is independent of the backhaul load which shows the inability of the ZBQoS scheduler to deal with variations in the available capacity of the backhaul link. The HZBQoS scheduler leads to better utilization of the network when employed under high load scenarios, and it provides throughput up to 40% greater than that given by the ZBQoS scheduler.

VI. RELATED WORK

Chung *et al.* [14] proposed one of the first QoS schemes that employed PONs for backhauling wireless networks. The architecture used by the authors was a two-upstream-wavelength PON (2W-PON) in which the ONUs have two different upstream transmission wavelengths. The scheme prioritizes real time and control packets by transmitting them on one wavelength while low priority traffic is sent on the other wavelength. However, this architecture is not common in current access networks.

Lim *et al.* [15] proposed two QoS mapping schemes for LTE-GPON integrated networks. The first is a one to one mapping between LTE QCIs and GPON queues. In situations which the number of LTE bearers is greater than the number of ONU queues, a second scheme, called Group Mapping is used. In this scheme, bearers are mapped onto 3 ONU queues. A problem of this scheme is that the Orthogonal Frequency-Division Multiple Access (OFDMA)-based GPON used in the performance evaluation has not been deployed yet.

The main problem with these approaches is that the traffic load and the DBA algorithms can impact the QoS provisioning for mobile users. Moreover, none of these proposals addresses the issue of coping with receiving less than the requested bandwidth.

VII. CONCLUSION

This paper proposes a QoS provisioning scheme for LTE/EPON integrated networks. We introduce a new QoS mapping scheme and indicate how an existing LTE scheduler should be modified to cope with variability in the capacity of mobile backhaul network links of EPONs. Simulation results show that the QoS mapping scheme in conjunction with a modified scheduler provides a lower packet loss ratio than does an unmodified scheduler. Moreover, with an unmodified scheduler, the PLR produced under high traffic load is greater than the maximum acceptable value. Furthermore, the proposed scheme improves the aggregated throughput of CBR traffic up to 40%, when compared to the throughput given by a scheduler without the proposed modification in overloaded mobile scenarios.

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REFERENCES

[1] W. Kiess, C. Choi, A. Khan, K. Kozu, and W. Kellerer, "Protection scheme for passive optical networks shared between a fixed and a mobile operator," in *Optical Fiber Communication Conference and Exposition (OFC/NFOEC) 2012 and the National Fiber Optic Engineers Conference*, 2012, pp. 1–3.

[2] T. Orphanoudakis, E. Kosmatos, J. Angelopoulos, and A. Stavdas, "Exploiting PONs for mobile backhaul," *IEEE Commun. Mag.*, vol. 51, no. 2, pp. S27–S34, 2013.

[3] GoMo News. (2013, May) FTTx & PON are good for mobile backhaul says Ovum. [Online]. Available: http://www.gomonews.com/fttx-pon-are-good-for-mobile-backhaul-says-ovum

[4] M. A. Esmail and H. Fathallah, "Physical layer monitoring techniques for TDM-passive optical networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 2, pp. 943–958, 2013.

[5] IDATE. (2012, Jun) World FTTx markets. [Online]. Available: http://www.idate.org/en/News/FTTx-World-Market_741.html

[6] E. Harstead, "Future bandwidth demand favors TDM PON, not WDM PON," in *Optical Fiber Communication Conference and Exposition (OFC/NFOEC) 2011 and the National Fiber Optic Engineers Conference*, 2011, pp. 1–3.

[7] S. Sesia, I. Toufik, and M. Baker, *LTE - The UMTS Long Term Evolution: From Theory to Practice*. Wiley, 2011. [Online]. Available: http://books.google.com.br/books?id=VF8MmzlcIKMC

[8] "IEEE std 802.3ah-2004," pp. 1–623, 2004.

[9] G. Kramer, B. Mukherjee, and G. Pesavento, "IPACT a dynamic protocol for an Ethernet PON (EPON)," *IEEE Commun. Mag.*, vol. 40, no. 2, pp. 74–80, 2002.

[10] G. Shen, R. S. Tucker, and C.-J. Chae, "Fixed mobile convergence architectures for broadband access: Integration of EPON and WiMAX [topics in optical communications]," *IEEE Commun. Mag.*, vol. 45, no. 8, pp. 44–50, 2007.

[11] C. A. Astudillo, J. F. Borin, and N. L. S. da Fonseca, "LTE time-domain uplink scheduler for QoS provisioning," in *IEEE Global Telecommunications Conf.*, Atlanta, USA, 2013, pp. 1480–1485.

[12] G. Piro. LTE-Sim - the LTE simulator. [Online]. Available: http://telematics.poliba.it/LTE-Sim

[13] T. Janevski, *Traffic Analysis and Design of Wireless IP Networks*. Norwood, MA, USA: Artech House, Inc., 2003.

[14] J. Chung, J. Park, B. Choi, Y. Park, J. Yoo, and B.-W. Kim, "Application of 2W-PON to the backhaul of a wireless network," *J. Optical Networking*, vol. 7, p. 905, Oct. 2008.

[15] W. Lim, M. Milosavljevic, P. Kourtessis, and M. John, "QoS mapping for LTE backhauling over OFDMA-PONs," in *14th International Conference on Transparent Optical Networks (ICTON)*, 2012, pp. 1–4.

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