STANDARD-COMPLIANT QOS PROVISIONING SCHEME FOR LTE/EPON INTEGRATED NETWORKS

CARLOS A. ASTUDILLO AND NELSON L. S. DA FONSECA

ABSTRACT

Passive optical networking has been recognized as a solution for next generation mobile backhaul network. Such technology allows service providers to reduce costs by using already deployed fiber to the x 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' QoS in an integrated network even under variation of the available bandwidth in the mobile backhaul network.

INTRODUCTION

Increasing demands for mobile broadband have motivated mobile operators to deploy Long Term Evolution (LTE) technology. LTE has been touted as a cutting edge mobile communication technology offering high data rates, 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 Mb/s in LTE and 1 Gb/s in LTE-Advanced as well as 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 PON (EPON) and Gigabit PON (GPON) are the two major standards for time-division multiplexing PON (TDM-PON), EPON being 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 this technology 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 eNB is a subscriber of the TDM-PON. The network considered in this article is an integrated network, called LTE/EPON, in which the optical network unit (ONU) and eNB are integrated into a single device, called the 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 mobile users in an LTE network. Therefore, the support of quality of service (QoS) requirements of mobile users can be jeopardized. Moreover, the provisioning of QoS requirements in such an integrated network needs to consider the QoS provisioning in both networks. In addition, any solution of an integrated network should not assume changes in the standards of these technologies.

This article 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.

Carlos A. Astudillo and Nelson L. S. da Fonseca are with the State University of Campinas.

 1536-1284/14/$25.00

The rest of the article is organized as follows. First, we briefly review the main QoS provisioning and resource allocation concepts in LTE and EPON networks. We then describe the integration of these two technologies. Next, we introduce the proposed standard-compliant QoS management scheme for LTE/EPON integrated networks, detail the simulation model and the scenarios used, and describe the results derived. We follow by describing related work. Finally, we conclude the article.

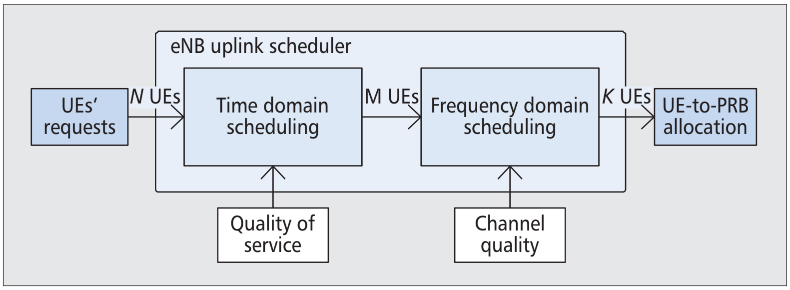

Figure 1. Uplink packet scheduling overview in LTE.

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.

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 for 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 percent, 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 by 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 devices (UEs). The PS used in this article is composed of two stages, time domain (TD) and frequency domain (FD), each 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 (TTl). The selected group is passed to the FD scheduler, which determines the physical resource blocks (the smallest allocable part of the spectrum) that 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 TTL. 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].

Ethernet Passive Optical Networks

A PON is composed of an optical line terminal (OLT) as well as various ONUs and splitters. The Ethernet PON at 1 Gb/s was specified in the IEEE 802.3ah standard [8]. The upstream channel is shared among ONUs using TDM with a dynamic bandwidth allocation (DBA) algorithm, also known as an inter-ONU scheduler, which 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 report 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 instead left it to the vendors to implement their own solutions. One DBA algorithm that 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, which depends on the defined maximum cycle length (T_{max} — 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 Gb/s EPON (10G-EPON). This standard can operate either symmetrically or asymmetrically. The former allows transmission at 10 Gb/s both downstream and upstream direction, whereas the latter only

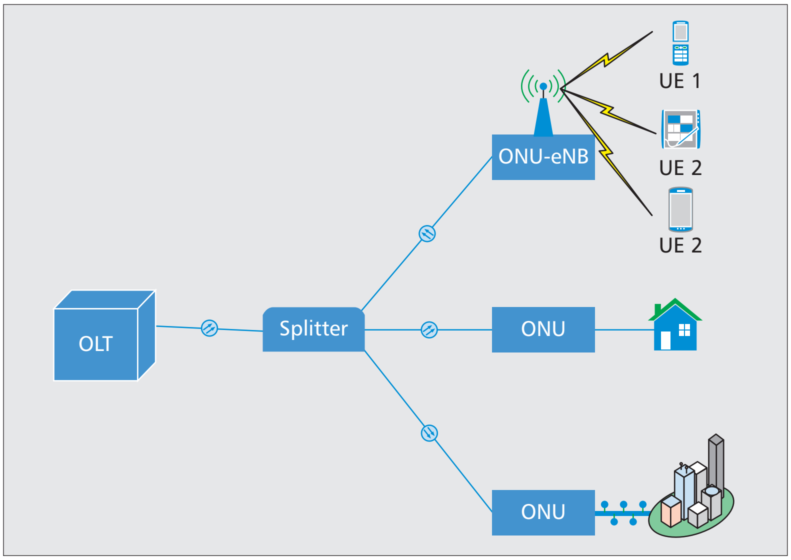

Figure 2. LTE/TDM-EPON integrated network architecture.

allows 1 Gb/s in the upstream direction. Since the MPCP protocol designed for 1 Gb/s was maintained for signaling at 10 Gb/s the DBA algorithms for 10G-EPON are compatible with those for EPON. Thus, the proposal in this article is valid for both standards.

Current EPONs can provide QoS within the differentiated services (DiffServ) framework that adopts a "class of service" identifier called DiffServ code point (DSCP), which is stored in the IP datagram header. Since EPON adopts the IEEE 802.1p standard for traffic prioritization, it can support up to eight classes of service (CoSs); that is, up to eight priority queues can be implemented in an ONU. Once the DSCP values have been mapped onto a CoS, incoming packets are classified and sent to one of the ONU queues.

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 modulated on the optical carrier. In R&F technology, the integration is done at either layer 2 or layer 3, leading to one of two different architectures [10]. The first independent architecture connects the ONU and eNB devices to a common Ethernet interface. The other hybrid architecture allows the integration of the software and hardware of both the ONU and eNB to a single physical box. One of the main advantages of this latter architecture, which is used in this article, 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 article.

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 that must be compensated by an LTE uplink scheduler located in the ONU-eNB so that the QoS requirements can be met.

QoS Provisioning in an Integrated Network

Figure 3 illustrates the functional modules of the integrated ONU-eNB device, which are the ONU-EPON module, eNB-LTE module, and ONU-eNB common control module. The ONU-EPON and eNB-LTE modules provide the functionalities of an ONU and an eNB, respectively. 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 RRM 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, 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 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.

QoS Mapping Scheme

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

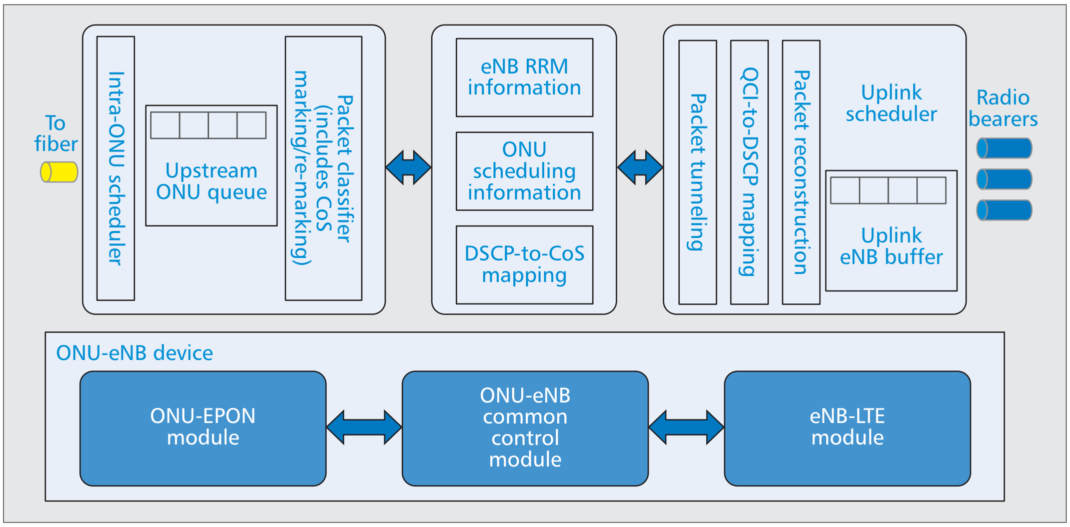

Figure 3. ONU-eNB functional architecture.

There are two major approaches to the integration of optical and wireless access technologies: Radio over Fiber and Radio and Fiber. In RoF radio signals are directly modulated on the optical carrier. In R&F technology, the integration is done at either layer 2 or layer 3, leading to one of two different architectures.

integrated network can capitalize on deployed EPONs. Another advantage of this scheme is that a preconfigured 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 to modify current LTE uplink schedulers to cope with less bandwidth than the requested to the backhaul network.

Use of Backhaul Information in LTE Schedulers

The proposed QoS mapping scheme requires 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:

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

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 received 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).

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:

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

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. 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., when 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

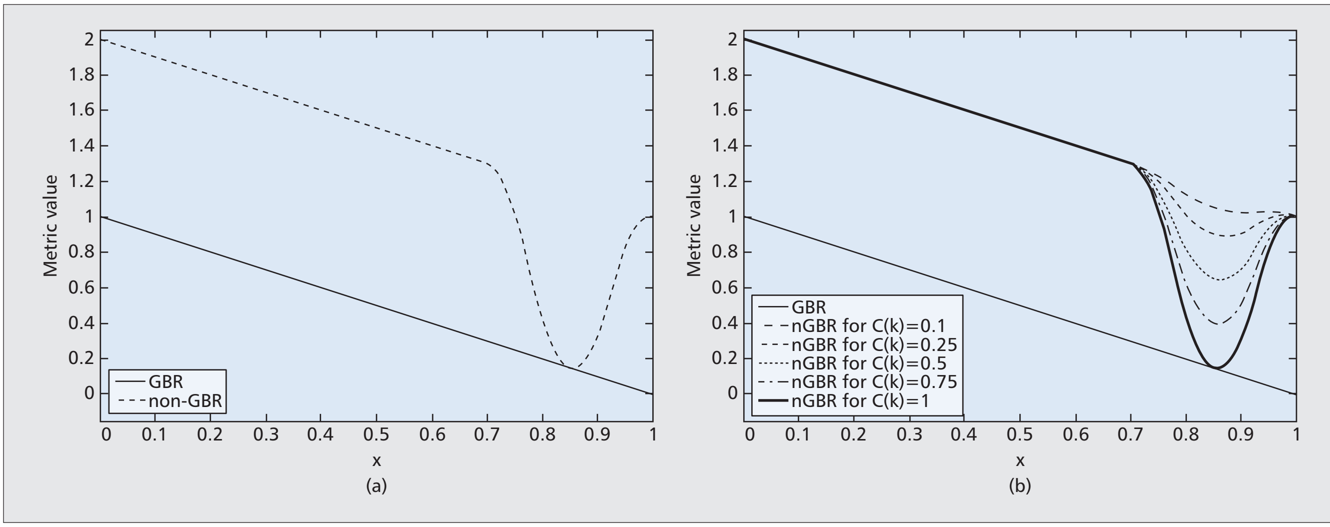

Figure 4. Delay-related metric values for GBR and nGBR bearers as a function of the ratio x: a) ZBQoS scheduler [11]; b) HZBQoS scheduler.

Service	VoIP	Video	CBR
Description	G.729 ON/OFF model	H.264 Trace-based*	1000 bytes every 8 ms
Bit rate	8.4 kb/s	242 kb/s	1 Mb/s
QCI	1	2	8
PDB	100 ms	150 ms	300 ms
GBR	8.4 kb/s	242 kb/s	N/A
Proportion	2 (40%)	2 (40%)	1 (20%)

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

Table 1. Traffic model and QoS requirements (LTE part).

$C(k)$, that is, with the variation in the mobile backhaul network load. We call this modified scheduler the hybrid Z-based QoS scheduler (HZBQoS).

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 medium access control (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 support of QoS for uplink transmissions, and dividing the uplink scheduling into time and frequency domains. The EPON module was developed in Java and 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 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.

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 Gb/s. 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 voice over IP (VoIP) traffic and two users transmitting video traffic, there is one user transmitting constant bit rate (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 CBR traffic uses nGBR 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 1 contains the traffic models employed in the LTE simulation and their QoS requirements. Table 2 summarizes the main configuration parameters used in the simulation.

SIMULATION RESULTS

The figures presented in this section show mean values, with confidence intervals having 95 percent 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 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 Mb/s; in the *heavily loaded* backhaul scenario (0.95), the mean traffic load is 30 Mb/s.

Figure 5a shows the PLR of video users. The HZBQoS scheduler is able to provide a low PLR 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 percent and increases with the traffic load, reaching 5 percent under heavy load. However, the maximum acceptable PLR for video traffic without affecting users' quality of experience is 1 percent [13]. Moreover, both schedulers produced a no loss service to VoIP traffic (not shown in the article) 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 packets lost (Figure 5a).

Figure 5c shows the aggregated throughput of CBR users. The throughput decreases as a consequence of provisioning the QoS requirements of real-time traffic in overloaded 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 provides throughput up to 40 percent greater than that given by the ZBQoS scheduler.

Parameter	Value
System type	Single cell
Cell radius	0.5 km
Channel model	Macrocell 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-eNBs	1
Optical speed	1 Gb/s
ONU load	19 Mb/s and 30 Mb/s
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 Mbytes
Maximum cycle length	10 ms
OLT scheduler	IPACT (limited policy)
Guard band	1 μs

Table 2. Simulation parameters.

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 where

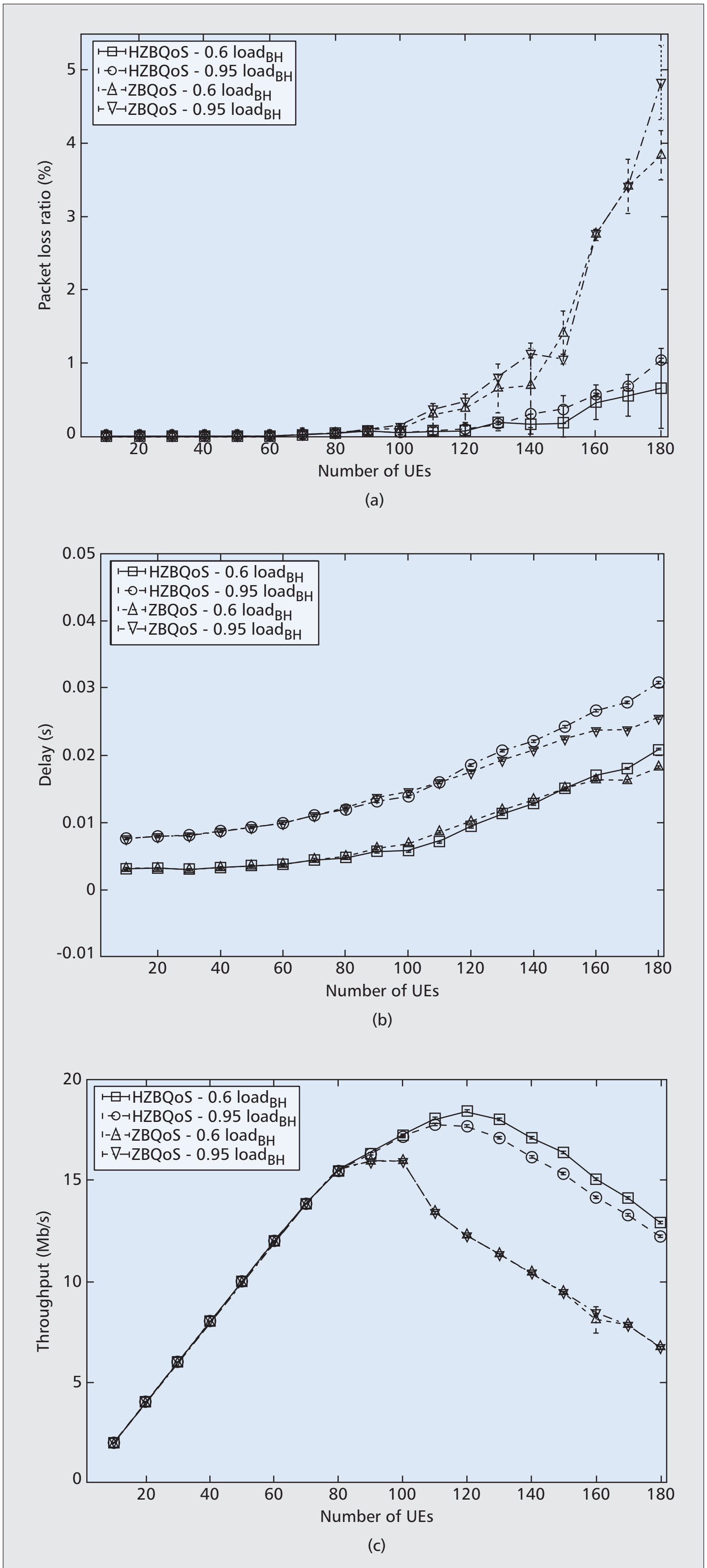

Figure 5. Performance evaluation results: a) packet loss ratio for video traffic; b) average total packet delay for video traffic; c) aggregated throughput for CBR traffic.

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 three ONU queues. A problem with 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 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.

Conclusion

This article 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 percent when compared to the throughput given by a scheduler without the proposed modification in overloaded mobile scenarios.

Acknowledgment

This work was supported by the Brazilian research agencies São Paulo Research Foundation (FAPESP) under process 2012/10582-4, Coordination for the Improvement of Higher Education Personnel (CAPES), National Council for Scientific and Technological Development (CNPq), and INCT FOTONICOM.

References

[1] W. Kiess *et al.*, "Protection Scheme for Passive Optical Networks Shared between a Fixed and a Mobile Operator," *OFC/NFOEC '12*, 2012, pp. 1–3.
[2] T. Orphanoudakis *et al.*, "Exploiting PONs for Mobile Backhaul," *IEEE Commun. Mag.*, vol. 51, no. 2, 2013, pp. S27–S34.
[3] GoMo News, "FTTx & PON are Good for Mobile Backhaul Says Ovum," http://www.gomonews.com/fttx-pon-are-good-for-mobile-backhaul-says-ovum, May 2013.
[4] M. A. Esmail and H. Fathallah, "Physical Layer Monitoring Techniques for TDM-Passive Optical Networks: A Survey," *IEEE Commun. Surveys & Tutorials*, vol. 15, no. 2, 2013, pp. 943–58.
[5] IDATE, (June 2012) "World FTTx Markets," http://www.idate.org/en/News/FTTx-World-Market_741.html.
[6] E. Harstead, "Future Bandwidth Demand Favors TDM PON, not WDM PON," *OFC/NFOEC '11*, 2011, pp. 1–3.
[7] S. Sesia, I. Toufik, and M. Baker, *LTE — The UMTS Long Term Evolution: From Theory to Practice*, Wiley, 2011.
[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, 2002, pp. 74–80.
[10] G. Shen, R. S. Tucker, and C.-J. Chae, "Fixed Mobile Convergence Architectures for Broadband Access: Integration of EPON and WiMAX," *IEEE Commun. Mag.*, Topics in Optical Communications, vol. 45, no. 8, 2007, pp. 44–50.

[11] C. A. Astudillo, J. F. Borin, and N. L. S. da Fonseca, "LTE Time-Domain Uplink Scheduler for QoS Provisioning," *IEEE GLOBECOM*, Atlanta, GA, 2013, pp. 1480–85.
[12] G. Piro, LTE-Sim — The LTE Simulator, http://telematics.poliba.it/LTE-Sim.
[13] T. Janevski, *Traffic Analysis and Design of Wireless IP Networks*, Artech House, 2003.
[14] J. Chung *et al.*, "Application of 2W-PON to the Backhaul of a Wireless Network," *J. Optical Networking*, vol. 7, p. 905, Oct. 2008.
[15] W. Lim *et al.*, "QoS Mapping for LTE Backhauling over OFDMA-PONs," *14th Int'l. Conf. Transparent Optical Networks*, 2012, pp. 1–4.

Biographies

CARLOS A. ASTUDILLO received his B.Sc. degree in electronics and telecommunications engineering from the University of Cauca, Colombia, in 2009. He is a Ph.D. student in computer science at the Institute of Computing, State University of Campinas, Brazil. In 2010, he was a Young Researcher at the New Technologies in Telecommunications R&D Group (GNTT), University of Cauca, supported by COLCIENCIAS. His current research interest is in QoS mechanisms for cellular networks.

NELSON L.S. DA FONSECA [SM] received his Ph.D. degree from the University of Southern California in 1994. He is a full professor at the Institute of Computing, State University of Campinas. He is the IEEE ComSoc Director of Conference Development. He served as Vice-President Member Relations, Director of the Latin America Region, and Director of Online Services. He is past Editor-in-Chief of *IEEE Communications Surveys and Tutorials*. He is a Senior Editor of *IEEE Communications Magazine*.