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Optimised QoS-aware DBA mechanisms in XG-PON for upstream traffic in LTE Backhaul

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***Abstract*—Passive Optical Networks (PON) are viewed as an attractive choice to provide flexible and cost-efficient backhaul for Long Term Evolution (LTE) cellular base stations (eNB). PONs, such as the 10-Gigabit capable PON (XG-PON), use a Dynamic Bandwidth Allocation (DBA) mechanism to multiplex the shared upstream medium between competing sending nodes. Due to the complex definitions of QoS for DBA in XG-PON, it is a challenge for the XG-PON to respect the Quality of Service (QoS) requirements for different aggregated upstream applications in the LTE backhaul, in particular voice, live video and best-effort Internet traffic. In this paper, we first evaluate two recent XG-PON-standard-compliant DBAs - XGIANT and Efficient Bandwidth Utilisation (EBU) - for mean queuing-delay performance, with regard to priority and fairness, when the realistically-generated upstream voice, video and best-effort applications are aggregated at the evolved Node B (eNB) in LTE. We show that neither XGIANT nor EBU satisfy the priority and fairness requirements for mean queuing-delay. We propose and evaluate two optimised DBAs - Deficit XGIANT (XGIANT-D) and Proportional XGIANT (XGIANT-P). Our evaluations of the optimised DBAs, in the ns-3 network simulator, show that both XGIANT-D and XGIANT-P are able to ensure strictly prioritised, low and fair mean-queuing-delays for eNB-aggregated voice, video and best-effort traffic in two loaded conditions in XG-PON upstream. XGIANT-D and XGIANT-P, when compared with XGIANT and EBU, also ensure lower packet losses for eNB-aggregated upstream traffic in the XG-PON-based LTE backhaul.**

I. INTRODUCTION

Passive Optical Networks (PON) are well-known for their high network capacity, low per-user cost, flexible bandwidth allocation and defined quality of service (QoS) support [17], [19], [21]. The Gigabit PON (GPON [11]) and Ethernet PON (EPON [8]) standards, along with their upgraded versions 10Gigabit-capable GPON (XG-PON [12]) and 10Gigabit-EPON (10G-EPON [9]) respectively, are widely regarded as defining the future for wired access networks. Long Term Evolution (LTE) is a popular cellular technology that offers high datarates and is now deployed widely. However, the cost of providing dedicated backhaul links for new LTE base stations is prohibitive, not least due to the need to cater for bandwidth-hungry mobile applications [17], [19].

A converged network in which PON is used as the backhaul for LTE is seen as promising, but there are a number of key challenges to overcome [2], [16], [17], [19], [21], including: 1) designing a simple and cost-effective converged network architecture, where the large datarate of PON can be efficiently utilised by LTE applications; 2) support for standard-compliant QoS (latency, reliability, priority, fairness etc.) policies in an LTE backhaul; 3) designing a resource allocation mechanism in PON, facilitating significant network sharing options between PON and LTE, while addressing realistic application profiles in LTE; 4) dynamically scheduling the upstream capacity of PON across multiple LTE base stations which aggregate applications from mobile users. These challenges largely prompt for a suitable Dynamic Bandwidth Allocation (DBA) in PON with appropriate QoS policies, so that aggregated upstream applications in LTE backhaul can be offered latency and datarate guarantees. Since a simple Multi-point Control Protocol (MPCP) for QoS is defined for EPON, DBA proposals for the EPON standard are abundant. For (X)GPON there have been only a few standard-complaint DBAs proposed, and the issue of handling QoS in an LTE converged network remains relatively unexplored.

In this paper, we first evaluate the suitability of two recently proposed XG-PON-standard-compliant DBAs, namely the XGIANT [4] and EBU [6] DBAs, in the context of XG-PON as the backhaul for LTE. Using our XG-PON module [23] and the existing LTE module [18] for the ns-3 network simulator, we evaluate XGIANT and EBU, originally designed for deterministic upstream traffic in stand-alone XG-PON, using realistically-generated voice, live video and best-effort traffic models in LTE upstream. Our results show that both XGIANT and EBU do not provide XG-PON-standard-compliant mean queuing-delay performance, with regard to relative priorities and improved fairness for the highly-bursty eNB-aggregated upstream applications in LTE backhaul. By optimising the QoS policies and introducing a new fairness policy for XGIANT DBA, we propose Deficit XGIANT (XGIANT-D) and Proportional XGIANT (XGIANT-P) DBAs. When evaluated for mean queuing-delays, the new DBAs support strict priorities between voice, video and best-effort traffic in the given order while providing improved fairness. We also validate the performance of all the DBAs using their impact on the provisioned instantaneous upstream datarates.

In the remainder of the paper, Section II introduces the QoS frameworks in LTE and XG-PON and summarises XGIANT and EBU. Section III presents our experimental environment used for the preliminary evaluations of XGIANT and EBU DBAs in Section IV. Optimised QoS and fairness policies of XGIANT-D and XGIANT-P are detailed in Section V, followed by their evaluation in Section VI. Section VII and VIII provide the literature review and conclusion, respectively.

II. BACKGROUND

A. LTE

LTE defines the following three major network components: 1) Mobile User Equipment (UE), which generates/receives data in LTE lastmile; 3) Evolved Node B (eNB), which is the base station in LTE, acting as a bridge between the UE and the core of the LTE network for the data and control plane interactions while controlling the bandwidth allocation of the wireless interface; 3) Evolved Packet Core (EPC), the core of the LTE network comprising the Mobility Management Entity (MME) to assist mobility of UE, the Serving Gateway (SGW) to route user data packets while acting as a mobility anchor for intra-LTE mobility, and the Packet Data Network Gateway (PDN GW) to provide connectivity for UE towards external data networks such as the Internet.

B. QoS in LTE

For distinct QoS guarantees for flows between UE and PDN GW, LTE uses the virtual concept of *Evolved Packet System (EPS) bearer*. An EPS bearer can be classified as a Guaranteed Bit Rate (GBR) or Non-GBR, based on priority and as a *Default* (always Non-GBR), or *Dedicated* (GBR or Non-GBR) bearer based on functionality. Depending on the number of distinct QoS classes required, a UE can be provisioned with multiple GBR or Non-GBR bearers, in addition to the *Default* bearer. In LTE, a bearer is identified by a QoS Class Identifier (QCI). LTE Release 8 defines QCI values 1-9, in descending priority, to classify bearers.

C. PON

A simple PON consists of an Optical Line Terminal (OLT), Optical Network Unit (ONU) and a passive splitter/jointer: the OLT is located at the core of service provider and connected to a core router; the ONU, placed near the customer premises, is connected to the OLT using shared optical fibre and a passive splitter/jointer. In the downstream direction, the OLT broadcasts frames to ONUs using Time Division Duplexing; in the upstream, ONUs transmit frames to the OLT using a Time Division Multiple Access (TDMA). TDMA transmission from multiple ONUs, with possible collisions between the OLT and the passive jointer requires PON to use a polling-based bandwidth allocation mechanism in the upstream. Standardisation has resulted in two distinct tracks of PON, namely (10G-) EPON and (X) GPON, mainly due to the differences in the downstream/upstream physical datarates and QoS definitions.

D. QoS in XG-PON

In XG-PON, the upstream data transmission opportunity ($grant\_size$) for each logical connection between the ONU and the OLT, known as an $AllocID$, is provisioned using a polling method. That is, in the 125-us-periodic upstream frame (US-FRAME), each $AllocID$ sends its upstream queue occupancy using the $DBRu$ field. The OLT, upon receiving the $DBRu$, allocates $grant\_size$ to the $AllocID$s, as provisioned by a DBA, and conveys the messages to the ONUs using the broadcast downstream frame every 125μs. The next $DBRu$ may piggyback the actual data transmission in case of a non-zero $grant\_size$. To provide QoS in the upstream, XG-PON defines several bandwidth types, Fixed, Assured, Non-Assured and Best Effort, in descending order of priority.

The QoS definitions in XG-PON, unlike in EPON, expect the DBA implementation to maintain a close bond with the

TABLE I
ALLOCATION OF DATA RATE FOR T-CONT TYPES IN XGIANT

T_k	$GDR_{T_{k,i}}$	$SDR_{T_{k,i}}$	Bandwidth Type
T1	MDR_{T_1}/N_1	-	Fixed
T2	MDR_{T_2}/N_2	-	Assured
T3	GDR_{T_3}/N_3	$\frac{MDR_{T_3}-GDR_{T_3}}{N_3}$	Assured, Non-Assured
T4	1 Word (4 Bytes)	MDR_{T_4}/N_4	Best Effort
$T_{k,i}$ = an $AllocID$, i of T-CONT type k, N_k = no. of AllocIDs in T_k			

125μs-period data transmission in the upstream, challenging the implementation of a QoS-aware DBA in XG-PON. EBU and XGIANT are two recent standard-compliant QoS-based DBA mechanisms found in the literature for XG-PON. Both XGIANT and EBU are based on the GIANT DBA and follow the same basic $grant\_size$ allocation policies for four Traffic Container (T-CONT) types (T1, T2, T3 and T4, in descending order of priority) in the XG-PON network. Both DBAs allocate $grant\_size$ (= $\frac{Data\ Rate}{US-FRAME\ size}$) to each $AllocID$, $T_{k,i}$ of T-CONT type k, based on Guaranteed Data Rate (GDR_{T_k}), and Maximum Data Rate (MDR_{T_k}). The two DBAs also employed the same methodology as in GIANT (fixed allocation for T1 and reservation based allocation for T2-T4) for bandwidth allocation to the T-CONT types, T_k, where k = 1, 2, 3 and 4. Since T1 traffic has a fixed allocation, the DBAs do not specify provision of MDR_{T1}; therefore T1 traffic is not included in their evaluation. The other T-CONT types ((k = 2, 3 and 4) are given upstream transmission opportunities in XG-PON, such that:

$$MDR_{T_2} = MDR_{T_3} = MDR_{T_4} = \frac{2}{3} * SI * C_{XG-PON} \quad (1)$$

where C_{XG-PON} is the effective upstream capacity of XG-PON (= 2.25 Gbps) and SI is the frequency at which the DBAs allocated $GDR_{T_{k,i}}$ and Surplus Data Rate ($SDR_{T_{k,i}}$) to each $T_{k,i}$. Table I summarises the $grant\_size$ allocation by XGIANT and EBU to the AllocIDs based on T-CONT types.

The difference in EBU and XGIANT was primarily in the SI values (SI_{min} for $GDR_{T_{k,i}}$ and SI_{max} for $SDR_{T_{k,i}}$) which determined the frequency at which each $T_{k,i}$ was provisioned $grant\_size$. EBU used SI_{min} = 5 and SI_{max} = 10, while XGIANT used SI_{min} = 1 and SI_{max} = 2. Hence, during a non-congested upstream traffic condition, when the total upstream traffic of XG-PON was $\leq C_{XG-PON}$, T2 (and T1) received a single round of $grant\_size$ allocation every 5 US-FRAMEs by EBU (or every US-FRAME by XGIANT); T3 received 3 rounds of $grant\_size$ allocation every 10 US-FRAMEs by EBU (or every 2 US-FRAMEs by XGIANT); T4 received a single round of $grant\_size$ allocation every 10 US-FRAMEs by EBU (or every 2 US-FRAMEs by XGIANT). Specifically, the 3 rounds of $grant\_size$ allocation for T3 was a result of 2 $GDR_{T_{3,i}}$ -based $grant\_size$ and a single $SDR_{T_{3,i}}$-based $grant\_size$. As the total upstream traffic load increases beyond C_{XG-PON}, the prioritisation of T-CONT types in XGIANT and EBU first dropped packets from the T4 AllocIDs, then from the T3 ones and finally from the T2 ones.

Since XGIANT provisioned $grant\_size$ at a higher frequency than EBU for the T-CONTs, XGIANT, along with its tuned GDR_{T_3}:MDR_{T_3} ratio, demonstrated better mean

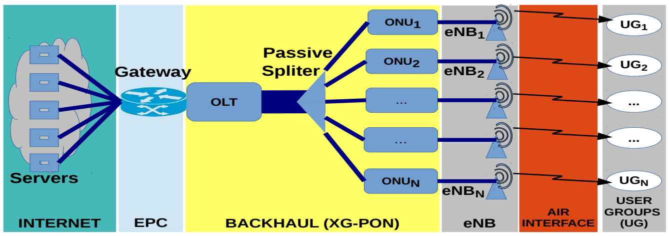

Fig. 1. Architecture of LTE network with XG-PON backhaul

TABLE II
RELATIONSHIP OF APPLICATION TYPE, QCI, DSCP AND T-CONT TYPE

Application Type	LTE QCI	DSCP	T-CONT Type
LTE Signalling	1	CS7 - 56	T1
voice	2	EF - 46	T2
video	3	CS4 - 32	T3
best-effort	8	BE - 0	T4

queuing-delay performance for T2-T4, for the upstream load ratio ($L_r = \frac{Total\ Upstream\ Traffic}{C_{XG-PON}}$) of 0.5 - 1.8 [4].

Since both XGIANT and EBU DBAs were designed for near-deterministic user traffic profiles depicting fixed-broadband lastmile and evaluated for discrete instances of L_r, their delay and datarate performance in the presence of eNB-aggregated (LTE-based) lastmile traffic will be unpredictable. For a given average upstream load in LTE, an eNB-aggregated upstream traffic can portray a high degree of temporal-variation in instantaneous datarate, resulting in highly bursty upstream traffic injected into each ONU in the upstream. As a result, a highly varying instantaneous L_r is seen in the XG-PON upstream, causing unpredictable $grant\_size$ allocation behaviour in XGIANT and EBU for the individual eNB-aggregated bursty lastmile traffic. We evaluate the performance of XGIANT and EBU in this scenario in the next two sections.

III. SIMULATION ENVIRONMENT

In order to evaluate the performance of the XGIANT and EBU DBAs in a converged network of XG-PON and LTE, we first implemented a standards-compliant integrated network architecture using the pre-existing XG-PON and LTE modules in the ns-3 simulator.

A. Integrated network architecture

Using the XG-PON and LTE modules in ns-3 and based on the suggestions in the literature [2], [5], [16], [19], we implemented the integrated network architecture of XG-PON and LTE as in Figure 1. The XG-PON is placed between the EPC and the eNB, so that PON is the only backhaul for LTE. We only model the data-plane interactions in the LTE backhaul, with MME, PDN GW and SGW combined into a single *Gateway*. The OLT and ONU are connected via an Ethernet link to the *Gateway* and the eNB, respectively.

B. Application Traffic Modelling

In our experiments we rely on application-dependent upstream traffic generation from LTE sources as follows:

- **Voice:** Our voice (over IP) traffic is an ON-OFF model; the ON state generates 160 Bytes-long frames at a constant 64 kbps rate, representing common high-definition voice codecs (eg: G.722 [13]). ON and OFF durations are exponential with a mean of 0.35s and 0.65s respectively [24].
- **Video:** The Poisson Pareto Burst Process (PPBP [3], Hurst parameter, H = 0.9 [22], rate = 300kbps, frame size = 795 Bytes) model in ns-3 is used for our video traffic, representing peer-to-peer video conference [15].
- **Best-Effort:** Best-effort Internet traffic is defined with moderate burstiness, long-range dependence and self-similarity (PPBP application, H = 0.5 [22], datarate = 2Mbps)

C. Mapping of QoS identifiers between LTE and XG-PON

In ns-3, we implemented the following standard-compliant mapping policy for each ONU-eNB pair, as proposed in the literature (eg: [5]). When an eNB receives a packet from a UE along with the corresponding QCI for the packet, the eNB imprints a unique Differentiated Services Code Point (DSCP) value in the external Internet Protocol (IP) packet header, corresponding to the QCI; the packet is then transmitted towards ONU, using the Ethernet link. The ONU receives these packets and associates a T-CONT type for each DSCP value; packets are queued at one of the four FIFO queues corresponding to the T-CONT type T_k in the ONU, leading to DBA-controlled upstream transmission of the same packet in XG-PON. Using this static mapping policy, a DBA in XG-PON can provide different QoS treatments at the backhaul, to every distinct eNB-aggregated application in the upstream.

Table II shows the conversion between the QCI values and the T-CONT types as used in our network architecture. As the performance of the signalling traffic in an LTE network is predictable due to its dependency only on its MDR_{T_1} value set by a service provider's requirements, we exclude T1 traffic in our experiments.

D. Number of UEs in LTE

We choose a ratio of 2:2:1 as used in [5], [24] for the number of UEs generating voice:video:best-effort traffic, while assuming that each UE would use only one application at any given time. Then, the total number of UEs attached to an eNB is selected uniformly at random in the range of 105 - 145 (mean = 125), with a step of 5 in between, so that the best-effort users are exact integers. These numbers ensure that the 75th percentile of the total instantaneously aggregated datarate per eNB does not exceed the upstream capacity ($\sim$70 Mbps) of the eNB in the LTE module for ns-3.

All UEs are placed randomly around the attached eNB, within a radius of 4km, while eNBs (each with a single cell) are placed in a straight line, with 6km of inter-eNB distance, to avoid interference between UEs of adjacent eNBs. All UEs remain fixed to their position throughout the simulation, as the objective in our experiments is to evaluate the transmission of per-eNB-aggregated traffic in LTE upstream. We use the Proportional Fair upstream scheduler in ns-3 to ensure best possible fairness in the LTE wireless interface for all UEs.

TABLE III
DATARATE RATIO OF ENB-AGGREGATED TRAFFIC

Scenario	Mean Datarate(Mbps) voice:video:best-effort	Total Mean Datarate(Mbps)	L_r
52-eNB	95 - 277 - 1288	1660	0.74
80-eNB	146 - 422 - 1967	2534	1.13

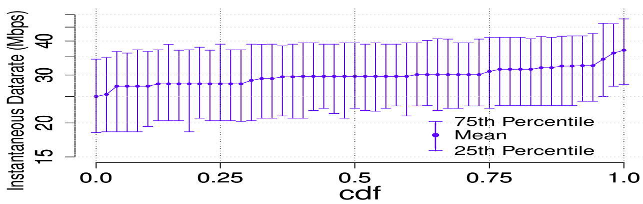

Fig. 2. Per-eNB instantaneous datarate for a random seed in 52-eNB scenario

E. Simulation Scenarios

To realise different upstream traffic loading in XG-PON we evaluated two scenarios in the LTE network, such that the XG-PON upstream is:

- under-loaded with 52 eNBs in LTE.
- fully-loaded with 80 eNBs in LTE.

by means of sum of mean datarate from the three applications in all the eNBs (Table III). However, the aggregation of realistically-generated (bursty) applications results in a range of total instantaneous (per-millisecond) datarate, in both scenarios, indicating that the XG-PON backhaul is experiencing a range of L_r due to the range of total instantaneous datarates per eNB. Figure 2 shows this behaviour for a random seed in the 52-eNB scenario; the mean, minimum and maximum values in the y-axis indicate the mean, 25th and 75th percentile of the total (aggregated for all the UEs of all 3 applications) instantaneous mean datarate per eNB, respectively; the x-axis represents the Cumulative Density Function (CDF) with regard to the number of eNBs in LTE. A similar behaviour was observed for the 80-eNB scenario as well.

In both the scenarios, each eNB is connected to a single ONU. Every eNB-ONU pair shares 3 individual connections between them, with one for each application/T-CONT type.

IV. EVALUATION OF XGIANT AND EBU DBAS

Here we evaluate the mean queuing-delay performance of XGIANT and EBU for the 52-eNB and 80-eNB scenarios using the simulation environment in Section III. Mean queuing-delay of a given $AllocID$ is the average queuing-delay of all the packets arrived at and transmitted from the T-CONT queue in the ONU. The two-way delay in XG-PON backhaul for an $AllocID$ is equal to its mean queueing-delay + 2 * propagation delay. Based on the relative mean queuing-delay performance of the $AllocID$s in each T-CONT type, the following additional metrics are evaluated:

- Strict Priority: In the XG-PON standard, a DBA is expected to provide lowest mean-delay value for highest priority T-CONT. Hence, in our experiments a mean queuing-delay of the packets of all the $AllocID$ in T2 (voice) $<$ T3 (video) $<$ T4 (best-effort) represents strict priority by the DBA
- Fairness: When all the $AllocID$s of a T-CONT type experience the same mean queuing-delay for a given FIFO queue size, the DBA is considered to be fair for the T-CONT type in XG-PON.

Each of our 20-second-simulated experiment was repeated 10 times, each with a different seed, in order to achieve mutually-exclusive variation in packet generation in applications and the random placement of UEs around the eNBs. Every ONU was configured with three 5KB FIFO queues in the upstream to accumulate T2, T3 and T4 traffic. Propagation delay between the OLT and any ONU was set at 0.4ms representing a distance of 60km.

Figure 3- 6 indicate the mean queuing-delay performance of XGIANT and EBU DBAs for the two scenarios. All plots indicate the average of the mean queuing-delays from 10 runs of each experiment while the error bars indicate the range of mean queuing-delays observed for the 3 T-CONT types.

In both scenarios we see that both XGIANT and EBU fail to provide strict priority among (all the $AllocIDs$ of) the three T-CONT types. For example, for the 52-eNB scenario XGIANT fails to provide lowest mean queuing-delay for some of the T2 $AllocIDs$ compared to the T3 $AllocIDs$ (Figure 3, at x = 0.7 - 1.0) in the 52-eNB scenario and EBU fails to provide lowest mean queuing-delay for most of the T2 $AllocID$s compared to T3 $AllocIDs$ (Figure 5, at x = 0.0 - 0.5). These failures are mainly due to the use of service timers and the provisioning of $MDR_{T2} + MDR_{T3}$ higher than C_{XG-PON} in XG-PON.

We also observe that all the $AllocIDs$ of all 3 T-CONT types experience highly unfair mean queuing-delay in XGIANT for the 52-eNB scenario. This is due to XGIANT not having a fairness policy. For the 80-eNB scenario, the impact of unfairness by XGIANT is minimal because each $AllocID$ is receiving a smaller $grant\_size$ in the scenario compared to the 52-eNB one. EBU, though able to maintain fairness among the $AllocIDs$ of T2 and T3 individually by employing an inter-ONU fairness policy, fails to provide fairness in mean queuing-delay for the T4 $AllocIDs$. This is due to the inter-ONU fairness failing to maintain fairness between the $AllocIDs$ of T4, whose traffic experiences congestion in both the 52-eNB and 80-eNB scenarios due to the highly-varying instantaneous L_r of best-effort traffic in LTE upstream.

These observations indicate that the QoS policies governing the $grant\_size$ allocation in both XGIANT and EBU DBAs are unable to provide strict priority and fairness in mean queuing-delays for the eNB-aggregated bursty voice, video and best-effort traffic with highly-varying instantaneous L_r. This behaviour disqualifies both XGIANT and EBU from being XG-PON-standard-compliant in LTE backhaul.

V. OPTIMISING XG-PON DBAS FOR LTE BACKHAUL

In this section, we discuss the design and implementation of two XG-PON-standard-compliant DBAs, designed to provide the required prioritisation and fairness among three aggregated application types in LTE backhaul. XGIANT and not EBU is chosen as the base DBA for optimisation due to the relative superiority of XGIANT in the mean-queuing delay

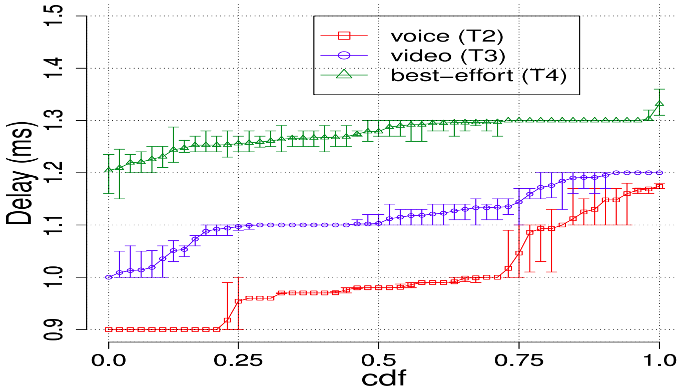

Fig. 3. Mean queuing-delay by XGIANT in 52-eNB scenario

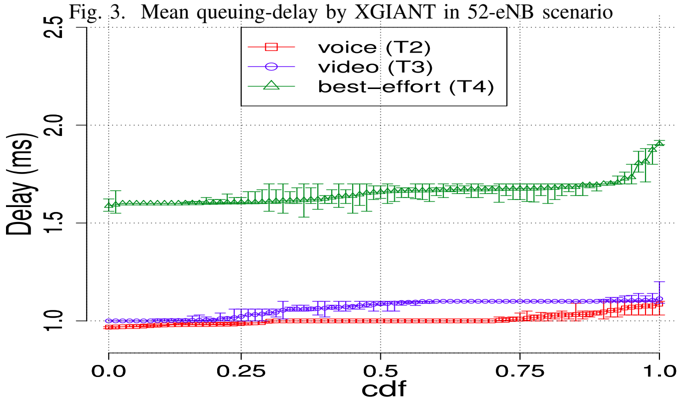

Fig. 4. Mean queuing-delay by XGIANT in 80-eNB scenario

performance in XG-PON [4]; two optimised variations are produced to evaluate the impact of the associated policies on the evaluation metrics.

A. Relative priority and burstiness smoothing of T2 and T3

Observations in section IV show that the failure of XGIANT and EBU to provide strict priority was mainly due to the T3 $AllocIDs$ receiving lower mean queuing-delays than the T2 $AllocIDs$. Our exhaustive experiments, tuning several parameters of the XGIANT DBA, indicated that different ratios of maximum datarate values between T2 and T3 (MDR_{T2} and MDR_{T3}) provided us with different relative mean-queuing-delay values between the $AllocIDs$ of T2 and T3. The setting of 0.7:0.4 times C_{XG-PON} for the ratio of MDR_{T2}:$MDRT3$ ensured lowest mean queuing-delays for all the T2 $AllocIDs$ for a range of upstream L_r in XG-PON.

We then removed the use of service timers in XGIANT and implemented a strictly alternating $grant\_size$ allocation in every US-FRAME for T3 $AllocIDs$, by using the guaranteed and maximum datarate values for T3 in XGIANT for T3. This results in the following alternating datarate (BW_{g1} or BW_{g2}) for each T3 $AllocID$ every other US-FRAME:

$$BW_{g1} = MDR_{T2} + \lambda_{T_3} * MDR_{T3} \leq C_{XG-PON} \quad (2)$$

$$BW_{g2} = MDR_{T2} + (1 - \lambda_{T_3}) * MDR_{T3} \leq C_{XG-PON} \quad (3)$$

where λ_{T_3} = GDR_{T3}:MDR_{T3} = 0.4. Thus, the aggregated voice traffic's burstiness is smoothed by the over-provisioned MDR_{T2} and the aggregated video traffic's burstiness is smoothed by the alternate (BW_{g1}/N_k or BW_{g2}/N_k) provision

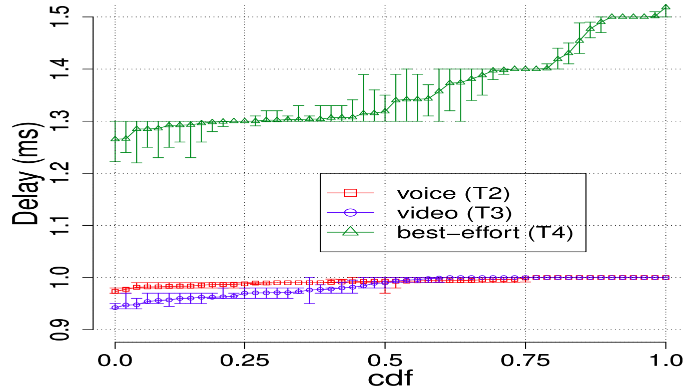

Fig. 5. Mean queuing- delay by EBU in 52-eNB scenario

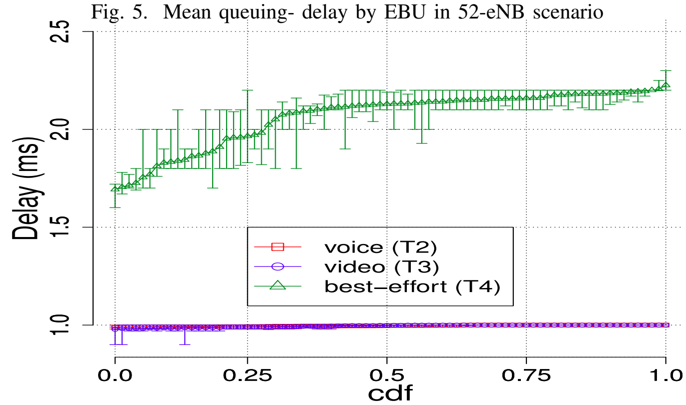

Fig. 6. Mean queuing-delay by EBU in 80-eNB scenario

of $grant\_size$ to T3, while maintaining lower mean queuing-delay for all the T2 $AllocIDs$.

B. Optimising T4 $grant\_size$ allocation

Even though MDR_{T2} and MDR_{T3} over-provisions the upstream capacity, the sum of the aggregated mean datarate of voice and video applications occupy a smaller portion of C_{XG-PON} (Table III) compared to that of best-effort, which has significant burstiness in datarate, even after aggregation. A closer look at the aggregated values of voice, video and best-effort traffic arrival at the ONU and the dual $grant\_size$ provision for T3 (Equation 2, 3) reveal that the total unused bandwidth in XG-PON upstream after provisioning for T2 and T3 (tot_unused_BW) gives two discrete sets of values. Taking advantage of this adaptive nature of tot_unused_BW, we propose the following DBA policies for best-effort, resulting in two optimised DBAs for XG-PON:

1. Deficit policy in XGIANT-D (Algorithm 1): Here we introduce a dynamic threshold ($threshold_i$) to vary the bandwidth allocated to each best-effort $AllocID$ ($T_{4,i}$). When BW_{g1} is allocated, the $threshold_i$ merely relies on the tot_unused_BW and total number of unserved T4 $AllocID$s (no_of_T4_unserved), resulting in a deficit ($deficit(T_{4,i})$) bandwidth for the $T_{4,i}$ due to the burstiness of best-effort traffic per-eNB. As in a deficit round robin scheduler, the $deficit(T_{4,i})$ is used in the subsequent BW_{g2}-allocated US-FRAME, to dynamically adjust the $threshold_i$, so that best-effort $AllocID$s with highly bursty traffic receive more bandwidth than the non-bursty ones (line 8, 10 in Algorithm 1).

Algorithm 1 : Calculate $grant\_size$ ($T_{4,i}$) in XGIANT-D

tot_unused_BW = US-FRAME_SIZE - tot_grant_size
if (BW_{g1} allocated US-FRAME) **then**
  $threshold_i = \frac{tot\_unused\_BW}{no\_of\_T4\_unserved}$
  deficit ($T_{4,i}$) = max{0, (DBRu($T_{4,i}$) - $threshold_i$)}
  tot_deficit_T4 += deficit ($T_{4,i}$)
else ▷ (BW_{g2} allocated US-FRAME)
  if (deficit ($T_{4,i}$) > 0) **then**
    $threshold_i = \frac{tot\_unused\_BW + tot\_deficit\_T4}{no\_of\_T4\_unserved}$
  else
    $threshold_i = \max\{0, \frac{tot\_unused\_BW - tot\_deficit\_T4}{no\_of\_T4\_unserved}\}$
  end if
end if
no_of_T4_unserved = no_of_T4_unserved - 1
grant_size($T_{4,i}$) = min {DBRu ($T_{4,i}$), $threshold_i$}

Algorithm 2 : Calculate $grant\_size$ ($T_{4,i}$) in XGIANT-P

1: **if** ($T_{4,i}$ = first_T4_served_in_this_US-FRAME) **then**
2:   tot_unused_BW = US-FRAME_SIZE - tot_grant_size
3:   BF= max{ 1, $\sqrt{tot\_T4\_DBRu/tot\_unused\_BW}$ }
4: **end if**
5: burst_request ($T_{4,i}$) = $\frac{BF * tot\_T4\_Req * DBRu(T_{4,i})}{tot\_unused\_BW}$
6: grant_size ($T_{4,i}$) = min{DBRu ($T_{4,i}$), burst_request ($T_{4,i}$)}

2. Proportional policy in XGIANT-P (Algorithm 2): Although the deficit policy is adaptive in using $threshold_i$ for allocating grant_size, the advantage of using the $threshold_i$ impacts the $AllocID$s served at the end of BW_{g2}-allocated US-FRAME than at the beginning due to reducing no_of_T4_unserved. Hence, in XGIANT-P, we introduce the dynamic Burst Factor (BF) to indicate the burstiness of all the best-effort $AllocID$s. BF ensures that the bandwidth allocation to each $T_{4,i}$ is impacted by a weighted DBRu ($T_{4,i}$) (line 5 in Algorithm 2), as in a weighted round robin scheduler.

C. Fairness in XGIANT-D and XGIANT-P

Due to the unpredictable bursty nature of aggregated voice, video and best-effort applications and the round-robin $grant\_size$ allocation within each T-CONT type, unfair allocation of $grant\_size$ to $AllocID$s of similar T-CONT types is inevitable. Considering the independent nature of each traffic profile, we propose an intra-T-CONT-type fairness policy in XGIANT-D and XGIANT-P, as opposed to the inter-ONU-fairness in EBU, to provide fair $grant\_size$ allocation to all $AllocID$s of T2, T3 and T4, individually. In intra-T-CONT-type fairness, the first served $AllocID$ of each T-CONT type in the entire XG-PON network is altered in a round-robin manner, independent of the rest of the T_k. For example, when in a given US-FRAME, the 1st $AllocID$ of T1, 8th of T2, 3rd of T3 and 15th of T4 are served first, in the subsequent US-FRAME, 2nd T-CONT of T1, 9th of T2, 4th of T3 and 16th of T4 are served first.

VI. Results and Discussion

Here we present the performances of XGIANT-D and XGIANT-P for mean queuing-delay and mean instantaneous datarate in XG-PON.

A. Queuing-Delay in the LTE backhaul

The mean queuing-delay and the associated metrics (priority and fairness) evaluated here are the same as in section IV, with figures Figures 7- 10 showing the mean queuing-delay performances of XGIANT-D and XGIANT-P for the 52-eNB and 80-eNB scenarios. Here also we repeated each of our 20-second simulated experiment for 10 different seeds, equal to the ones in section IV. Each value in the y-axis indicates the average of mean queuing-delays observed for the 3 T-CONT types, while the error bars indicate the range of the mean queuing-delays over all 10 runs; the x-axis represent the CDF with regard to the number of eNBs in each scenario.

All four figures show that both XGIANT-D and -P respect the priority between all the $AllocID$s of all the T-CONT types, due to the relative over-provision of MDR_{T2} against MDR_{T3} and the dual stage $grant\_size$ allocation for T3 (BW_{g1} or BW_{g2}). Between the two DBAs, XGIANT-D DBA provides lowest mean queuing-delay for voice (T2), while compromising on the mean queuing-delay for best-effort (T4) traffic. XGIANT-P provides lower mean queuing-delays for best-effort (T4), in both the scenarios, while maintaining (joint-)lowest delay for voice (T2) and video (T3) $AllocIDs$. This is because in XGIANT-D can never over-provision per-US-FRAME bandwidth due to tot_unused_BW calculated every US-FRAME. As a result while the T4 $AllocIDs$ receive smaller $grant\_size$ in XGIANT-D than in XGIANT-P resulting in T4 $AllocIDs$ receiving higher-than-XGIANT-P mean queuing-delays while T2 $AllocIDs$ receiving lower-than-XGIANT-P mean queuing-delays; since XGIANT-P uses the BF, resulting in possible over-provision and therefore larger $grant\_size$ when $L_r > 1.0$, we see that in both the 52 and 80-eNB scenarios XGIANT-P provides lower mean queuing-delay for best-effort (T4) compared to XGIANT-D, when total instantaneous datarate is more than C_{XG-PON}.

Compared to XGIANT-D, XGIANT-P provide better fairness in mean queuing-delay between all the $AllocIDs$ in each T-CONT type individually, due to its controlled over-provision of $grant\_sieze$ to the T4 $AllocIDs$. XGIANT-P also provides consistent mean-queuing delays for all the T2 $AllocIDs$ and T4 $AllocIDs$ across all the seeds, thereby indicating its robustness against mean queuing-delay variation (or jitter) across per-eNB load variation in the 10 seeds.

Comparisons of these mean queuing-delay values against those of XGIANT and EBU also show that both XGIANT-D and XGIANT-P perform better in terms of strict priority and fairness for per-eNB aggregated traffic due to optimised MDR_{T2}:MDR_{T3} ratio, deficit/proportional policies for T4 and intra-T-CONT-type fairness used in our optimised DBAs.

Overall, our optimised DBAs ensure a maximum mean queuing-delay of ~1ms for voice and video and a higher but $<$ 1.5ms for best-effort, when T-CONT queue values are equal to

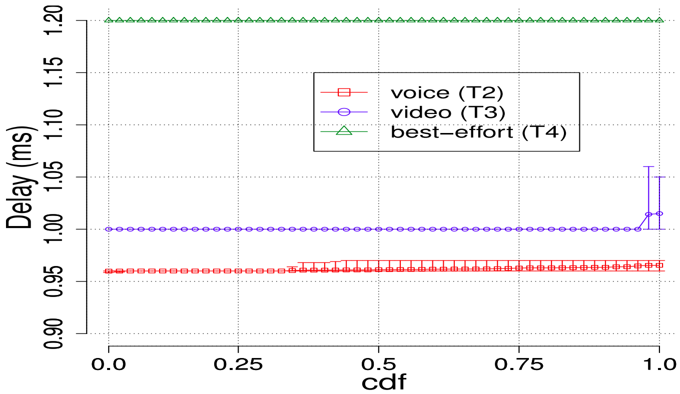

Fig. 7. Mean queuing-delay by XGIANT-D in 52-eNB scenario

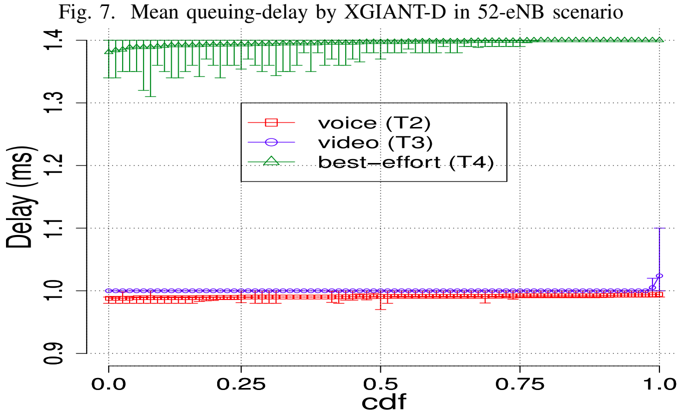

Fig. 8. Mean queuing-delay by XGIANT-D in 80-eNB scenario

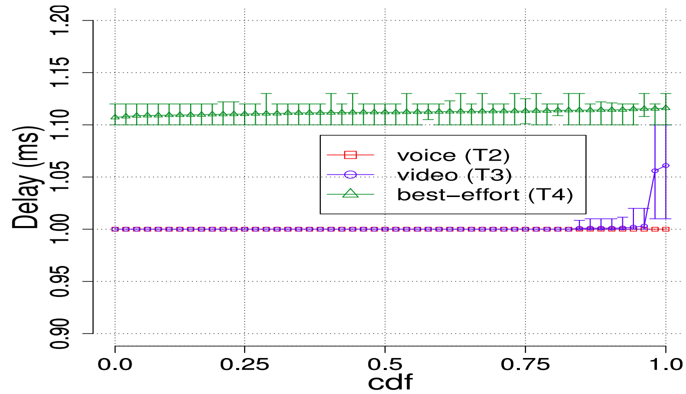

Fig. 9. Mean queuing-delay by XGIANT-P in 52-eNB scenario

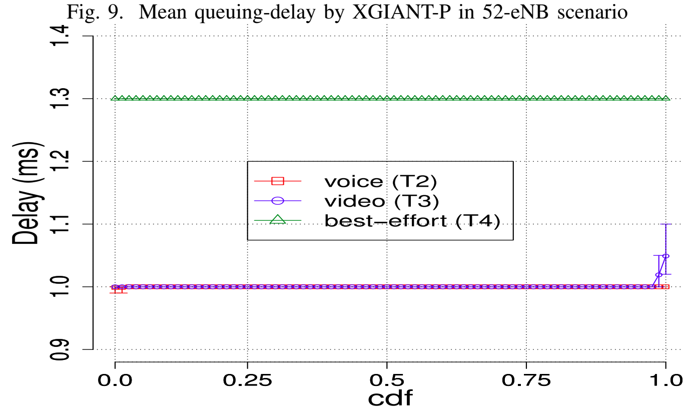

Fig. 10. Mean queuing-delay by XGIANT-P in 80-eNB scenario

half the Bandwidth Delay Product (=5KB). These values prove the ability of our optimised DBAs to satisfy the literature-recommended two-way delays in LTE backhaul (10ms in [17], 5ms in [10] and 10ms in [20]) while ensuring strict priorities between and fairness for all 3 aggregated applications.

B. Loss of datarate in the backhaul

To validate the mean queuing-delay performance of our optimised DBAs in terms of datarate, we plot the differences in mean instantaneous (per-millisecond measured) datarate for aggregated applications in 52-eNB (Figure 11) and 80-eNB scenarios (Figure 12). ΔDatarate in indicates the differences in instantaneous mean datarate between traffic transmitted across XG-PON and that aggregated at eNB. A zero value indicates that the DBA provisions the exact eNB-aggregated mean instantaneous datarate across XG-PON; a negative value indicates packet loss and positive value shows expedited datarate in XG-PON due to the extended holding of packets in T_k buffers. Each CDF line represents all the values from all 10 runs, as each value in ΔDatarate is a possible value associated with each DBA.

Figures 11 and 12 show that while all DBAs ensure lossless bandwidth provision for voice, video traffic shows a mix of expedited and lost datarate and best-effort suffers the highest loss of datarate from all DBAs. Expedited video traffic by all DBAs is due to dual-stage $grant\_size$ allocation: XGIANT shows heavy expediting of video traffic due to having a very high value for MDR_{T3} (=0.67*C_{XG-PON}) while EBU shows heavy loss in video datarate due to its extended holding of T3 traffic in the small 5KB T-CONT queue for 5 US-FRAMEs, resulting in more packet drops between subsequent $grant\_size$ allocation. Between the two optimised DBAs, XGIANT-D shows no loss of video traffic in both scenarios while XGIANT-P shows certain degree of voice traffic loss across XG-PON due to the absence of or use of T4 over-provision in the DBAs, respectively.

For best-effort, EBU shows highest datarate drop (packet loss) in both the scenarios, again because of EBU provisioning $grant\_size$ every 10th US-FRAME; XGIANT-D and XGIANT-P are able to outperform XGIANT with lowest loss in the 80-eNB scenario, though moderately lossy in the 52-eNB scenario, due to employing adaptive QoS policies for T4 $grant\_size$ allocation.

Overall, XGIANT-D and XGIANT-P also ensure fairer mean datarate loss (more horizontal line in CDF plot) for the entire LTE network, validating their fair treatment of per-eNB-aggregated bursty LTE traffic in terms of packet loss.

VII. Related Work

There are several proposals in the literature for the integration of EPON and LTE. For example, Astudillo et. al. [5] proposed a standard-compliant QoS provisioning scheme for an integrated EPON and LTE network architecture, along with a QoS mapping scheme; their Z-Based QoS Scheduler (ZBQoS) and Hybrid ZBQoS for LTE used feedback from a basic EPON DBA to dynamically throttle Non-GBR traffic bandwidth allocation in LTE. Lim, et. al. [14] proposed a multi-queue based QoS mapping scheme and DBA mechanisms for the EPON based backhaul for mobile traffic.

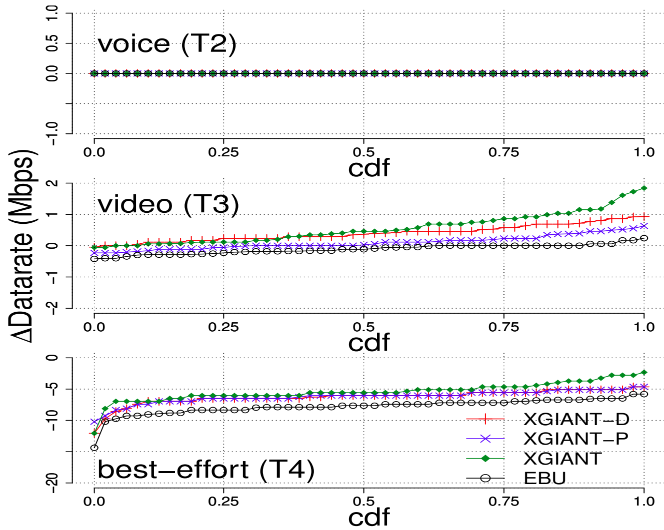

Fig. 11. Difference in mean datarate in 52-eNB scenario

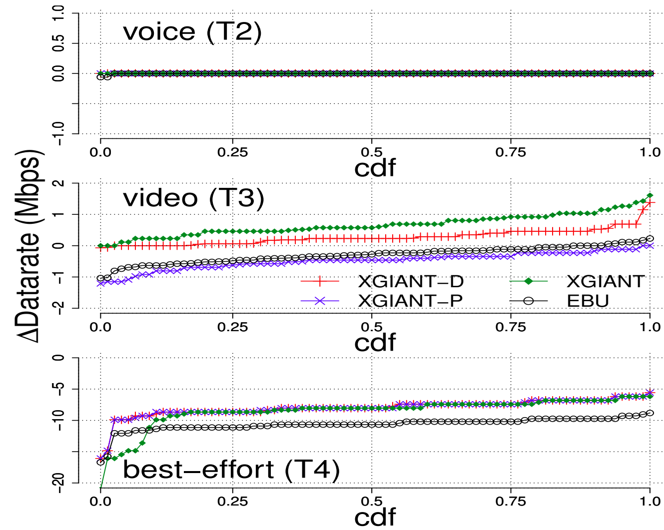

Fig. 12. Difference in mean datarate in 80-eNB scenario

However, the convergence of (X)GPON and LTE has received considerably less attention. The closest work to ours is proposed by Hwang et.al [7] using a GPON-LTE converged network architecture (GLCNA) and Synchronous Interleaved DBA with a centralised bandwidth allocation by OLT for UEs in GLCNA. Their results show several hundreds of milliseconds of delay for scenario T2-T4, when GPON upstream is fully utilised, while using simple LTE traffic distributions and large queue values. The details of their simulator are not given.

In this work, we present XG-PON-standard-compliant optimised DBAs, which can assure the QoS requirements of aggregated traffic in the LTE backhaul. We also evaluate our optimised DBAs using standard-complying XG-PON and LTE modules in ns-3, and realistic traffic models.

VIII. Conclusion

PON is increasingly seen as a very attractive solution for flexible and cost-effective LTE backhaul. In this paper, we have implemented a standards-compliant network architecture and QoS mapping scheme for the convergence of XG-PON and LTE, along with two DBAs for XG-PON that were optimised to suit the QoS requirements for voice, video and best-effort Internet traffic. We demonstrated, by simulation, the ability of our optimised DBAs to provide prioritised and fair QoS (latency and datarate) in the LTE backhaul, improving upon the recent XGIANT and DBAs proposed in the literature. In the future, we will look at admission control and virtual carrier aggregation in XG-PON-based LTE backhaul

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References

[1] "The NS-3 network simulator," URL: http://www.nsnam.org, 2015.

[2] P. Alvarez, N. Marchetti, D. Payne, and M. Ruffini, "Backhauling mobile systems with XG-PON using grouped assured bandwidth," in *2014 19th Eur. Conf. Networks Opt. Commun. -*. IEEE, Jun. 2014, pp. 91–96.

[3] D. Ammar, T. Begin, and I. Guerin-Lassous, "A new tool for generating realistic internet traffic in NS-3," in *SIMUTools*, Mar. 2011, pp. 81–83.

[4] J. A. Arokkiam, K. N. Brown, and C. J. Sreenan, "Refining the GIANT dynamic bandwidth allocation mechanism for XG-PON," in *2015 IEEE Int. Conf. Commun.* IEEE, Jun. 2015, pp. 1006–1011.

[5] C. Astudillo and N. Da Fonseca, "Standard-compliant QoS provisioning scheme for LTE/EPON integrated networks," *IEEE Wirel. Commun.*, vol. 21, no. 3, pp. 44–51, Jun. 2014.

[6] M. S. Han, H. Yoo, and D. S. Lee, "Development of Efficient Dynamic Bandwidth Allocation Algorithm for XG-PON," *ETRI J.*, vol. 35, no. 1, pp. 18–26, Feb. 2013.

[7] I.-S. Hwang, T.-J. Yeh, M. Lotfolahi, B.-J. Hwang, and A. Nikoukar, "Synchronous Interleaved DBA for Upstream Transmission over GPON - LTE Converged Network," in *Int. MultiConference Eng. Comput. Sci.*, 2015.

[8] IEEE, "802.3ah: Ethernet in the First Mile," 2004.

[9] IEEE, "IEEE 802.3av: 10G-EPON Task Force," 2009.

[10] ITU-R, "M.2134: Requirements Related to Technical Performance for IMT-Advanced Radio interface(s)," 2008.

[11] ITU-T, "G.984.x:Gigabit-Capable Passive Optical Networks," Oct. 2008.

[12] ITU-T, "G.987.1: XG-PON General Characteristics," 2010.

[13] ITU-T, "G.722 : 7 kHz audio-coding within 64 kbit/s," 2012.

[14] W. Lim, M. Milosavljevic, P. Kourtessis, and M. John, "QoS mapping for LTE backhauling over OFDMA-PONs," in *2012 14th Int. Conf. Transparent Opt. Networks*. IEEE, Jul. 2012, pp. 1–4.

[15] Microsoft, "How much bandwidth does Skype need?" 2015. [Online]. Available: https://support.skype.com/en/faq/FA1417/

[16] J. E. Mitchell, "Integrated Wireless Backhaul Over Optical Access Networks," *J. Light. Technol.*, vol. 32, no. 20, pp. 3373–3382, Oct. 2014.

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

[18] G. Piro, N. Baldo, and M. Miozzo, "An LTE module for the ns-3 network simulator," in *WNS-3 in conjunction with SIMUTools*, 2011.

[19] C. Ranaweera, E. Wong, C. Lim, and A. Nirmalathas, "Next generation optical-wireless converged network architectures," *IEEE Netw.*, vol. 26, no. 2, pp. 22–27, Mar. 2012.

[20] J. Robson and N. O. B. P. Group, "Guidelines for LTE Backhaul Traffic Estimation," *Next Generation Mobile Networks (NGMN)*, 2011.

[21] A. G. Sarigiannidis, M. Iloridou, P. Nicopolitidis, G. Papadimitriou, F.-N. Pavlidou, P. G. Sarigiannidis, M. D. Louta, and V. Vitsas, "Architectures and Bandwidth Allocation Schemes for Hybrid Wireless-Optical Networks," *IEEE Com. Surv. Tutorials*, vol. 17, pp. 427–468, 2015.

[22] A. Singh, I. Abeywickrama, K. Andreas, X. Li, and C. Goerg, "Statistical Analysis of Traffic Aggregation in LTE Access Networks," in *IFIP Wirel. Mob. Netw. Conf.*, 2013.

[23] X. Wu, K. N. Brown, C. J. Sreenan, P. Alvarez, M. Ruffini, N. Marchetti, D. Payne, and L. Doyle, "An XG-PON module for the NS-3 network simulator," in *SimuTools '13*. ICST, Mar. 2013, pp. 195–202.

[24] Y. Zaki, T. Weerawardane, C. Gorg, and A. Timm-Giel, "Multi-QoS-Aware Fair Scheduling for LTE," in *2011 IEEE 73rd Veh. Technol. Conf. (VTC Spring)*, vol. 51, no. 2. IEEE, May 2011, pp. 1–5.