Next Generation Optical-Wireless Converged Network Architectures

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Abstract

This article provides a comprehensive analysis on implementing the next-generation optical-wireless integration architectures. The different approaches to implementing a complete fixed-mobile converged network that ensures desired quality of service for various applications are explored. This discussion is specifically focused on LTE-10GEPON integration networks where passive optical networks are used as the backhaul to LTE. Special attention is given to address the issue of providing proper means to enable intercommunication between neighboring base stations, which is one of the crucial considerations in next-generation wireless networks. We propose potential 10GEPON-LTE converged network architectures and comparatively analyze the benefits gained from each of the integration architectures by elaborating on the operational and control structures. Our performance analysis provides insight into QoS-rich next-generation optical-wireless converged networks.

Today, bandwidth- and quality of service (QoS)-intensive next-generation (NG) broadband applications have become important elements in telecommunication networks. To cope with the ever increasing demand for bandwidth, various access network technologies that can provide more than hundreds of megabits per second bandwidth have been developed in the last few decades. Among these broadband access technologies, passive optical networks (PONs) have been recognized as the most cost-effective solution to facilitate high bandwidth and fault-tolerant access to end users. However, in some situations, the PON itself might not be a suitable solution where mobility is an important concern, or might not be a cost-effective solution depending on geographical restrictions. To overcome these shortcomings, optical-wireless integration networks have been proposed where the end users are served by either wired or wireless access. On the other hand, PONs have been identified as one of the most competent economical solutions for backhauling NG wireless broadband access networks (NG-WBANs).

The Ethernet PON (EPON)-WiMAX integrated network is one of the optical-wireless integration options that has been studied extensively [1, 2]. Nevertheless, Long Term Evolution (LTE) developed by the Third Generation Partnership Project (3GPP), which can support up to 100 Mb/s of data rate in the downlink, is becoming more popular among service providers. Although both LTE and mobile WiMAX (802.16m) technologies are considered NG-WBANs, LTE has an added advantage over mobile WiMAX in that it uses the evolution of existing Universal Mobile Telecommunications System (UMTS) infrastructures, currently being used by mobile service providers worldwide [3]. On the other hand, time-division multiplexed (TDM) 10-Gigabit EPON (10GEPON), which supports up to a 10 Gb/s symmetric data rate, is becoming more popular as an NG-PON technology since it provides higher transmission capacity with the lowest per-user cost among PON technologies [4]. Thus, 10GEPON and LTE are natural candidates for a cost-effective NG complete fixed-mobile converged network. Furthermore, it is envisioned that the 10GEPON-LTE converged network will combine the advantages of high capacity and high-speed backhaul from 10GEPON with extensive mobility the LTE network can support.

In [5], an integration network that uses LTE and native Ethernet-based wavelength-division multiplexing (WDM) PON is presented, and the authors have considered a ring-topology-based PON for their proposed architecture. To the best of our knowledge, backhauling NG-WBANs using tree-based TDM-PON with the ability of direct communication between base stations has not been studied so far. However, such integration is one of the most cost-effective approaches to achieve a fully converged network as most PONs deployed today are tree-based. In this article, we discuss the key challenges in implementing the 10GEPON-LTE converged network, which meets both the LTE and 10GEPON networks' stringent requirements. To this end, we propose three feasible 10GEPON-LTE converged architectures which are implemented on top of the tree-topology-based PON. The benefits gained from each of these architectures are discussed by comparing operational and control structures, and QoS performance.

10GEPON and LTE Network

LTE is an all-IP network that provides seamless mobility and required QoS for triple-play services [6]. A typical LTE network architecture is shown in Fig. 1. As illustrated in Fig. 1, the radio access network (RAN) of LTE consists of only evolved nodeBs (eNBs), which are basically radio base stations. These eNBs are capable of allocating radio resources among its connected user equipment (UE) in a distributed manner without the involvement of any core network elements. The neighboring eNBs are interconnected via the X2

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interface, which facilitates direct communication between neighboring cells. Likewise, all eNBs are connected with the LTE core network (also referred to as evolved packet core or EPC) via the S1 interface, which is dedicated to data and control plane signaling transport. The EPC consists of a mobility management entity (MME), a serving gateway (S-GW), and a packet data network gateway (PDN-GW). These core network elements facilitate proper management of LTE network elements and provide links to other networks. In LTE, the concept referred to as the *evolved packet system bearer* is used to support QoS for diverse services across the network [6]. Here, each bearer consists of a QoS class identifier (QCI), which is characterized by priority and other QoS requirements. Nine different QCIs are used in the LTE network to provide guaranteed QoS for diverse applications such as voice, video on demand, and e-health.

10GEPON is the heir of EPON and is standardized as IEEE 802.3av [7]. In 10GEPON, no active element is placed in the optical path between the optical line terminal (OLT) located at the central office and optical network units (ONUs) located at customer premises. Two different wavelength channels are used in 10GEPON for the uplink and downlink transmissions. In the uplink transmission, the medium access is controlled by Multipoint Control Protocol (MPCP), where the OLT allocates time slots among its connected ONUs to avoid data collision. In MPCP each ONU reports its present queue status to the OLT using REPORT messages, and the OLT grants a time slot for each ONU based on a dynamic bandwidth allocation (DBA) algorithm and notifies the granted time slot to each ONU using a GATE message. The ONUs transmit their uplink data only during the designated time slot. In the downlink transmission, on the other hand, the OLT broadcasts all the frames to all of its connected ONUs. Each ONU filters out the frames that are not destined to it based on the unique physical logical link identity (LLID) assigned by the OLT upon registration. 10GEPON uses differentiated classes of service to support a queue-oriented QoS mechanism where eight different priority queues are maintained by each ONU.

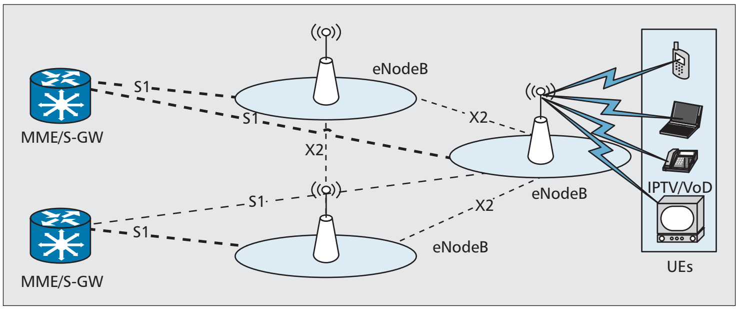

Figure 1. *LTE network architecture.*

Key Challenges in Implementing NG Optical-Wireless Converged Networks

Building a simple and cost-effective architecture that can effectively support high bandwidth and QoS-intensive applications is one of the key challenges in implementing a fully converged network. In addition, developing a resource allocation protocol for the converged architecture that complies with both the MPCP-based PON DBA and distributed resource allocation mechanisms in LTE is also an important consideration.

In early wireless access network technologies prior to LTE, there was no mechanism for direct communications between neighboring base stations. LTE facilitates this by introducing the X2 interface, which provides an efficient means to communicate control plane signaling and user plane traffic, especially when handovers take place between neighboring cells [6]. A recent estimate forecasts that the traffic traversing the X2 interface could reach up to 10 percent of the core-facing traffic, and the latency of this traffic should be less than 30 ms to maintain the required QoS [8]. Moreover, the X2 interface has been considered one of the most important requirements in future LTE releases (LTE Advanced) where the targeted latency is less than 10 ms together with 1 Gb/s downlink data rate [3, 8]. Thus, proper implementation of the X2 interface that can guarantee the required QoS is a crucial consideration in building a fully converged NG optical-wireless network. To this end, we propose potential 10GEPON-LTE converged architectures that conform to 10GEPON and LTE standards and their requirements.

10GEPON-LTE Integration Architectures

In this section, we discuss potential 10GEPON-LTE integration architectures in detail. However, it is important to note that although our discussion is centered around the 10GEPON-LTE converged network, architecture-wise these architectures are compatible with other TDM-PON systems and fourth-generation (4G) WBAN technologies such as 10GPON (10 Gigabit PON) and mobile WiMAX, respectively. In the following subsections, we discuss the operation, control structures, and key features of each of the proposed converged architectures.

Native 10GEPON-LTE Integration Architecture

The native 10GEPON-LTE integration architecture (NGLIA) is shown in Fig. 2a. In this architecture, the native 10GEPON tree architecture is used to backhaul the LTE access network. The integrated ONU and eNB (ONU-eNB) is connected to the OLT via a 1:*N* passive splitter, and each OLT is connected to the LTE core network elements. Furthermore, since one serving gateway (S-GW) is capable of handling high numbers of eNBs, several OLTs can be connected to one S-GW as shown in Fig. 2a. NGLIA is a simple integration architecture that does not require any additional equipment or modifications. Thus, the implementation cost of this architecture is minimal.

On the down side, in NGLIA, the X2 interface is logically and physically supported through the OLT. Consequently, considerable packet delays might occur during handovers. Nevertheless, an appropriate MPCP-based DBA algorithm can be employed to improve QoS performance by efficiently allocating bandwidth among its connected ONU-eNBs. In addition, QoS performance can be further improved by implementing an efficient intra-ONU-eNB scheduling mechanism in ONU-eNB to distribute the available bandwidth effectively among its UE, together with an appropriate QoS mapping mechanism between LTE QCI and 10GEPON priority classes.

Loopback Integration Architecture (LIA)

The LIA is shown in Fig. 2b. As the name implies, the main difference between this architecture and NGLIA is the implementation of a loopback mechanism at the passive splitter. That is, upstream frames transmitted by each ONU-eNB are looped back at the passive splitter to all other ONU-eNBs connected to the same splitter. This kind of mechanism can easily be realized using an $(N + 1) \times (N + 1)$ passive star coupler (SC) [9]. Most important, introduction of the SC does not change the passive nature of the network. However, as shown in Fig. 2b, an additional fiber connecting each integrated ONU-eNB and SC is required to provide the loopback path. This fiber carries the uplink data back to the ONU-eNBs using the same uplink wavelength (λ_u), and each ONU-eNB contains an additional receiver to receive these looped-back frames.

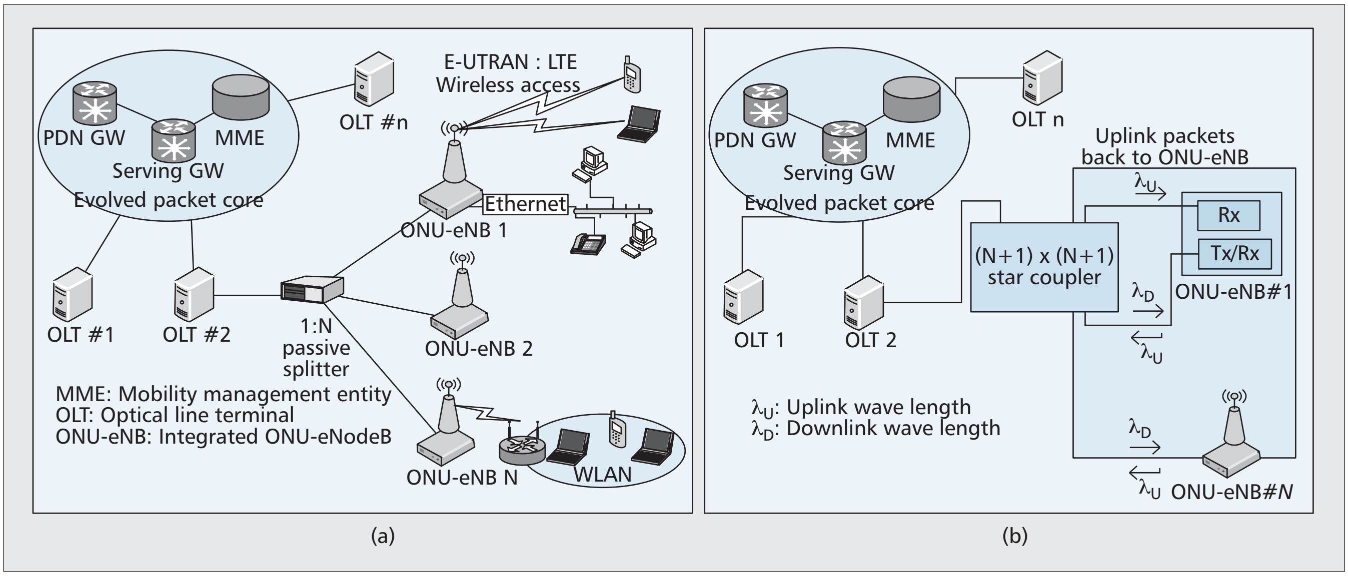

Figure 2. *10GEPON-LTE integration architectures: a) native 10GEPON-LTE integration architecture; b) loopback integration architecture.*

The main advantage of LIA is its ability to support the direct communication among ONU-eNBs connected to same OLT (inter ONU-eNB communication) through the SC. In LIA, the inter ONU-eNB traffic does not need to traverse the OLT as in NGLIA. From LTE's perspective, the handover signaling that needs to be communicated between neighboring eNBs can be effectively routed through the SC by creating logically meshed X2 interface complying with the LTE standard. As a result, delay and jitter in handover traffic, which hugely contributes to the overall network performance of the converged network, can effectively be reduced. Moreover, this architecture increases the downlink throughput since the X2 interface traffic as well as any other inter ONU-eNB traffic can be routed via the SC without consuming downlink bandwidth.

Since the upstream frames are looped back, each ONU-eNB receives a copy of the REPORT messages sent from all other ONU-eNBs connected to the same OLT. Hence, each ONU-eNB is aware of the queue status of all other ONU-eNBs, and this information is updated during every cycle. Once the data transmission cycle is completed, identical DBA algorithms are executed at each ONU-eNB to allocate bandwidth for the next cycle. Even the algorithm is executed separately at each ONU-eNB: since the algorithm and its inputs are identical, the output bandwidth allocations are also identical across ONU-eNBs. Thus, ONU-eNBs can transmit data without any collision by transmitting the data in a predefined sequence. Note that ONU-eNBs could be synchronized with OLT using the clock information extracted from the downlink data. Thus, the bandwidth allocation can be handled in a distributed manner (i.e., ONU-eNBs decide the uplink bandwidth allocations by themselves) conforming to the distributed resource allocation nature of LTE. In addition, several other distributed DBA algorithms can also be found in the literature [9]. However, since all uplink frames sent by each ONU-eNB are received by all other ONU-eNBs as well as the OLT, a proper frame filtering mechanism is required to filter out only the required frames to avoid unnecessary processing delays at both the ONU-eNB and OLT. One such efficient frame filtering mechanism is discussed below.

In EPON, the initially standardized original 16-bit-wide LLID field is later divided into a mode bit (MB) and a new LLID that is only 15 bits wide. The MB is introduced to support the point-to-point shared medium emulation (SME) modes in EPON. Even though the SME modes have not been used so far, legacy MB still exists, even in the latest 10GEPON standard [7]. As specified in the standard, the ONUs accept any received frame if the MB of the received frame is equal to 0 and the LLID value matches the ONU's LLID; if MB is equal to 1 and the LLID value does not match the ONU's LLID; or if the received frame has the broadcast LLID.

In LIA, this legacy MB can be used to provide an efficient frame filtering mechanism. In our proposed mechanism, the standardized frame format is kept unchanged. However, only the filtering rules at the OLT, LLID, and MB tagging mechanism at the ONU-eNBs are slightly modified in order to achieve a competent frame filtering mechanism while keeping all the other protocols unchanged. Figure 3 illustrates the proposed LLID and MB tagging, and the associated filtering rules. Although there is no specific filtering mechanism specified for OLT in the standard [7], to support efficient inter-ONU-eNB communication, especially in the uplink direction, our mechanism includes a simple filtering rule for the OLT. That is, the OLT only accepts frames received from ONU-eNBs if and only if a frame has broadcast LLID or LLID of its registered ONU-eNBs with MB set to zero.

The MB and LLID tagging rule at the integrated ONU-eNB is as follows. If a frame originated from an UE attached to one ONU-eNB, is destined to another ONU-eNB connected to same OLT, the LLID is set to the source LLID and the MB is set to one. On the other hand, if a frame originated from UE attached to an ONU-eNB is destined to the OLT, the mode bit is set to zero. Consequently, inter-ONU-eNB frames will be accepted by other ONU-eNBs connected to the same OLT but will be discarded at the OLT since MBs in these frames are set to one. In contrast, frames destined to an OLT will be discarded by all other ONU-eNBs but accepted only by the OLT as the MBs in these frames are set to zero. Therefore, the frame processing efficiency at the OLT as well as at the ONU-eNBs can be improved by using this filtering mechanism. More specifically, when our proposed filtering mechanism is used, OLT can discard the inter ONU-eNB frames; similarly, ONU-eNBs can discard the core-facing frames by simply looking at the LLID and MB without performing any further medium access control (MAC) layer processing.

Loopback integration architecture together with this proposed mechanism can significantly reduce the processing delay at the OLT and increase the downlink throughput, which ultimately improves QoS in the converged network, especially in the X2 interface.

Remote Node Integration Architecture (RNIA)

Figure 4a shows a 10GEPON-LTE integration architecture that uses two active remote nodes (RNs). In comparison to the NGLIA and LIA, this RNIA shows significant differences in its structure and operation. As illustrated in Fig. 4a, the feeder fiber from the OLT is first split into two by using a 1:2 passive splitter and then each of these two separate paths are again split into *n* paths by using two 1:*n* passive splitters. The active RNs are deployed immediately before each of the 1:*n* splitters. These RNs have the intelligence to perform MAC layer functionalities such as storing MAC addresses and LLIDs of connected ONU-eNBs and forwarding packets according to the stored data [10].

The same LLID filtering mechanism which we have proposed for the LIA can be implemented in the RNIA to achieve efficient frame transmission. Consequently, RNs and ONU-eNBs can filter frames by looking at the LLID and corresponding MB without performing any MAC layer processing. As a result, the extra processing delay caused by the introduction of an RN can be significantly reduced. Most important, this architecture provides fully meshed connectivity for LTE RAN by facilitating X2 interface via the RN. In the uplink, frames originating from one ONU-eNB and destined to another ONU-eNB connected to the same RN are rerouted by the RN back to the downstream. Since the converged architecture has two RNs that connect to two separate groups of ONU-eNBs, some amount of free bandwidth is available in the downlink of an RN to ONU-eNB at any given time as these RNs filter out the frames that are not destined to their connected ONU-eNBs. Consequently, the X2 interface signaling and user plane traffic can be routed back to the ONU-eNBs without any congestion at the RN with the aid of this spare bandwidth even though the OLT may have a congested downlink. Moreover, since traffic traversing among the ONU-eNBs connected to the same RN is routed through the RN, a significant amount of OLT downlink bandwidth can be saved.

Since the received frames are regenerated at the RN, this architecture is also suitable for situations where ONU-eNBs are required to deploy far from each other and/or distant from the OLT, such as in rural areas. Moreover, the overall delay performances can be further improved by implementing a DBA algorithm that takes advantage of the existence of multiple RNs in the network. That is, when an ONU-eNB that is connected to one RN sends uplink data to the OLT, ONU-eNBs connected to the other RN can transmit data destined to ONU-eNBs connected to the same RN.

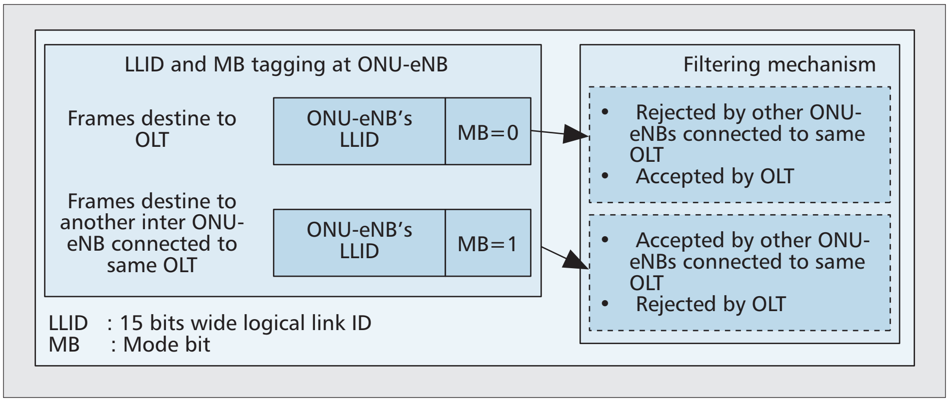

Figure 3. *LLID, MB filtering, and tagging mechanism.*

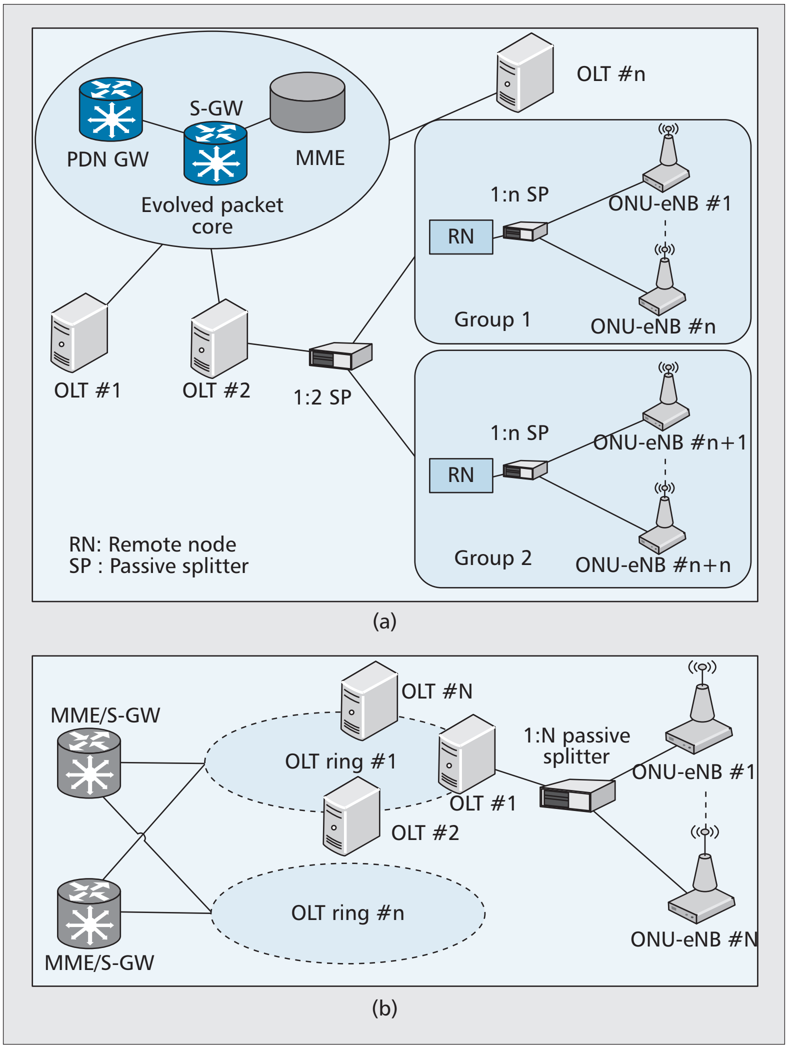

Figure 4. *10GEPON-LTE integration architectures: a) remote node integration architecture; b) OLT ring protection architecture.*

Other Integration Architectural Aspects

In large telecommunication network deployments, service resiliency is a crucial aspect. The previously discussed converged network architectures are more focused on achieving high network performance. However, it is also important to consider the reliability and robustness of the converged networks, which depend on the architectures and topologies used for implementation. In simple terms, networks should have a recovery mechanism to provide uninterrupted service to end users when one or more network elements fail. To provide such reliance to end users, ring-based converged network

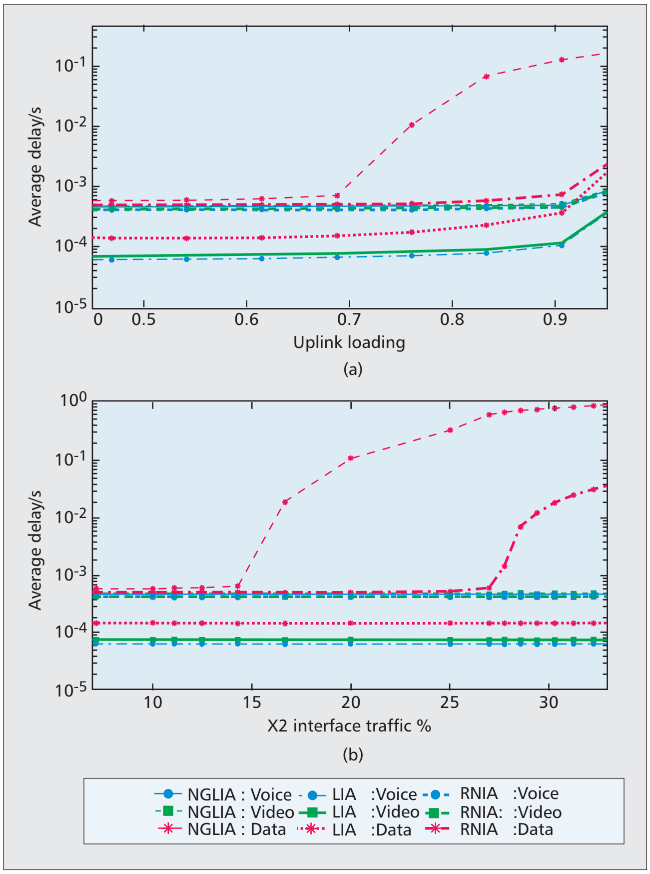

Figure 5. T*he variation of delay in the X2 interface with (a) the uplink loading (b) with % of traffic in X2 interface.*

architecture as shown in Fig. 4b can be implemented. In this architecture, OLTs are connected in a ring, and each ring is connected to MME/S-GWs using a mesh topology complying with the LTE core network requirements. The converged access networks connected to the OLT ring topology can be any combination of NGLIA, LIA and RNIA. This OLT ring-based architecture improves the survivability of the converged network by providing redundancy links between each OLT and EPC. Since frames originating from one ONU-eNB and destined to another ONU-eNB connected to the same OLT ring can be routed via the OLT ring instead of through the EPC, end-to-end packet delay can be reduced. Thus, this architecture can be effectively used not only to improve the reliability but also to improve the QoS of the converged network.

Performance Evaluation

An event driven simulation developed in C++ is carried out to evaluate and compare the QoS performances of voice, video and data traffic classes in NGLIA, LIA and RNIA. In our traffic model, the voice packets are assumed to arrive in every 20 ms with a fixed size of 200 bytes, and the variable bit rate traffic is assumed to have a Poisson arrival with uniformly distributed variable packet size between 64 to 1518 bytes. The percentages of voice, video and data traffic are considered as 3 percent, 54 percent and 43 percent respectively. The amount of inter ONU-eNB traffic that traverses the X2 interface is taken as 10 percent of the core facing traffic [8]. The number of ONU-eNBs connected to OLT is taken as 16, each with a limited buffer size of 10 Mbytes. 10 Gb/s symmetric line rate is considered to simulate the 10GEPON network.

A symmetric architecture is considered for the evaluation of RNIA in which each RN is connected to eight ONU-eNBs. Processing delays at the RN and OLT are assumed to be constant at 100 μs and 200 μs, respectively [10]. The latency that occurs within the air interface of the LTE access network is omitted from our evaluation as it is common for all the integration architectures considered. Therefore, the packet delay values indicated in our results do not represent the actual packet delay in the converged network. However, this does not affect the comparative packet delay analysis of the integration architectures, which is the purpose of our investigation. Furthermore, a deployment scenario in which both wireless and wired subscribers are connected to ONU-eNBs is considered for the sake of generality. The propagation delay within the optical links is taken as 5 ms/km. The splitter in NGLIA, the SC in LIA, and the RNs in RNIA are assumed to be located 20 km from the OLT and 5 km from the integrated ONU-eNBs. The loading level is defined as the fractional traffic load with respect to 10 Gb/s maximum capacity whereby a loading level 1 represents 10 Gb/s of traffic load. The uplink traffic load is defined as the sum of all ONU-eNBs' traffic which are destined to OLT and to other ONU-eNBs. Each architecture was simulated for 15s and with differing number of packets, that is dependent on the level of link loading. For example, when the uplink loading is 0.9, the number of packets simulated for voice, video and data classes were in the orders of 10^6, 10^7, and 10^7, respectively. The proposed LLID and MB-based filtering mechanism is implemented in both LIA and RNIA, and the same centralized DBA algorithm (i.e. OLT allocates the uplink time slot for each ONU-eNB) is used in all architectures.

Packet Delay

Figure 5a plots the variation of delay in different QoS classes in the X2 interface as a function of uplink loading. A typical heavy loaded 9 Gb/s downlink with accompanying contribution from inter ONU-eNB traffic is considered for this evaluation. In RNIA, traffic originating from one ONU-eNB and destined to another ONU-eNB connected to same OLT but to a different RN, has to go through the OLT whereas the traffic is routed via RN if the communication is between two ONU-eNB connected to same RN. Thus, delay is calculated by averaging the delay of these two types of inter ONU-eNB traffic. As shown in Fig. 5a, the LIA shows the best delay performances among all three architectures for all traffic classes. This is because in LIA, a separate channel is used to implement the X2 interface; consequently, data transport in the X2 interface is not affected by downlink traffic congestions whereas the X2 interface traffic shares the same downlink bandwidth with other downstream traffic in NGLIA and RNIA. Note that the delay of data traffic in NGLIA is increased significantly when the uplink loading is increased beyond 0.7. This is because, when the uplink loading increases, data traversing the X2 interface is also increased. Accordingly the total traffic load towards downstream is increased resulting higher queuing delays at the OLT. In contrast, for loading levels beyond 0.7, RNIA shows significant delay improvements compared to NGLIA due to the routing of part of the X2 interface traffic via RNs.

Figure 5b shows the variation of average packet delay in the X2 interface as a function of percentage of traffic traversing the X2 interface. Without loss of generality, 6.5 Gb/s of uplink and 9 Gb/s of downlink are assumed for this simulation. It can be seen from Fig. 5b that LIA provides better performance even for high percentages of X2 interface traffic. In contrast, the average delay of RNIA and NGLIA are increased significantly when the traffic percentage of X2 interface is increased from 14 percent and 27 percent respectively. This is due to the increase of downlink traffic congestion.

In Fig. 6 we present the variation of maximum packet delays

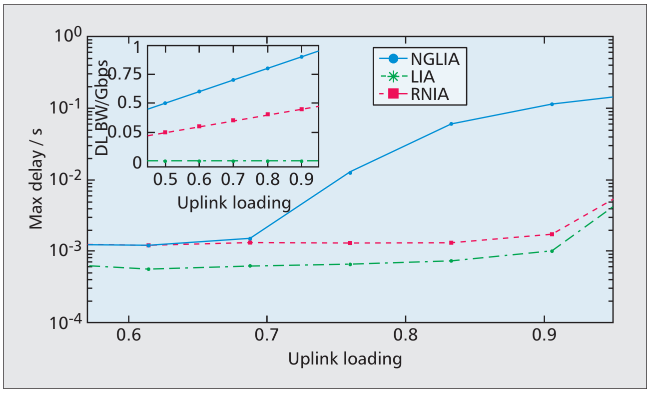

Figure 6. *Maximum delay and downlink bandwidth (DL BW) consumption with uplink loading.*

occurring in each of the architecture as a function of uplink loading. For this simulation, 9 Gb/s downlink traffic load is considered. Our results indicate the upper bound of the delay performances. It is clear that the LIA maintains the maximum delay in all traffic classes at < 1 ms for uplink loading below 0.91, while RNIA maintains the maximum delay at slightly above 1 ms. Conversely, the NGLIA shows significant increase in maximum delay when uplink loading increases from 0.7, and it exceeds 100 ms when uplink loading increases beyond 0.9.

Downlink Bandwidth Utilization

The downlink bandwidth consumption of the inter-ONU-eNB traffic in each architecture with the uplink loading is shown in the inset of Fig. 6. Our results show that LIA yields minimum OLT downlink bandwidth consumption by X2 interface traffic among all three integration architectures, whereas NGLIA results in the maximum. This is because in LIA, all inter-ONU-eNB traffic is routed through the SC using a separate channel without consuming the OLT's downlink bandwidth. On the other hand, inter-ONU-eNB traffic is routed though the OLT in NGLIA, resulting in significant downlink bandwidth consumption, which, in turn, results in high packet delays, as shown in Fig. 6. In contrast, since part of the X2 interface traffic is routed through the RN in RNIA, inter-ONU-eNB traffic consumes less portion of OLT's downlink bandwidth than in NGLIA.

Other Considerations

The most promising architecture for real world deployment is dependent on various factors such as QoS performance, existing network infrastructures, scalability, and cost, among other factors. NGLIA is a straightforward solution and might also be the most cost-effective option. However, the QoS performance in the X2 interface is lower compared to other architectures. As the simulation results indicate, LIA provides the best QoS performance for the X2 interface. In addition, LIA would be more cost effective than RNIA for an already deployed PON since the additional cost involved in implementing dual distribution fiber based SC-PON is claimed to be less than 0.3 percent as compared to the standard PON deployment [9]. The operational cost would also be comparable to NGLIA. For RNIA, although management costs are higher due to the inclusion of an active RN, this architecture is most suitable for rural deployments. This is because RNIA facilitates long reach access to NG-WBANs while maintaining the required QoS. Although clearly beyond the scope of the present article, a detailed cost and scalability comparison in addition to the already discussed QoS performance between all three architectures is warranted in the future.

Conclusions

In this article, we comparatively analyze the potential architectures suitable for NG optical-wireless integration. Specifically, we consider 10GEPON-LTE integration, which is most likely to be the most prominent and cost-effective integration option due to the rising popularity of these access technologies. To this end, we propose and evaluate three different 10GEPON-LTE integration architectures to which we referred as NGLIA, LIA, and RNIA. We elaborate on the operational and structural considerations of these architectures and evaluate the QoS performance of inter ONU-eNBs communication, which is one of the key considerations of NG-WBANs. The simulation results indicated that the minimum packet delay in the X2 interface and the maximum downlink bandwidth utilization can be achieved using the LIA followed by RNIA and NGLIA, respectively.

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