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Title of retracted article:	**A Simple and Cost-Effective EPON-Based Next Generation Mobile Backhaul RAN Architecture**
Author(s):	Ajaz Sana, Syed R. Zaidi, Shahab Hussain, Mohammad Nizamuddin
* Corresponding author.	Email: ajaz.sana@bcc.cuny.edu
Journal:	Wireless Engineering and Technology (WET)
Year:	2017
Volume:	8
Number:	1
Pages (from - to):	1 - 19
DOI (to PDF):	http://doi.org/10.4236/wet.2017.81001
Article page:	https://www.scirp.org/journal/paperinformation.aspx?paperid=73752
Retraction date:	2020-6-2

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 ○ Journal owner (publisher)
 ○ Institution:
 ○ Reader:
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Date initiative is launched: 2020-5-24

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Expression of Concern:
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Editor guiding this retraction: Prof. Yi Huang (EiC of WET)

Scientific Research Publishing

Wireless Engineering and Technology, 2017, 8, 1-19
http://www.scirp.org/journal/wet
ISSN Online: 2152-2308
ISSN Print: 2152-2294

A Simple and Cost-Effective EPON-Based Next Generation Mobile Backhaul RAN Architecture

Ajaz Sana[1], Syed R. Zaidi[1], Shahab Hussain[2], Mohammad Nizamuddin[3]

[1]Department of Engineering, Physics & Technology, Bronx Community College of the City University of New York, New York, USA
[2]Nokia, Westford, USA
[3]Department of Electrical Engineering, City College of the City University of New York, New York, USA
Email: Ajaz.Sana@bcc.cuny.edu, Syed.Zaidi@bcc.cuny.edu, shussain@gradcenter.cuny.edu, Nizammudin@ccny.cuny.edu

How to cite this paper: Sana, A., Zaidi, S.R., Hussain, S. and Nizamuddin, M. (2017) A Simple and Cost-Effective EPON-Based Next Generation Mobile Backhaul RAN Architecture. *Wireless Engineering and Technology*, **8**, 1-19.
http://dx.doi.org/10.4236/wet.2017.81001

Received: September 2, 2016
Accepted: January 20, 2017
Published: January 23, 2017

Abstract

This study proposes a novel, simple and cost-effective PON-based next generation mobile backhaul RAN architecture that enables redistribution of some of the intelligence currently centralized in the Mobile Packet Core (MPC) platform out into the access nodes of the RAN. Specifically, this work proposes a fully distributed ring-based EPON architecture that enables the support of a converged PON-4G/5G mobile WiMAX/LTE access networking transport infrastructure to seamlessly backhaul both mobile and wireline multimedia traffic and services.

Keywords

LTE, WiMAX, 4G, EPON, TDM PON

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1. Introduction

The phenomenal growth of mobile backhaul to support the emerging fourth-generation (4G) traffic that includes mobile WiMAX and cellular Long-Term Evolution (LTE), requires rapid migration from today's legacy circuit switched T1/E1 wireline and microwave backhaul technologies to a new fiber-supported, all-packet-based mobile backhaul infrastructure [1] [2] [3] [4]. Mobile backhaul sometimes referred to, as the Radio Access Network (RAN), is used to backhaul traffic from individual base stations (BSs) to the Radio Network Controller (RNC) which is then connected to the mobile operator's core network or gateway. In contrast with the typically centralized 2G/3G RAN infrastructure, the 4G architecture specifically LTE has fundamentally different RAN design requirements. Hence, a cost-effective fiber supported all-packet-based mobile backhaul RAN architecture that is compatible with these inherently distributed and packet-oriented NG RAN architectures, is needed to efficiently scale current mobile backhaul networks. However, deploying a new fiber-based mobile backhaul infrastructure is a costly proposition mainly due to the significant cost associated with digging the trenches in which the fiber is to be laid.

This underlying potential prompted many carriers around the world to consider the use of the fiber-based Passive Optical Network (PON) access infrastructure as an all-packet-based converged fixed-mobile optical access networking transport architecture to backhaul both mobile and typical wireline traffic. A PON connects a group of Optical Network Units (ONUs) located at the subscriber premises to an Optical Line Terminal (OLT) located at the service provider's facility. While the economies for commercially deploying TDM-PON in the access arena as a near-term converged fixed-mobile optical networking transport infrastructure are quiet convincing, however, several technical issues must be addressed first before mainstream TDM-based PONs could be used as viable optical access networking technology that enables the support of a truly unified PON-4G access networking architecture or just a 4G mobile backhaul RAN architecture. The most notable issue is, TDM-PON is a centralized access architecture-relying on a component at the distant OLT to arbitrate upstream traffic, while 4G is a distributed architecture where, in particular, the 4G LTE standard requires a new distributed RAN architecture and further create a requirement to fully meshing the BSs (the X2 interface for LTE BS-BS handoffs requires a more meshed architecture) [1] [2] [3]. Thus, a converged PON-4G access infrastructure (or just a PON-based 4G mobile backhaul RAN) must be capable of supporting a distributed architecture as well as distributed network control and management (NCM) operations. The major weakness is that, mainstream PONs are typically deployed as tree topologies and the tree-based topology can neither support the distributed access architecture nor intercommunication among the access nodes (ONUs) attached to the PON. The key challenge in devising a truly unified PON-4G access architecture is how to reconcile the traditionally centralized PON's architecture and NCM operations with the typically distributed 4G's architecture and NCM operations.

Though numerous hybrid Fiber-Wireless network architectures have been expected to utilize the fiber-based PON access infrastructure to backhaul mobile traffic [5] [6] [7] [8], most of these architectures, however, have utilized the typically centralized tree-based PON topology, which can only support a centralized RAN architecture. Since both wireless and wireline segments of these hybrid architectures are assumed to be centralized, the key design requirements and challenges associated with overlaying a fully distributed mobile RAN segment (e.g., 4G LTE) over a typically centralized PON-based wireline segment, still remain unresolved. The purpose of this paper is to propose a novel, simple, and cost effective PON-based 4G mobile backhaul RAN architecture that enables redistribution of some of the intelligence (e.g., bandwidth/QoS provisioning) currently centralized in the Mobile Packet Core (MPC) platform out into the access nodes of the RAN. Specifically, this project devises a fully distributed ring-based EPON architecture that enables the support of a converged PON-4G mobile WiMAX/LTE access networking transport infrastructure to seamlessly backhaul both mobile and wireline multimedia traffic and services. We quantify the merits of utilizing a distributed EPON-based mobile WiMAX RAN architecture and those of traditional mobile WiMAX backhaul infrastructure. The salient feature of the proposed architecture is that it supports a fully distributed control plane that enables intercommunication among the access nodes (ONUs/BSs) as well as signaling, scheduling algorithms, and handoff procedures that operate in a distributed manner. We outline some of the key technical requirements associated with devising a truly unified fixed-mobile 4G LTE/flat mobile WiMAX access transport architecture that is built on top of a typically centralized PON infrastructure.

The proposed architecture supports several key networking features that significantly improve the performance of both the RAN and MPC in terms of handoff capability, overall network throughput and latency, and QoS support. Though we have chosen Ethernet-based PON and mobile WiMAX as representative techniques for fixed PON and 4G mobile access technologies, the proposed architecture and related operation principles are also applicable to other PON and 4G access networks such as GPON and LTE.

The rest of the paper is organized as follows: Section 2 gives an overview of the standalone ring-based EPON architecture and Section 3 discusses how to evolve the ring-based architecture to an all-packet-based converged fixed-mobile optical access networking transport infrastructure. Section 4 presents some of the key salient features enabled by the proposed architecture. Section 5 reports simulation results and Section 6 offers some concluding remarks.

2. Overview of the Standalone Ring-Based EPON Architecture

Figure 1 illustrates the proposed standalone ring-based PON architecture [9]. An OLT is connected to N ONUs via a 20 km trunk feeder fiber, a passive 3-port

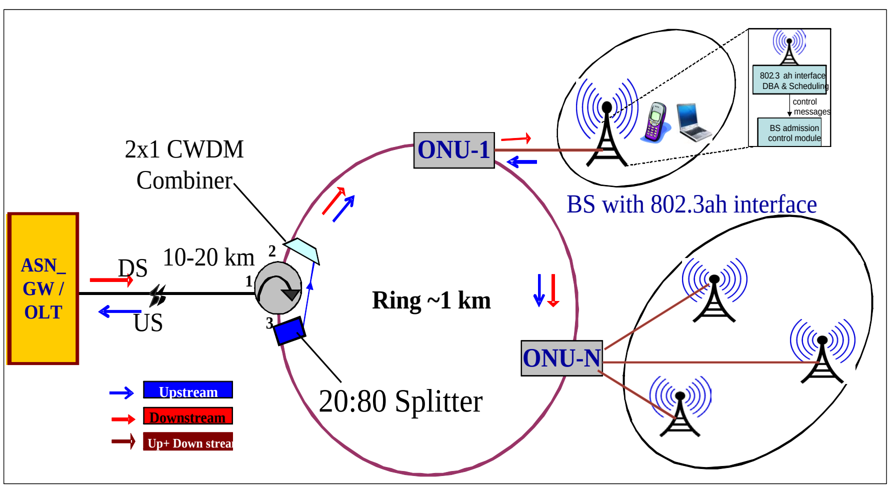

Figure 1. EPON-based RAN architecture.

optical circulator, and a short distribution fiber ring. The ONUs are joined with point-to-point links in a closed loop around the access ring. The links are unidirectional. Both downstream (DS) and upstream (US) signals (combined signal) are transmitted in one direction only. The US signal is transmitted sequentially bit by bit around the ring from one node to the next where it is terminated, processed, regenerated, and retransmitted at each node (ONU). Since US transmission is based on a TDMA scheme, inter-ONU traffic (LAN data and control messages) is transmitted along with upstream traffic destined to the OLT (MAN/WAN data) within the same pre-assigned time slot. Thus, in addition to the conventional transceiver maintained at each ONU (a λup US transmitter (Tx) and a λd DS receiver), this approach requires an extra receiver (Rx) tuned at λup to process the received US/LAN signal.

DS signal is coupled with the ring at port 2 of the optical circulator. After recombining it with the re-circulated US signal via the 2 × 1 CWDM combiner placed on the ring directly after the optical circulator, the combined signal then circulates around the ring (ONU1 through ONUN) in a Drop-and-Go fashion, where the DS signal is finally terminated at the last ONU. The US signal emerging from the last ONU is split into two replicas via the 20:80 1 × 2 passive splitter, placed on the ring directly after the last ONU as shown in Figure 1. The first replica (80%) is directed towards the OLT via circulator ports 1 and 3, where it is then received and processed by the US Rx (housed at the OLT), which accepts only MAN/WAN traffic, discards LAN traffic, and process the control messages, while the second replica (20%) is allowed to recirculate around the ring having been recombining with the DS signal via the 2 × 1 CWDM combiner.

The detailed ONU architecture is shown in Figure 2. Each ONU attaches to the ring via the input port of a 1 × 2 CWDM DMUX housed at each ONU (incoming signal at point A in Figure 2) and can transmit data onto the ring through the output port of a 2 × 1 CWDM combiner (outgoing signal at point E

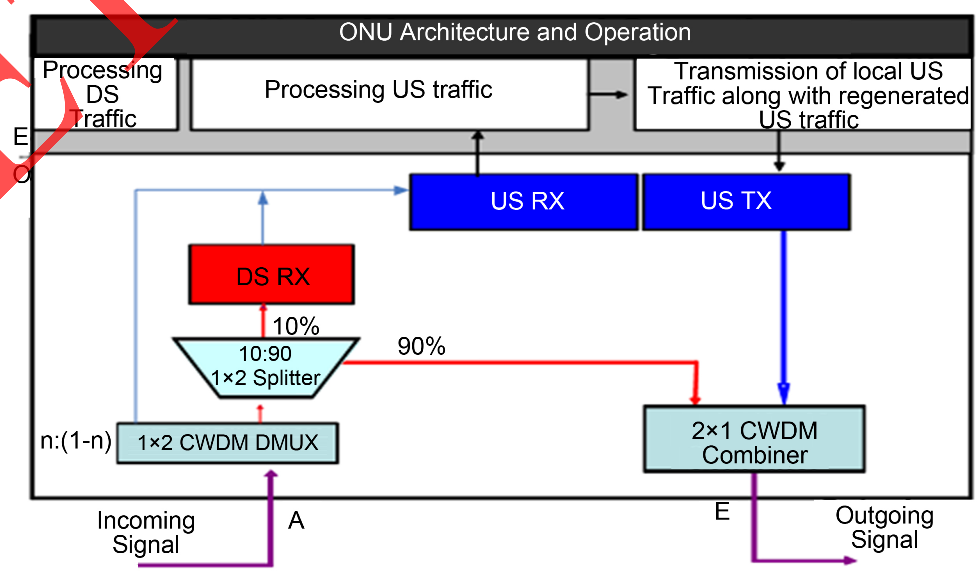

Figure 2. ONU architecture.

in Figure 2). At each ONU, the incoming combined signal is first separated into its two constituent: DS and US signals via the 1 × 2 CWDM DMUX housed at the ONU. As can be seen from Figure 2, the separated US signal is then received and processed via the US Rx housed at the ONU, where it is regenerated and retransmitted along with the ONU's own local control and data traffic.

As can also be seen from Figure 2, the separated DS signal is coupled with the input port of the (10:90) 1 × 2 passive splitter, which splits the DS signal into a small (10%) "Drop-signal-portion" and a large (90%) "Express-signal-portion". The small portion (Drop-Signal) is then received and processed by the DS Rx housed at the ONU. The remaining large portion emerging from the 90% output splitter's port (Express-Signal) is further transmitted through the ring to the next ONU, where it is, once again, partially split and detected at the corresponding DS Rx and partially transmitted towards the rest of the ring. Note that the Express-Signal recombines again with the retransmitted US signal (all previous ONU's regenerated US signals plus its own US signal) via the 2 × 1 CWDM combiner to form the outgoing combined signal (incoming signal for next ONU) that circulates around the ring.

3. Proposed EPON-Based Converged Fixed-Mobile Optical Access Networking Architecture

The standalone ring-based EPON architecture can be evolved around an all-packet-based converged fixed-mobile optical access networking transport infrastructure (or just 4G mobile backhaul RAN) by simply interconnecting (overlying) the ONUs with the 4G's BSs (WiMAX or LTE) and the OLT with LTE's access gateway (AGW) or WiMAX's access service node (ASN). Under this simple overlay (independent) model, the PON and 4G systems are operated independently where the RAN system is assumed to have its own NCM operations, independent of those for the PON. The BS is assumed to be collocated with an ONU or treated as a generic user attached to it. The ONU and BS can be interconnected as long as they support a common standard interface. Thus, the OLT, ASN/AGW, ONUs, and 4G BSs, are all assumed to support a common standard interface (e.g., 802.3ah Ethernet interface). Each ONU is assumed to have two different Ethernet port ranges; the first port range will support wired users, while the second port range will support mobile users. The port ranges will be used by the ONUs to identify and differentiate between mobile users versus fixed users.

3.1. Fully Distributed Control Plane

This work uses the control and management messages defined by the IEEE 802.3ah multi-point control protocol (MPCP) standard [10] that facilitate the exchange of control and management information between the ONUs/BSs and OLT. The protocol relies on two Ethernet control messages, GATE (form OLT to ONUs/BSs) and REPORT (from ONUs/BSs to OLT and between ONUs/BSs) messages in its regular operation. Direct communication among ONUs/BSs is achieved via the US wavelength channel {control messages along with both LAN and US data share the same US channel bandwidth (in-band signaling)}, which is terminated, processed, regenerated, and retransmitted at each ONU. Since control messages are processed and retransmitted at each node, the ONUs can directly communicate their US/LAN queue status and exchange signaling and control information with one another in a fully distributed fashion. Likewise, BSs can also directly communicate the status of their queues and radio resources and exchange signaling and control messages with one another. The control plane utilized among the ONUs/BSs can thus support a distributed PON-4G RAN architecture, where each access node (ONU/BS) deployed around the ring has now a truly physical connectivity and is, thus, capable of directly communicating with all other access nodes, in conformity with 4G standards.

Each access node maintains a database about the states of its queue and the state of every other ONU/BS's queue on the ring. This information is updated each cycle whenever the ONU receives new REPORT messages from all other ONUs. During each cycle, the access nodes sequentially transmit their REPORT messages along with both US and LAN data in an ascending order within their granted timeslots around the ring from one node to the next, where each REPORT message is finally removed by the source ONU after making one trip around the ring. The REPORT message typically contains the desired size of the next timeslot based on the current ONU's buffer occupancy. Note that the REPORT message contains the aggregate bandwidth of both fixed and mobile data buffered at each ONU's/BS's queue (requested size of next timeslot).

An identical dynamic bandwidth allocation (DBA) module, which resides at each access node (ONU/BS), uses the REPORT messages during each cycle to calculate a new US timeslot assignment for each ONU. ONUs sequentially and independently run instances of the same DBA algorithm outputting identical bandwidth allocation results each cycle. The execution of the algorithm at each ONU starts immediately following the collection of all REPORT messages. Thus, all ONUs must execute the DBA algorithm prior to the expiration of the current cycle so that bandwidth allocations scheduled for the next cycle are guaranteed to be ready by the end of the current cycle. Once the algorithm is executed, the ONUs sequentially and orderly transmit their data without any collisions, eliminating the OLT's centralized task of processing requests and generating grants for bandwidth allocations.

3.2. Dynamic Bandwidth Allocation and QoS Support & Mapping

Based on bandwidth demands, ONUs can be classified into two groups, namely: 1) lightly loaded ONUs that have bandwidth demands less than B_{MAX} 2) heavily loaded ONUs that have bandwidth demands more than B_{MAX}. B_{MAX} is defined as follows where, T_G is guard band interval, N is number of ONU's, T_{MAX} is EPON maximum cycle period and R_{EPON} is EPON data rate.

Bandwidth demand here is the aggregate of wired and wireless demand.

$$B_{\text{MAX}} = \frac{1}{N}\left[R_{\text{EPON}}\left(T_{\text{MAX}} - \left(N * T_G\right)\right)\right]$$

During each cycle, the DBA module keeps track of the unclaimed bandwidth from the set of lightly loaded ONUs. It then redistributes this excess bandwidth to other heavily loaded ONUs based on their requested bandwidth *i.e.* two ONUs requesting bandwidths B1 and B2 more than B_{MAX} will be assigned excess bandwidths proportional to B1 and B2. During each cycle, the lightly loaded ONUs with $R_i < B_{\text{MAX}}$ will contribute a total remainder cycle bandwidth:

$$B_{\text{Cycle\_Remainder}} = \sum_{i}^{L} \left(B_{\text{MAX}} - R_i \right)$$

The heavily loaded ONUs with $R_i > B_{\text{MAX}}$ will require a total over the limit cycle bandwidth:

$$B_{\text{Cycle\_OverLimit}} = \sum_{i}^{H} \left(R_i - B_{\text{MAX}} \right)$$

The total remainder cycle bandwidth can be fairly distributed amongst the heavily loaded ONUs to expand their maximum transmission window as follows:

$$\Delta B_i^{\text{extra}} = B_{\text{Cycle\_Remainder}} \left[\frac{R_i - B_{\text{MAX}}}{B_{\text{Cycle\_OverLimit}}} \right]$$

The granted bandwidth, B_{GH}, for a heavily loaded ONU_i is given by:

$$B_{GH} = \Delta B_i^{\text{extra}} + B_{\text{MAX}}$$

If R_i is the requested bandwidth of ONUi, B_{Granted} is the bandwidth granted using the proposed limited service-based distributed DBA scheme, then B_{Granted} can be expressed as:

$$B_{\text{Granted}} = \begin{cases} R_i & \text{If} \quad R_i \le B_{\text{MAX}} \\ R_i & \text{If} \quad R_i > B_{\text{MAX}} \,\&\, B_{\text{Cycle\_Remainder}} \ge B_{\text{Cycle\_OverLimit}} \\ B_{GH} & \text{If} \quad R_i > B_{\text{MAX}} \,\&\, B_{\text{Cycle\_Remainder}} < B_{\text{Cycle\_OverLimit}} \end{cases}$$

We call this process as Inter-ONU scheduling.

After each ONU is given fair share of its bandwidth then it runs Intra-ONU scheduling module to distribute its total granted bandwidth to wired and wireless users. Intra-ONU scheduling algorithm is given as follows:

$$B_{\text{wimax\_granted}} = \begin{cases} R_{\text{wimax}} & \text{if} \quad R_{\text{wimax}} \le 0.4B_{\text{granted}} \\ 0.4B_{\text{granted}} + \left\{ 0.6B_{\text{granted}} - R_{\text{wired}} \right\} & \text{if} \quad R_{\text{wimax}} > 0.4B_{\text{granted}} \,\&\, R_{\text{wired}} < 0.6B_{\text{granted}} \end{cases}$$

$$B_{\text{wired\_granted}} = \begin{cases} R_{\text{wired}} & \text{if} \quad R_{\text{wired}} \le 0.6B_{\text{granted}} \\ 0.6B_{\text{granted}} + \left\{ 0.4B_{\text{granted}} - R_{\text{wimax}} \right\} & \text{if} \quad R_{\text{wired}} > 0.6B_{\text{granted}} \,\&\, R_{\text{wimax}} < 0.4B_{\text{granted}} \end{cases}$$

where R_{wimax} is the bandwidth demand from WiMAX users and R_{wired} is the bandwidth demand from the wired users. Moreover, $B_{\text{wimax\_granted}}$ and $B_{\text{wired\_granted}}$ is the bandwidth granted to WiMAX and wired users respectively. Since, typically the wired data rate is more than wireless, it is given more share.

Typical mobile WiMAX MAC is centralized and connection-oriented. A connection identifier (CID) identifies each WiMAX connection. The main mechanism for providing a connection-based QoS is to classify and associate packets traversing the MAC interface to IP Service Flows (SFs), where each existing SF is identified by a 32-bit SF identifier (SFID) and is characterized by a set of QoS parameters. A CID is then mapped into an SFID provided that the SF has already been admitted (active SF). Once the MS's CIDs are terminated at the BS, they are mapped into the appropriate mobility tunnels based on their CIDs. The BS's packet classifier then maps their constituent IP SFs into their appropriate priority queues based on CIDs attached to the IP packets. To allow for traffic separation in the PON-based transport network (IP cloud connecting the BSs to the OLT/ASN), the BS maps each CID into a corresponding DiffServ Code Point (DSCP) in order to translate CID to transport-based QoS (DSCP). Using this mapping function, packets on a given CID associated with specific QoS parameters are marked with a specific DSCP for forwarding in the transport network. The MPC performs the mapping for DL packets.

On the other hand, EPON technology does not allow this type of CID-based connection. Rather, it supports only enhanced QoS through prioritization where packets are classified, stored in different priority queues and, then, scheduled for service according to their priorities. In a typical centralized EPON, QoS support is implemented via two independent scheduling mechanisms [10]: 1) inter-ONU scheduling: an aggregate bandwidth is allocated to each ONU by the OLT. 2) intra-ONU scheduling: each ONU makes a local decision to allocate the granted bandwidth and schedules packets transmission for up to eight different priority queues in the ONU. In the case of the proposed architecture, however, instances of the same DBA algorithm are executed simultaneously at each ONU. Thus, both scheduling mechanisms (inter and intra-ONU scheduling) are performed at each ONU-BS in a fully distributed approach, leading to the notion of integrating both scheduling mechanisms at the ONU. This enables the proposed distributed architecture to provide better QoS support and guarantees.

For simplicity, we assume that each ONU maintains three separate priority queues that share the same buffering space. We consider three priority classes P0, P1, and P2, with P0 having the highest priority and P2 having the lowest. These classes are used for delivering voice (CBR), video stream (variable-bit-rate or VBR), and best-effort (BE) data, respectively, as they allow easy mapping of DiffServ's Expedited Forwarding (EF), Assured Forwarding (AF), and BE classes into 802.1D classes. Since both EPON and mobile WiMAX classify data traffic in a differentiated services mode, an effective mapping mechanism is required between EPON priority queues and CID-based WiMAX IP flows. Specifically, the mapping has to identify which WiMAX IP flow should be stored in which EPON priority queue for equivalent QoS. EPON has up to eight different priority queues in each ONU, while mobile WiMAX supports five classes of service including Unsolicited Grant Service (UGS), extended real-time Polling Service (ertPS), real-time Polling Service (rtPS), non real-time Polling Service (nrtPS), and Best Effort (BE). In this work we assume that WiMAX UGS queues are mapped into EPON P0 queue, rtPs into P1, and BE into P2.

3.3. MAC Architecture of Hybrid ONU-BS

Ranging sub channel (responsible for uplink scheduling and channel allocation) informs BW requirement to the Hybrid ONU-BS and that requirement conveyed to OLT for BW assignment for that particular ONU for Wireless requirement. This can be a quick solution to connectionless PON and connection oriented WiMAX integration as shown in Figure 3.

4. Key Salient Networking Features Enabled by the Distributed EPON-Based Ran Architecture

The distributed ring-based architecture along with the supporting control plane enable the proposed EPON-based RAN architecture to support several key salient networking features that significantly enhance the performance of both the RAN and MPC in terms of handoff capability, overall network throughput and latency, and QoS support. These include:

4.1. Significance of Local Mobile LAN Traffic

Local mobile LAN traffic is defined here as bidirectional multimedia traffic exchange (including VOIP, video, and data sessions) between two mobile users served by two different BSs that are either collocated or attached with/to two different ONUs on the same ring (same PON domain). In the proposed EPON-based RAN architecture, this traffic is directly routed on the ring from the source BS directly to the destination BS and vice-versa as local LAN traffic, without the direct participation of either the OLT or the MPC (e.g., ASN/ AGW).

This is significant as the volume of VOIP calls and/or multimedia data exchange between all local mobile users that are served by the many different BSs attached to the same ring, is substantial. In a typical mobile WiMAX and/or LTE RAN, however, this traffic represents bidirectional US/DS data exchange between the two mobile users, which must be routed first from the source BS to the MPC (US traffic) and then from the MPC to the destination BS (DS traffic), and vice-versa.

Thus, a substantial volume of local mobile traffic and associated signaling overhead as well as the lengthy and complex processing of this traffic (e. g., sessions (LTE bearers/mobility tunnels) switch/set-up, retain, and tear-down and associated signaling commands from the BSs to the MPC and vice-versa) have been offloaded from the overburdened MPC to the access nodes (ONUS/ BSs) of the RAN. This has a significant impact on the performance of the MPC. First, it frees up a sizable fraction of the badly needed network resources as well as processing on the centralized serving nodes (e.g. ASN/AGW) in the MPC to handle Internet-bound traffic more efficiently. Second, it frees up capacity and sessions on the typically congested mobile backhaul from the BSs to the MPC and vice-versa.

4.2. Enhanced Handoff Capabilities

In both mobile WiMAX and LTE standards, hard handoff (HHO) is mandatory.

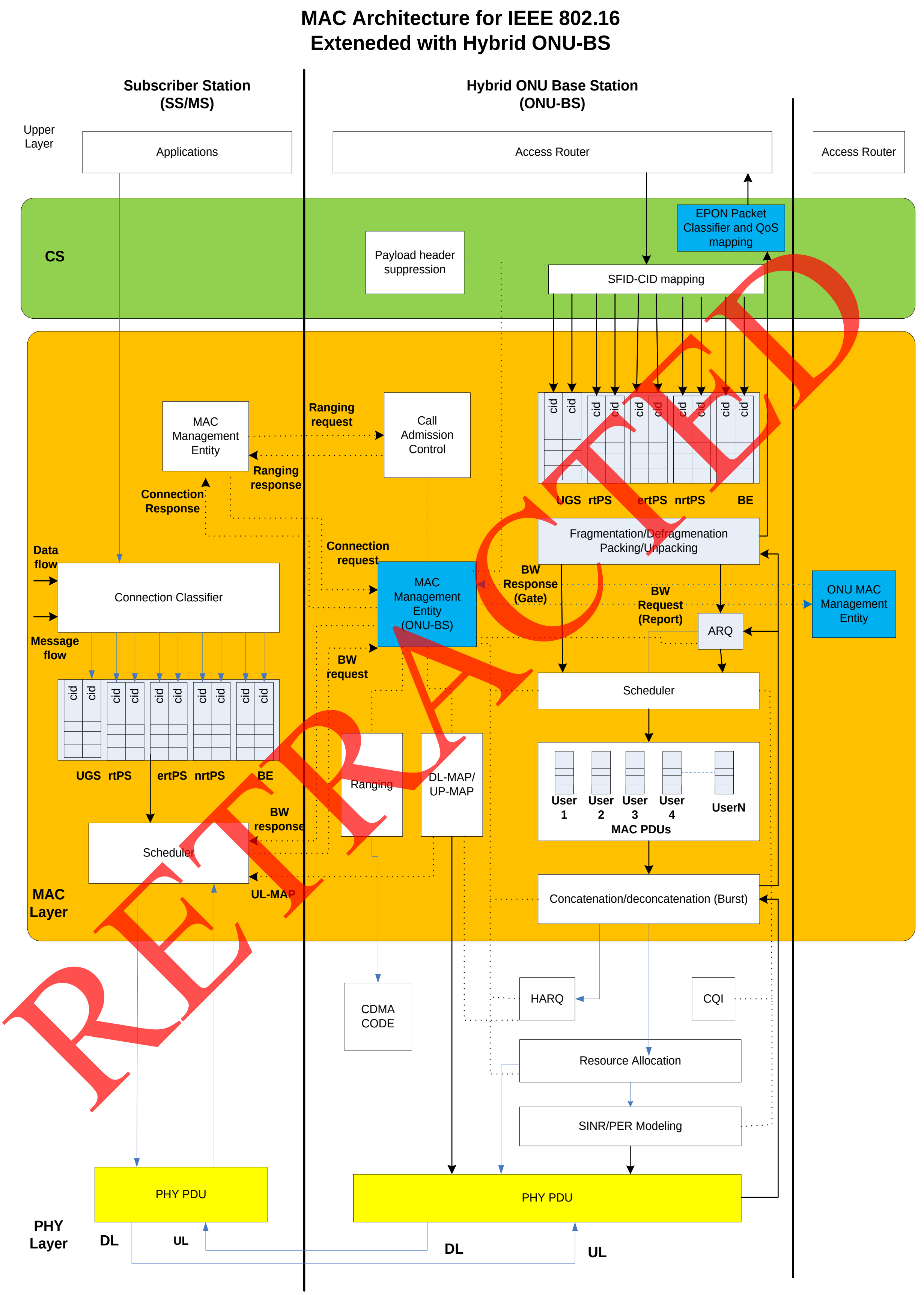

Figure 3. MAC architecture of hybrid ONU-BS.

The HHO is a break-before-make procedure, in which WiMAX mobile station (MS) and/or LTE user equipment (UE) breaks its connections with the serving BS (SBS) before setting up new connections with the target BS (TBS) and this is when traffic interruption and packet loss take place. By exploiting both the distributed nature of the ring-based RAN architecture and the supporting control plane, the proposed architecture enables the support of seamless and speedy inter-BS HOs in which, as the simulation results will show, packet loss is almost totally avoided and VoIP and other real-time IP applications can be adequately supported during HO. This is accomplished as follows:

1) When a MS/UE enters a domain served by the PON-RAN, it needs to register itself to the domain OLT's access router and updates the new location in its home subscriber server (HSS). As long as the MS/UE is roaming within the same PON-RAN domain, it does not need to reregister again.

2) The physical connectivity of both the SBS and TBS attached to the ring allows direct data exchange and intercommunications among them during HO (compare the simplicity and reduced latency and signaling overhead of this direct approach versus that of the typical 4G indirect bidirectional lengthy intercommunications and logical connectivity among the SBS and TBS via the MPC). Thus, once the TBS accepts the HO command, the SBS may immediately start to forward the buffered data (which have not yet been successfully sent to the MS), to the TBS directly on the ring as local LAN traffic. This is significant for creating the typical 4G logical connectivity among the SBS and TBS, which requires the lengthy process of signaling to the ASN/ AGW to coordinate the mobility-tunnel set up/switch from the SBS to TBS (and vice-versa) via the MPC, is totally avoided as well as the direct participation of the ASN/AGW/OLT.

3) For the HO to complete, the TBS signals the OLT/ASN to inform it that the HO is complete and to update its records with the new TBS, *i.e.*, to add TBS (and corresponding target ONU (TONU) that is collocated or attached with/to the TBS) to the forwarding list for the MS. Then, under the typical 4G RAN scenario, to resume normal operation and forward DS traffic to the TBS (or MS), the typical lengthy process of setting up a mobility tunnel form the MPC to the TBS is essential. Under the proposed PON-based RAN architecture, however, the scheduler at the OLT just simply redirects the MS's DS traffic from the DS queue that was serving the SONU/SBS before the HO (the OLT houses N dedicated DS queues, each serving one of the N ONUs-BSs attached to the ring) to the new DS queue that is now serving the TONU/TBS. To further reduce the signaling latency and packet loss during the HO, the OLT may concurrently broadcast DS traffic destined to the MS to both the SBS and TBS.

Seamless mobility that enables the support of VoIP and other real-time IP applications is one of the most important functionalities of the proposed converged architecture. The converged architecture must support seamless distributed HO procedures that conform to the distributed nature of the WiMAX architecture. In WiMAX, there is no soft handover support and at each HO, the user context (defines the radio-bearer configurations) and the coupling of mobility tunnels and radio bearers need to be relocated from one eNB to the other. LTE defines three mobility states of the MS, WiMAX-DETACHED, WiMAX-IDLE, and WiMAX-ACTIVE. In WiMAX-ACTIVE, when a MS roams between two WiMAX BS cells, "backward" handover is carried out. Based on measurement reports from the BS, the source cell determines the target cell and queries the target cell if it has enough resources to accommodate the MS. The target cell prepares radio resources before the source cell commands the MS to handover to the target cell. Because data buffering in the DL occurs at the BS, mechanisms to avoid data loss during inter-BS HOs are more critical compared to the 3G architecture where data buffering occurs at the centralized RNC and inter-RNC HOs are less frequent. The proposed architecture efficiently addresses this issue as described shortly. In this paper, HO is in scenario of intra-OLT HO. In this HO between two neighboring BSs (cells) that are located on the same ring and managed by the same OLT (same PON domain).

When a MS enters a domain served by a new PON-RAN, it needs to register itself to the new domain OLT's access router and update the new location in its home subscriber server (HSS). This is done by the new OLT that initiates a location update request to the HSS indicating the change of location to a new OLT. As long as the UE is roaming within the same PON-RAN domain, it does not need to re-register again. The remaining procedures follow the typical LTE registration process. Intra-OLT Handoff: the message sequence diagram of the intra-OLT HO procedure between the source and the target is shown in Figure 4.

Figure 4 shows both the control plane signaling messages (solid arrows) and the flow of the user data plane packets (dashed arrows). The MS sends measurement reports to the source BS, which may decide on the execution of a HO based on these reports. The source sends the coupling information and the MS context to the target requesting the preparation of a HO (HO Request Context Transfer). The target performs admission control to check whether the established QoS bearers of the MS can be accommodated in the target cell.

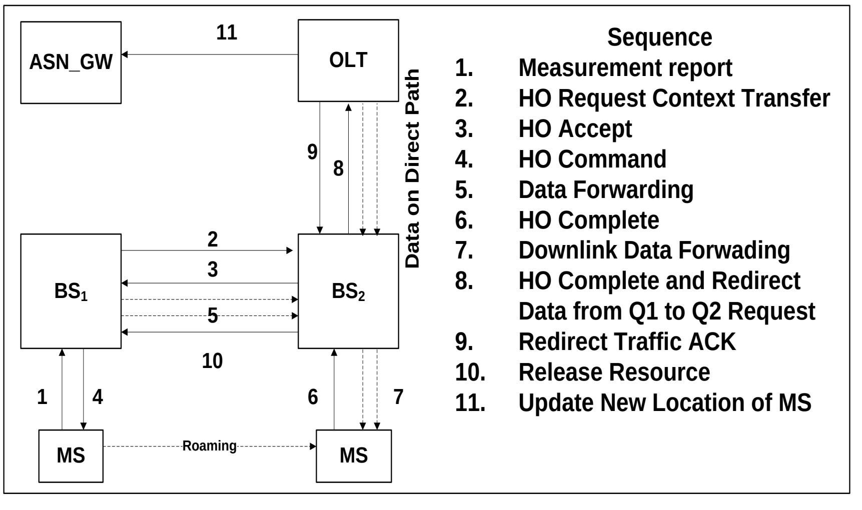

Figure 4. Sequence of the intra-OLT HO procedure between the source and the target.

Overall, the proposed EPON-based RAN architecture introduces several significant advantages over typical mobile WiMAX and/or LTE RAN and the advantages include: 1) significant reduction in the signaling overhead and handoff latency; 2) offloading a sizable fraction of the local mobile sessions switch/set-up and tear-down and associated lengthy and complex signaling processing from the overloaded MPC to the RAN's access nodes; 3) re-registration procedures to the HSS when the MS/UE moves from a BS to another is avoided as long as the MS/UE roams within the coverage area served by the BSs attached to the ring; 4) during inter-BSs HOs, no path switch/setup command is needed since the path (mobility tunnels) from MPC to the MS/UE remains unchanged.

5. Performance Evaluation

In this section, we first compare the performance of the proposed EPON-based mobile WiMAX RAN with that of the typically centralized WiMAX RAN. Two simulation programs were developed using OPNET, one for the typical WiMAX RAN and the other one for the EPON-based RAN. The performance metrics used here are network utilization, handoff throughput, and end-to-end (ETE) delay, where ETE delay is defined here as the time that elapses between the times of arrival of packets at the MS queues and the time of their arrival at the OLT/ASN (US traffic) or at the TBSs around the ring (local mobile LAN traffic). We consider the practical case of non-uniform traffic load in which, during a given period, some BSs might be lightly loaded/idle, while other BSs might be heavily loaded as shown in Table 1. At a given total network load, different BSs have different average traffic loads. Under this non-uniform traffic load scenario, the significance of utilizing PON-based RAN architecture is clearly established.

The following are the system parameters used for simulating the EPON- based RAN architecture: 1) a PON with 16 ONUs, each serving varying number of BSs (a minimum of one BS to a maximum of 10 BSs), depending on the varying traffic load.; 2) aggregate access link data rate from the MSs to a given ONU is 100

Table 1. Unevenly loaded base stations scenarios.

Heavily Loaded BSs		Lightly Loaded BSs		Total Network Load
BSs	BS Load	BSs	BS Load	
1	0.8488	15	0.1051	0.24
3	0.8488	13	0.1051	0.39
5	0.8488	11	0.1051	0.54
Super Heavily Loaded BSs		**Moderately Loaded BSs**		**Total Network Load**
BSs	BS Load	BSs	BS Load	
1	1.85	15	0.3262	0.68
2	1.85	14	0.3262	0.83
3	1.85	13	0.3262	0.98
4	1.85	12	0.3262	1.13
5	1.85	11	0.3262	1.28

Mb/s; 3) the RAN DS line rate (from the OLT/ASN to the ONUs/ BSs) is assumed to be same as the US line rate (from the ONUS/BSs to the OLT/ASN) and is equal to 1 Gb/s; 4) the average distance between the OLT/ASN and ONS/BSs is 20 km; 5) the buffer size in each ONU/BS is 1 Mbyte; 6) the maximum EPON cycle time is 2 ms for US transmission, while a standard fixed periodic cycle of 5 ms is assumed for WiMAX US transmission (from the MSs to the BS); 7) the IEEE 802.3ah MPCP REPORT/GATE message is 64 bytes; 8) we assume that all network traffic is just mobile traffic initiated by WiMAX' MSs, *i.e.*, traditional EPON's fixed wired end-user's traffic is assumed to be zero; 9) the total mobile traffic is divided equally among US mobile traffic and local mobile LAN; 10) the mobile traffic model used here is as described above in Section III B, with the three WiMAX CoSs (UGS, rtPs, and BE) are mapped into the three EPON CoSs (P0, PI, and P2), respectively; 11) the DBA scheme reported in [9] is used here to provision EPON US traffic, whereas the proportional fairness algorithm is used to provision WiMAX US traffic.

To have a fair comparison, all EPON-based RAN parameters listed above are also used for simulating the typical WiMAX except for the following: each and every dedicated link data rate of the typical WiMAX RAN in either US (16 dedicated point-to-point links between the ONUs/BSs and the OLT/ASN) or DS (16 dedicated point-to-point links between the OLT/ASN and the ONUs/BSs) direction is set to 62.5 Mbps. Thus, the aggregated link data rate in either direction is: 62.5 Mbps × 16 = 1 Gbps, which is equal to that of the EPON-based RAN.

Figure 5 shows the uplink utilization versus time at a given single network load of 0.83 and versus the total network load, respectively, for both the typical WiMAX and EPON-based RAN architectures. Figure 5 demonstrates that EPON-based RAN has much higher level of usefulness as well as stability with

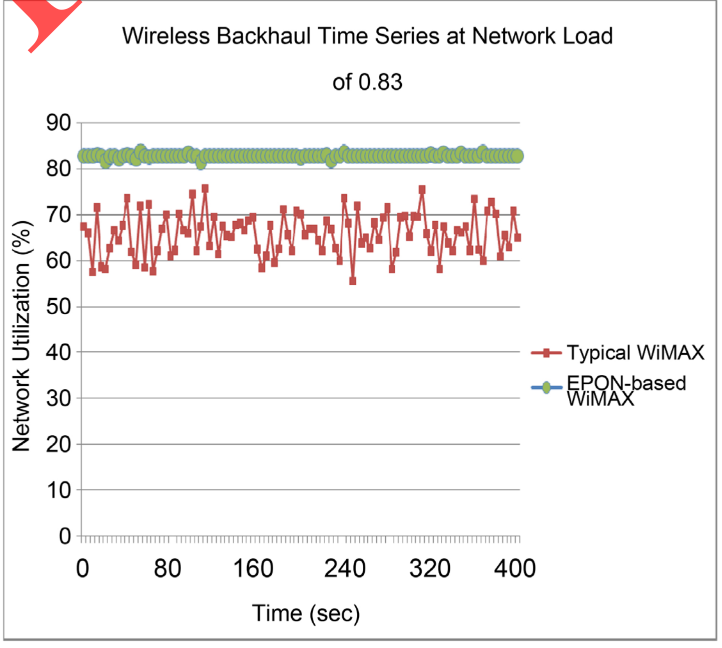

Figure 5. Uplink utilization time series at network load = 0.83.

less variation with time compared to typical WiMAX. This enhances the network's stability and predictability. Figure 6 shows that the average uplink throughput EPON-based RAN architecture is much higher than typical WiMAX architecture at higher total network load.

Figure 7 shows the ETE network delay for both rtPs and BE traffic for both the typical WiMAX and EPON-based RAN architectures. It can be seen from the figure that at lower load, the typical WiMAX has lower delay that the EPON-based RAN. This is expected as typical WiMAX traffic utilizes dedicated point-to-point links and the queuing delay are still almost zero. However, at higher traffic load, as expected, the EPON-based RAN exhibits much lower delay.

5.1. Packet Loss Analysis of EPON-Based WiMAX-Ring vs Typical WiMAX-Star Network

In this section, we compare the performance of our proposed EPON-based WiMAX network deployed in Ring architecture with EPON-based WiMAX

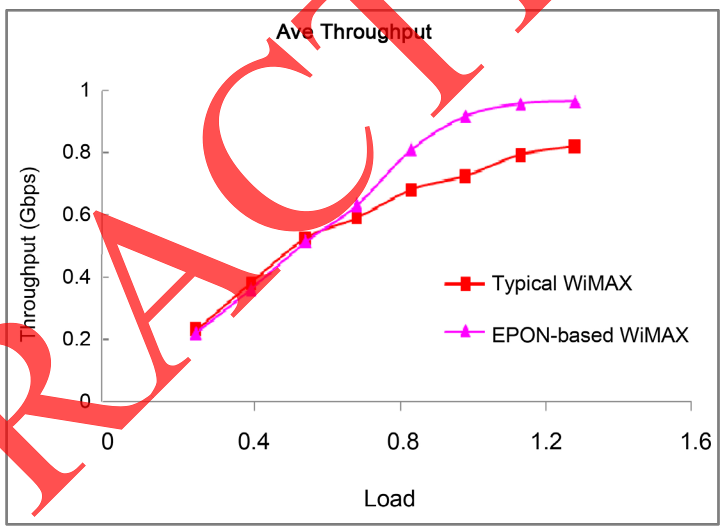

Figure 6. Uplink ave throughput.

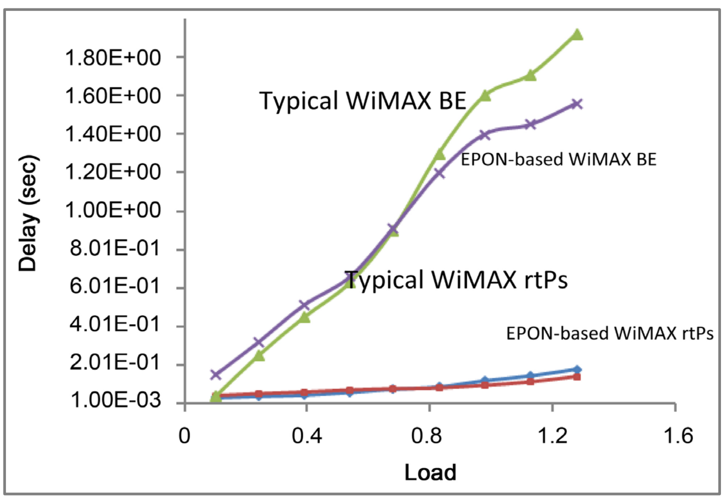

Figure 7. Average network ETE delay for rtPs and BE traffic.

deployed in typical star configuration. The primary focus of analysis is the packet loss measurement as we vary the local US traffic load. Simulation model used here is same as used in the previous sections, however the typical WiMAX network in this case is also EPON-based meaning that BS's of typical WiMAX network are integrated with ONU's. Moreover simulation is performed in a way to see the effect of packet loss in the DS as a function of US local traffic. Simulation is run three times and results are averaged as shown in Figure 8 and Figure 9.

As evident from Figure 8 and Figure 9, both ring and star EPON-WiMAX networks have similar packet drop pattern when the US local traffic load is 0.

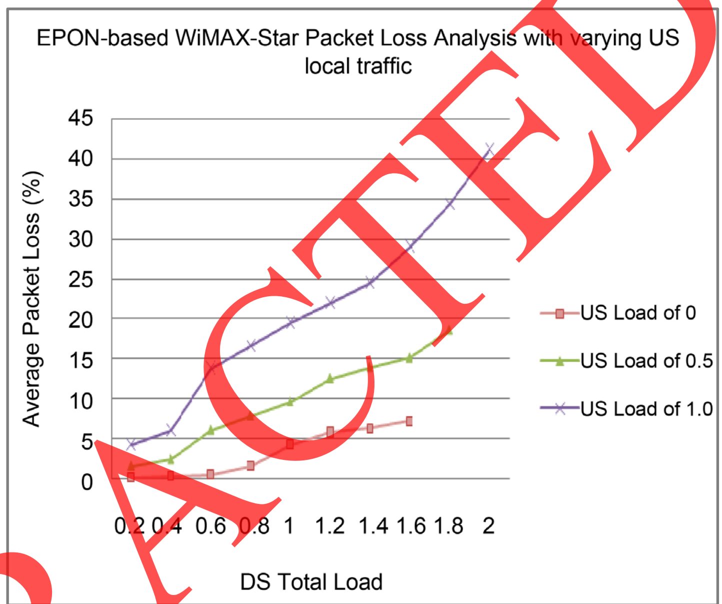

Figure 8. Average packet loss of DS traffic as a function of US local load in EPON-based WiMAX Star network.

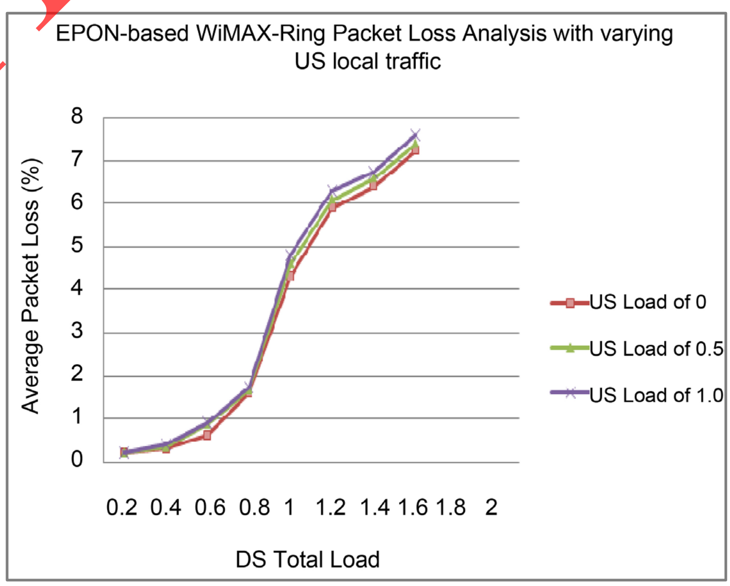

Figure 9. Average packet loss of DS traffic as a function of US local load in EPON-based WiMAX ring network.

However as the US local load is increased, EPON-based Ring network has similar packet loss pattern as when the US load was 0. On the other hand, this is not the case with typical star network where the packet loss increases exponentially when the local US traffic is increased as shown in Figure 8. The increase of packet drop in case of star network is attributed to the fact that the US traffic has to reach OLT from where it is transmitted as DS. Therefore, it obviously over-burdens the queues and US/DS resources. However, in the WiMAX-Ring network, the local US traffic is routed within the ring itself by the ONU's and this not only off-loads the OLT but also saves precious network resources and hence increasing the local US traffic doesn't affect the performance of the network. This is the key advantage of the proposed EPON-based WiMAX-Ring network.

5.2. Handover Scenario

One significant benefit of using WiMAX ring network would be less handover delay and packet drop. To validate this, we use a scenario where MS node moves from its Home Agent BS 4 to Foreign Agent BS 5. Uni-directional best effort application traffic is configured between MS and the server at the rate of 64 Kbps. MS from BS 4 has trajectory that starts moving around 110 seconds. Its movement converges to BS 5 between 115 to 120 seconds. Same scenario is set up for both traditional WiMAX backhaul and WiMAX BS's connected to ring network.aq. Parameters collected for comparison are the traffic received/dropped and handover delay vs. time. Handover delay is computed from the time the Mobile Station sends a MOB_MSHO-REQ message starting the handoff process until initial ranging with the new Serving BS successfully completed.

Figure 10 shows the throughput versus time for a MS during HO when moving

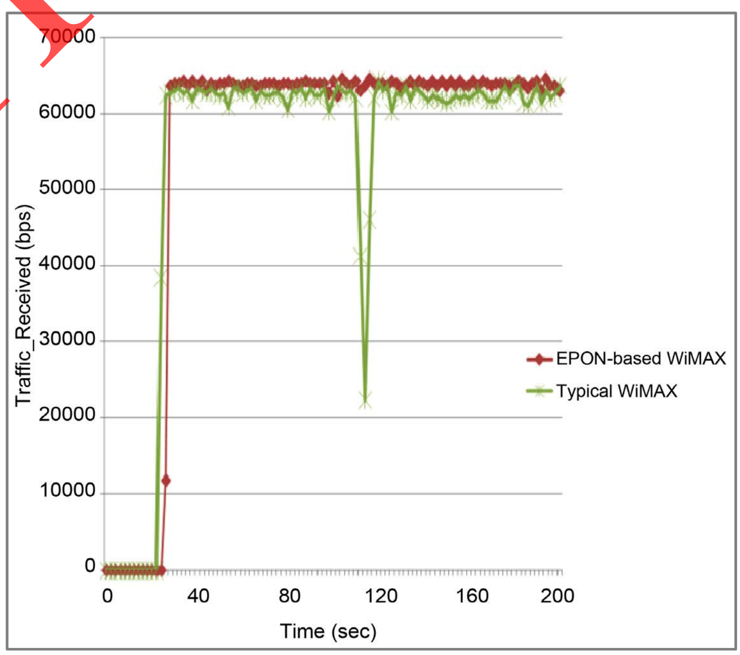

Figure 10. Traffic throughput during MS handoff.

away from the SBS attached to ONU1 and approaching the TBS attached to a neighboring ONU2 for both the typical WiMAX and EPON-based RAN architectures. A unidirectional BE application traffic is configured between MS and the server at the rate of 64 Kbps. The MS has trajectory that starts moving around 110 seconds and converges to the TBS between 115 to 120 seconds. Same scenario is set up for both traditional WiMAX and EPON-based RAN. Parameters collected for comparison are the traffic received/dropped and HO latency. HO latency is computed from the time the MS sends a MOB_MSHO-REQ message to initiate the HO process until initial ranging with the TBS is successfully completed. As expected, EPON-based RAN show lower HO latency (15 ms versus 20 ms) and almost no packets drop as compared to typical WiMAX.

6. Conclusion

This study presents a simple and cost effective PON-based 4G mobile backhaul RAN architecture supporting several key salient networking features that collectively contributes towards significant enhancement of the performance of both the RAN and MPC in terms of handoff capability, overall network throughput and latency, and QoS support. We quantify and compare between the merits of utilizing a distributed EPON-based mobile WiMAX RAN architecture and that of traditional WiMAX mobile backhaul infrastructure. Some of the key technical requirements associated with devising a truly unified fixed-mobile 4G LTE/flat mobile WiMAX access transport architecture that is built on top of a typically centralized PON infrastructure are also outlined in the work.

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