A Fully Distributed 10G-EPON-based Converged Fixed–Mobile Networking Transport Infrastructure for Next Generation Broadband Access

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***Abstract*—This work proposes and devises a self-healing hybrid tree/ring-based 10G-EPON architecture that enables the support of a converged PON–4G LTE access networking transport infrastructure to seamlessly backhaul both mobile and wireline business and residential services. The salient feature of the proposed architecture is that it supports a fully distributed control plane that enables intercommunication among the access nodes (optical network units—ONUs) as well as signaling, scheduling algorithms, and fault detection and recovery mechanisms. The distributed control plane enables each and every ONU to independently detect, manage, and recover most of the networking failure scenarios. This paper outlines and addresses the key technical requirements and differences between a PON-based converged architecture that utilizes a typically centralized architecture as the wireless segment of the hybrid architecture (e.g., Wi-Fi) versus one which utilizes a fully distributed architecture (e.g., 4G LTE). Physical layer performance simulations for the proposed architecture are also presented that show error free performance for the scalable architecture.**

***Index Terms*—Fiber–wireless; LTE; Next generation PON; Passive optical networks.**

I. INTRODUCTION

Passive optical network (PON)-based fiber-to-the-curb/home (FTTC/FTTH) access networks are being deployed around the globe based on two time-division multiplexed (TDM)-based standards: ITU-T G.984 Gigabit PON (GPON) and IEEE 802.ah Ethernet PON (EPON) [1–5]. 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. The ITU-T GPON standard supports asymmetric 2.5 Gbps downstream (DS)/1.25 Gbps upstream (US) channel capacity, while the IEEE EPON standard supports symmetric 1 Gbps. Since all users attached to a TDM-PON share a single DS/US transmission channel, the average dedicated bandwidth that can be supported in either direction is usually limited to a few tens of Mbps per user. With the growing demand for advanced multimedia services, it is anticipated that at least 100 Mbps per household will be required by 2015, and 1 Gbps by 2020 [6].

While current generation PON technologies seem to offer a satisfactory solution for present bandwidth demands, they certainly will not be able to meet future demands. To address this issue, the IEEE and ITU full service access network (FSAN) community have commissioned studies on defining possible smooth migration scenarios from the current Gigabit-class PON systems toward the next generation of PON (NG-PON) access systems that are compatible with the current PON systems but with much higher bandwidth [7–10]. The outcome of these studies, which is eloquently summarized in [9,10], endorses two potential candidate system architectures for NG-PON. The first is a 10G TDM-PON evolutionary growth architecture, termed NG-PON1, which supports coexistence with legacy PONs on the same optical distribution network (ODN) and is viewed as a mid-term upgrade. The second is a revolutionary disruptive architecture (termed NG-PON2) with no requirements in terms of coexistence with current PONs on the same ODN, and is regarded as a longer term solution.

NG-PON1 is further subdivided into two different 10G standards: the ITU-T XG-PON (X taken as the Roman sign for 10) and the IEEE 10G-EPON. The ITU-T XG-PON supports two mainstream systems including asymmetric 10/2.5 (DS/US) Gbps PON (termed XG-PON1), and symmetric 10/10 Gbps PON (termed XG-PON2). Likewise, IEEE 10G-EPON supports both asymmetrical 10/1 and symmetrical 10/10 Gbps solutions. Although many operators including BT and Verizon have performed several trials to test the 10G PON technology, most of these operators see no pressing need for 10G technology yet, as current/near-term wireline access bandwidth demand/growth does not justify the rollout of NG-PON [6]. However, as bandwidth demand increases, the economics change, thus making the deployment of NG-PON justifiable.

A. Motivation

To expedite and justify the near-term deployment of NG-PONs, in addition to wireline services typically supported

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by the current PON technology, a new access service that dramatically drives the demand for PON bandwidth must augment today's PON services. One of the most promising market segments that is expected to drive the demand for substantial PON services is mobile backhaul. Mobile backhaul, sometimes referred to as the radio access network (RAN), is utilized to backhaul traffic from individual base stations (BSs) to the radio network controller (RNC), which then connects the mobile operator's core network. Specifically, the exponential increase in mobile backhaul capacity required to support the fourth generation (4G) data-centric traffic including 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.

This, along with the inevitable trend toward all-IP/Ethernet transport protocols and packet-switched networks, has prompted many carriers around the world to consider the potential of utilizing the fiber-based NG-PON access infrastructure as an all-packet-based converged fixed–mobile optical access networking transport architecture to backhaul both mobile and typical wireline traffic. Because LTE is emerging as the global standard for wireless carriers worldwide and has been positioned as the dominant NG mobile technology (e.g., Verizon Wireless, AT&T, and T-Mobile are among the major U.S. wireless carriers that have opted for LTE), LTE is considered as the wireless segment of the envisioned NG converged architecture presented in this work. Thus, the envisioned NG-PON-based converged architecture is tailored to support the fully distributed LTE RAN architecture, as well as to conform to the 4G LTE standards [11–13].

Given the large investments many fixed-line carriers are making or have already made in PON-based FTTH/FTTC access infrastructure, the combination of NG-PON and native Ethernet, albeit with carrier-class enhancements, with a fiber-based access infrastructure is the most promising mix of technologies that ensures a cost-effective and future-proof converged fixed–mobile access transport infrastructure. The economic advantage of utilizing the existing fiber-based PON access infrastructure with Ethernet functionality is quite compelling compared to the choice of continuing to invest in legacy technology and/or the costly proposition of building up a new packet-based mobile backhaul infrastructure.

While the economics for commercially deploying NG-PON in the access arena as a near-term converged fixed–mobile optical networking transport infrastructure are quite compelling, two key outstanding technical hurdles must be addressed first before mainstream TDM-based PONs evolve as viable optical access networking technology that enables the support of a truly unified PON–4G LTE access networking architecture. These are as follows:

1. TDM-PON is a centralized access architecture relying on a component at the distant OLT to arbitrate upstream traffic and to detect and recover distribution and trunk fiber breaks, while 4G is a distributed architecture where the 4G LTE standards require a new distributed RAN architecture and further create a requirement to fully mesh the BSs [11–13]. Thus, a converged PON–4G LTE access infrastructure must be capable of supporting distributed networking functionalities and architecture. Exacerbating the problem is that mainstream PONs are typically deployed as tree topologies. However, tree-based topology can neither support distributed access architecture, nor intercommunication among the access nodes (ONUs) attached to the PON. The key challenge in devising a truly unified PON–4G LTE access architecture is how to reconcile the traditionally centralized PON architecture and network control and management (NCM) operations with the typically distributed 4G architecture and NCM operations.
2. Due to the inherent lack of simple and efficient resilience capabilities in tree-based PON topologies, specifically against failures in the distribution network, service resilience over previous generations of PONs has not been a strong requirement from operators. Since a single wavelength failure may affect the premium services delivered to thousands of fixed–mobile end users, the reliability offered by a converged access network to the services and customers it supports is one of the most important considerations in designing and deploying such a converged transport network. Thus, the envisioned converged access architecture must support efficient resilience mechanisms against both node (ONU) and distribution/trunk fiber failures.

In this paper, we propose a novel NG-PON-based converged fixed–mobile optical access networking transport architecture that addresses the aforementioned hurdles. Several simple, efficient, distributed fault detection and recovery schemes, supported by the distributed control plane, provide the required self-healing mechanisms for the proposed architecture. The proposed protection schemes are capable of protecting against both node and distribution/trunk fiber failures. We show that the purposely selected hybrid tree/ring topology featuring the distributed architecture along with the inherent self-healing mechanism of a ring-based architecture is the key for enabling

(a) direct intercommunication/connectivity among the access nodes (ONUs/BSs), allowing for the support of a distributed PON–4G RAN access architecture as well as for simply fully meshing the access nodes, in conformity with the 4G LTE standards, and
(b) support of fully distributed fault detection and recovery schemes, where, as will be shown below, each and every ONU can independently detect, manage, and recover most of the networking failure scenarios. This guarantees the reliable delivery of both fixed and mobile services.

Note that the proposed architecture builds upon a novel fully distributed approach and so is likely to be disruptive. Furthermore, because it does not support coexistence with legacy PONs on the same ODN, it can be classified as an NG-PON2-based architecture. Numerous hybrid fiber–wireless network architectures that utilize the fiber-based PON access infrastructure to backhaul mobile traffic have been proposed in the literature [14–20]. Most of these architectures, however, have assumed Wi-Fi as the wireless segment of the hybrid architecture, which is, similarly to the wireline PON-based segment, typically a centralized architecture. To the best of our knowledge, this is the first work that considers a fully distributed RAN architecture, e.g., 4G LTE, as the wireless

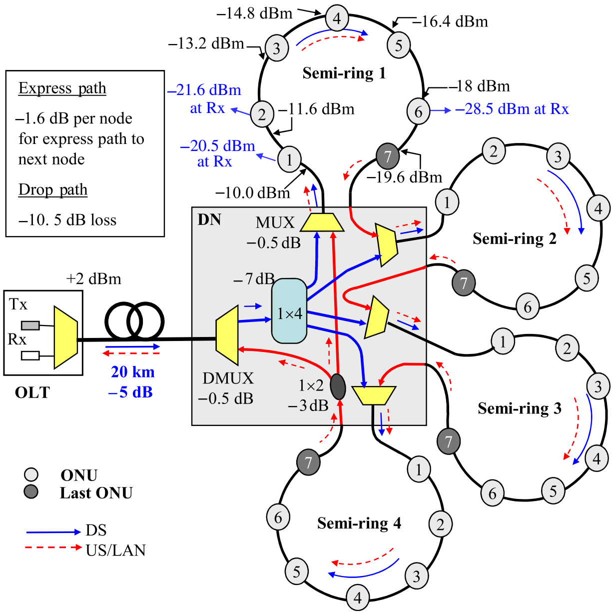

Fig. 1. (Color online) The proposed basic topology of the hybrid tree/ring PON architecture.

segment of a converged architecture. In addition, our proposed hybrid architecture meets the recommendation of the IEEE 802.3av 10G-EPON standard [7] and we show that it can support the required number of ONUs while meeting the reach, number of ONUs, and other performance requirements without the need of amplification often required in ring topologies [7]. It is important to emphasize that the detailed procedure of how to fully integrate the two access technologies (integrated model) is beyond the scope of this paper [21]; the focus of this work is, rather, on devising an NG-PON2-based networking architecture that enables the support of a unified access transport infrastructure for NG-PON and mobile 4G LTE technologies.

The rest of this paper is organized as follows. Section II presents the proposed self-healing hybrid tree/ring-based 10G-EPON architecture. Section III presents several fully distributed fault detection and recovery schemes, and Section IV discusses the recovery time and scalability analysis of the proposed architecture. Section V presents the NG-PON1-based converged fixed–mobile optical access networking architecture. Section VI presents simulation results, and Section VII offers some concluding remarks.

II. THE PROPOSED SELF-HEALING HYBRID TREE/RING-BASED 10G-EPON ARCHITECTURE

A. Normal State Operation

Figure 1 illustrates the proposed NG-PON1-based architecture. The OLT is connected to a set of ONUs via a 20 km trunk feeder fiber, a passive distribution node (DN), and a relatively short distribution fiber ring that is divided into four logical shorter semi-rings. Each semi-ring at the end of the trunk is assumed to have a 1–2 km diameter and interconnects a set of N ONUs for a total of $4N$ ONUs. The DN houses a 1×4 passive splitter, a (50:50) 1×2 passive splitter, a CWDM coupler (DMUX), and four 2×1 CWDM combiners (MUX). The set of ONUs are joined by point-to-point links in a closed loop. The links are unidirectional; hence, both DS and US signals (combined signal) are transmitted in one direction only.

The US signal is transmitted sequentially, bit by bit, around the ring (semi-ring 1 through semi-ring 4) 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 λ_{up} US transmitter (Tx) and a λ_{d} DS receiver (Rx)), this approach requires an extra receiver tuned at λ_{up} to process the received US signal.

The 1×4 splitter splits the DS signal originating from the OLT into four replicas. Each replica is directed to one of the four distribution semi-rings (via one of the four 2×1 CWDM MUXs housed at the DN), where each DS signal replica propagates through its corresponding semi-ring in a drop-and-go fashion until it reaches the last ONU of its own semi-ring, where it is terminated. As shown in Fig. 1, before entering its own semi-ring, each DS signal replica recombines with the re-circulated US signal emerging from the last ONU of the preceding semi-ring to form the combined signal. The combined signal then circulates around the ring, where the US component of the combined signal continues to circulate from one semi-ring to the next. The US signal emerging from the very last ONU (ONU$_N$ of the fourth semi-ring) is then split into two replicas via the 50:50 1×2 passive splitter housed at the DN (Fig. 1). The first replica (50%) is directed toward the OLT via the CWDM DMUX, where it is then received and processed by the upstream optical receiver (which accepts only MAN/WAN traffic, discards LAN traffic, and processes the control messages), while the second replica is allowed to re-circulate around the ring after recombining with the DS signal replica directed to the first semi-ring.

The detailed ONU architecture is shown in Fig. 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 Fig. 2) and can transmit data onto the ring through the output port of a 2×1 CWDM MUX (outgoing signal at point E in Fig. 2). At each ONU, the incoming combined signal is first separated into its two constituents: DS and US signals via the 1×2 CWDM DMUX housed at the ONU. As can be seen from Fig. 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. Note that the architectures of all the $4N$ ONUs are identical except for the last ONU of each semi-ring, where both the 2×1 CWDM combiner and the 1×2 passive splitter are removed from each of these four last ONUs (the DS signal is terminated and is not transported any further). Hence, the four last ONUs have lower insertion loss compared to the other ones. This minor difference between the general node and the last node, even though it may pose some inventory requirements, since two types of ONU node architecture are required, helps in obtaining a longer reach and subsequently a larger

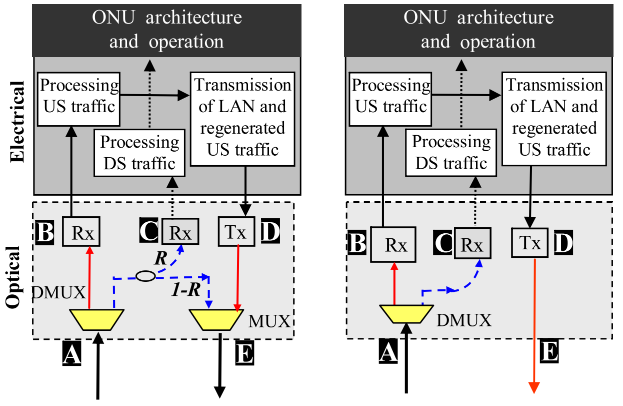

Fig. 2. (Color online) (a) ONU node architecture, (b) last ONU node architecture.

number of served ONUs. Note that it is the signal received by the Rx of the node next to the last node of each semi-ring (e.g., ONU_{N-1}), which experiences the worst ODN loss.

As can also be seen from Fig. 2, the separated DS signal is coupled to the input port of the $(R:1-R)$ 1×2 passive splitter (R is a small percentage whose default value is assumed here to be 10%), which splits the DS signal into a small ($R = 10\%$) "drop-signal-portion" and a large ($1-R = 90\%$) "express-signal-portion." The small portion (drop-signal) is then received and processed by the DS receiver 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 toward the rest of the ring. Note that the express-signal recombines again with the retransmitted US signal (all previous ONUs' regenerated US signals plus its own US signal) via the 2×1 CWDM combiner to form the outgoing combined signal (incoming signal for the next ONU) that circulates around the ring.

Since the four semi-rings form a closed loop, US traffic will circulate indefinitely unless removed. The process of removing, regenerating, and retransmitting the second replica of the upstream signal at each node (ONU) is implemented as follows: first, the US optical Rx (housed at each ONU) terminates all upstream traffic, examines the destination MAC address of each detected Ethernet frame, and then performs one or more of the following functions:

(1) the source node removes its own transmitted frames that complete one trip around the rings through re-circulation;

(2) once the destination address of the LAN traffic matches the node's MAC address, it is copied and delivered to the end users;

(3) all upstream traffic (including LAN and control frames), excluding that which matches items 1 and 2 above, is processed, regenerated, and then retransmitted by each node.

Three comments are in order here:

1. Since each ONU's upstream data has to traverse all remaining ONUs before reaching the OLT, this leads not only to forwarding overhead (and thus reduced effective throughput) but also increased delay. However, since US data are terminated and processed at each ONU, two significant benefits, which outweigh the shortcoming of bandwidth inefficiency, are automatically acquired:
   (i) Elimination of the typical utilization of the 10 Gbps US burst-mode transmitter/receiver and associated design challenges at the ONU/OLT. This facilitates and expedites the near-term deployment of symmetrical 10/10 Gbps NG-PON solutions.
   (ii) Alleviation of the typical limited US power budget problem, specifically for the most stringent 10G-EPON high power budget (>30 dB) class specifications (PR/PRX30) for symmetric DS/US 10 Gbps transmission.
2. Terminating US data at each hop (ONU) in such a multi-hop topology increases the delay and/or latency in the network. However, as will be discussed in Section IV below, in the case of a failure (a main focus of this work), when the protection switching process is activated, the switching time is much longer than all other delay components combined and, therefore, the dominant delay in the network in that case is mainly determined by the switching time. Another potential shortcoming of such multi-hop topology is that numerous optical-to-electronic-to-optical (OEO) conversions at each node may result in substantial energy consumption. The impact of the additional OEO in the energy consumption requires a detailed analysis to appropriately assess the energy efficiency of the proposed architecture, which is beyond the scope of this paper.
3. Finally, because the proposed ONU architecture is built upon a novel fully distributed approach, and serves a different range of application space as described earlier, it cannot coexist with legacy ONUs on the same ODN.

B. Protected State Architecture

The protected architecture, shown in Fig. 3, is identical to that of the normal working architecture except for the following additional components: i) a redundant trunk fiber and distribution fiber ring; ii) a redundant transceiver pair located at the OLT; iii) an automatic protection switching (APS) module located at each ONU; and iv) a redundant DN. As expected, due to the additional insertion losses of the additional components, the number of served ONUs is reduced. This also occurs at the typical tree PON architectures where redundancy can potentially reduce the number of served ONUs to half.

The APS module attached to each ONU monitors the state of its adjacent distribution fiber paths and the state of the ONU, and performs both fault detection and the APS functions. Each APS module houses low-loss 2×2 bidirectional optical switches (OSs) used for switching between working and protection fibers (Fig. 4). It also includes two detection circuits comprised of a 1×2 CWDM filter (to separate the combined DS/US signal), a control circuit to configure the OS, and a p–i–n detector (except the first ONU (ONU_1) of each semi-ring, which has two p–i–n detectors at the first detection circuit). The first detection circuit of each ONU (except the first ONU of each semi-ring, i.e., four ONU_1s) is used to detect only the US signal via

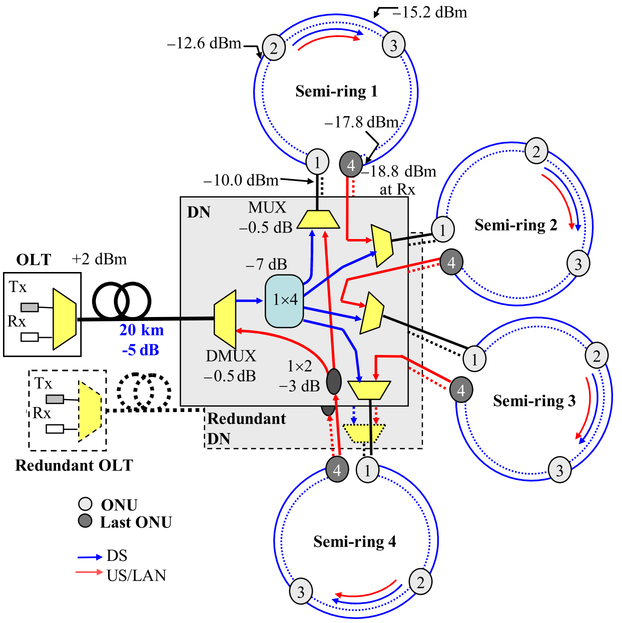

Fig. 3. (Color online) The proposed basic topology of the hybrid tree/ring PON architecture with protection scheme.

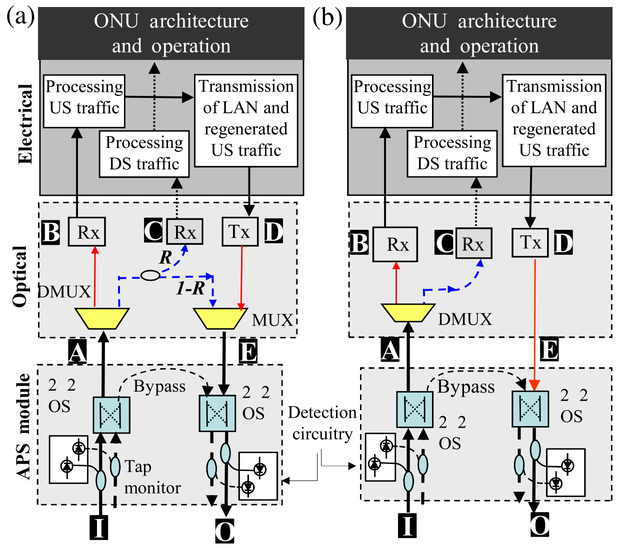

Fig. 4. (Color online) (a) ONU architecture with protection, (b) last ONU node with protection.

tapping a small portion (about 1%) of the incoming combined (DS/US) signal and passing it through the CWDM filter. On the other hand, the first detection circuit of each of the four ONU_1s is used to detect both US and DS signals. Likewise, the second detection circuit of each ONU is used to detect the outgoing US signal via tapping a small portion (about 1%) of the outgoing combined signal.

The failure scenarios in this paper are classified as trunk failure, general distribution link failures, and general node (ONU) failures. A general distribution link is defined here as a fiber segment that connects two adjacent ONUs except the following two special links, which require different detection and recovery mechanisms: (1) the distribution fiber segment that connects the first ONU of each semi-ring and the DN (the "first link"), for a total of four first links; (2) the distribution fiber segment that connects the last ONU of each semi-ring and the DN (the "last link"), for a total of four last links. All nodes around the ring are general nodes except the last ONU (ONU_N) of each semi-ring, which also requires different recovery mechanisms. As will be shown below, all links and nodes that are at the trunk-ring junction (trunk, first, and last links, first and last ONUs) have special significance.

It is important to emphasize that the proposed ONU architecture adds up some additional cost and complexity compared to legacy TDM-PONs, e.g., the DN including all its passive components, extra receiver at each ONU, the cost of relaying US traffic in the distributed part of such a multi-hop network, the additional cost incurred by the fact that the last ONU of each semi-ring is slightly different from all other network ONUs, and the two OSs for the APS module. This additional cost, however, may represent a very small fraction of the revenue generated via the new 4G mobile services supported by the proposed architecture (mobile backhaul). Note also that the elimination of the burst-mode Rx at the OLT, as well as the lower optical power for the Tx of the US paths relaxes the stringent requirements on these components and improves the cost benefit of the system.

Furthermore, while APS for protection purposes may have been used in other architectures in the past, it is the distributed architecture along with the utilization of the APS approach that enables the development of several fully distributed fault detection and recovery schemes, which are more efficient and economical compared to those of legacy tree-based TDM-PONs that are typically centralized. ITU-T G.983.1 recommended four possible protection schemes for legacy TDM-PONs, which duplicate fibers and equipment at the ONUs and OLT. These schemes are all centralized and can significantly alter the cost-effectiveness of PONs since they require many redundant components, as well as many spare fiber connections to each ONU. Also, the redundancy reduces the number of served ONUs to half of those served in tree PON architectures without the redundancy.

III. FULLY DISTRIBUTED FAULT DETECTION/RECOVERY MECHANISMS

In this section, we present several fully distributed fault detection and recovery schemes, where the proposed mechanisms are independently initiated and managed by the affected ONU. These distributed schemes are applicable to all networking failure scenarios except for four special failure scenarios, namely, trunk, first link, last link, and last node failures. In each of these four special cases, as will be shown below, all first and last ONUs as well as the OLT jointly participate in the detection and recovery process.

A. Fault Detection Mechanisms

In the event of a failure, normal ONU transmissions stop and the synchronization between the ONUs and the OLT is

TABLE I
ONU1 FAILURE DETECTION TABLE

Special fiber failure	US signal	DS signal
Trunk	✓	×
Last link	×	✓
First link	×	×

lost. This nullifies the timeslots granted to the ONUs for the US cycle. Once the failure recovery is complete, a new US cycle is initiated and timeslots must be recalculated for each ONU. This requires reestablishment of synchronization between the ONUs and the OLT. As will be shown below, this process is managed by the affected ONU. When a failure occurs, the REPORT message transmitted by the affected ONU typically contains a failure indication alarm message that includes specific instructions to both the OLT and any remote node that will be involved in the recovery process. Since the US signal is always present on the ring and trunk (a control message is always transmitted independently of the presence of US data), general failure detection scenarios (general distribution link and node failures) will primarily be based on the ONUs detecting the presence/absence of the US signal on their incoming/outgoing fibers.

If the first control circuit of a given ONU_n detects the absence of the US signal on its incoming working fiber; a general distribution link failure is assumed. This is the link that interconnects ONU_{n-1} with ONU_n. On the other hand, each of the three special links (trunk, first, and last distribution links) requires its own different failure detection mechanism. As shown in Table I, all three failure scenarios are detected and managed by one of the four first ONUs that is impacted by the failure, and each requires monitoring of both the US and DS signals. Thus, only four nodes are required to monitor both US and DS signals.

The detection and recovery processes for each node on the ring are identical, except for the last node (ONU_N) of each sub-ring, which requires a different mechanism. If the first control circuit of a given ONU_n detects the presence of the US signal on its incoming working fiber, while the second control circuit detects the absence of the same signal on its outgoing working fiber, a node (ONU_n) failure is assumed. While ONU_n detects its own failure, as will be shown, managing the failure is delegated to the next node on the ring (ONU_{n+1}).

For instance, the very first ONU (ONU_1 of semi-ring 1) manages the failures of both the very last link and node (ONU_N) of semi-ring 4, while ONU_1 of semi-ring 2 manages the failures of the last link and node of semi-ring 1. Thus, any one of the four ONU_1s may manage all four special failure scenarios including the three special links plus the last node failures (for instance, ONU_1 of semi-ring 2 manages the failures of the last link and node of semi-ring 1, the first link failure of its own semi-ring 2, as well as a trunk failure). Note that all of the four ONU_1s can concurrently detect and manage the trunk failure (absence of DS signal).

B. Recovery Process

In general, the recovery process is implemented via the participation of three cooperating network nodes including the affected node (ONU_n), OLT, and either ONU_{n-1} (for a link failure) or ONU_{n+1} (for a node failure). Note that the proposed fault detection and APS recovery mechanisms presented below for a single failure can also be combined to recover from combinations of concurrent double failures including trunk, distribution fiber, and node failures.

General link recovery: The successful completion of the recovery process of a given general link failure scenario involves the following steps:

1. To avoid false failure detection, once the affected node (e.g., ONU_n) detects a failure, it must wait for a predetermined timeout (T_{wait}).
2. ONU_n then performs the following three functions:
   (i) stops US transmission;
   (ii) switches to the incoming protection fiber; and
   (iii) floods the network with a failure indication alarm message (first REPORT message) that includes instructions to ONU_{n-1} (switch its transmission from outgoing working to outgoing protection fiber), all other ONUs (stop US transmissions), and OLT (stop DS transmission).
3. ONU_n keeps flooding the network with the failure message expecting its failure frame to loop back to it via ONU_{n-1}'s outgoing protection fiber. Once ONU_n receives back its failure frame, it starts flooding the OLT with a second REPORT message requesting DS resynchronization frames.
4. Once the OLT receives a resynchronization request from ONU_n, it transmits RESYNC frames to each ONU via the DS channel, and then resumes DS transmission. Upon receiving these frames, ONU_n initiates a new cycle (the recovery process is now complete) by transmitting its normal REPORT control message to all other ONUs.

Then, all ONUs sequentially send their REPORTs; once all reports are exchanged for dynamic bandwidth allocation (DBA) calculation of the new cycle, new grants are calculated and normal operation resumes.

General node recovery: The recovery process of a general node failure involves the following steps:

1. Once the APS module attached to a given node (e.g., ONU_n) detects its failure, it waits for a predetermined time period (T_{wait}) and then initiates the process of reconfiguring its OS to the bypass mode by switching the incoming signal directly to the outgoing protection fiber. Due to its failure, ONU_n cannot broadcast a failure indication message to its adjacent node (ONU_{n+1}) or to any other node.
2. While ONU_n's APS module is initiating the switching process, ONU_{n+1} detects the absence of the US signal on its incoming working fiber and erroneously assumes a distribution link failure between itself and ONU_n. ONU_{n+1} then starts the process of a general link recovery. Note that ONU_n cannot receive or process ONU_{n+1}'s request message. However, since it has already configured its OS to the bypass mode, it is indirectly implementing the request message.

(3) Once ONU$_{n+1}$ switches to the incoming protection fiber and ONU$_n$ switches to the outgoing protection fiber (i.e., ONU$_n$ is bypassed), ONU$_{n+1}$ receives back its failure message and proceeds with step (3) of the general link recovery process.

(4) Upon receiving resynchronization frames from the OLT, ONU$_{n+1}$ initiates a new cycle by transmitting its normal REPORT message to all other ONUs that reply with their own REPORT messages back to ONU$_{n+1}$. The absence of a REPORT message from ONU$_n$ is used by ONU$_{n+1}$ to correctly classify ONU$_n$'s failure now as a node failure.

(5) ONU$_{n+1}$ then starts the US-DBA calculation for the new cycle without ONU$_n$'s REPORT; new grants are calculated and normal operation resumes.

Special failures recovery: The recovery mechanism of each of the four special failure scenarios including the three special links (trunk, first, and last links), as well as the last node failure is almost identical and, in each case, requires the participation of nine nodes: OLT, four ONU$_1$s, and four ONU$_N$s, where all of these nodes must switch to the protection fiber (all four ONU$_1$s switch to the incoming protection fiber, while all four ONU$_N$s switch their transmissions from the outgoing working fiber to the outgoing protection fiber). All steps associated with the recovery of a general link/node failure are also applicable in these special cases except that the OLT's role is now expanded to include switching to the trunk protection fiber. There are two options to trigger the OLT's switching process. The first is to extend ONU$_1$'s failure indication alarm message to include an additional request to the OLT to switch its transmission to the protection fiber. The second option is a self-triggering mechanism, where the OLT itself must independently implement the switching process.

In the case of trunk, very last link, or node failure (of semi-ring 4), since the connectivity between ONU$_1$s and OLT is lost, the self-triggering mechanism is used; the OLT independently detects the absence of the US signal, stops all DS transmissions, and switches to the protection trunk fiber. In the case of any of the four first link failure scenarios, connectivity between ONU$_1$s and the OLT is not lost and the OLT relies on ONU$_1$'s request to switch its transmission to the protection trunk fiber (the self-triggering mechanism cannot be used in this case).

IV. RECOVERY TIME AND SCALABILITY ANALYSIS

Recovery time is defined here as the time elapsed from when a failure occurs to when service is fully restored and a new cycle resumes. The total recovery time is the sum of several delay components including timeout, fault detection time, REPORT/GATE transmission time/propagation delays/processing times, and OS switching time. In general, the switching time is much longer than all other delay components combined and, therefore, the total recovery time is mainly dominated by the switching time (about 13 ms) [22].

The scalability of the proposed working state architecture is mainly limited by the concatenated insertion losses encountered by the DS signal at each node. Since the US signal is regenerated at every node, typical limited US power budget problems, as well as the utilization of the 10 Gbps US burst-mode Tx/Rx and associated design challenges at the ONU/OLT, are totally eliminated. To examine the performance impact of the DS power budget under the assumption of a fixed (10:90) tap ratio at each ONU, we consider the worst-case scenario by calculating the total ODN loss incurred by the DS signal on its optical path from the OLT to the second to last ONU (ONU$_{N-1}$ of any one of the four semi-rings). The total ODN loss is due to all the passive optical elements (e.g., splitters, combiners, fibers, connectors, switches and splices) forming the optical path.

TABLE II
PARAMETERS USED IN THE MODEL

Type of loss	Path I–A–B (drop)	Path I–A–E–O (express)
Splitter—10/90 (A)	10.0	0.45
CWDM	0.5	2 × 0.5
Access ring fiber loss	0.0	0.125
Switch (I–A)/(E–O)	0.5	2 × 0.5
Total IL (dB)		
Working	10.5	1.60
Protected	11.0	2.60

There are two types of loss encountered by the DS signal at each node. The first type is along the path I–A–B in Fig. 4 (drop-component, IL$_{\mathrm{Drop}}$) and the second type is along the path I–A–E–O (express-component, IL$_{\mathrm{Express}}$). Table II quantifies both types of loss assuming typical commercially available CWDM components. The total ODN loss incurred by the downstream signal on its path to ONU$_{N-1}$ is

$$\mathrm{IL}^{\mathrm{ONU}_{N-1}}_{\mathrm{Total\_Loss}} = \mathrm{IL}^{\mathrm{fiber}}_{\mathrm{trunk}} + \mathrm{IL}_{1\times 4\ \mathrm{splitter}} + 2\mathrm{IL}_{\mathrm{CWDM}} + (N-2)\mathrm{IL}^{\mathrm{ONU}}_{\mathrm{Express}} + \mathrm{IL}^{\mathrm{ONU}}_{\mathrm{Drop}} + \mathrm{IL}^{\mathrm{fiber}}_{\mathrm{Ring}}. \qquad (1)$$

Assuming a 20 km trunk feeder fiber (with an insertion loss of 0.25 dB/km loss), the first ONU is 20 km away from the OLT, and the last ONU is 23.2 km away from the OLT (the ring circumference is about 3.2 km; 1 km diameter), and the IEEE 802.3av 10G-EPON highest power budget class (PR/PRX30) parameters [7] with a DS Rx (APD w/FEC) sensitivity of −28.5 dBm and OLT Tx optical power of +2 dBm [7], the total number of ONUs that can be adequately supported is equal to seven ONUs per semi-ring, when no protection is included (see Fig. 1). Thus, the proposed architecture can adequately support 28 ONUs in this case. For the hybrid tree/ring architecture that incorporates a protection mechanism, the signals encounter the additional OS and tap losses at each node. Assuming a 0.5 dB insertion loss per OS, the total number of ONUs that can be adequately supported by the protected architecture is reduced to four ONUs per semi-ring (Fig. 3). Thus, overall, the proposed architecture can adequately support 16 ONUs.

A. Scaling the Proposed Architecture

In the discussion of the previous section, we have used a fixed split ratio in all ONUs (e.g., 10/90). Nevertheless, doing so allows for higher optical power reaching the Rxs of the very first set of ONUs, while the power in the succeeding ONUs decreases continuously as the signal propagates through the ring resulting in wastage of optical power across this very first set of ONUs. For example, as shown in Fig. 1, the optical powers received by the DS Rxs at the first and second ONUs in each semi-ring are about −20.5 dBm and −22.1 dBm, respectively. Hence, there are excess optical powers of more than 8 dB and 6.5 dB at these Rxs (assuming a receiver sensitivity of −28.5 dBm) that could be used more efficiently throughout the rest of the system.

To scale the number of access nodes (ONUs) in the PON system, an ONU design that makes use of optimized optical splitters at each of the ONUs to adjust the received optical power (drop-signal) at levels equal to or barely above the Rx sensitivity is required. In this way, the excess optical power at the very first set of ONUs can be redirected and more efficiently used at the succeeding ONUs. First, we denote the two outputs of the $R:1-R$ 1×2 splitter as P_{OUT1} ("drop-signal" that is received by the DS Rx) and P_{OUT2} ("express-signal" that is transported to the next ONU). The tap split ratio is optimized at each ONU by selecting an appropriate R value that allows the optical power P_{OUT1} to be equal to or barely above the Rx sensitivity ($P_{\mathrm{Rx-sens}}$), while allowing the remaining optical power (P_{OUT2}) to be used in the rest of the system. The optimization algorithm is implemented as follows:

(1) The OLT Tx optical power (+2 dBm) [7], the ONU DS Rx sensitivity (−28.5 dBm) [7], and the ILs of the drop path ($\mathrm{IL}_{\mathrm{Drop}}$) and the express path ($\mathrm{IL}_{\mathrm{Express}}$) listed in Table II are taken as the inputs to the algorithm.

(2) The algorithm sets the initial tap split ratio R to 1% at the first ONU of each semi-ring (i.e., 1% of the signal will be directed to the ONU's DS Rx and 99% will be transported to the next ONU) and calculates the values of P_{OUT1} and P_{OUT2}; it then compares their values against the DS Rx sensitivity ($P_{\mathrm{Rx-sens}} = -28.5$ dBm) and performs one the following:
  (i) if $P_{\mathrm{OUT1}} \geq P_{\mathrm{Rx-sens}}$ and $P_{\mathrm{OUT2}} > P_{\mathrm{Rx-sens}} + \mathrm{IL}_{\mathrm{Drop}} + \mathrm{IL}_{\mathrm{accessfiber\_span}}$, R is registered as optimum and the algorithm proceeds to the next ONU and executes the same round of calculations,
  (ii) else if $P_{\mathrm{OUT1}} < P_{\mathrm{Rx-sens}}$ and $P_{\mathrm{OUT2}} > P_{\mathrm{Rx-sens}} + \mathrm{IL}_{\mathrm{Drop}} + \mathrm{IL}_{\mathrm{accessfiber\_span}}$, then R is incremented by a 1% step and another round of calculations is initiated at the same ONU,
  (iii) else if $P_{\mathrm{OUT1}} < P_{\mathrm{Rx-sens}}$ & $P_{\mathrm{OUT2}} < P_{\mathrm{Rx-sens}} + \mathrm{IL}_{\mathrm{Drop}} + \mathrm{IL}_{\mathrm{accessfiber\_span}}$, then this ONU is registered as the last ONU and R is set to 100%, which, as described above, corresponds to having no tap at the last ONU.

Figure 5 compares the system reach between the fixed 10:90 split ratio and the optimized split ratio approach. As can be seen from Fig. 5, the number of ONUs that can be adequately supported by the proposed hybrid architecture can be increased from seven to 11 ONUs when no protection scheme is implemented. On the other hand, when the APS mechanisms are included, the number of supported ONUs per semi-ring is seven (compared to four in the case of the fixed 10/90 split ratio). Thus, under the optimized split ratio, the number of ONUs that can be adequately supported by the proposed hybrid tree–ring self-healing architecture is scaled from 16 ONUs (fixed split ratio architecture) to 28 ONUs. We should note here that utilizing the optimized splitting ratio introduces some operational difficulties as ONUs will not be interchangeable. However, tunable or adjustable split ratio optical power splitters can be used to make the ONU design independent of the ONU location within the system [23,24]. Note that these tunable optical splitters do not need to be dynamically controlled. On the contrary, the split ratio can be set in the proper setting during the system provisioning and setup, without the need for dynamic tunability.

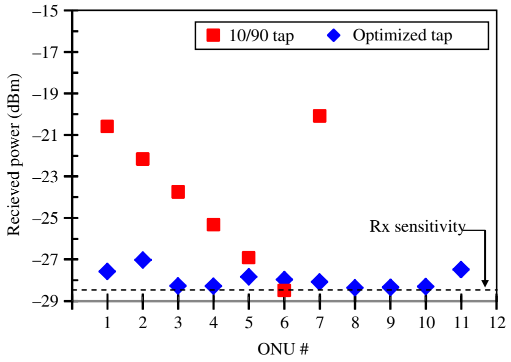

Fig. 5. (Color online) Power received at each ONU DS Rx under a fixed tap ratio of 10/90 and the optimized split ratio scheme.

It is anticipated that NG-PONs will target higher numbers of ONUs (64–128) compared to that supported by the proposed architecture (maximum of 32 ONUs). However, this is not a limitation since, under the proposed architecture, each ONU is tailored to support, in addition to typical wireline traffic, the aggregate mobile traffic of a few 4G BSs (four BSs, with about 50–100 Mbps traffic capacity in and out of each 4G BS). This means that the average aggregate bandwidth to be supported by the proposed ONU architecture (300–500 Mbps) is much higher than that to be supported by typical NG-PON ONUs (10 Gbps/128 ONUs = 78 Mbps/ONU). Thus, the proposed 10G-EPON architecture need only accommodate a smaller number of ONUs (e.g., 20–32 ONUs) compared to that of a typical NG-PON, which, as shown above, can be adequately supported by the proposed architecture. To scale beyond this number, a hybrid WDM/TDM scheme with 2–3 wavelength channels in either DS or US direction can be utilized. This can be achieved by replacing the 1×4 passive optical splitter in the DN with a WDM DMUX having M (e.g., $M > 16$) ports. Each port can support one semi-ring (with seven ONUs and protection scheme) and hence the total number of supported ONUs for the network can be $M \times 7$. For typical arrayed waveguide DMUXs with 16 or 32 ports and insertion loss of ~5.5 dB, the total number of served ONUs can exceed 100. Note that with this approach there is no need for a modification of the ONU architecture. In addition, our analysis was based on the specifications of the IEEE 802.3av 10G-EPON standardization [7] which specifies a +2 dBm OLT Tx. However, in an NG-PON2 architecture it may not be necessary to strictly follow the NG-PON standard. Hence, a higher optical power may be used. The use of a typical high power Tx (e.g., power +10 dBm) scales the network to 56 and 36 without and with protection, respectively. A combination of the two techniques (e.g., higher optical power Tx and WDM/TDM hybrid) can further increase the number of served ONUs.

V. NG-PON2-BASED CONVERGED FIXED-MOBILE OPTICAL ACCESS NETWORKING ARCHITECTURE

A. Overview of 4G Cellular LTE Architecture

LTE is a part of a broader Third Generation Partnership Project (3GPP) system called evolved packet system (EPS) that comprises a new all-IP mobile core network, the so-called "evolved packet core (EPC)" on the core side and LTE on the access side [11–13]. LTE consists of a new enhanced BS, called "Evolved NodeB (eNB)" per 3GPP standards. Specific EPC logical components are the mobility management entity (MME) in the control plane and the serving gateway (S-GW) and packet data network gateway (P-GW) in the bearer plane. In practice, both gateways can be implemented as one physical network element (defined as access gateway (AGW)), depending on deployment scenarios and vendor support. The EPS represents a migration from the traditional hierarchical system architecture to a flattened architecture that minimizes the number of hops and distributes the processing load across the network.

To illustrate some of the key technical challenges associated with devising a truly unified fixed–mobile 4G LTE access transport architecture that is built on top of a typically centralized PON infrastructure, it is first important to understand the novel and radical changes associated with the evolving 4G LTE RAN architecture [11–13]. First, the 3G-RNC is eliminated from the data path and its typical functions are incorporated into the eNB, including all radio control functions such as radio resource management, handover control, admission control, etc. Thus, the distributed nature of the LTE RAN architecture calls for new radio control algorithms and procedures that operate in a distributed manner. Second, with RNC functionality distributed to the eNBs, LTE creates a requirement for fully meshing the eNBs—some 10,000 to 40,000 for a mobile operator running a network in a "mature" market, to support inter-eNBs handover.

The implications of these radical changes are significant as they directly impact the proposed converged architecture, because it must, at a minimum, comply with these sweeping requirements as well. Thus, in a truly PON-based converged fixed–mobile 4G LTE access architecture, in addition to the stringent requirements for fully meshing the access nodes (ONUs/eNBs), regardless of how the eNBs and ONUs are interconnected, each eNB must independently implement typical radio control functions in a distributed approach without resorting to a central control entity (e.g., RNC/AGW), in conformity with LTE standards. This calls for a drastically different PON access architecture in which all the typically centralized OLT-based NCM operations are migrated to and independently implemented by the access nodes in a distributed manner.

B. Proposed Converged Access Architecture

The proposed NG-PON1 architecture can be evolved to an all-packet-based converged fixed–mobile optical access networking transport infrastructure by simply interconnecting (overlaying) the ONUs with the 4G's BSs (Mobile WiMAX and/or LTE). The ONU and eNB can be interconnected as long as they support a common standard interface (e.g., 802.3ah Ethernet interface). Under this simple overlay (independent) model, the PON and 4G systems are operated independently by considering an LTE BS (eNB) as a generic user attached to an ONU and/or collocated with it. The RAN architecture is assumed to have its own NCM operations, independent of those for the PON architecture. The proposed architecture eloquently complies with both of LTE's radical changes mentioned above via the purposely selected simple ring topology, which enables direct intercommunication/connectivity among the ONUs/eNBs, allowing for the support of a distributed PON–RAN access architecture as well as for simply meeting the stringent requirement to fully mesh the ONUs/eNBs.

C. Fully Distributed Control Plane

This work utilizes the control and management messages defined by the IEEE 802.3ah multi-point control protocol (MPCP) standard [2] that facilitate the exchange of control and management information between the ONUs/eNBs and OLT. The protocol relies on two Ethernet control messages, namely, GATE (from OLT to ONUs/eNBs) and REPORT (from ONUs/eNBs to OLT and between ONUs/eNBs) messages in its regular operation. Direct communication among ONUs/eNBs is achieved via the US wavelength channel where control messages along both LAN and upstream MAN/WAN data share the same US channel bandwidth (in-band signaling). The US wavelength channel is terminated, processed, regenerated, and retransmitted at each ONU/eNB.

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, eNBs 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/eNBs can thus support a distributed PON–RAN architecture, where each access node (ONU/eNB) 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 LTE standards.

Since the US channel is shared among all ONUs/eNBs, a distributed DBA scheme is required to efficiently and fairly provision US/LAN traffic among ONUs/eNBs. The control plane utilizes a time-division multiple access (TDMA) arbitration scheme to implement fully distributed DBA and packet scheduling algorithms in which the OLT/AGW is excluded from the arbitration process. It assumes a cycle-based upstream link, where the cycle size can have fixed or variable length confined within certain lower and upper bounds to accommodate the dynamic upstream traffic conditions. Note that under normal operation, all ONUs are synchronized to a common reference clock extracted from the OLT's downstream traffic. The synchronization scheme is necessary for the execution of the distributed DBA schemes.

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/eNB's queue (requested size of next timeslot).

An identical DBA module, which resides at each access node (ONU/eNB), 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 [5]. 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. An execution of the DBA algorithm produces a unique and identical set of ONU assignments. It is critical that the algorithm produces a unique outcome for any arbitrary set of inputs. Once the algorithm is executed, the ONUs sequentially and in order transmit their data without any collisions, eliminating the OLT's centralized task of processing requests and generating grants for bandwidth allocations.

Thus, supported by the distributed control plane, most of the typical radio control functions including radio resource management, handover control, admission control, etc., can be independently implemented at each eNB in a distributed approach without resorting to a central control entity (e.g., RNC/AGW), in conformity with LTE standards. Likewise, most of the typical wireline control functionalities including DBA, queue management, packet scheduling, and restoration algorithms can be independently implemented at each ONU in a distributed approach without resorting to a central control entity (e.g., OLT). These functionalities are typically implemented at the distant OLT/RNC in today's standalone centralized PON/RAN systems. A unique feature of this architecture, which requires further research, is the significance of local mobile LAN traffic. It is defined here as bidirectional traffic sourced from a mobile user that is served by a given BS (access node) attached to the ring and destined for another mobile user that is served by another BS (destination access node), which is also attached to the same ring (same PON domain). This traffic is directly routed on the ring from the source eNB directly to the destination eNB and vice versa as LAN traffic, without the direct participation of either the OLT or the EPC. Thus, a substantial volume of traffic as well as the lengthy and complex processing of this traffic has been offloaded from the EPC/OLT to the access nodes. This local traffic represents bidirectional upstream data exchange (including VOIP, video, and data sessions) between any two mobile users served by two different eNBs that are attached to the same ring. This is significant as the volume of voice calls and/or multimedia data exchange between local mobile users is substantial.

VI. Physical Layer Simulation

To demonstrate the capability of the proposed architecture, a physical layer simulation testbed was implemented using the VPIphotonics™ (VPI Systems Inc) simulation tool [25]. We modeled the architecture presented in Fig. 1 (without protection) and Fig. 3 (with protection) and with an ONU design that makes use of the optimized split ratio scheme. Since the US signal is regenerated at every node, typical limited upstream power budget problems (due to splitting loss at each node), as well as receiver dynamic range problems (long/short optical network paths and different splitting factors) are totally eliminated. In other words, the proposed architecture completely eliminates the typical utilization of the 10 Gbps US burst-mode transmitter/receiver and associated design challenges at the ONU/OLT. Furthermore, it alleviates the typical limited US power budget problem, specifically for the most stringent 10G-EPON high power budget (>30 dB) class specifications (PR/PRX30) for symmetric DS and US 10 Gbps transmissions [7]. Thus, we focus our simulation study on the DS transmission path.

The optical performance was tested for the IEEE 802.3av 10G-EPON most stringent DS power budget class (PR/PRX30) parameters with a DS Rx (APD with FEC) sensitivity of −28.5 dBm and OLT Tx optical power of +2 dBm [7]. The parameters used in our model are shown in Table II. An electro-absorption modulated laser with DS Tx optical power of +2 dBm and extinction ratio (ER) of 9 dBm was used [7]. For a target BER of 10^{-3}, a $Q = 4.8$ dB was used to obtain the aforementioned BER. As defined in the standards [7,8], if a system operates at a BER of 10^{-3}, the use of forward error correction (FEC) techniques and in particular Reed–Solomon code (255, 223), which is assumed here, allows for error free operation. Since this is an unamplified system, chromatic dispersion and optical crosstalk are the two dominant physical layer impairments.

Note, however, that since DS and US/LAN signals copropagate in the same direction, optical crosstalk can be a limiting factor if proper attention is not given to this when engineering the network. This crosstalk limitation arises from either the optical MUX/DMUXs or the OSs. In the 10G-EPON case the DS wavelengths are in the range of 1560–1580; hence thin film filter-based MUX/DMUXs are more appropriate, since they have a wider passband compared to fused fiber WDM couplers. This is required so that the IL of the DS signal is independent of the selection of the Tx wavelength. However, the thin film filter MUX/DMUXs have lower port isolation for one of the two ports (e.g., 12 dB), whereas the other port has high port isolation (e.g., 30 dB) [26].

It is critical to study the optical power for each of the DS and US/LAN signals as they enter the DMUX. The difference in port isolation can be addressed by varying the optical power

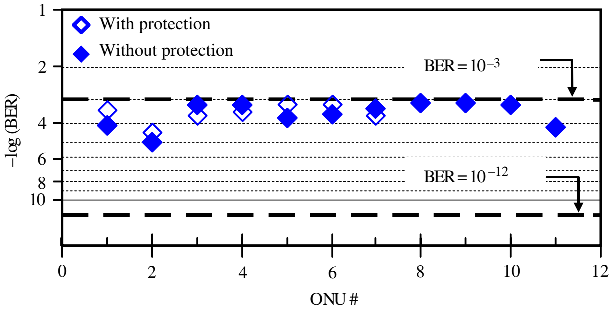

Fig. 6. (Color online) BER performance at each ONU under the optimized splitting ratio scheme. Only one semi-ring is shown for simplicity.

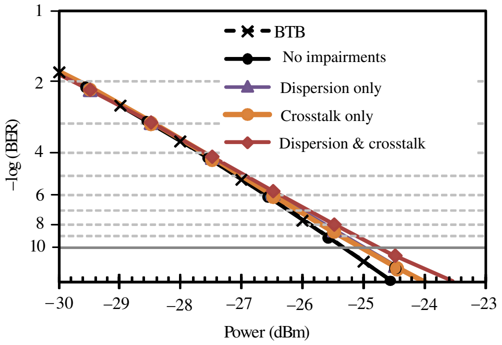

Fig. 7. (Color online) Contribution to BER degradation due to different impairments for the worst-case scenario.

of the incoming combined DS–US/LAN signals. Hence, we engineer the network so that the DMUX isolation and the unequal optical powers between the incoming DS and US/LAN signals work to our benefit. This is implemented as follows.

We select the optical power of the US/LAN Tx at −7 dBm so that adequate optical power is received at the OLT Rx. At the same time, the DMUX is selected with the poorer isolation port for the LAN port (e.g., crosstalk from the DS signal is 12 dB) because the optical power of the DS signal at the input of the DMUX is lower than the US/LAN signal. Note that the thin filter design can accommodate such a configuration. Commercially available DMUXs can be tailored to the preferred optical isolation configuration [26]. This approach allows us to engineer and operate the network with low crosstalk values for both DS and US/LAN paths and accomplish optimum BER performance. Figure 6 shows the DS signal BER performance at each ONU for any of the semi-rings, which also includes the impact of dispersion and crosstalk impairments on the system performance. Note that the ONUs for one semi-ring only are shown since all semi-rings in our architecture are equivalent and have equivalent BER performance. As shown in Fig. 6, all ONUs show BER $< 10^{-3}$ as required by the standards [7]. Error free operation is also obtained for the US/LAN paths. Similar results were obtained for the simulations that assumed an OLT Tx with +10 dBm optical power. Error free performance was achieved for the 56 and 36 ONUs supported by the network, without and with protection, respectively.

In order to better understand and determine the individual impacts of each of these impairments on the overall system performance, the following steps are implemented:

1. The back-to-back (BTB) Rx performance is evaluated.
2. The system performance without impairments (e.g., the dispersion and crosstalk mechanisms are disabled) is determined as follows: all optical transmitters that can produce optical out-of-band crosstalk are turned off and the fiber is replaced with attenuators with equivalent ILs.
3. The system with the presence of only the crosstalk terms is obtained by turning on all Txs that can produce out-of-band crosstalk terms, while keeping the attenuators that simulate only the fiber IL.
4. All optical transmitters that produce optical out-of-band crosstalk are turned off and the fiber is used in the system with the proper dispersion value; hence the system performance is determined in the presence of chromatic dispersion alone.
5. Finally, the actual system performance is determined in the presence of both dispersion and crosstalk impairments.

Figure 7 shows the BTB, system with no impairments, dispersion only, crosstalk only, and actual system performance (with both impairments) for the protected network for the worst-path scenario (signal originating from OLT and terminating at ONU$_{N-1}$). Worst-case performance is obtained at this ONU due to the combination of higher dispersion and lower received power. We see that when dispersion is taken into account, a power penalty of <0.5 dB (measured at a BER of 10^{-12}) is observed, and when we add the crosstalk the power penalty is <0.6 dB.

VII. CONCLUSION

We have presented a novel fully distributed optical access networking architecture for deploying NG-PON solutions in the access arena as an all-packet-based converged fixed–mobile optical transport networking infrastructure. We describe the performance of a self-healing hybrid tree/ring-based 10G-EPON architecture that enables the support of a converged PON–4G LTE access networking transport infrastructure to seamlessly backhaul both mobile and wireline business and residential services. The fully distributed control plane enables intercommunication among the access nodes, as well as signaling and fault detection and recovery mechanisms that operate in a distributed manner.

Several simple and efficient fully distributed fault detection and recovery schemes that provide the required self-healing mechanisms were described. In addition to the added flexibility and reliability of a distributed scheme, the proposed architecture eliminates the OLT's centralized task of failure detection and subsequent recovery scenarios. This reduces the additional processing complexities and delays at the OLT. Furthermore, through physical layer performance simulations we showed that the proposed architecture can support error free operation of 44 and 28 ONUs in the unprotected and protected topologies, respectively, when Tx optical power according to the IEEE 802.3av 10G-EPON standardization is used. Note that the number of ONU nodes supported by the system exceeds that mentioned in the IEEE 802.3av 10G-EPON standards. In addition, development of an NG-PON2 network allows for utilization of Txs with higher optical power than that specified in the current standards, and as such the numbers of supported nodes can increase to 56 and 36 for unprotected and protected schemes, respectively, when a typical +10 dBm optical power is used for the Tx.

Future work relates to the cost and energy consumption requirements analysis and comparison of the proposed architecture with other alternatives.

ACKNOWLEDGMENTS

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