Efficient OEO-based Remote Terminal Providing a Higher Power Budget of an Asymmetric 10/1G-EPON

Kwang-Ok Kim[1,2]/Jie-Hyun Lee[1]/Sang-Soo Lee[1]
[1]Department of Optical Internet Research
Electronics and Telecommunications Research Institute
218 Gajeong-ro, Yuseong-gu, Daejeon, 305-700, Korea
E-mail: {kwangok, jhlee, soolee}@etri.re.kr

Youn-Seon Jang[2]
[2]Department of Electronics Engineering
Chungnam National University
99 Daehak-ro, Yuseong-gu, Daejeon, 305-764, Korea
E-mail: jangys@cnu.ac.kr

Abstract—**This paper proposes the design of an efficient Optical-Electrical-Optical (OEO)-based Remote Terminal (RT) that can provide the higher power budget required for a long-reach transmission in an asymmetric 10 Gbit/s Ethernet Passive Optical Network (10/1G-EPON). The current 10/1G-EPON specification supports a maximum physical distance of only 20km in a 32-way split due to a power budget limitation. However, many service providers prefer a transmission reach of over 40km in a 64-way split for an efficient access network design. In this paper, the proposed OEO-based RT provides quad-port architecture for a cost-effective design, supports a high power budget of 58 dB through 3R signal regeneration, and offers over a 50 km reach and 128-way split per port with no modification of a legacy 10/1G-EPON system. In addition, it can satisfy a Packet Loss Rate (PLR) of 10^-10 in the downstream and upstream paths.**

Keywords-10Gbit/s EPON, Remote Terminal, Long Distance EPON, Reach Extender

I. INTRODUCTION

A 10 Gbit/s Ethernet Passive Optical Network (10G-EPON) is one of the fastest access technologies for providing next-generation ultra-broadband services to subscribers. In the current Fiber-to-the-Home (FTTH) optical access system, 1 Gbit/s EPON (1G-EPON) is being extensively utilized, particularly in Asian countries such as Japan, Korea, and China. However, with the recent growth of user traffic, a 10G-EPON is expected to provide end users with a more comfortable online environment in the near future [1].

The 10G-EPON specification was ratified as the IEEE 802.3av standard in 2009, and supports two configuration modes: symmetric mode, operating at a 10 Gbit/s data rate in both directions; and asymmetric mode, operating at a 10 Gbit/s in the downstream direction and 1 Gbit/s in the upstream direction [2]. Additionally, to reduce the costs for laying fibers and equipment, 1G-EPON and 10G-EPON use the same outside plant. In particular, an asymmetric 10G-EPON (i.e., 10/1G-EPON) can be easily applied to the Single Family Unit (SFU) market as a cost-effective next-generation solution, as its upstream transmission is identical to that of 1G-EPON, and its downstream transmission relies on the maturity of 10Gbit/s Ethernet devices.

The current 10/1G-EPON is defined into three classes of power budget: PRX10, PRX20, and PRX30. For compatibility with the PX10 and PX20 power budgets defined for a 1G-EPON, a 10/1G-EPON should mainly use the PRX10 and PRX20 power budgets [2][3][4]. These power budgets support channel insertion losses of 20 and 24 dB, respectively. Therefore, a legacy 10/1G-EPON can support a physical distance of only 20 km for Single Mode Fiber (SMF) in a 1:32 split ratio [5].

However, many network operators worldwide have placed an increased emphasis on combining an optical access network with a metro network by consolidating their central offices (COs) through a long-distance EPON solution. This combination results in a considerable reduction in Capital Expenditure (CAPEX) and Operating Expenditure (OPEX) budgets. In particular, EPON service providers require the high power budget to support long distances and a high split ratio such as 1:64@40 km. In addition, they hope to discover a solution satisfying the following key questions [5]: how to leverage the EPON architecture in rural areas, how to further increase subscriber density in their COs, how to decrease the connection cost per subscriber, and how to serve more people at a larger distance from the COs using IEEE802.3 EPON equipment.

To satisfy these requirements, we suggest the cost-effective 3R-type Optical-Electrical-Optical (OEO)-based Remote Terminal (RT) that can provide a higher power budget of 58 dB in a legacy 10/1G-EPON without modification. We also demonstrate the performance of the OEO-based RT using a commercialized 1G-EPON system.

The remainder of this paper is organized as follows. In Section II, we briefly review related work, while in section III we describe the detailed structure and design scheme of the proposed OEO-based RT. In Section IV, we show experimental results proving the effectiveness of our method and provide an analysis of its performance. Finally, we present a brief summary of our work in Section V.

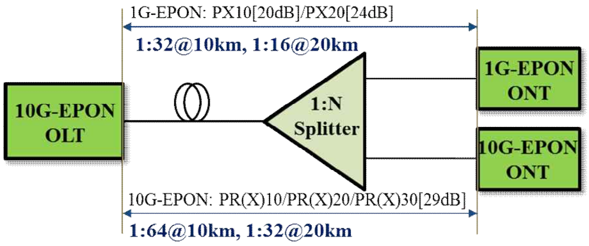
II. RELATED WORK

A long-distance 10/1G-EPON helps with network evolution, and reduces network levels and nodes from an increased high power budget. It can also provide significant cost savings by reducing the amount of electronic equipment and real estate required at a local exchange. Moreover, it can support service to small towns, suburbs, and rural areas [6].

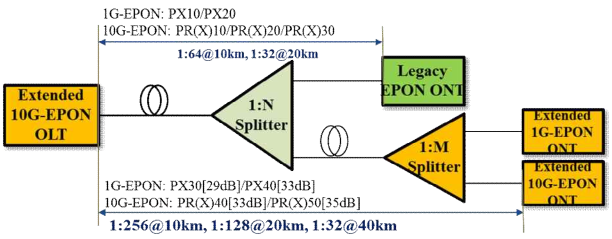
To achieve these purposes, the IEEE802.3 extended EPON study group is standardizing a new definition of the power budgets or reach extender solutions that can support a higher power budget [5]. Recently, several methods were suggested by the extended EPON study group. The first method is to define new power budget classes (i.e., PRX40 and PRX50) through an increase in the receiver sensitivity and launch power of the transmitter. The second method is to use an extender box providing optical amplification (OA) or OEO for passing data streams. The final method is to decrease Optical Distribution Network (ODN) loss through an improved splitter design [7][8].

As a first option, the current extended EPON study group is focusing mainly on the Physical Media Dependent (PMD) development of new power budget classes for application in the Multiple Dwelling Unit (MDU) market, as many operators would prefer a completely passive solution. However, much of the market demand for high split ratios of over 1:64 also requires a 40 km reach through a high power budget of over 35 dB. Among the methods described above, only the use of an extender box can easily satisfy this requirement. In an extended EPON study group, the line cost and power consumption per subscriber are also primary considerations when designing a high power budget solution for a 10G-EPON [9].

Figure 1 shows the 10G-EPON link structure ratified by the IEEE802.3av, and suggested by the extended EPON study group. This 10G-EPON can support a maximum transmission reach of 20 km in a 1:64 split ratio when using a PR(X)30 with a high power budget of 29 dB, as shown in Figure 1-(a). An extended PMD solution is provided through the insertion of an optical amplifier within the transceiver, and can support a power budget of 35 dB using the newly defined PR(X)50 PMD, as shown in Figure 1-(b). A 10G-EPON using a PR(X)50 PMD can support a long distance of up to 40 km in a 1:32 split ratio without an extender box in the remote node, and can also support a high split ratio of 1:128@20 km and a very high split ratio of 1:256 within a very short distance of 2 km [10].



(a)



(b)

Figure 1. EPON link structure: (a) Standardized 10G-EPON line structure ratified by the IEEE802.3av Working Group, and (b) the 10G-EPON link structure suggested by the ExPMDs Study Group.

However, an efficient 10/1G-EPON extender box solution supporting a cost-effective design, low power consumption, and a power budget of about 58 dB using the already developed PRX30 PMD has yet to be reported. Therefore, to support a physical distance of over 40 km and a greater than 1:64 split ratio under the worst-case ODN design scenarios without any problems, a 10/1G-EPON must apply a remote terminal as an extender box utilizing an active device. Active in-field components are also acceptable to many operators.

In this paper, our proposed OEO-based 10/1G-EPON RT can efficiently provide a high power budget of 58 dB using the following functions: 3R signal retiming, remote management through a Simple Network Management Protocol (SNMP) agent and an embedded Optical Network Unit (ONT), and upstream burst-to-continuous signal conversion.

III. PROPOSED OEO-BASED REMOTE TERMINAL FOR LONG-DISTANCE ASYMMETRIC 10G-EPON

Figure 2 illustrates the 10/1G-EPON link structure applied to the proposed OEO-based 10/1G-EPON RT in the remote node to support a long distance and high split ratio. A 10/1G-EPON system utilizing the 10/1G-EPON RT can provide a physical reach of over 60 km using an existing PX20 or PRX30 PMD in the trunk fiber, and can support a 1:256 or 1:64 high split ratio for a 5 or 10 km reach, respectively, using standardized 10/1G-EPON PMDs under the worst-case ODN design scenarios without any problems. That is, when considering an optical fiber loss of 0.4 dB/km, the 10/1G-EPON applied to our 10/1G-EPON RT can easily support a high split ratio of 1:256@ over 60 km from a central office to end users. This makes a flexible access network configuration possible.

The 10/1G-EPON RT mainly provides wavelength conversion and a signal retiming function based on 3R signal regeneration between a 10/1G-EPON OLT and 10/1G-EPON ONTs or 1G-EPON ONTs. In addition, it provides an optional upstream burst-to-continuous signal conversion to support WDM multiplexing in the trunk fiber. In particular, because the 10/1G-EPON RT is necessary for electrical power, it requires a remote management function and low-cost, low-power design.

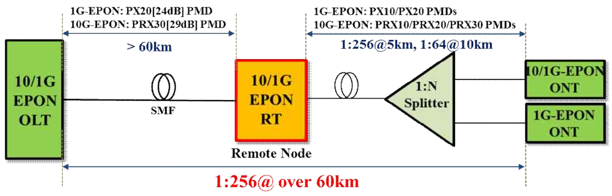


Figure 2. 10/1G-EPON link structure applied to the proposed OEO-based RT.

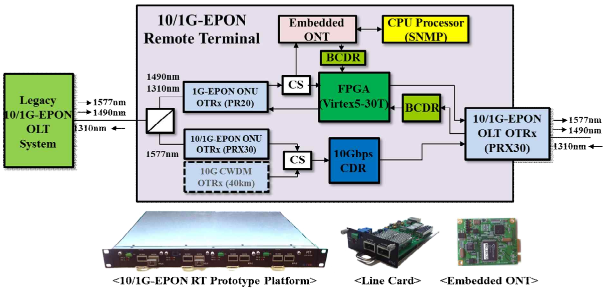


Figure 3. The design architecture and prototype of the 10/1G-EPON RT.

Figure 3 shows the design architecture and prototype of the developed 10/1G-EPON RT. The 10/1G-EPON RT is composed of a 3-port edge WDM filter for interconnection with the 10/1G-EPON OLT, a single FPGA for retiming of a 1 Gbit/s downstream signal, an embedded ONT for SNMP packet transmission to the 10/1G-EPON OLT, a CPU processor providing SNMP for remote management, a Burst-mode Clock & Data Recovery (BCDR) device for retiming of the burst-mode upstream signal, a Crosspoint Switch (CS) device for electrical signal division, a 1G-EPON ONU transceiver for receiving and transmitting a 1 Gbit/s optical signal, a 10/1G-EPON ONU transceiver for receiving a 10 Gbit/s downstream optical signal, and a 10/1G-EPON OLT optical transceiver for inter-connection with the ODN.

The 10/1G-EPON RT divides a 10 Gbit/s wavelength signal into 1 Gbit/s wavelength signals using a 3-port edge WDM filter. These wavelength signals are then inserted into each EPON ONU transceiver, and an optical signal is then converted into an electrical signal. These electrical signals are retimed by an FPGA and 10Gbit/s CDR in the electrical domain. The retimed signals then are retransmitted to the optical domain using a 10/1G-EPON OLT transceiver. In contrast, the signal retiming for a 1 Gbit/s signal in the upstream is performed using a BCDR device, which then converts the retimed upstream burst-mode signal into a continuous-mode signal through the FPGA.

The 10/1G-EPON RT is designed using a quad-port architecture, and provides a signal retiming function through a Virtex-5 FPGA (XC5VLX-30T) for lower design costs and power consumption. However, the signal retiming function for a 10 Gbit/s downstream signal is performed using a commercialized low-cost 10 Gbit/s CDR device. Each port of the 10/1G-EPON RT was also designed as a plug-and-play type.

To provide remote management of the 10/1G-EPON RT, an embedded ONT is activated using a 10/1G-EPON OLT system with a CS device, BCDR device, and FPGA. An embedded ONT is provided using a compact-type of commercialized 1G-EPON ONU MAC as shown in Figure 3. That is, the 10/1G-EPON RT is connected with a 1 Gbit/s data channel of the 10/1G-EPON OLT, and only port 0 of the 10/1G-EPON RT is supported.

An embedded ONT receives a downstream signal through a CS device, and transmits an upstream signal to the 10/1G-EPON OLT using a BCDR device and FPGA, as

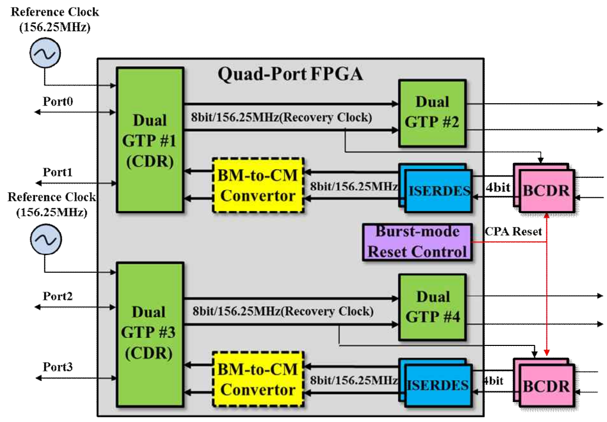


Figure 4. A Internal structure of the FPGA for the signal retiming of 1 G-EPON.

shown in Figure 3. This upstream signal is merged with the upstream signal of port 0. The CPU processor gathers and manages the status of the installed optical transceivers based on the SFF-8472 and FPGA through a local CPU interface. The CPU processor is also connected directly with a User Network Interface (UNI) port of an embedded ONT at the electronic domain using a CS device without an external optical tap (e.g., an optical splitter), which is unlikely to have been used in previous methods. The 10/1G-EPON RT can use as a hybrid-type remote terminal by replacing the 10/1G-EPON and 1G-EPON ONU optical modules with 10 Gbit/s and 1 Gbit/s Coarse Wavelength Division Multiplexing (CWDM) optical modules.

Figure 4 illustrates the internal architecture of the signal retiming logic in the FPGA used to recover the 1G-EPON signals. Because the 10/1G-EPON OLT transceiver does not require a burst-mode reset signal, the 10/1G-EPON RT can easily provide a signal retiming function using the CDR within the FPGA for a downstream signal and the BCDR device for an upstream signal.

In the downstream direction, the FPGA provides a 3R signal retiming using a recovery clock extracted from the CDR, which is included in the dual Gigabit Transfer Protocol (GTP). The dual GTP extracts a 156.25 MHz recovery clock and 8-bit data from a 1.25 Gbit/s continuous-mode downstream signal using an external 156.25 MHz reference clock. This recovery clock is then used as a reference clock source necessary for an external BCDR device. On the other hand, in the upstream direction, the 10/1G-EPON RT performs a signal recovery using the BCDR device and transmits this recovered signal to an Input Serializer/Deserializer (ISERDES) as shown in Figure 4.

Also, a burst-mode reset signal for a BCDR device is generated by a Loss of Signal (LOS) output from the 10/1G-EPON OLT transceiver. The BCDR device aligns with the input data within the 12-bit start of the preamble, and changes a 1-bit serial signal into a 4-bit parallel signal to provide the lower clock speed at the data transmission to the FPGA. The burst-to-continuous convertor in the FPGA optionally changes a burst-mode signal into a continuous-

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mode signal through the insertion of a particular pattern (e.g., h'55) during the guard time.

In this paper, our proposed OEO-type 10/1G-EPON RT can provide low-power consumption and a cost-efficient design through a quad-port structure using a single FPGA and generalized low-cost EPON optical transceivers.

IV. Experimental Setup and Performance Results

The experimental setup for a performance measurement of the proposed OEO-based 10/1G-EPON RT is shown in Figure 5. As there is no commercialized 10/1G-EPON systems at present, we used the existing 1G-EPON system and a 10 Gbit/s jig board for the performance test of the 10/1G-EPON RT. The legacy 1G-EPON system generates downstream and upstream signals with a line rate of 1.25 Gbit/s, while the 10 Gbit/s jig board transmits a downstream signal with a line rate of 10.3125 Gbit/s using a Pulse Pattern Generator (PPG).

For the 1 Gbit/s path link configuration, we used a single legacy 1G-EPON OLT and two 1G-EPON ONTs, and connected the trunk fiber using a 50 km SMF between the 1G-EPON OLT and 10/1G-EPON RT. In addition, we configured a fixed 5 dB attenuator and 128-way split as the drop fiber between the 10/1G-EPON RT and 1G-EPON ONUs. For the 10 Gbit/s path link configuration, we also connected the trunk fiber using a 20 km SMF between the 10 Gbit/s jig board and 10/1G-EPON RT, as the 10/1G-EPON PMDs used in this experimental setup are unable to provide a transmission reach of 40 km owing to a dispersion problem.

The 1G-EPON used optical modules supporting both the IEEE 802.3ahTM-2004-PX20 and PX10 [3][4], while the 10/1G-EPON RT used a 1G-EPON ONU optical module supporting an IEEE 802.3ahTM-2008-PX20, a 10/1G-EPON OLT, and an ONU optical module compliant with an IEEE802.3avTM-10/1GBASE-PRX30 [2]. The 1.25 Gbit/s and 10.3125 Gbit/s optical signals generated were merged using a 3-port edge WDM filter, and then separated again into 1.25 Gbit/s and 10.3125 Gbit/s optical signals using a 3-port edge WDM filter in the 10/1G-EPON RT. The 10/1G-EPON RT transmits the retimed 1.25 Gbit/s and 10.3125 Gbit/s optical signals to the optical splitter via the 10/1G-EPON OLT optical module. The optical power budget in the trunk fiber is adjusted using a Variable Attenuator (VA) value. In this experimental setup, the insertion losses in the trunk and drop fibers are about -12.8 dB and -26.8 dB, respectively.

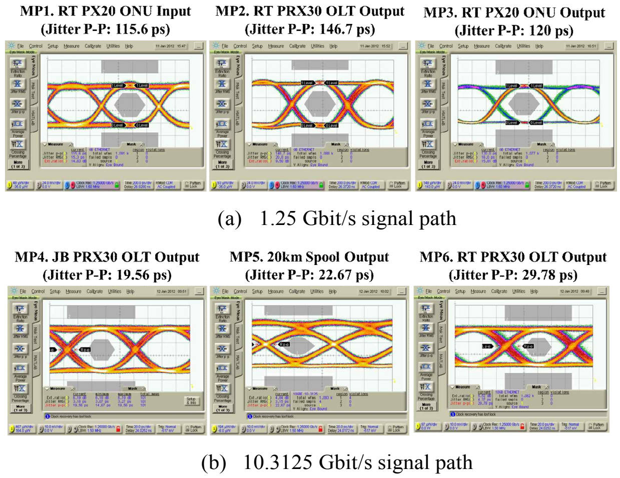

Figure 6. An optical eye diagram measured at MPs.

Figure 6 shows the optical eye diagrams of each Measure Point (MP) in the experimental setup for the proposed 10/1G-EPON RT. Our 10/1G-EPON RT performs signal retiming using a recovery clock extracted through a 1 Gbit/s CDR within the FPGA and 10 Gbit/s CDR device, and this re-timed signal is recovered by the 1G-EPON ONUs. In a 1.25 Gbit/s path, the downstream optical signal measured at MP1 is received by the 1G-EPON ONU optical module installed in the 10/1G-EPON RT through a 50 km SMF and two 3-port edge WDM filters. In an optical eye diagram measured at MP2 and MP3, shown in Figure 6-(a), we can see a clear eye-pattern satisfying the optical eye mask

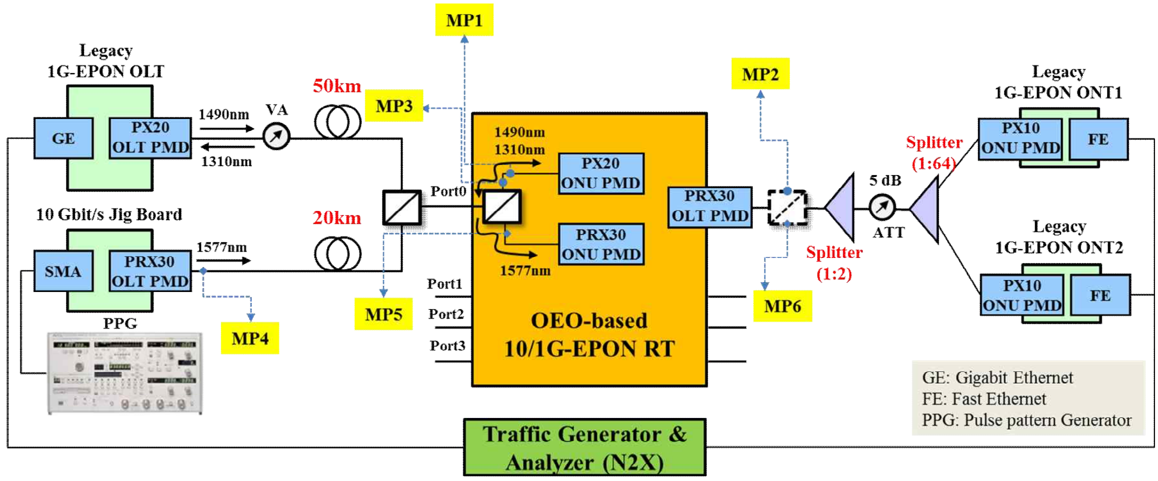

Figure 5. Experimental setup for the performance measurement of the proposed OEO-based 10/1G-EPON RT.

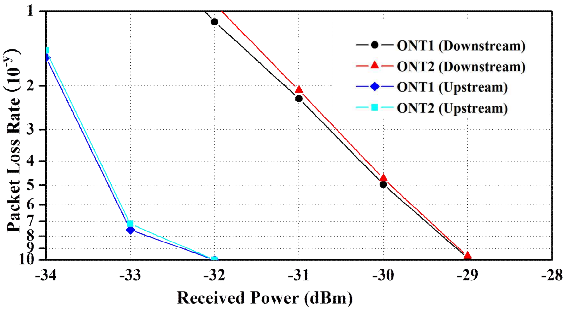

Figure 7. The PLR results measured at 1.25 Gbit/s EPON link.

adapted from the IEEE Gigabit Ethernet standard through 3R signal regeneration. We can confirm that a jitter of about 31 ps is added by the signal recovery. In a 10.3125 Gbit/s path, MP5 shows the results of a transmission dispersion caused by the 20 km SMF. We can also confirm that the output optical signal measured at MP6 satisfies the optical eye mask adapted from the IEEE 10.3125 Gbit/s Ethernet standard by the 3R signal retiming, as shown in Figure 6-(b), although a slight amount of jitter is added. This means that is possible to support a transmission reach of over 20 km through our proposed 10/1G-EPON RT, including a legacy 10G-EPON PMD in a 10 Gbit/s channel.

Using a commercially available router tester (Agilent N2X), the performance of the proposed 10/1G-EPON RT was evaluated in terms of packet loss rate (PLR) through Ethernet frames with random lengths ranging from 64 to 1518 bytes. We transmitted 10^10 frames for the PLR test.

Figure 7 shows the PLR results measured at the 1.25 Gbit/s path of the proposed 10/1G-EPON RT using a legacy 1G-EPON system according to the VA value. Because a 1G-EPON OLT uses a continuous-mode transmitter with a Distributed Feedback Laser Diode (DFB-LD) and a burst-mode receiver with an Avalanche Photodiode (APD), we can be certain that the upstream optical link budget increases by about 3 dB more than that of the downstream. Our experimental results confirm that the 1G-EPON system supports a physical distance of 50 km in a 1:128 split ratio using the proposed OEO-based 10/1G-EPON RT, and satisfies a PLR of 10^-10 for up to -29 dBm in a downstream path, and -32 dBm in an upstream path. This means that the

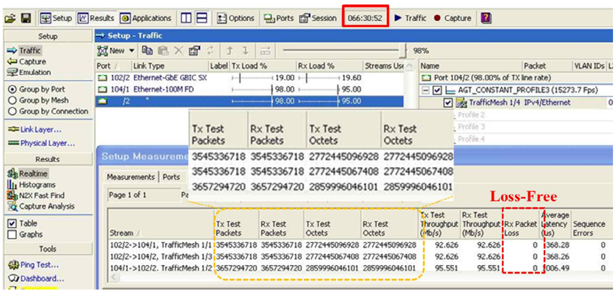

Figure 8. The results of a long-term test for the 10/1G-EPON RT.

TABLE I. TECHNOLOGY COMPARISON

Items	***Standard 10/1G-EPON***	***Extended 10/1G-EPON***	***RT-based 10/1G-EPON***
Power Budget	Max. 29 dB	Max. 35 dB	Max. 58 dB
Reach & Split Ratio	1:32@ 20km	1:32@ 40km	1:128@ 80km Note.1
BW per User	300Mbps	300Mbps	100Mbps
Upstream Mode	Burst	Burst	Burst & Continuous
WDM application	No	No	Yes
Remote Node	Passive	Passive	Active
Cost per User	Middle (100% / 32)	High (130% / 32)	Low (180% / 128)
Cost of trunk fiber	1	1	1/8 Note.2

Note.1. Using a PRX30 PMD type at the EPON ONU.

Note.2. When a CWDM solution is applied to the trunk fiber.

10/1G-EPON RT is able to provide transmission service at a distance of about 70 km with a 128-way split, when we take into account a budget loss of a 0.4 dB/km in an optical fiber.

Figure 8 shows the results of a packet transmission test of a legacy 1G-EPON system using our proposed 10/1G-EPON RT during a 66-hour period. During this test, we transmitted a 100 Mbit/s packet from a 1G-EPON OLT to each 1G-EPON ONU, while assigning a 98 Mbit/s packet at each 1G-EPON ONU for measurement of the upstream PLRs. From Figure 8, we can confirm the possibility of loss-free service in the downstream and upstream paths.

Table 1 shows the results of a technology comparison of 10/1G-EPON using the proposed OEO-based 10/1G-EPON RT, a 10G-EPON standardized by IEEE802.3av-2009, and an Extended 10/1G-EPON suggested by IEEE802.3 extended EPON study group [2][5]. As the table shows, with the exception of an active component used in a remote node, our proposed 10/1G-EPON RT can provide greater efficiency with respect to power budget, distance and user accommodation, cost per subscriber, and long-distance trunk fiber costs. However, to make up for the weak point above, we adopted quad-port architecture at the proposed 10/1G-EPON-RT.

V. CONCLUSION

We proposed and experimentally demonstrated an efficient OEO-based 10/1G-EPON RT based on quad-port architecture to overcome the physical limitations of a legacy 10/1G-EPON system. We also confirmed that our proposed 10/1G-EPON RT can achieve a high power budget of 58 dB through 3R signal retiming using a legacy 10/1G-EPON PMD, and can be a cost-effective solution for a long-distance 10/1G-EPON system.

Our experimental results verified that the proposed RT can provide a distance of more than 40 km in a 1:64 split ratio, which many service providers desire. If 10/1G-EPON PMDs use the PRX30 power budget class, the 10/1G-EPON

RT can be expected to support a reach of over 80 km in a 1:128 split ratio with no modifications of the legacy 10/1G-EPON standard.

In our future work, we will perform a feasibility test with either a commercialized 10/1G-EPON system or an evaluation system, and apply CWDM multiplexing to a trunk fiber with a 10/1G-EPON Central Office Terminal (COT) performing wavelength conversion between the EPON and CWDM.

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