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

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***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. The current 1G-EPON RT included within this proposed 10/1G-EPON RT is being the pilot service at a large residential apartment over 2,000 subscribers.**

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

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 nations, including Japan, South 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], [2].

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 [3]. 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. 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 [4], [5].

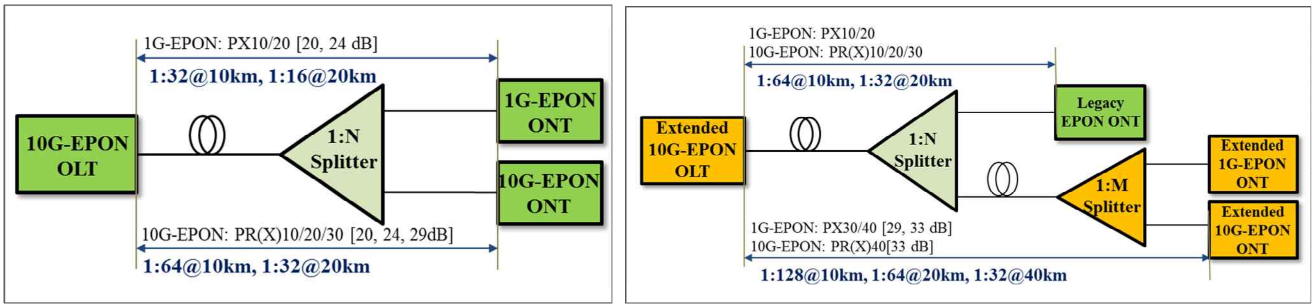
However, many network operators worldwide have placed an increased emphasis on combining an optical access network with a metro network by consolidating their central offices (COs) through a long-distance EPON solution. This combination results in a considerable reduction in capital expenditure (CAPEX) and operating expenditure (OPEX) budgets. In particular, EPON service providers require the high power budget to support long distances of 40 km and a high 64-way split. In addition, they hope to discover a solution satisfying the following key questions: 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 [6].

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 a 58 dB in a legacy 10/1G-EPON without modification. We also demonstrate the performance of the OEO-based RT using a commercialized EPON optical line terminal (OLT) and 64 optical network terminals (ONTs) [1].

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. We also present the pilot service site for Giga internet service in S. Korea. Finally, we present a brief summary of our work in Section V.

II. RELATED WORK

An extended EPON solution helps with network evolution, and reduces network levels and nodes from an increased high power budget. It can also provide significant



(a) (b)

Figure 1. EPON link structure: (a) 10G-EPON link structure ratified by the IEEE802.3av standard, and (b) the 10G-EPON link structure suggested by the IEEE P802.3bk extended EPON working group.

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 [7].

To achieve these purposes, the IEEE P802.3bk extended EPON working group is standardizing a new definition of the power budgets or reach extender solutions that can support a higher power budget [12]. Recently, several methods were suggested by the extended EPON working group. The first method is to define new power budget classes (i.e., PX30, PX40, PR(X)40) through an increase in the receiver sensitivity and launch power of the transmitter. The second method is optionally 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 [8-9].

As a first option, the current extended EPON working 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 33 dB [13].

Among the methods described above, only the use of an extender box can easily satisfy this requirement. In an extended EPON working group, the line cost and power consumption per subscriber are also primary considerations when designing a high power budget solution for a 10G-EPON [10].

Figure 1 shows the 10G-EPON link structure ratified by the IEEE802.3av standard, and suggested by the IEEE P802.3bk extended EPON working group [3]. This 10G-EPON can support a maximum transmission reach of 10 km in a 1:64 split ratio when using a PR(X)30 with a high power budget of 29 dB under worst-case ODN design scenarios without any problems, 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 33 dB using the newly defined PR(X)40 PMD, as shown in Figure 1-(b). A 10G-EPON using a PR(X)40 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 at the distance of 10 km and a very high split ratio of 1:256 within a very short distance of 2 km [11].

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 legacy 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: bit-level 3R-based signal retiming, remote management through a simple network management protocol (SNMP) agent and an embedded ONT, and upstream burst-mode to continuous-mode signal conversion to support the wavelength division multiplexing (WDM)-enabled reach extension.

III. PROPOSED OEO-BASED REMOTE TERMINAL FOR ASYMMETRIC EXTENDED 10/1G-EPON

Figure 2 illustrates the 10/1G-EPON link structure applied to the proposed OEO-based 10/1G-EPON RT in the remote office to support a long distance and high split ratio. A extended 10/1G-EPON system utilizing the 10/1G-EPON RT can provide a physical reach of over 60 km using an existing PRX30 PMD in the feeder fiber, and can support a 1:128 high split ratio for a 10 km reach, respectively, using the legacy PRX30 PMD supporting the link budget of 29 dB under the worst-case ODN design scenarios without any problems.

That is, when considering an optical fiber loss of 0.4 dB/km, the extended 10/1G-EPON applied to our 10/1G-EPON RT can easily support a high split ratio of 1:128 at a 80 km reach from a central office to end users. This is possible to make the flexible access network configuration. The 10/1G-EPON RT mainly provides wavelength conversion and a signal retiming function based on 3R-based signal regeneration between a 10/1G-EPON OLT and 10/1G-EPON ONTs or 1G-EPON ONTs at the remote office.

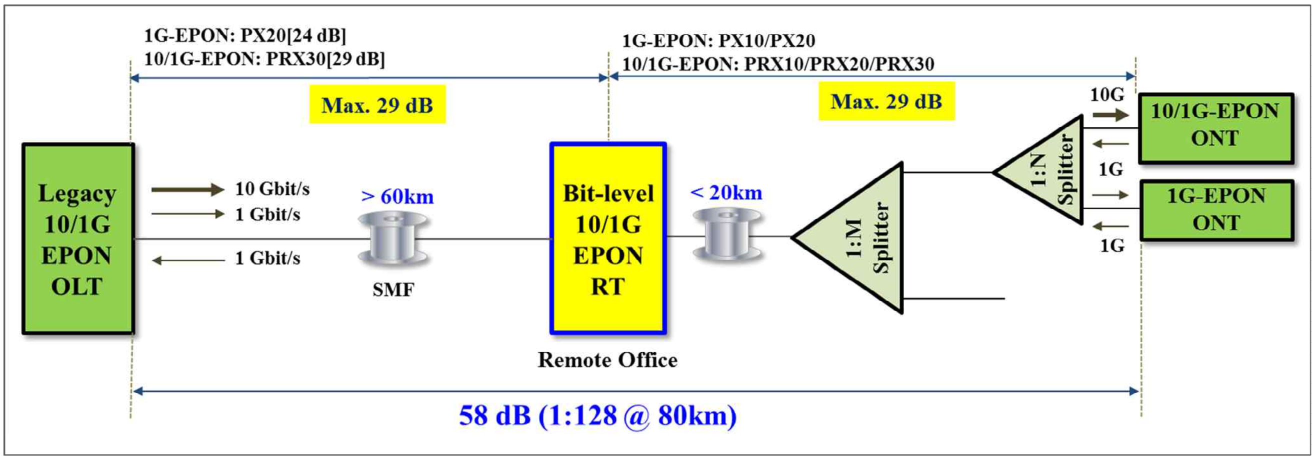


Figure 2. The extended asymmetric 10/1G-EPON link structure utilizing the proposed bit-level OEO-based RT.

In addition, it provides an optional upstream burst-to-continuous signal conversion to apply continuous mode WDM solutions 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. The extended asymmetric 10/1G-EPON provides the transmission rate of 11 Gbit/s at a downstream direction and 1 Gbit/s at an upstream path the allows to access of the asymmetric 10/1G-EPON ONTs and symmetric 1G-EPON ONTs as shown in Fig. 2.

Figure 3 shows the design architecture and quad-port prototype of the proposed 10/1G-EPON RT. The proposed 10/1G-EPON RT is composed of a 3-port edge WDM filter for interconnection with the 10/1G-EPON OLT equipment, a single low-cost FPGA(Field Programmable Gated Array) for the 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 and data recovery (BCDR) device for retiming of the burst-mode upstream signals, 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 interconnection with the ODN [15].

The 10/1G-EPON RT divides a 10 Gbit/s wavelength into 1 Gbit/s wavelength channel using a 3-port edge WDM filter. These wavelength channels 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 10 Gbit/s CDR in the electrical domain. The retimed signals then are retransmitted to the optical domain using a 10/1G-EPON OLT transceiver. In

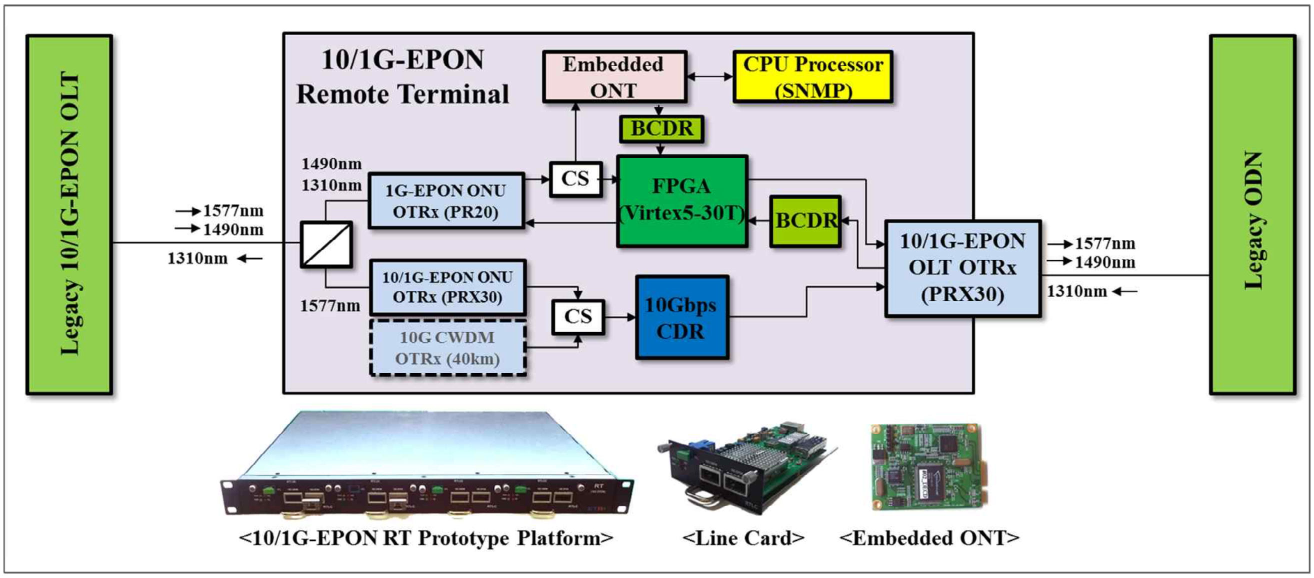


Figure 3. The design architecture and prototype of the proposed 10/1G-EPON RT.

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 proposed 10/1G-EPON RT is designed using a quad-port architecture, and provides a signal retiming function through a Virtex-5 FPGA (i.e., 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. That is, the 10/1G-EPON RT can support a total transmission rate of 44 Gbit/s in the downstream and 4 Gbit/s in the upstream by using the cheaper solutions.

To provide remote management of the 10/1G-EPON RT, an embedded ONT is activated using a 10/1G-EPON OLT system through 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 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 proposed 10/1G-EPON RT can use optionally 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 WDM (CWDM) optical modules.

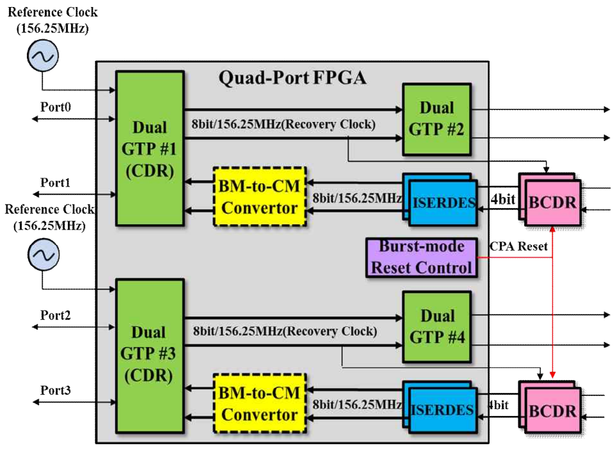


Figure 4. A Internal structure of the FPGA based on a quad-port for the signal retiming of 1G-EPON.

Figure 4 illustrates the internal architecture of the signal retiming logic within the FPGA based on a quad-port 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 and deserializer (ISERDES) as shown in Figure 4. This burst-mode parallel is transmitted the continuous-mode 1.25 Gbit/s to EPON OLT through the GTP block and BM-to-CM convertor [14].

Also, a burst-mode reset signal for the burst-mode upstream signal detection at 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 within the FPGA optionally changes a burst-mode signal into a continuous-mode signal through the insertion of a particular pattern (e.g., h'55 or 8B/10B idle) during a laser off time.

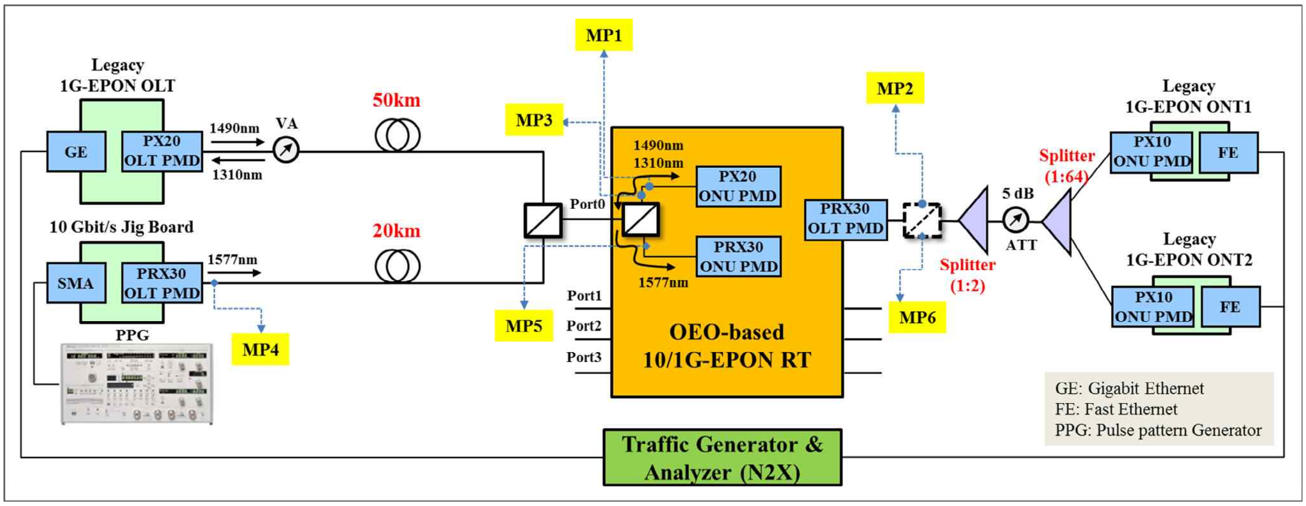
In this paper, our proposed OEO-type 10/1G-EPON RT can provide low-power consumption and a cost-efficient design through a quad-port structure using a single cheaper FPGA and legacy cheaper EPON optical transceivers.

IV. Experimental Setup and Results

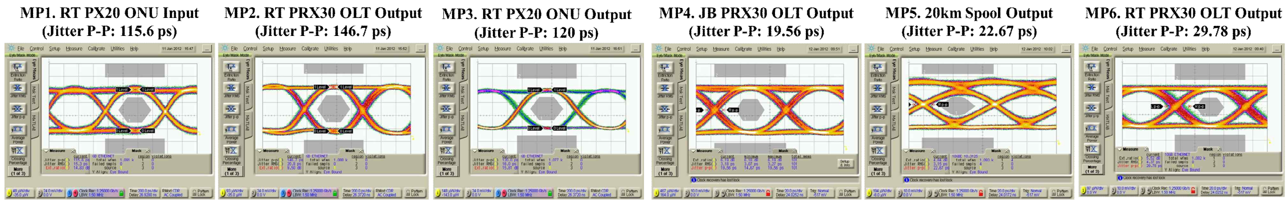
A. Experimental setup

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



(a)



(b) (c)

Figure 5. Experimental setup for the performance measurement and optical eye-diagrams observed at MPs of the proposed OEO-based 10/1G-EPO N RT: (a) experimental setup link, (b) 1.25 Gbit/s optical diagrams, and (c) 10.3125 Gbit/s optical diagrams.

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, while the 10/1G-EPON RT used a 1G-EPON ONU optical module compliant with an IEEE 802.3ahTM-2008-PX20 supporting the link budget of 28 dB, and a 10/1G-EPON OLT/ONU optical module compliant with an IEEE802.3avTM-10/1GBASE-PRX30.

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.

B. *Optical eye digrams and analysis*

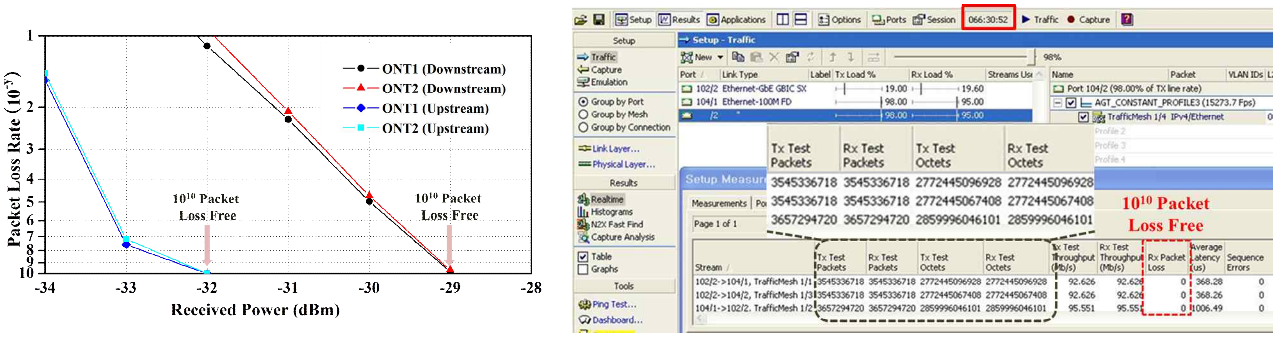
Figure 5 shows also the optical eye diagrams of each measurement point (MP) in the experimental setup link for the proposed 10/1G-EPON RT. Our 10/1G-EPON RT performs signal retiming using a recovery clock extracted through a 1 Gbit/s CDR within the FPGA and 10 Gbit/s CDR device, and this retimed signal is again 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 Fig. 5-(b), we can see a clear eye-pattern satisfying the optical eye mask adapted from the IEEE Gigabit Ethernet standard through a bit-level 3R-based 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 problem caused by the 20 km SMF. We can also confirm that the output optical eye diagram 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 Fig. 5-(c), 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.

C. *Packet transmission results and analysis*

Using a commercially available router tester (i.e., Agilent N2X), the performance of the proposed 10/1G-EPON RT was evaluated in terms of packet loss rate (PLR) through



(a) (b)

Figure 6. The packet transmission results measured at 1.25 Gbit/s EPON link with two ONTs: (a) PLR results, and (b) result of a long-term test.

Ethernet frames with random lengths ranging from 64 to 1518 bytes at a downstream and upstream path. We transmitted 10^{10} frames to two ONTs for the PLR test.

Figure 6 shows the packet transmission results measured at the 1.25 Gbit/s path of the proposed 10/1G-EPON RT using a legacy 1G-EPON OLT/ONTs according to the VA value. Because a 1-Gb/s EPON OLT and ONU transceivers use an avalanche photodiode (APD) and a positive intrinsic negative photo-detector (PIN-PD), respectively, we can show that the upstream 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 loss-free service up to -29 dBm in a downstream path, and -32 dBm in an upstream path as shown in Fig. 6-(a). This means that the 10/1G-EPON RT is able to provide transmission service at a distance of about 50 km with a 128-way split at PLR of the minimum 10^{-10}, when we take into account a budget loss of a 0.4 dB/km in an optical fiber.

Figure 6-(b) shows the result of a long-term packet transmission test of the proposed 10/1G-EPON RT. Over a 66-hour period, we transmit a packet load of 19 % (i.e., 190 Mbit/s) from an EPON OLT to each EPON ONT, and assign a packet load of 98 % (i.e., 98 Mbit/s) at each EPON ONT to measure the upstream PLRs, as a commercialized EPON ONT supports a Fast Ethernet port. From Fig. 6-(b), we can confirm the possibility of 10^{10} packet loss-free service in the downstream and upstream paths.

D. BMT environment and analysis

The 1G-EPON RT technologies included in the proposed 10/1G-EPON RT are commercialized since last year and we have performed the benchmark test (BMT) to multiple system operators (MSOs) (i.e., CJ HelloVision) in S. Korea on October 2012.

Figure 7 shows the experimental setup environment for the BMT of commercialized 16-port 1G-EPON RT platform with an existing EPON OLT and 64 ONU. For BMT, we configured a physical distance of 50 km with a 64-way split using a commercialized EPON OLT (i.e., Ubiquoss U9024a), 64 ONTs (i.e., Ubiquoss C504L), and the 16-port 1G-EPON RT platform. We applied a 50 km service profile map applying a window discovery size of 40,800 (i.e., 40,800 x 16-byte = 652 µs) and a maximum propagation delay time of 15,625 (i.e., 250 µs) to the EPON OLT.

As shown in Fig. 7, we configured a trunk fiber using two 20-km SMFs, a fixed attenuator of 10 dB and a VA to adjust the downstream signal power to -27 dBm in front of the 1G-EPON RT. For the drop section, we used a 10-km SMF, followed by a 1:4 optical splitter, and four 1:16 optical splitters. The loss budgets of the feeder and drop sections are

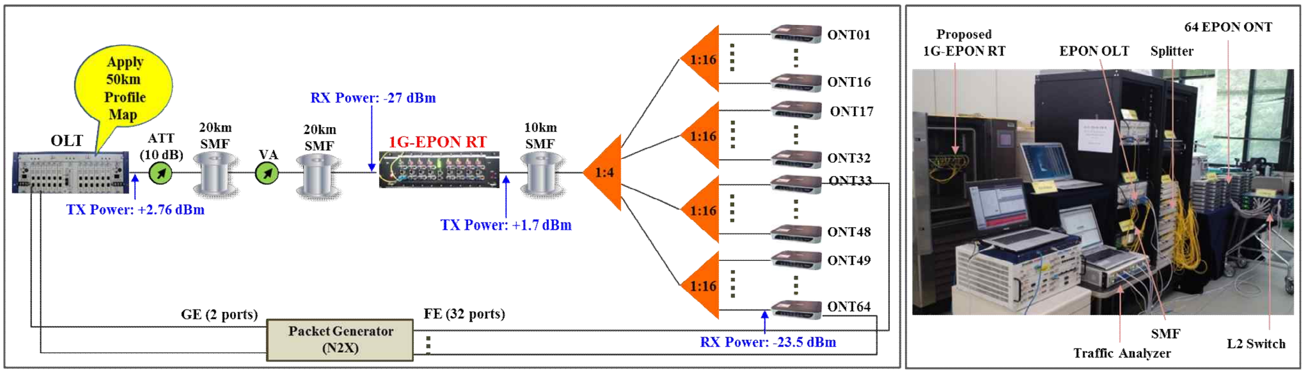


Figure 7. An experimental setup environment for the BMT with 1G-EPON RT platform.

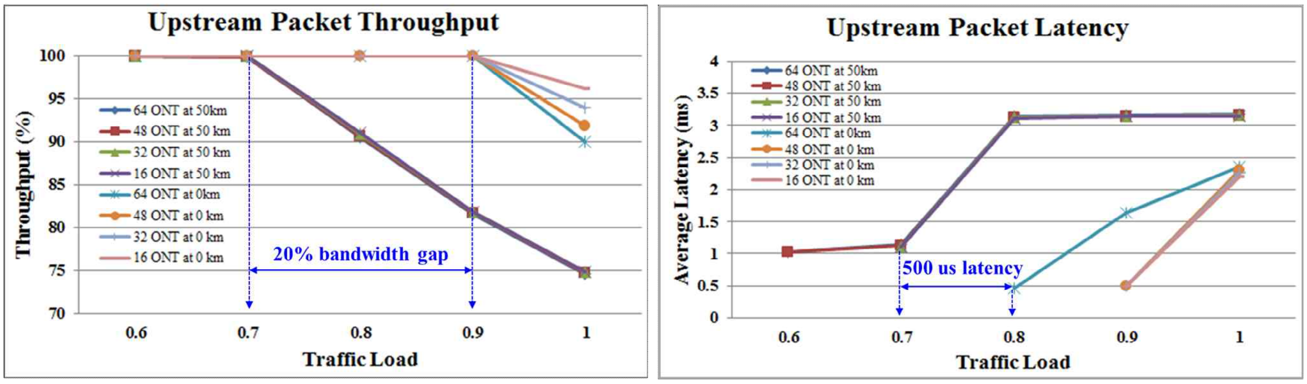


Figure 8. Upstream packet throughput and latency according to the traffic load at a single ONT.

29.8 and 25.2 dB, respectively.

Because the downstream throughput does not degrade depending on the transmission reach, at the only upstream path, we measured the maximum packet throughput that can be transmitted from one of the ONT and the average latency according to the traffic load in a single ONT.

For the measurement of the maximum packet throughput, we transmitted the packet with random lengths ranging from 64 to 1,518 bytes to only a single ONT. As shown in Fig. 8, although an EPON link at a back-to-back link (i.e., 0 km transmission reach) supports the maximum upstream packet throughput of about 920 Mbps, however, the extended EPON link of 50 km transmission reach utilizing the 1G-EPON RT platform provides a maximum packet throughput of about 700 Mbps regardless of the number of registered ONTs.

This is because of an an increased window discovery size (i.e., 391 μs) than existing window discovery (i.e., 261 μs) and an arrival time delay of the gate message (i.e., 300 μs) in order to allow 50-km reach. A maximum average latency is 3.2 ms at a traffic load of above 80 % (i.e., 800 Mbit/s) , as the input packet rate is faster than the bandwidth allocation time. Therefore, when extending an EPON with a 1G-EPON RT, to support over a 50-km transmission reach, a greater

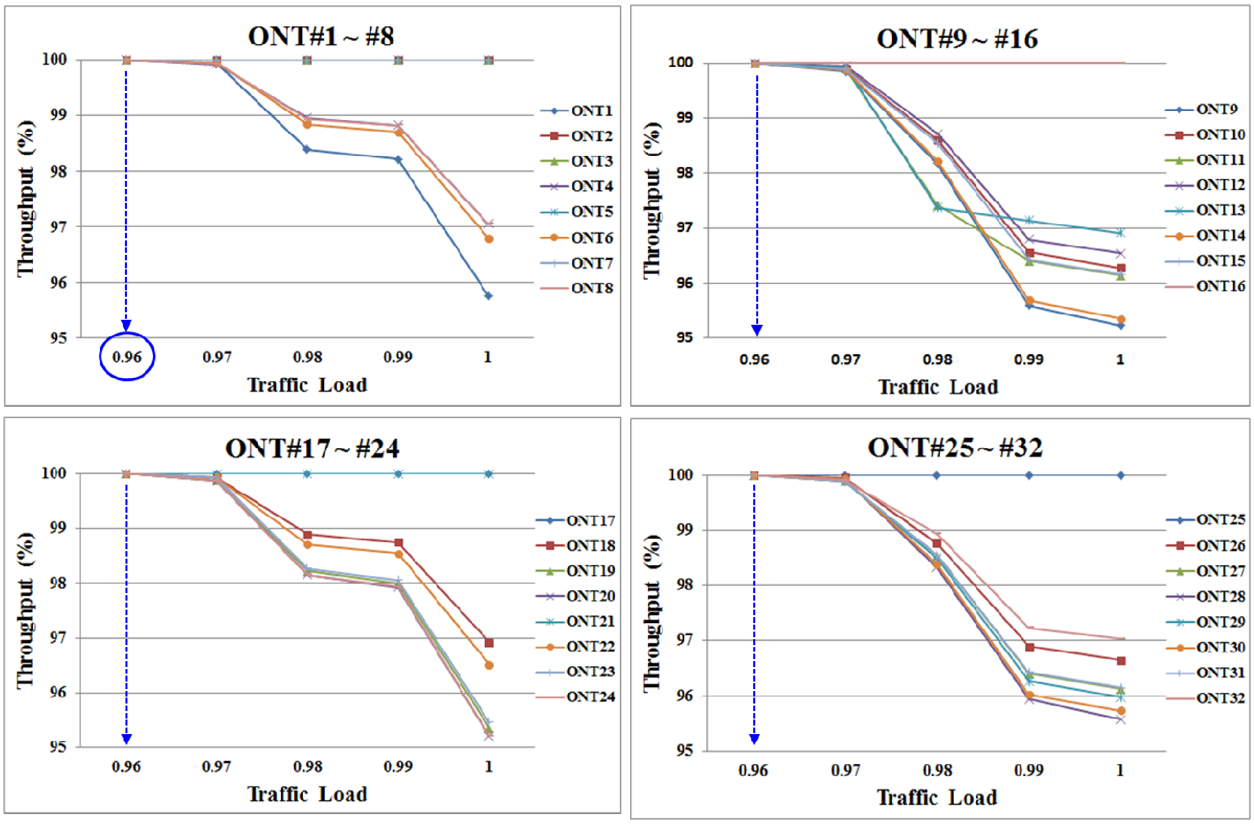


Figure 9. The downstream packet throughput according to the traffic load of a 32 ONTs.

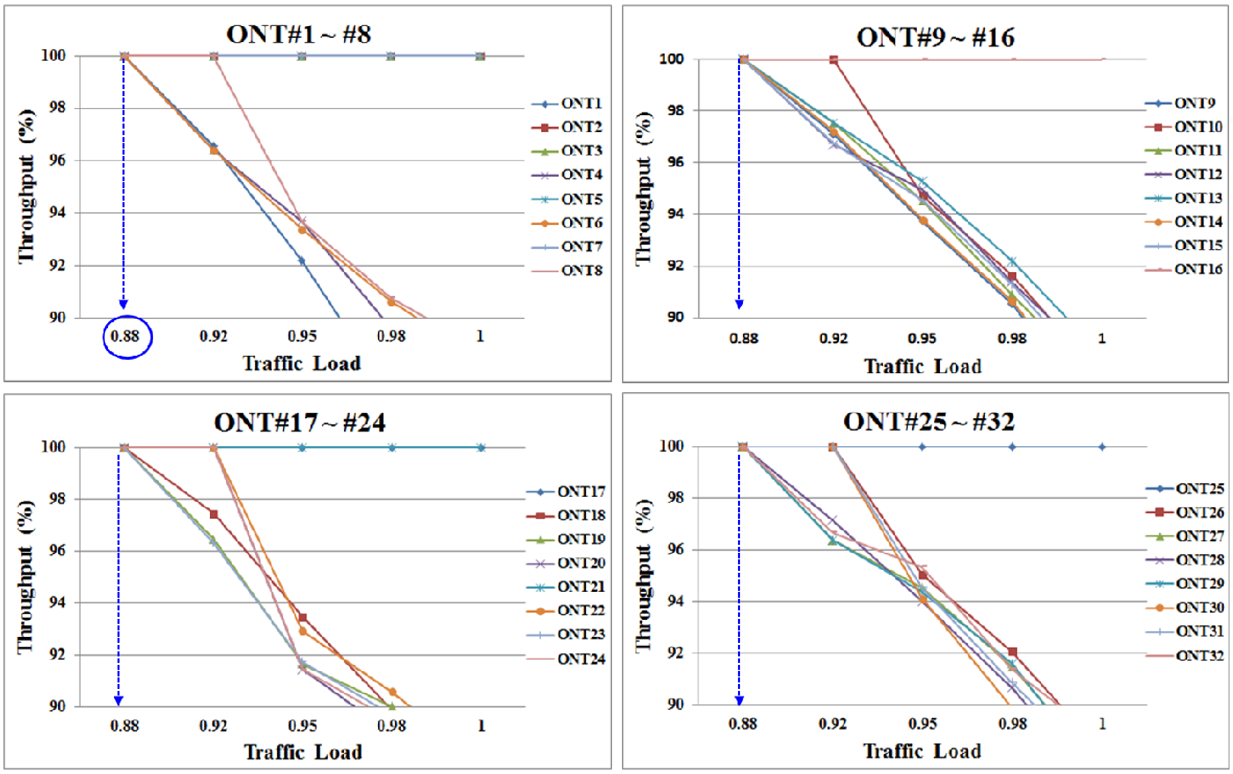


Figure 10. The upstream packet throughput according to the traffic load of a 32 ONTs.

byuffer size should be considered at the ONTs to cope with the increased latency of Gate message.

For performance analysis in actual environment, we transmitted 10^9 packets to 32 ONTs among 64 ONTs. Here, the downstream and upstream bandwidths per ONT were assigned about 30 and 28 Mbps, respectively.

Figures 9 and 10 show the results of packet throughput measured at the downstream and upstream paths according to the traffic load with 32 ONTs.

From the experimental results, we can confirm that the 1G-EPON RT platform satisfies the packet throughput of 100 % when traffic load is 96 % (960 Mbit/s) at the downstream path as shown in Fig. 9. On the other hand, at the upstream path, it can confirm that the 1G-EPON RT platform satisfies the packet throughput of 100 % when traffic load is 88 % (880 Mbit/s) as shown in Fig. 10. This is

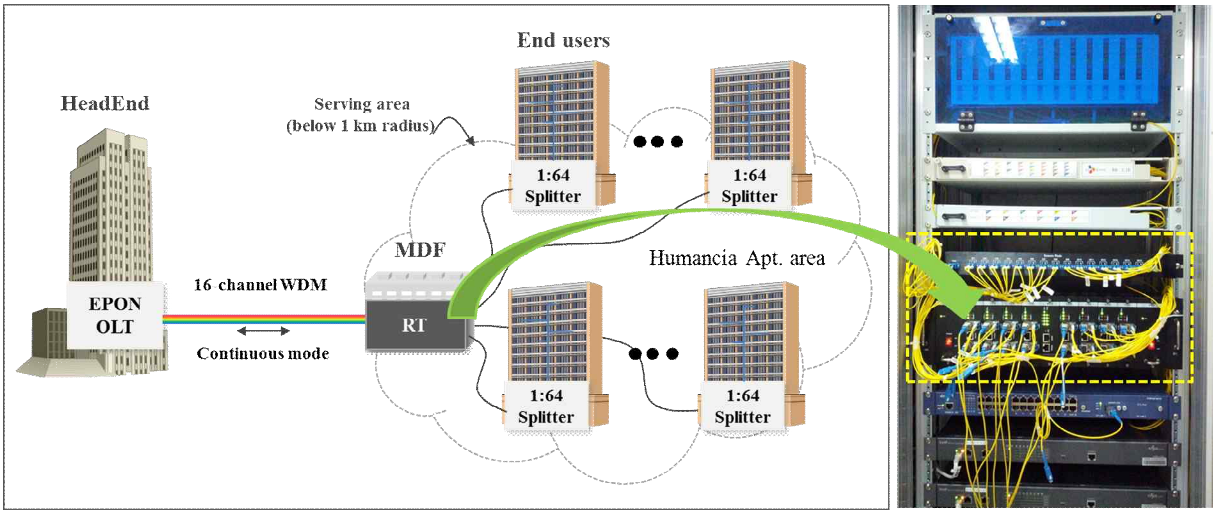


Figure 11. The results of long-term packet transmission and pilot service site.

because the packets are distribute to 32 ONTs. Therefore, the input packet rate at each ONT is lower than the asigned bandwidth allocation time from EPON OLT.

From the experimental results, we confirm that it provides loss-free service during a 1.6×10^{10} and 1.48×10^{10} packet transmission at the downstream and upstream path, respectively, when the received power at 1G-EPON RT platform is -27 dBm. Consequently, the extended EPON link based on the 1G-EPON RT platform can provide the maximum downstream bandwidths of 960 Mbps and upstream bandwidth of 880 Mbps similar to legacy EPON performance under the condition of packet loss-free.

E. Pilot services and link structure

The currently 16-port 1G-EPON RT had been installed with a DWDM solution at the feeder section to provide a Giga internet service at Gimpo area by Korean cable operator (i.e., CJ HelloVision) as shown in Fig. 11. The 1G-EPON RT had commercial service at the main distribution frame (MDF) within Humancia apartment to accommodate 2,234 subscribers, respectively, on December, 2012.

Each port of 1G-EPON RT platform is connected to end users through a 1:64 optical splitter as shown in Fig. 11. Therefore, cable operator can support a bandwidth of 16 Gbps per optical fiber, and reduce significantly the leased cost of the optical fiber using the designed a 16-port hybrid-type 1G-EPON RT platform.

F. Technical comparisons

Table I 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 IEEE P802.3bk working group. 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.

TABLE I. TECHNOLOGY COMPARISON

Items	*IEEE802.3av 10/1G-EPON*	*IEEE P802.3bk 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.

V. CONCLUSION

We proposed and experimentally demonstrated an efficient bit-level OEO-based 10/1G-EPON RT based on quad-port architecture to overcome the physical limitations of a legacy asymmetric 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-based signal retiming using an existing 10/1G-EPON PMD without new PMD solution, and can be a cost-effective solution for an extended asymmetric 10/1G-EPON system.

Our experimental results verified that the proposed 10/1G-EPON 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 commercial 10/1G-EPON OLT/ONTs, and apply WDM multiplexing to a trunk fiber with an asymmetric 10/1G-EPON wavelength converter performing wavelength conversion between the EPON and WDM.

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