Low-Cost, Low-Power, High-Capacity 3R OEO-Type Reach Extender for a Long-Reach TDMA-PON

Kwangok Kim, JieHyun Lee, Sangsoo Lee, Jonghyun Lee, and Younseon Jang

This paper proposes a low-cost, low-power, and high-capacity optical-electrical-optical-type reach extender that can provide 3R frame regeneration and remote management to increase the reach and split ratio with no change to a legacy time division multiple access passive optical network. To provide remote management, the extender gathers information regarding optical transceivers and link status per port and then transmits to a service provider using a simple network management protocol agent. The extender can also apply to an Ethernet passive optical network (E-PON) or a gigabit-capable PON (G-PON) by remote control. In a G-PON, in particular, it can provide burst mode signal retiming and burst-to-continuous mode conversion at the upstream path through a G-PON transmission convergence frame adaptor. Our proposed reach extender is based on the quad-port architecture for cost-effective design and can accommodate both the physical reach of 60 km and the 512 split ratios in a G-PON and the physical reach of 80 km and the 256 split ratios in an E-PON.

Keywords: TDMA-PON, reach extender, long-reach. PON, 3R retiming, optical access, FTTH.

I. Introduction

A time division multiple access passive optical network (TDMA-PON) is a promising optical access technology for providing gigabit bandwidth to subscribers. A TDMA-PON is divided into an Ethernet PON (E-PON) and a gigabit-capable PON (G-PON), according to the transmission protocol, and consists of a single optical line terminal (OLT) at the central office (CO), an optical distribution network (ODN) including a passive splitter, and a multiple optical network terminal/units (ONT/ONUs) near the end user's location [1].

The current G-PON supports a maximum physical distance of 20 km on a 64-way split, due to a power budget of 28 dB [2]. On the other hand, an E-PON only supports a maximum physical distance of 20 km on a 16-way split or 10 km on a 32-way split, due to a power budget of 26 dB [3]. However, many network operators recently required the long-reach solution of a TDMA-PON for designing a green network and combining an optical access network with a metro network.

For this purpose, the ITU-T G984.6 working group recommended a standard to increase the overall fiber length and the splitting ratio of a legacy G-PON in 2009 [4]. This standard considers a mid-span extension method that uses an active extension node in the middle of the optical network. There are several ways to implement an optical reach extender, such as by using optical amplifier (OA)-type, optical-electrical-optical (OEO)-type, or hybrid-type methods [5].

In this paper, we propose and design a low-cost, low-power, and high-capacity 3R OEO-type reach extender that can provide full compatibility with a legacy TDMA-PON for supporting a long-reach solution.

Section II reviews the related works, while section III describes the detailed structure and design scheme of the

proposed OEO-type reach extender. Section IV shows the experiment results proving the effectiveness of our method and provides an analysis of its performance. Finally, section V provides some concluding remarks.

II. Related Work

A long-reach TDMA-PON can be configured more easily than a legacy TDMA-PON due to an increased link budget. It can also provide significant cost savings by reducing the electronic equipment and real estate required at the local exchange. Moreover, it can support service to small towns and suburban and rural areas.

Recently, several solutions for a G-PON reach extension were suggested in [6]-[8]. Nesset and others [6] reported on an OA-type reach extender that uses a newly developed high-gain semiconductor OA (SOA) module working at 1,310 nm at the upstream, along with coarse wavelength division multiplexing (WDM), as shown in Fig. 1(a). This reach extender provides a link budget of 54 dB through an SOA with 25 dB gain. However, it requires burst mode coarse WDM technology because there is no burst-to-continuous conversion function. Dr. Yusuke Ota, President of Zenko Technologies Inc., proposed an OEO-type reach extender that uses a reset-less OLT transceiver based on technology developed by Zenko. This OEO-type reach extender is illustrated in Fig. 1(b) and resembles the work presented in [7]. This solution can easily provide signal retiming as a 2R repeater through G-PON OLT and ONU optical modules. However, a reset-less G-PON OLT transceiver is an expensive solution and cannot additionally support continuous mode transmission according to the ITU-T G.984.6 standardization. It is also difficult to apply a remote management function. The designs in Fig. 1 can be easily applied in the case of an E-PON, which does not use a reset signal.

In 2009, Benyuan and Nesset [8] reported on an experimental demonstration of a G-PON reach extension of up to 50 km with a 32-way split using a Raman amplification of the upstream signal with 1,240 nm quantum-dot pump lasers, as shown in Fig. 2. This solution can take advantage of all passive access networks. However, it cannot provide full compatibility within a legacy G-PON due to the use of a dual fiber, and it is difficult to apply at the installed G-PON link. In addition, it can transmit only a burst mode signal at the upstream.

Until now, an efficient reach extender supporting a cost-effective design, low power consumption, and high power gain of over 55 dB has not been reported yet. Therefore, in this paper, we propose a quad-port reach extender based on a 3R regenerator that provides OEO conversion using a
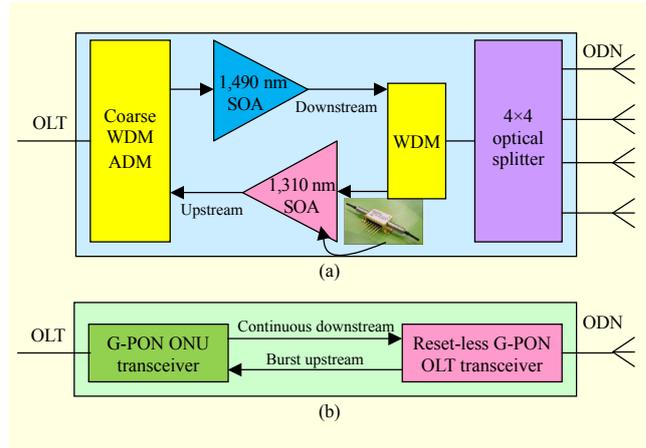

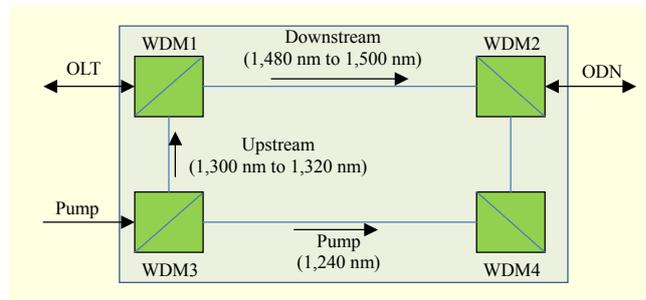Fig. 1. Structure of previous reach extender: (a) OA-type and (b) OEO-type.

Fig. 2. Structure of Raman amplifier-based reach extender.

commercially available TDMA-PON OLT/ONU optical transceiver and a signal retiming logic fully compatible with a legacy TDMA-PON.

Our proposed reach extender can efficiently provide 3R retiming using the following functions: remote management through a simple network management protocol (SNMP) agent, the burst mode reset control for a limiting amplifier (LA) and the burst mode clock and data recovery (BCDR), and the burst-to-continuous signal conversion.

III. Proposed Quad-Port OEO-Type Reach Extender

Because the reach extender uses electrical power in the remote node, it requires a remote management function and a low-cost, low-power design. Figure 3 illustrates the architecture of the proposed 3R regenerator-based quad-port reach extender based on signal retiming logic [9]. The proposed reach extender is composed of signal retiming logic, a TDMA-PON embedded ONT for SNMP packet transmission, a CPU processor providing SNMP for remote management, a BCDR, and legacy TDMA-PON OLT/ONU transceivers. It also provides an E-PON or a G-PON reach extension through signal retiming logic, such as a clock and
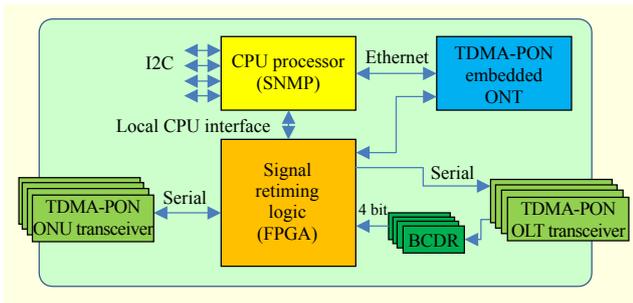
Fig. 3. Proposed OEO-type reach extender using signal retiming logic.

Fig. 4. Design structure for signal retiming in E-PON.

Fig. 5. Design structure for signal retiming in G-PON.

data recovery (CDR) or G-PON transmission convergence (GTC) frame-level function. The reach extender is designed using quad-port architecture, utilizing a Virtex-5 field programmable gate array (FPGA) (XC5VLX50T) to ensure lower design cost and power consumption than that of existing reach extender technologies [6], [7].

To provide remote management, the CPU processor gathers and manages the status of the installed optical transceivers based on SFF-8472 or signal retiming logic through a local CPU interface. It is also connected directly with an embedded ONT at the electronic domain without an external tap, such as an optical splitter, which is unlikely to have been used in previously reported technologies. An embedded ONT uses a commercial ONT medium access control (MAC), and an SNMP packet is transmitted to or received from the service provider.

Therefore, our reach extender receives an optical signal from a TDMA-PON ONU transceiver and then retimes it via an FPGA in the electrical domain. It then retransmits it to the optical domain via a TDMA-PON OLT transceiver. In addition, our reach extender can be applied as a common platform for a long-reach E-PON or G-PON.

1. Design of Signal Retiming Logic in E-PON

Figure 4 shows the design architecture of the signal retiming logic within an FPGA for signal recovery in an E-PON. Because an E-PON OLT optical transceiver does not require a reset signal, it can easily provide a signal retiming using the continuous mode CDR and the burst mode CDR.

In the downstream direction, the design provides simple 3R retiming with a recovery clock extracted from the CDR, which is included in a dual gigabit transfer protocol (GTP). The dual GTP extracts a 156.25 MHz recovery clock and 8-bit data from a 1.25 Gbps continuous mode downstream signal with 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, it
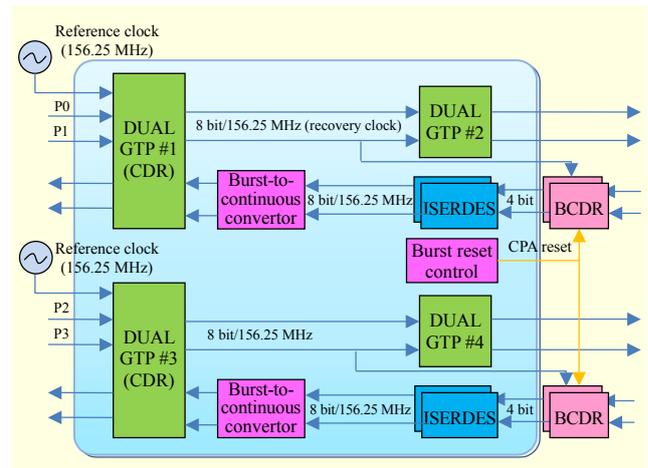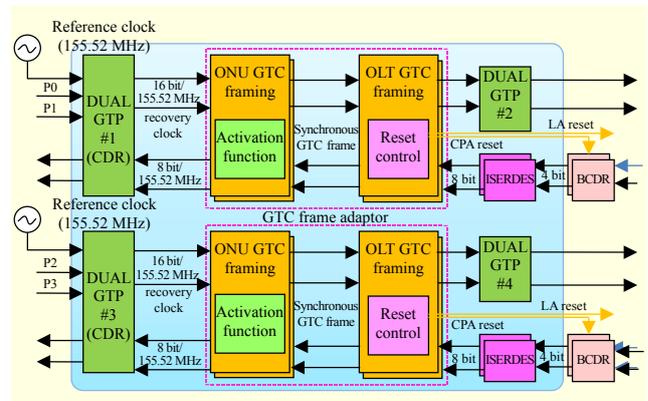
performs signal recovery via an external BCDR and an input serialization and deserialization (ISERDES) in an FPGA. Also, the reach extender generates a reset signal for a BCDR based on a loss of signal (LOS) outputted from an E-PON OLT transceiver. The BCDR aligns with the input data within the 12-bit start of the preamble. The burst-to-continuous convertor changes a burst mode signal into a continuous mode signal through the insertion of a particular pattern.

2. Design of Signal Retiming Logic in G-PON

Figure 5 shows the design architecture of the signal retiming logic for signal recovery at the G-PON. This signal retiming logic is used as a transmission convergence (TC) layer function.

In a G-PON system, this proposed reach extender provides 3R retiming through the method of GTC frame regeneration based on the ITU-T G984.3 standardization and performs an activation procedure with an OLT to search exactly the start and stop points of the upstream GTC frame transmitted from each ONU. Because a G-PON uses a very short length 44-bit

preamble, reset signals are required for the fast phase locking and clock extraction of a commercialized BCDR and G-PON OLT transceiver [10]. In the ranging process, the reach extender periodically asserts the reset signal with a 2-byte length that is about every 50 μs because it has no information about an arrival time of upstream frames. If the activation procedure of the reach extender is completed, the extender aligns synchronously with all ONUs, and it can then search the arrival time of an upstream GTC frame through an upstream bandwidth map (BWMap) extracted from a downstream GTC frame. Thus, our reach extender performs burst mode signal retiming using an upstream BWMap extracted from a synchronous GTC frame [11]. The reach extender generates the dying gaps information through an embedded ONT.

In the downstream direction, our reach extender extracts a 155.52 MHz recovery clock and 16-bit data from 2.488 Gbps of continuous mode input data via a dual GTP using a 155.52 MHz external reference clock. ONU GTC framing performs the functions of a GTC framing sublayer and generates a synchronous GTC frame within a period of 125 μs. This downstream GTC frame, which is regenerated using a recovery clock, is retransmitted to ONUs via an OLT GTC framing block, a dual GTP, and a G-PON OLT transceiver. In the upstream direction, 1.244 Gbps of burst optical signals are changed into 4-bit electrical burst data via a GPON OLT transceiver and BCDR, and this burst data is then converted into 8-bit burst data using the recovery clock at ISERDES in an FPGA. OLT GTC framing extracts an upstream GTC frame transmitted from each ONU using the allocation size. This

Algorithm. BRC

Input: 48 bits Upstream Bandwidth Map
Output: 1 bit Burst Resets for LA and CDR
1. Write BWMap Memory Function
   {ONUID, First_Sstart, Last_Sstop, # of map per ONU}
2. Read BWMap Memory Function
   i = # of map per ONU
   if $i > 0$ then
      if Timer (125 μs) = 1 then
        read memory;
      else if Timer = Sstop then
        read memory;
      $i \Leftarrow i - 1$;
   else
      exit ();
   end;
3. Reset Control Function
   if (First_Sstart − PLOu length + Offset = Timer) then
      LA Reset $\Leftarrow$ '1';   CPA Reset $\Leftarrow$ '1';
   else
      LA Reset $\Leftarrow$ '0';   CPA Reset $\Leftarrow$ '0';
   end;

// Timer: clock counter period of 125 μs (0 ~ 19439)
// First_Sstart: first arrival time of burst GTC frame per ONU
// Last_Sstop: finish time of burst GTC frame per ONU
// PLOu length: burst overhead size + guard time
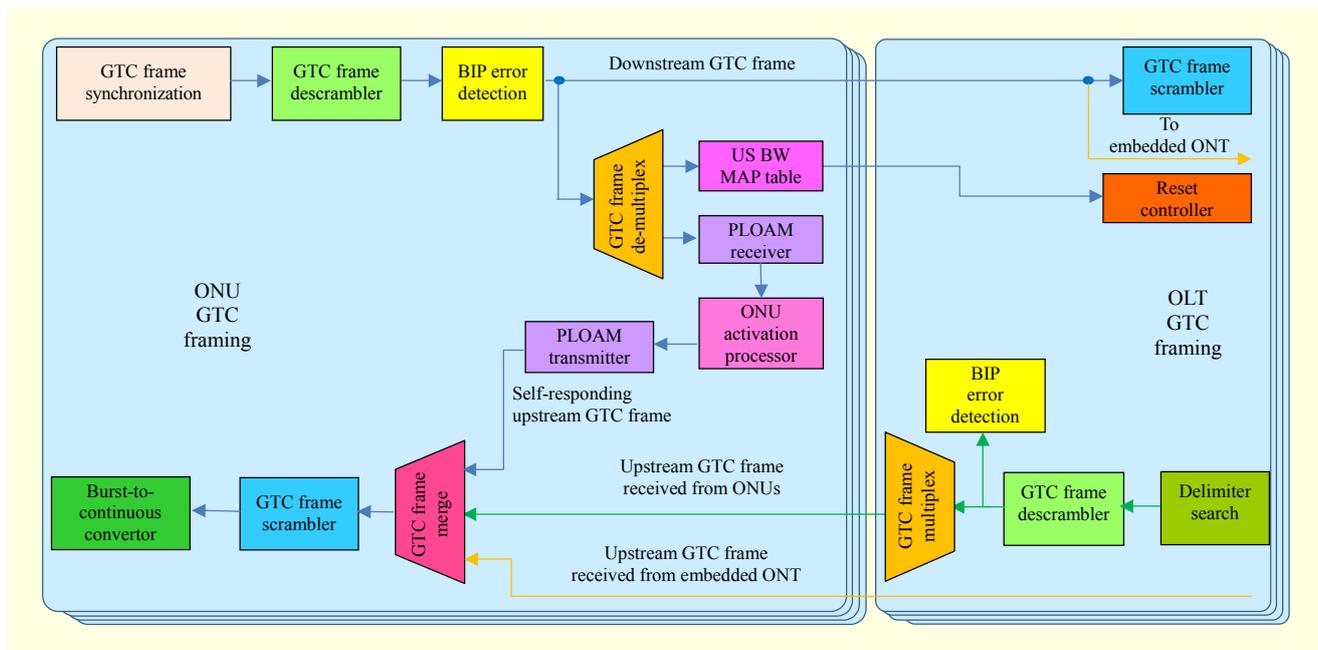// Offset: latency time from LA to MAC.

Fig. 6. Architecture of GTC frame adaptor.

extracted GTC frame is merged with the self-responding GTC frame and the GTC frame received from an embedded ONT and provides an extension of burst overhead, including a preamble and a delimiter. This frame then transmits to a G-PON OLT via ONU GTC framing and a dual GTP. Figure 6 shows the internal architecture of the GTC frame adaptor within an FPGA. The reach extender converts a burst mode signal into a continuous mode signal in the upstream direction by using the insertion of stuffing patterns, such as 0×55 or 0×CC, at the guard time.

ONU GTC framing performs the following functions: a GTC frame regeneration using physical synchronization (Psync) searching, descrambling and scrambling using an X^7+X^6+1 polynomial, a loss of frame (LOF) check using a 29-bit super frame counter, an 8-bit bit-interleaved parity (BIP) check, the processing of a physical layer operations, administration, and maintenance (PLOAM) message and a BWMap, a GTC frame merging from three upstream paths, and a burst-to-continuous signal conversion for WDM interfacing according to the ITU-T G984.6 standardization. That is, the main function of an ONU GTC framing is activated with a G-PON OLT for providing burst reset signals to a BCDR and G-PON OLT transceiver according to the burst reset control (BRC) algorithm. On the other hand, OLT GTC framing provides the following functions: scrambling for a downstream GTC frame, BRC using a BWMap, 20-bit delimiter searching, descrambling for an upstream GTC frame, the extraction of an upstream GTC frame received from a G-PON ONT, and 8-bit BIP checking per G-PON ONT.

3. Link Protection Method

Our reach extender can support link protection using a quad-port architecture, as shown in Fig. 7. The proposed reach extender configures an active port and a standby port using two ports. If an optical fiber or a TDMA-PON ONU transceiver is faulty on the active side, the selector switches from the active port to the standby port based on an LOS signal. However, it cannot provide such protection seamlessly. Therefore, all ONUs are again ranged using the OLT through a standby port. The CPU processor sends the restoration status information to the service provider using an SNMP agent [12].
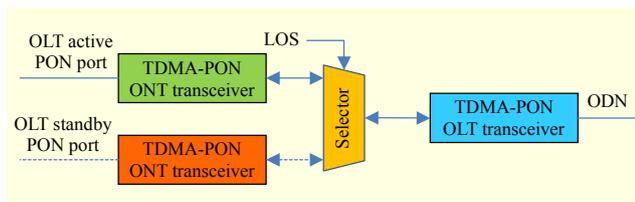

Fig. 7. Link protection structure in feeder section.

The proposed OEO-type reach extender can provide a low-power and low-cost design through a quad-port architecture in a single FPGA and generalized TDMA-PON optical transceivers.

IV. Experiment and Results

1. E-PON

A. Experimental Setup

The experimental setup for the long-reach E-PON with the proposed OEO-type reach extender is shown in Fig. 8(a).

For the link configuration of the long-reach E-PON, we use a legacy E-PON OLT and three ONTs and connect the feeder fiber using a 50 km single-mode fiber (SMF) spool between the E-PON OLT and reach extender. We also connect an ODN using a 1:128 optical power splitter between the reach extender and E-PON ONTs and use E-PON OLT/ONU commercial transceivers supporting IEEE 802.3ah-2008 1000BASE-PX20. An optical power budget in the feeder fiber is adjusted using a variable attenuate (VA) value. In this experimental setup, the insertion loss at the feeder fiber and ODN is about −16 dB and −18.5 dB, respectively.

B. Results and Performance Analysis

Figure 8(b) shows eye-patterns measured at three test points (TPs): TP1, TP2, and TP3. In this experiment, our reach extender performs signal retiming with a recovery clock
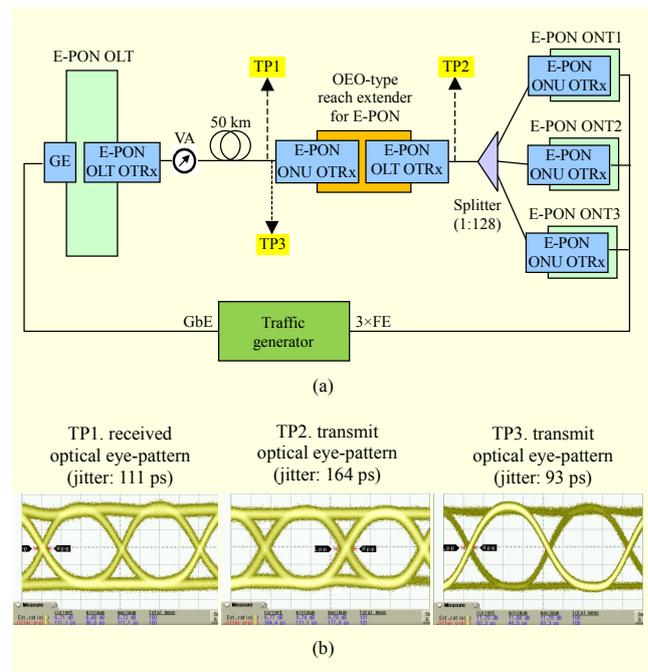

Fig. 8. Experimental environment in E-PON reach extender: (a) experimental setup and (b) measured eye-patterns
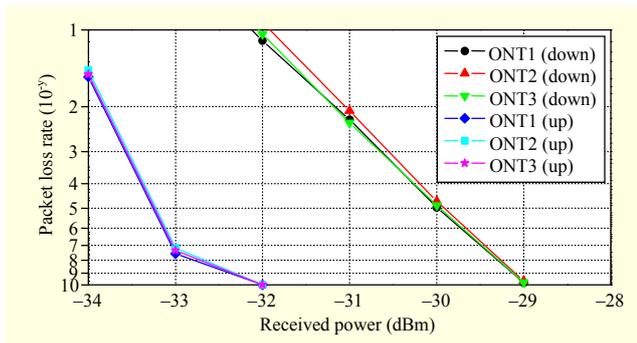
Fig. 9. PLR results measured in long-reach E-PON.

extracted through a CDR in a dual GTP, and the retimed signal is recovered by the E-PON ONT. Nevertheless, a clear eye-pattern measured in the downstream and upstream directions can clearly be observed. A jitter of about 50 ps is added via signal retiming logic in the reach extender. To verify the transmission test of a long-reach E-PON, we transmitted 1 Gbit/s and 100 Mbit/s packets with random lengths ranging from 64 bytes to 1,518 bytes in the downstream and upstream paths and measured the packet loss rates (PLRs).

Figure 9 shows the PLR results measured at the long-reach E-PON according to the VA value. Because an E-PON OLT uses a burst mode receiver with an APD-TIA, the upstream optical link budget is increased by about 4 dB more than the downstream. With this experiment result, we confirmed that the long-reach E-PON using the proposed OEO-type reach extender satisfies a PLR of 10^{-10} up to –29 dBm at a downstream path, as well as –32 dBm at an upstream path. It is possible to provide transmission service at a distance of 80 km and a 64-way split per port.

2. G-PON

A. Experimental Setup

The experimental setup for our OEO-type reach extender in the environment of a long-reach G-PON is shown in Fig. 10(a). A legacy G-PON OLT system is connected to a G-PON ONU transceiver within an OEO-type reach extender via a 50 km SMF spool. Also, a G-PON OLT transceiver within the OEO-type reach extender reconnects to G-PON ONTs via a 10 km SMF spool and 1:128 optical splitters. The G-PON transceivers use a Class B+ commercial product. In this experimental setup, the insertion loss of feeder fiber and ODN is about –15.7 dB and –28.5 dB, respectively.

B. Results and Performance Analysis

Figure 10(b) shows an eye-pattern of each TP measured in the experimental setup. In this experimental setup, our reach extender performs signal recovery, and the recovered signal is
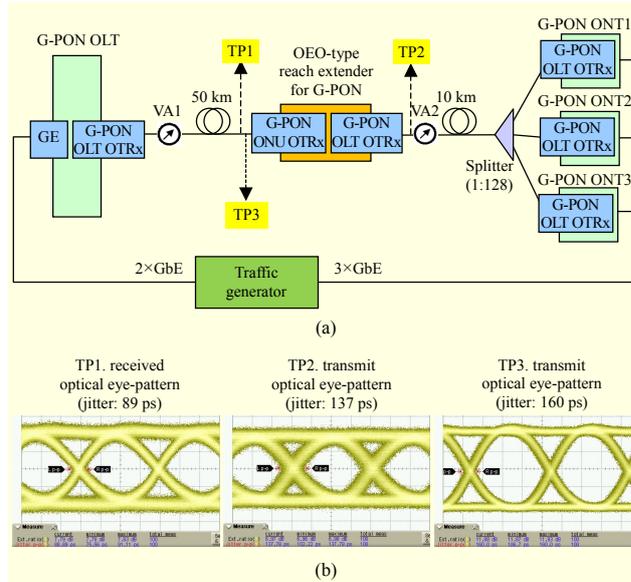

Fig. 10. Experimental environment in G-PON reach extender: (a) experimental setup and (b) measured eye-patterns.

again recovered by a G-PON ONT, just as in an E-PON. We can confirm that an output eye-pattern (TP3) provides a bigger eye opening than an input eye-pattern (TP1) through frame regeneration at the GTC frame adaptor. A jitter of about 80 ps is added into the proposed OEO-type reach extender. The jitter measured at the upstream is increased because the G-PON transmits a burst signal with a recovery clock in a G-PON ONT. That is, this result shows the possibility of transmission service with a 60 km reach on 128 split ratios per PON port of a G-PON OLT.

Using a commercially available router tester (Agilent N2X), the performance of the long-reach G-PON is evaluated in terms of PLR through Ethernet packets with random lengths ranging from 64 bytes to 1,518 bytes, just as in the E-PON test.

The PLR results of packet transmission measured at the feeder fiber of the long-reach G-PON are shown in Fig. 11. An optical power received at the reach extender is adjusted using the VA1 value. For measurement of the downstream PLRs, we transmit 800 Mbit/s packet from a G-PON OLT to each G-PON ONT, while we also assign 300 Mbit/s traffic at each G-PON ONT for measurement of the upstream PLRs.

In this downstream PLR result, we confirm that the long-reach G-PON using our reach extender satisfies a PLR of 10^{-10} in downstream transmissions until about –29 dBm. When downstream forwarding error correction (FEC) is used within a G-PON, the long-reach G-PON can satisfy a PLR of 10^{-10} for up to –32 dBm. As a result, we can increase the link budget by about 3 dB through the use of FEC. If the received power is about –31 dBm or less, the PLR is drastically increased due to a deactivation of G-PON ONTs. In this upstream PLR result, if
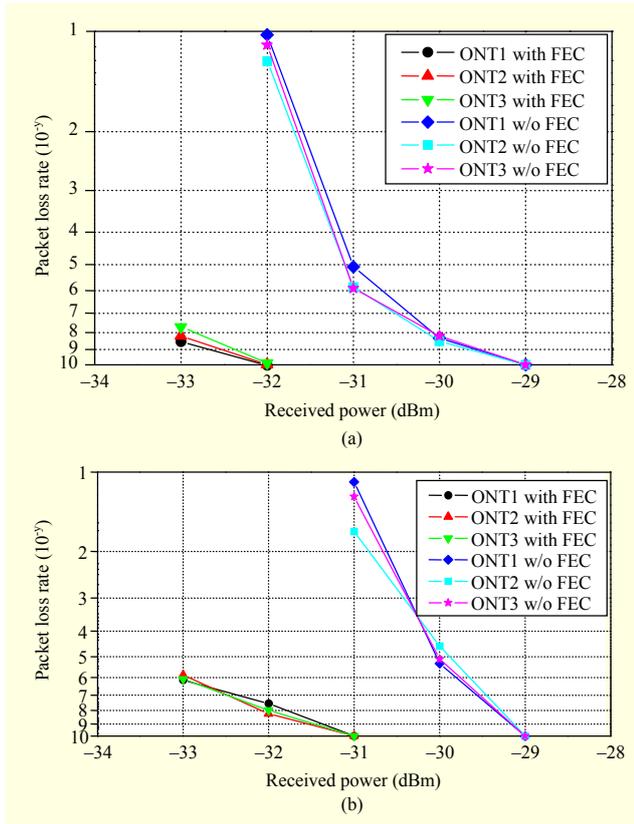
Fig. 11. (a) Down stream and (b) upstream PLR results according to VA1 and use of FEC.

Fig. 12. PLR results measured in downstream and upstream paths according to VA2.

Table 1. Performance comparison.

Item	OA-type reach extender [6]	OEO-type reach extender [7]	Proposed reach extender
Layer	L0 (optical amplifier)	L1 (2R repeater)	L1 (3R regenerator)
Upstream mode	Burst	Burst	Continuous
System configuration	1,490 nm SOA, 1,310 nm SOA, two WDM filters	G-PON OLT/ONU optical module	G-PON OLT/ONU optical module, single FPGA
Total link budget	54 dB	56 dB	59 dB
Optical margin	2 dB	4 dB	7 dB
Split ratios/ distance	1:64* 60 km	1:128 60 km	1:128 60 km
PON link management	No	No	Yes (BIP, LOF)
Power consumption	8 W/Port	6 W/Port	6 W/Port
Design cost	Middle	High	Low

* Due to approximate 3 dB margin

the received optical power is below –33 dBm, the PLR measurement is impossible due to G-PON deactivation. When the received power is –31 dBm, an upstream PLR is drastically increased more than a downstream PLR because burst mode GTC frames in the upstream are discarded due to inaccurate BRC using an upstream bandwidth map error. In this result, we can achieve a PLR of 10^{-10} up to a received power of –29 dBm. In Fig. 11, the maximum penalty for a PLR of 10^{-10} is below 1 dB.

Figure 12 shows the results of a PLR for downstream and upstream transmissions according to the VA2 value in ODN. The loss budget between the G-PON OLT and reach extender is set as –29 dBm. In this result, a long-reach G-PON based on the proposed reach extender satisfies PLR=10^{-10} up to –30 dBm in all ONTs. This means that an ODN can support a 20 km reach with 128 split ratios. However, when loss budget is higher than –31 dB, we observe that the downstream PLR difference is larger than 10 times for each ONT because error rate of G-PON encapsulation method delineation caused by a BIP error is different for each ONT.

As shown in Figs. 11 and 12, we can achieve a PLR of 10^{-10} under a link budget of –59 dB in the long-reach G-PON applied in our reach extender. This is superior to the OA-type
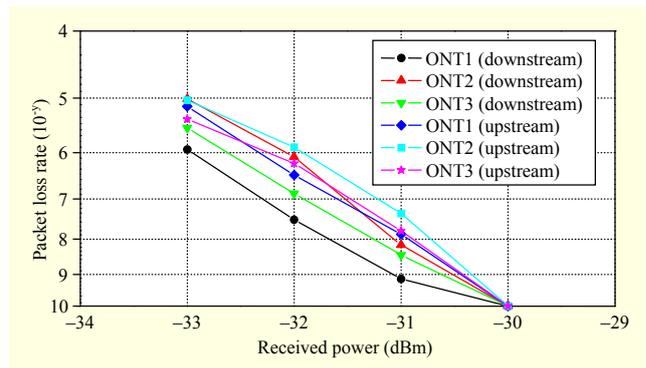
reach extender [6] with a link budget gain of about 5 dB.

Table 1 shows the comparison results between our reach extender and reported reach extender technologies. Data on the power consumption and performance of individual components were extracted from different product data sheets and research papers. Our results show that our reach extender is more efficient with respect to link budget, power consumption, and design cost than other technologies.

V. Conclusion

We proposed and experimentally demonstrated an efficient 3R OEO-type reach extender based on a quad-port architecture

to overcome the physical limitations of a legacy TDMA-PON. Our proposed reach extender can provide a low-cost, low-power, and high-capacity design for a legacy TDMA-PON without modification of the system equipment. The proposed reach extender can also provide remote management via an embedded ONT and SNMP agent and support burst-to-continuous mode conversion with respect to the upstream through a GTC frame adaptor. In addition, it can configure 1+1 link protection at the feeder section through the quad-port architecture.

In particular, our results show that our proposed reach extender can support a distance of 60 km in a 128-way split ratio through an increased link budget of about 59 dB with full compatibility in a G-PON. The long-reach TDMA-PON applied with our reach extender can support a PLR of 10^{-10} in downstream and upstream transmissions. If the G-PON uses FEC, it can increase the link budget by 61 dB.

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Kwangok Kim received his BS in information and communication engineering from Chosun University, Gwangju, Rep. of Korea, in 1999, and his MS in electronic engineering from Chonnam National University, Gwangju, Rep. of Korea, in 2001. Currently, he is a senior researcher at ETRI and a PhD student at Chungnam National University, both in Daejeon, Rep. of Korea. His research interests include passive optical network technologies such as TDMA-PON, WDM-PON, and OFDMA-PON.

JieHyun Lee received her BS and MS in electronic engineering from Chungnam National University, Daejeon, Rep. of Korea, in 2000, and the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Rep. of Korea, in 2003, respectively. Currently, she is a senior researcher at ETRI, Daejeon, Rep. of Korea, and a PhD student at Chungnam National University. Her research interests include 10 Gbps WDM-PON and CPRI optical source.

Sangsoo Lee received his BS and MS in applied physics and his PhD in the area of DWDM transmission technology from Inha University, Incheon, Rep. of Korea, in 1988, 1990, and 2001, respectively. In 1990, he joined the Optical Communication Department at ETRI, Daejeon, Rep. of Korea. He has conducted research in 2.5 Gbps-, 10 Gbps-, and 40 Gbps-based DWDM optical transmission and the ROADM system. His current research activities are in optical access network, WDM-PON, and energy-efficient network technology. Dr. Lee is the head of the Optical Access Research Team of ETRI.

Jonghyun Lee received his BS and MS in electronic engineering and his PhD in communication engineering from Sungkyunkwan University, Seoul. Rep. of Korea, in 1981, 1983, and 1993, respectively. In 1983, he joined ETRI, Daejeon, Rep. of Korea. His current research activities are in optical communication systems and optical Internet technology. Dr. Lee is the head of the Department of Optical Internet Research at ETRI.

Younseon Jang received her BS in electronics engineering from Kyungpook National University, Daegu, Rep. of Korea, in 1992, and her MS and PhD in electrical and electronics engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Rep. of Korea, in 1994 and 1999, respectively. From 1999 to 2006, she was a senior member of the research staff at ETRI, Daejeon, Rep. of Korea. In 2006, she joined the faculty of Chungnam National University, Daejeon, Rep. of Korea, where she works as an assistant professor in electronics engineering. Her current research interests include WDM-PON, channel resource management in cognitive radio systems, positioning, navigation, and timing (PNT) data networking, and MAC protocol in underwater acoustic sensor networks. Prof. Jang is a member of IEEE, IEICE, and KICS.