First Real-Time Symmetric 50G TDM-PON Prototype with High Bandwidth and Low Latency

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***Abstract*—50G TDM-PON has been defined to be the next generation of fiber access network system. 50G TDM-PONs are classified into asymmetric and symmetric types with different upstream line rates. Here we reported, for the first time, a real-time symmetric 50G TDM-PON prototype. The line rates for both downstream and upstream are 50Gb/s based on NRZ modulation format. This equipment also supports low latency and high precision synchronization.**

Keywords—passive optical network, power budget, low latency, synchronization

I. Introduction

The time-division multiplexed passive optical network (TDM-PON) has been the most popular and important infrastructure to realize fiber to the home/building (FTTH/FTTB) since it was invented in the late 1980s. Due to its point to multipoint architecture with a passive optical splitter at the remote node, the TDM-PON is not only cost-effective, but also convenient to maintenance. In the past few years, 10-gigabit PONs (10G-EPON [1] and XGS-PON [2]) have seen a significant growth in deployment as an evolution from the earlier PON generations. Even with deployment of 10G-class PON is still on the rise, the thoughts of the industry must turn to what comes next. With more and more bandwidth hungry Internet broadband services like VR/AR applications and ultra-high definition (UHD) video, and more and more unpredictable emerging technology development, the existing PON systems cannot meet the bandwidth requirements of future services. In addition, there is a number of strong interactive applications require extremely large upstream bandwidth, such as VR gaming and UHD online meeting.

In order to solve this capacity crunch, ITU-T has defined 50G TDM-PON to be one of the most promising candidates for next generation fiber access network system. The first version of global standard for 50G TDM-PON has already been published in 2021 [3]. The downstream line rate is 50Gb/s based on NRZ modulation format, while the upstream have three different rates: 12.5Gb/s, 25Gb/s and 50Gb/s. Specific line rate combinations can be selected for different use cases. Except traditional FTTH applications, 50G PONs are also suitable for 5G small cell backhaul. Compared to the construction of D-RAN which requires a huge amount of both fiber resources and transmission equipment, using PON based on existing optical distribution network (ODN) can significantly reduce the total cost of network construction and minimize the additional optical fiber resources [4,5]. In this case, there will be more strict requirements on time delay and synchronization for the PON system.

As a promising scheme for the next generation of access networks, 50G TDM-PON has been intensively studied in the past few years. By using externally modulated laser (EML) with semiconductor optical amplifier (SOA) at the optical line terminal (OLT) side, and 25G-class avalanche photodiode (APD) with digital signal processing (DSP) technology at optical network unit (ONU) side, the 50Gb/s downstream with E2-class power budget was achieved [6]. The real-time asymmetric 50G PON prototype with 25Gb/s upstream was demonstrated in [7]. The field trail proved this equipment is capable of carrying 5G small cell backhaul [8]. For 50Gb/s upstream, it has been shown based on separate devices that by using SOA as preamplifier, a power budget of class N1 was reached [9]. However, there is no real-time symmetric 50G PON prototype reported so far.

In this paper, we demonstrate the first real-time symmetric 50G TDM-PON prototype. The line rates for both down-stream and upstream are 50Gb/s based on NRZ modulation format. The OLT line card is compatible with the commercial chassis. This equipment supports low latency and high precision synchronization. We measured the throughputs and time delay in both directions using an Ethernet test center. The time and clock synchronization precision were also characterized.

II. Physical Layer Scheme and Characterization

One of the most challenging part of the symmetric 50G PON is the physical layer solution. In order to meet class C+ power budget in both directions, not only the bandwidth of all optical and electronic devices need to be dramatically increased, the transmitter power and receiver sensitivity should also be improved. The physical layer scheme of our PON system is shown in Fig. 1. For the 50Gb/s downstream link, the schematic setup is exactly the same as [6]. It is noted that a DSP pre-equalizer is employed at the transmitter side, which is a 7-tap FIR filter. Because of the APD used in our system is in 25G-class bandwidth, a DSP equalizer at the receiver side is used to compensate the impairment of inadequate receiver bandwidth and the fiber dispersion. The algorithm of the equalizer is classical FFE+MLSE.

For the upstream of 50Gb/s burst-mode signal, at the ONU transmitter side, the low-cost direct-modulated laser (DML) is selected. The FEC encoded signal from the ONU MAC travels through the SerDes interface and enters the pre-equalizer which is a 15-tap FIR filter. After the DAC, the electronic signal is controlled by a burst-mode driver to create a periodic on and off shape, and finally modulated by a 50G DML and sent into the optical fiber. At the receiver side, the after converting into electrical signal by an APD, there is a burst-mode (BM) TIA to amplify the photocurrent from each ONU and send into the DSP unit. After a burst-mode ADC, the digital signal will complete the clock and data recovery (CDR)

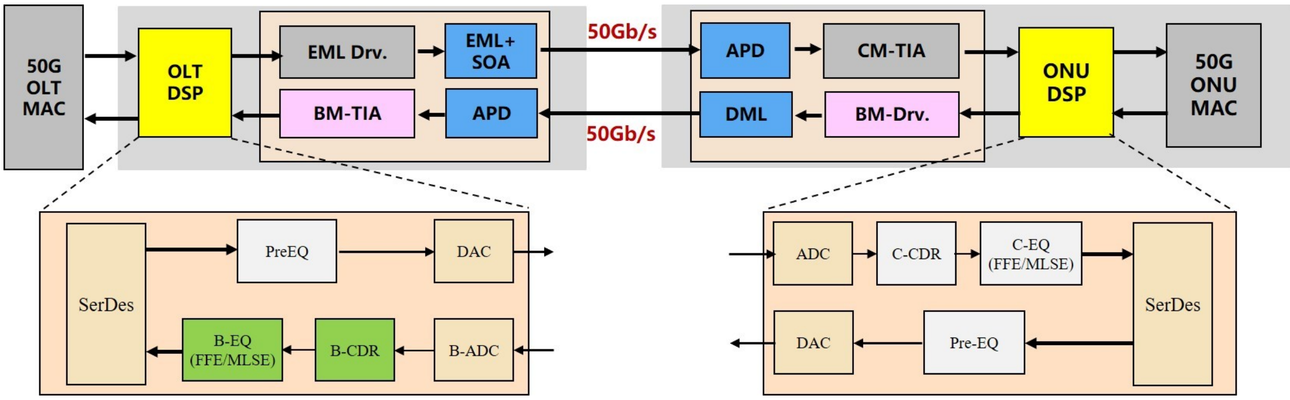

Fig. 1. Schematic setup of physical layer transmission link for 50Gb/s NRZ signal in both directions.

and equalization, and finally sent into the OLT MAC through the SerDes interface.

In the downstream transmitter, the EML used in our equipment has a central wavelength of 1342.1nm. After amplifying with a SOA, the output power is measured to be 10.8dBm. We also measured the eye diagram of the 50Gb/s NRZ signal, the result right after EML is shown in Fig. 2(a) and the result after 20km fiber is shown in Fig. 2(b). We can see that the eyes are clearly opened for both cases. The extinction ratios (ERs) are over 10.5dB for both cases. The TDEC before and after transmission is 2.8dB and 3.7dB, respectively.

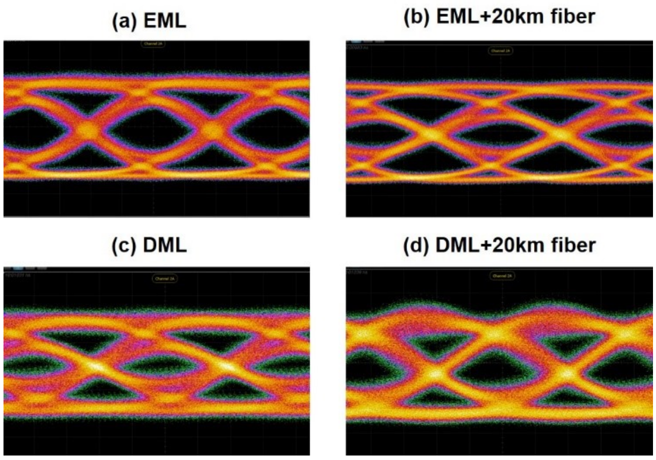

Fig. 2. The eye diagram of 50G EML (a) before and (b) after 20km fiber; and the eye diagram of 50G DML (c) before and (d) after 20km fiber.

For the upstream direction, the DML has a central wavelength of 1305.8nm, which is capable of realizing coexistence between 50G PON and existing XG(S)-PON. The output power coupled into the fiber was 7.8dBm. We also measured the eye diagram of 50Gb/s NRZ signal created by the DML, the results before and after 20km fiber are shown in Fig. 2(c) and 2(d). Due to the pre-equalizer sacrifices the ER to compensate the TDEC, the ER for both cases is just over 5dB. As a result, the TDEC value before and after fiber transmission is only 4.1dB and 2.8dB, respectively.

There is another crucial device to realize the reception of upstream burst-mode signal that is 50G BM-TIA. The main function is to amplify the photocurrents with different amplitude from different ONUs to be a similar voltage level. In order to test its performance, we create two bursts with 15dB differential optical power. The temporal waveforms are shown in Fig. 3. The yellow waveform is for the signal before BM-TIA and the pink one represents the signal after the TIA. We can see that after amplification, two signals have a similar amplitude, and the settling time of the BM-TIA is around 150ns. Further optimization of the chip circuit is required to reduce the settling time to be within 50ns, so that the total preamble for each burst could be even shorter.

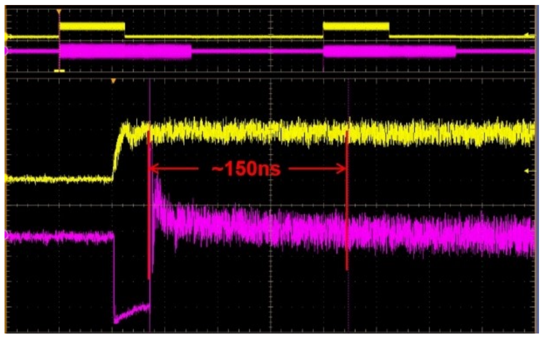

Fig. 3. Temporal waveforms of the burst-mode signal from two DMLs before and after the BM-TIA.

Next, we characterize the receiver sensitivities for both directions. The BER performances of 50Gb/s NRZ signals in both downstream and upstream directions are shown Fig. 4. For 50Gb/s downstream, the sensitivities for back-to-back and 20km fiber transmission cases were -27.8dBm and -27.2dBm, respectively. The resulted power budget is over 37dB due to the high sensitivity of the APD and also the strong DSP equalizer. For the upstream direction, the results were not as good as downstream because of the nature of burst signal. For back-to-back case, the sensitivity was -25.8dBm. After 20km transmission, the result degraded to be -25.1dBm. Typically, in the normal dispersion regime, the sensitivity could be better after fiber transmission if the DML has a positive chirp. But this is not the case for the fiber used in this experiment. The total power budget for upstream transmission is 32.9dB. This results could be improved by adding a SOA preamplifier at the OLT receiver side.

III. Test Results of the Prototype

For this symmetric 50G TDM-PON prototype, both the OLT MAC and ONU MACs were built based on FPGAs. The volume of the ONU is slightly larger than the commercial product, while the OLT line cards are compatible with the existing commercial chassis. Each OLT line card supports eight 50/50G PON ports. The optical module of the OLT side was packed in a pluggable QSFP-28 type.

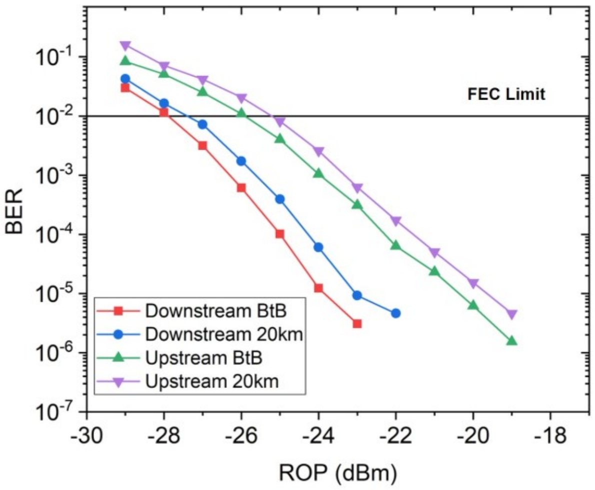

Fig. 4. BER performances of 50Gb/s NRZ signals for both directions.

We used an Ethernet test center to characterize the system performances, the experimental setup is shown in Fig. 5. The OLT uplink board was connected with the test center through multiple 10GE optical interfaces. The PON link contains 20km of G.652 single-mode fiber and a 1:4 optical splitter. Two ONUs were registered under the same PON link. Each ONU was connected with the test center via four 10GE optical interfaces. We send packets in both directions to test the throughput and latency performances of the prototype.

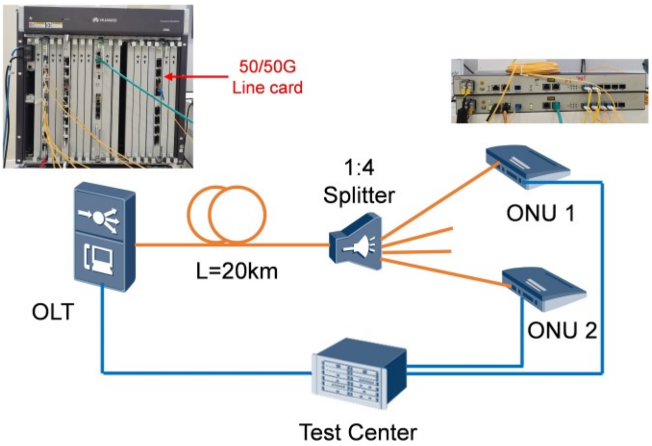

Fig. 5. Experimental setup for the characterization of the real-time 50G TDM-PON, (inset) photos of the OLT and ONUs under test.

A. Throughputs

We measured the maximum throughputs it can reach without any packet loss, the results are shown in Fig. 6. We can see that the two ONUs have a similar results. The aggregate throughputs under single PON link for downstream and upstream are 40Gb/s and 26.3Gb/s, respectively. The downstream throughput almost reached the theoretical limit of the LDPC FEC that is 40.75Gb/s. However, the upstream throughput is much smaller than the theoretical value. One of the reasons is that the processing ability of the MAC based on FPGA is not good enough to support LDPC FEC encoder. What we used here is a self-developed FEC, which occupied 30% of the overhead and the BER threshold is only 3E-3. Another reason is that some of the 50G electronic devices include DML driver and ADC are not in burst-mode. Much more enable and disable time (few µs) is required in order to eliminate the crosstalk between adjacent bursts. Also, the preamble for the CDR algorithm could be further squeezed. In comparison, we also test the upstream throughput with only one ONU activated, the result improved to be 30.2Gb/s due to one burst overhead was eliminated.

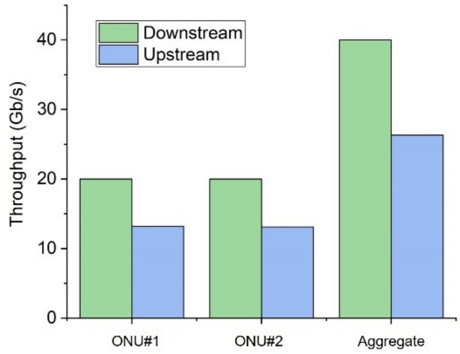

Fig. 6. Throughputs of the symmetric 50G TDM-PON prototype in both directions with two ONUs activated.

B. Latency

Low latency is an important feature in many use cases. In this PON system, we applied two low latency techniques. The first one is dedicated activation wavelength (DAW). In traditional PON system, there is a 250-µs quiet window will open periodically to check if any new ONU is about to registered, and exchange its serial number and ranging information with the OLT. Here we move it to the XG(S)-PON upstream wavelength, so that the maximum latency of each 50G PON ONU could be reduced by approximately 250µs.

Another low latency technique is multiple bursts per frame. In traditional PON system, there is only one time slot within each frame for every ONU. Then the burst for each ONU arrives every 125µs. For the multiple burst per frame system, it will allocate multiple bursts for each ONU within the same frame. In our system, there is two bursts per frame, which means the packets for each ONU arrives every 62.5µs. In this case, the awaiting time is shrunk, so both average latency and maximum latency is reduced.

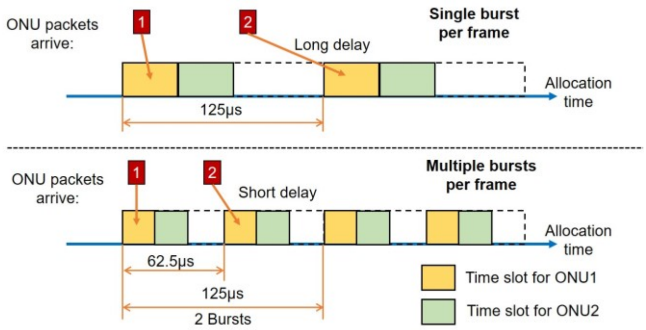

Fig. 7. Illustration of the low latency scheme of multiple bursts per frame.

We removed the 20km feeder fiber to test the latency performances of the PON system alone. We fixed the packet length to be 512 bytes. The measured results were shown in Table 1. We can easily find out that in downstream direction, both average and maximum latency are pretty low for all cases. Let's focus on the upstream direction. In normal mode, the average and maximum latency are 20.3µs and 374.3µs, respectively. Typically, the upstream latency of a PON system is larger than this value since here we have only two ONUs activated. After the DAW turned on, the maximum latency reduced by ~250µs, corresponding to the quiet window time. When we configured two bursts per frame, both average latency and maximum latency is further reduced. The final round-trip average latency for this system is only 73.4µs.

TABLE I. MEASURED BACK-TO-BACK LATENCY RESULTS

		Normal	DAW	Multi-bursts
Average latency (µs)	Upstream	78.1	77.8	53.1
	Downstream	20.3	20.2	20.3
Maximum latency (µs)	Upstream	374.3	128.8	101.9
	Downstream	30.8	31.2	31.4

C. *Synchronization*

In order to carry 5G small cell backhaul services, a high-precision time and clock synchronization is required for the 50G TDM-PON systems. In this symmetric 50G PON system, both 1588v2 and SyncE protocols are supported. We employed a synchronization performance tester connected with both OLT and one of the ONUs to measure the precision of time synchronization. We keep running the test for 10 minutes and the result is shown in Fig. 8. According to the result, the time synchronization precision between the OLT and ONU is stably fixed at 29ns during the entire measuring time. This precision is good enough for the 5G wireless base station backhaul bearing.

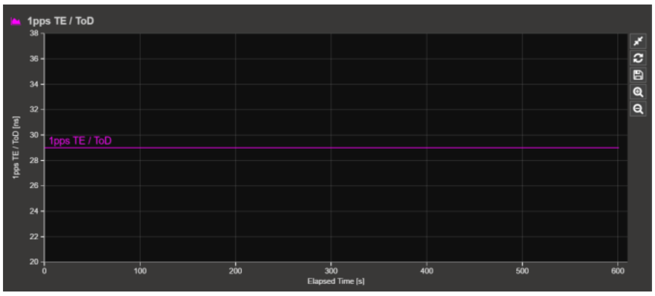

Fig. 8. Result for time synchronization measurement over 10 minutes.

IV. CONCLUSIONS

We have demonstrated the first real-time symmetric 50G TDM-PON prototype that can fit in the commercial chassis with eight ports per line card. The line rates for both downstream and upstream are 50Gb/s based on NRZ modulation format. The optics and electronic devices at the OLT side were packed in a QSFP-28 optical module. The DSP chipset was used for signal equalization and CDR. The throughputs in downstream reached 40Gb/s. For the upstream, the throughputs were 26.3Gb/s for multiple ONUs, and 30.2Gb/s for single ONU. The upstream throughputs could be dramatically improved in the future by optimizing the burst-mode electronic components to reduce the signal settling time. By using low latency techniques, the average round-trip latency is only 73.4µs. A time synchronization precision of 29ns is also achieved. This work paves the way for future development of high-speed TDM-PON, and accelerates the progress of next generation of fiber access networks.

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