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# High speed and low latency passive optical network for 5G wireless systems

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## ABSTRACT

***To satisfy the latency and bandwidth demands of 5G mobile networks and next-generation residential/commercial services, we offer a high-speed and low-latency passive optical network (PON) driven by time controlled-tactile optical access (TIC-TOC) technology. We demonstrate 48-hour real-time packet transmission up to 50 Gb/s without packet loss using channel bonding in a single optical distribution network. (ODN) with a split ratio of 1:64 and a reach of 20 km. Additionally, there is proof that 5G mobile services have a delay of less than 400 milliseconds. We also confirm that the overall throughput may be increased to 100 Gb/s by adding additional channels.***

***Keywords***—*NG-EPON, Multilane-based PON, 50 Gb/s PON, Channel bonding, Low-latency DBA*

## 1. INTRODUCTION

Recent developments in a variety of new services, such as 4K ultra high definition (UHD) video streaming, flying saucers, and augmented reality reality (VR/AR), have called for a constant expansion of wireless communication, and optical connectivity will be crucial in supporting these new services [1-3]. In the ITU-5G R's vision, high packet throughput of 20 Gb/s per cell, 100 Mb/s user seen data rate, and less than 1 ms latency are a few key performance indicators (KPIs) [2-3]. Now that we have faster wireless networks, the length of the wireless path is shorter, and the installation of optical fibre is closer to the user. There is something for everyone when it comes to single wavelength based 10 Gb/s speed optical access thanks to the variety of mature specifications available.

Passive optical networks (PON) now require 25 Gb/s per wavelength connection in order to meet the bandwidth and latency requirements of next-generation wireless and wired services.

These techniques mostly focused on PON with numerous wavelengths. Numerous research projects are being carried out to offer practical solutions for future access networks that must manage mobile, residential, and commercial services in a single optical distribution network, which necessitates high bandwidth and low latency (ODN). The main objective of these methods was the multi-wavelength PON. Time and wavelength division multiplexing PON (TWDM-PON), which is described

in full in the second next-generation PON (NG-PON2) by the ITU-T, is a popular technique [4-6]. Four wavelengths are layered in a single fibre at a 10 Gb/s rate to make up the NG-PON2. In order to retrieve data, the filter of the optical network unit (ONU) selects a particular wavelength. Since each ONU has the same capacity of 10 Gb/s, the bit rate for each ONU is set at 10 Gb/s. One method to achieve high capacity PON utilising multi-wavelength is to increase the processing speed of each wavelength to 25 Gb/s and use channel-bonding [7]. In the beginning, we could increase PON capacity in response to traffic increases using a single speed ONU in ODN. An optical line terminal (OLT), which utilises a single wavelength, can only support 25 Gb/s ONUs. Then, depending on traffic development, a typical ONU may use two wavelength pairs and transmit and receive data at a speed of 50 Gb/s. In accordance with IEEE802.3ca's next-generation Ethernet PON (NG-EPON) [8–9], OLT also supports 25G and 50G ONUs. Channel bonding enables multi-speed ONUs to coexist in a single ODN, and the relationship between a single ONU's bit rate and the number of channels is inverse. In order to promote faster data speeds, the Broadband Forum is also looking into channel bonding technology [10]. The multilane-based PON technology [11], which delivers 50 Gb/s per wavelength with intricate modulation for a 100 Gb/s or higher PON, is also taken into consideration. There are still many technological issues that need to be resolved before the 50 Gb/s per wavelength option can be implemented. PON connectivity offers a more affordable option in situations when power resources are limited. Low latency and high capacity in a 25 Gb/s per wavelength reliant PON to support 5G service have received relatively little research, despite the fact that there have been numerous investigations into the implementation of high-speed PON with 25 Gb/s per wavelength and channel-bonding [12–14].

In this study, we show a time controlled tactile optical access (TIC-TOC) based 100 Gb/s PON with low-latency dynamic bandwidth allocation and channel bonding (DBA). Channel bonding enables up to four channels in both the downstream and upstream directions. To maximise bandwidth utilisation and minimise delay, four service classes are served by each ONU using low latency oriented packet scheduling (LOPS). We successfully demonstrated real-time packet transmission of 50 Gb/s in 64-way power split over 20 km of single mode fibre (SMF) for 48 hours using an FPGA-based OLT and ONU prototype. Additionally, it is demonstrated that 5G mobile networks have a 400 millisecond or less delay. To demonstrate bandwidth increase up to 100Gb/s, channel bonding is employed.

The channel-bonding and low-latency DBA-based high-speed PON activity principles are discussed in Section II. The real-time demonstration configuration for high-speed and low-latency PON is then mentioned in section III. Section IV examines 50 Gb/s packet transmission results, low latency computation, long-term stability, and capabilities. It also discusses the optical connection output with a 25 Gb/s NRZ transceiver in the O-band. There is an upgrade to 100 Gb/s available.

## 2. HIGH SPEED AND LOW LATENCY PON

The TIC-TOC technology uses packet-level channel bonding over several wavelengths and cyclic-based DBA to provide a data rate of up to 100 Gb/s with a latency of less than 1 ms. With four wavelengths, the overall bandwidth may reach 100 Gb/s, with each operating at a data rate of 25 Gb/s. Each ONU may handle several wavelengths, unlike the NG-PON2. Transmission at a single wavelength over a finite data rate is made possible by channel bonding. As a result, channel bonding allows multi-speed ONUs to coexist in a single ODN.

A coexisting multi-speed ONU in a PON operation scenario is shown in Figure 1. The PON will be utilised for mobile fronthaul/backhaul, business services, and traditional residential services in the same ODN [15–16]. Different QoS dependent on the type of service is anticipated, together with assured high bandwidth and low latency of less than 1 ms, to manage 5G mobile traffic. For a low latency link to mobile traffic, a cyclic-based DBA with a 250 second cycle time is used. Since polling-based bandwidth allocation is used, a standard PON often has a latency of several milliseconds or more.

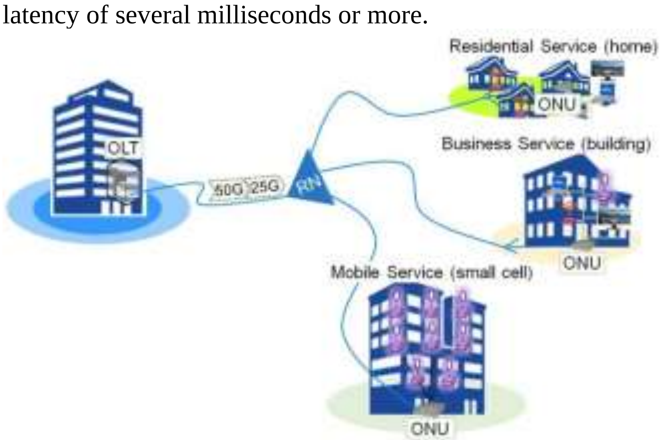



**Fig. 1. Future high-capacity and low latency PON accommodating mobile, business, residential services in a single ODN**

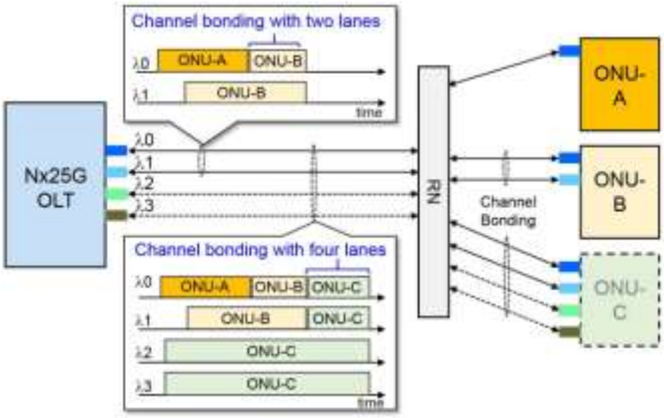


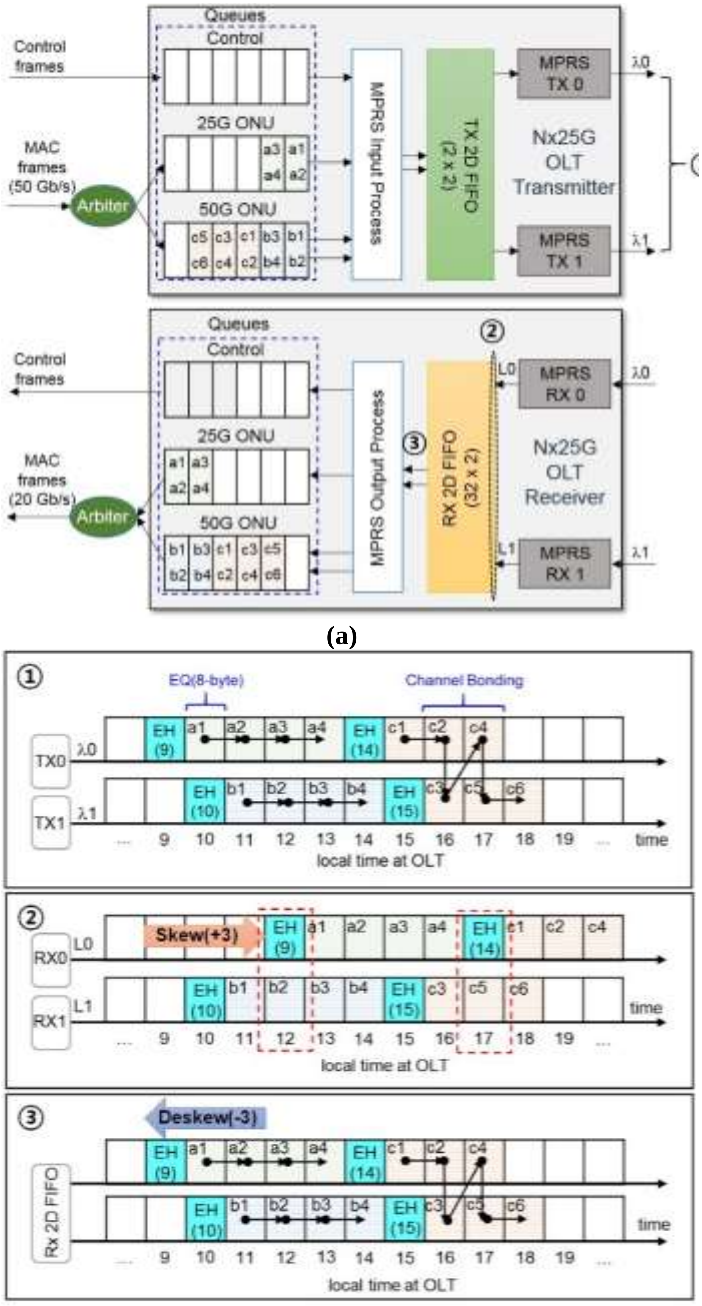

**Fig. 2. Concept of channel bonding in TDM/WDM hybrid PON**

*A. Channel Bonding Scheme*

The idea of multilane channel bonding in TDM/WDM hybrid PON is shown in Fig. 2. Data overlapping over two or four lanes was implemented by channel bonding. The ONU-A sends data at a rate of 25 Gb/s through lane 0 (0), whereas the ONU-B and the ONU-C use channel bonding to transmit data at rates of 50 Gb/s through two lanes (0, 1) and 100 Gb/s through four lanes (0, 1, 2, 3), respectively. As a result, channel bonding makes it possible for multi-speed ONUs to coexist in a single ODN. It is possible for ONU-A and ONU-B to transmit data over lane 0 (0) and/or lane 1 (1), respectively, in the case of channel bonding with two lanes, as indicated in the upper portion of Fig. 2. When ONU-data A's transmission is finished, ONU-B can start transmitting data simultaneously using lanes 0 and 1. If not, ONU-B can only transfer data using lane 1 (1). As a result, ONU-B has a throughput that ranges from 25 to 50 Gb/s. The ONU-C may utilise 4 lanes, ranging from lane 0 to lane 3, when channel bonding with a four channel. Regardless of data transfer in lanes 0 and 1, the ONU-C always utilises lanes 2 and 3. In the time domain, other ONUs share lanes 0 and 1. As a result, the ONU-throughput C's can go as high as 100 Gb/s. In order to achieve high data throughput of 50 Gb/s rate or greater and to efficiently utilise the bandwidth among the multi-speed ONUs in the high-speed PON, channel bonding is crucial technology [17]. The functional block structure and an illustration of envelope frame processing for channel bonding in OLT are shown in Figure 3. Channel bonding is carried out in the Ethernet protocol layer's multipoint reconciliation sublayer (MPRS) [8–9]. The variable-length envelope frames, which are made up of an envelope header and payload, are the subject of channel bonding. A number of MAC frames are included in the envelope payload. At the MPRS, eight-byte envelope quantum (EQ) frames for a single logical link ID (LLID) are interleaved on two lanes. Three queues for storing control frames for the multipoint control protocol (MPCP) or for operation, maintenance, and administration are part of the channel bonding, as shown in Fig. 3(a) (OAM). Each ONU receives the user MAC frames via the arbiter. Each queue's MAC frames are accepted by the input process, which converts them into EQs and stores them in the TX FIFO. Then, using the 25 Gb/s gigabit media independent interface, two subsequent transfers are fed with EQs pulled from this buffer by the MPRS TXs (25GMII). The MPRS RXs, on the other hand, accept two consecutive envelope frames from XGMII and store them in the correct row of the RX FIFO in accordance with the envelope position alignment marker (EPAM) present in the envelope header. The output procedure takes EQs out of the RX FIFO and feeds them into the correct queues that the LLID has designated.

As seen in Fig. 3(b), the 25G ONU queue-stored MAC frame (a1, a2, a3, and a4) is sent in EQ units on lane 0, and the EPAM into envelope header is assigned into 9 using the current local time. The 50G ONU queue-stored MAC frame (b1, b2, b3, and b4) is broadcast into lane 1 with an EPAM of 10. However, channel bonding is used in this instance when the second MAC frame (with values from c1 to c6) is transmitted over two lanes with two envelope frames. On the receiver side of the OLT, the data sequence is modified to c3, c5, c1, c6, c2 and c4 if the envelope frame comes recently in three cycles at lane 0. As a result, for data reordering in channel bonding, the skew correction in the OLT receiver is crucial. The IEEE NG-EPON standardization's tolerance for skew compensation with 16 EQ (16 x 8byte) was met by the PON prototype utilised in this experiment. By comparing the local time with the EPAM present in the envelope header, it is possible to determine the time difference needed to operate skew correction. The received EQs can typically be realigned without an ordering issue when the skew is adjusted in RX FIFO.




(a)

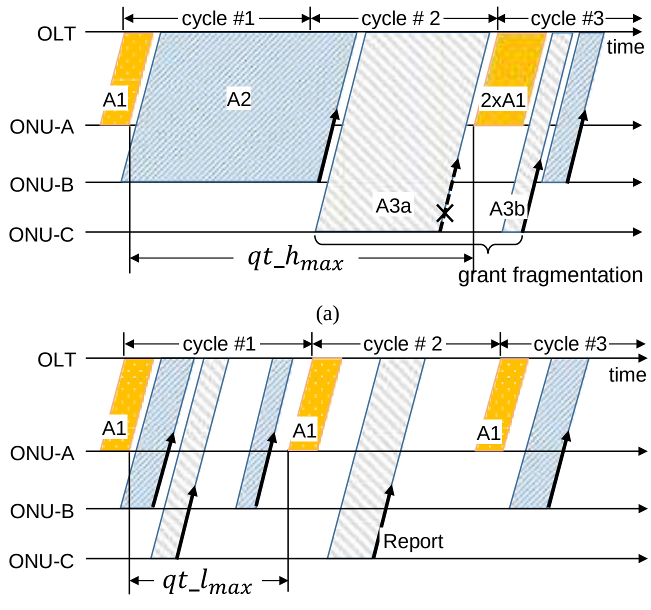
(b)

**Fig. 3. Functional block diagram and example of envelope frame processing for channel bonding (a) block diagram (b) envelope frame processing**

*B. Low latency DBA*

In PON, the two main types of bandwidth allocation are static bandwidth allocation (SBA) and dynamic bandwidth allocation (DBA). In SBA, a fixed bandwidth is regularly allocated, whereas in DBA, the bandwidth allocation is flexible depending on the queue status. While the DBA offers strong bandwidth utilisation and rather poor latency performance, the SBA can offer low latency but low bandwidth consumption. The SBA and DBA therefore have a trade-off relationship.

Several DBA techniques can be used in PON to efficiently utilise bandwidth and cut down on delay. The interleaved polling with adaptive cycle time (IPACT)-based online DBA technique aims to increase network usage and inter-ONU fairness [18]. It was suggested to apply the fast class-of-service oriented packet scheduling (FCOPS) using credit polling technique to offer end customers differential service and high network usage [19]. The upstream transmission delay in the prior DBA, however, is several milliseconds. PON needs assured bandwidth and low latency of less than 1 ms to support 5G mobile traffic. We have created low latency oriented packet scheduling (LOPS) based DBA to fulfil this requirement. Each ONU's class queues are classified into gold, silver, bronze, and best effort categories for the differential services (BE). According to the needed quality of service (QoS), input packets could be sorted into the appropriate class queues, such as the gold queue for leased lines, the silver queue for expedited forwarding (EF), and the bronze queue for assured forwarding (AF). The gold class also includes the low latency service. In LOPS, the upstream bandwidth is initially statically cycle-based-allocated to the gold class, and then the remaining bandwidth is dynamically credit-based-weighted-fair-queuing (WFQ)-allocated to the other classes, similar to FCOPS. Since the bandwidth is allotted to the gold class at least once within a maximum of two cycles of the LOPS algorithm, the latency and bandwidth of this class are guaranteed. As a result, 5G mobile traffic with low latency in the gold class and efficient bandwidth use for commercial and residential applications may be feasible.




(a)

(b)

**Fig. 4. Concept of bandwidth allocation with low latency oriented packet scheduling (LOPS) (a) under high traffic load (b) under low traffic load.**

The LOPS's concept of bandwidth allocation is depicted in Fig. 4. In this diagram, the ONU-A is allocated the gold class, while the ONU-B and ONU-C are respectively given the silver, bronze, and BE grades. Cycle #n denotes the n-th cycle of a fixed duration, such as 125, 250, and so forth. A 20 kilometres distance from an OLT, ONU has a 200 second round trip delay. The OLT must wait at least two cycles to get the second message from this ONU after receiving the first report message when the cycle duration is 125 s. At cycles #(n+1) and #(n+2), the bandwidth calculated by a report message received at cycle #n is assigned. First off, ONU-A is given priority when static time (A1) is assigned during cycle #1. ONU-B is subsequently given the computed time (A2) because it falls within cycle #2. The grant is divided in the following step since the calculated time (A3) for ONU-C exceeds the end of cycle #2. As a result, ONU-C receives an allocable partial time (A3a) during cycle #2, and the remaining time (A3b) will be given to ONU-A during cycle #3 after the static time has been given to that organisation. ONU-A receives twice as much time (2A1) at cycle #3 because the static time was not allotted to it at cycle #2. The queuing delay is the amount of time spent at the front of the gold class queue prior to input data being sent to an ONU. If no packet loss occurs during the allocated time, equations (1) and (2) show the maximum queuing delay (qt hma) and the maximum latency, respectively (A1).

$$qt\_h_{max} = 2 \times T_{cycle} - T_{alloc} \qquad (1)$$

$$latency\_hmax = qt\_hmax + Fdelay$$

$$= 2 \times T_{cycle} - T_{alloc} + F_{delay} \qquad (2)$$

where Tcycle signifies a cycle length and Talloc is the amount of time (A1) allotted to ONU-A. Fdelay represents an uplink propagation delay that takes the fibre delay into account. When $Fdela$ is fixed, the maximum latency grows while Tcycle rises and Talloc falls.

Assuming a low traffic load scenario in which the required bandwidth is allocated within a single cycle, the static time (A1) could be allocated to ONU-A per cycle, as shown in Fig. 4. (b). Equation represents the maximum latency ($latency\_l_{max}$) in this situation (3). As a result, the latency lmax is enhanced by one cycle duration ($T_{cycle}$) over the $latency\_h_{max}$.

$$latency\_lmax = qt\_lmax + Fdelay$$

$$= T_{cycle} - T_{alloc} + F_{delay} \qquad (3)$$

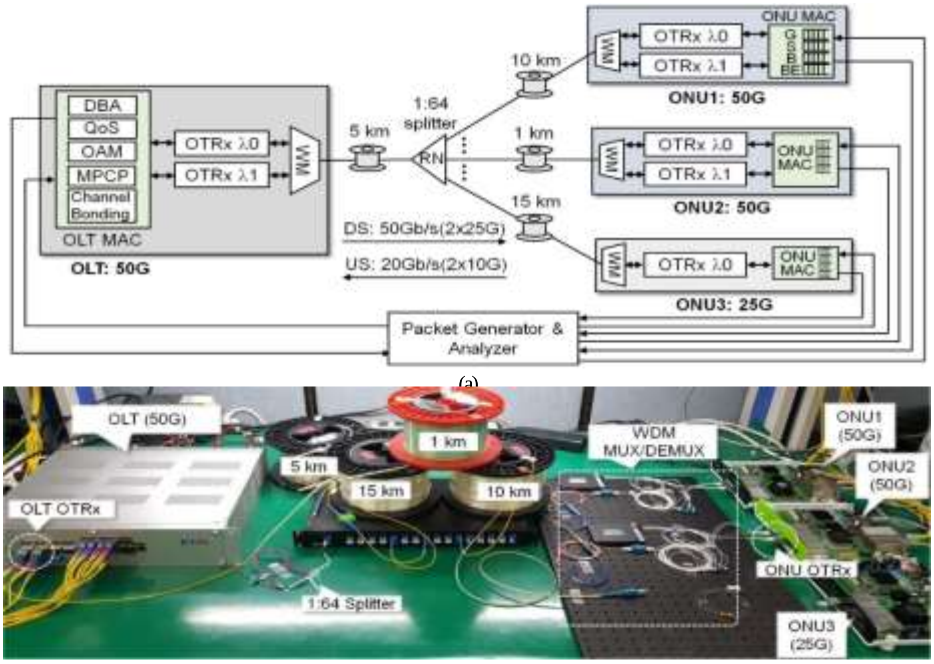
In equation (2) and (3), the latency is guaranteed within the $latency\_h_{max}$, regardless of traffic load condition.

## 3. EXPERIMENTAL SETUP

A test setup for a high-speed and low latency PON for a 5G wireless network is shown in Fig. 5(a). Time controlled tactile optical access (TIC-TOC) is the name given to the prototype since it can guarantee bandwidth and have minimal latency for a 5G wireless network. We made the assumption that ONU1 will be used for 5G mobile backhaul while ONU2 and ONU3 would be used for commercial or residential services. The ONU1 and ONU2 utilised two WDM channels to provide 50 Gb/s downstream and 20 Gb/s upstream bandwidth for mobile and enterprise services. The ONU3 uses a single WDM channel to support 25 Gb/s and 10 Gb/s of capacity. PON MAC in FPGA, PON transceivers, and multiple 10 Gb/s Ethernet (10GbE) interface make up the implemented OLT and ONU. These are also expandable up to 4 × 25 Gb/s.

The PON MAC includes LOPS based DBA, QoS, OAM, MPCP and channel bonding functions to manage multiple ONUs with operating 2 × 25 Gb/s downstream signals and 2 × 10Gb/s upstream signals. We implement pluggable PON OLT and ONU transceivers based on an avalanche photo-diode (APD) receiver optical subassembly (ROSA) to accommodate 2 × 25 Gb/s downstream signals and 2 × 10 Gb/s upstream signals in ODN with 20 km SMF and 64-split cost effectively as shown in Fig. 5(b). The modulation format for the upstream and downstream signal transmission was non-return to zero (NRZ). A small form-factor pluggable package is used to implement the pluggable PON transceiver.

Without the need for extra dispersion compensation, 25 Gb/s signal transmission can be accomplished in the O-band between 1260 and 1360 nm with negligible chromatic dispersion. The 25 Gb/s OLT transceiver operates at 1295 nm and 1300 nm, respectively. The wavelength MUX (WM) multiplexes the 2 25 Gb/s downstream signals before launching them to a feeder cable (5 km).




**(b)**

**Fig. 5. Experimental setup for the demonstration of high-speed and low latency PON for 5G wireless network (a) link configuration with 50 Gb/s OLT, 25 Gb/s**

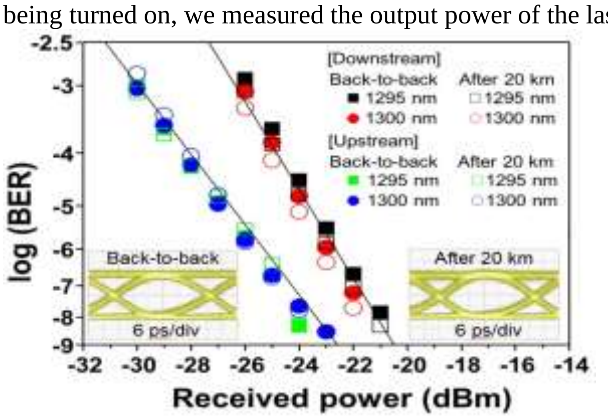
ONU, and two 50 Gb/s ONUs, (b) picture of implemented testbed. We configure the length of distribution fibres differently, in which the transmission distance between OLT and ONUs is different in real deployment. From OLT to ONU1, ONU2, and ONU3, respectively, are 15 km, 6 km, and 20 km. WDM downstream signals are de-multiplexed by the ONU WM and received using the ONU transceivers after travelling via the distribution fibres and 1 64 splitter.

The ONU transceiver utilised a 10 Gb/s BM direct modulation laser (DML) transmitter at 1270 nm or 1330 nm for compliance with IEEE 10G-EPON BM upstream transmission to enable burst-mode (BM) upstream transmission. WDM upstream burst packets are de-multiplexed at the OLT WM after being transmitted through ODN, and they are then received by a 10 Gb/s BM receiver at the OLT transceiver. We looked on the effectiveness of packet transfer using channel bonding and low-latency DBA using a packet generator and analyzer. The OLT automatically locates and registers ONUs using the MPCP protocol for the real-time PON demonstration. After that, the OLT modifies each ONU's service level (gold, silver, bronze, and best effort) and executes a DBA via MPCP operation.

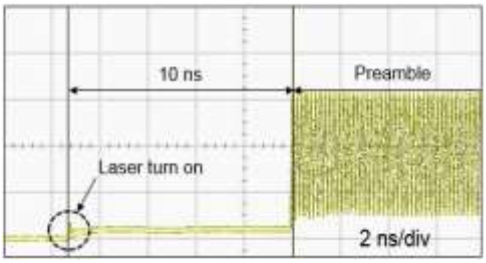
## 4. RESULTS AND DISCUSSIONS

*A. Link Performance*

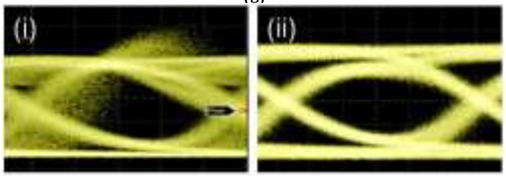
With 25 Gb/s downstream signals and 10 Gb/s upstream signals, we evaluated the bit-error-rate (BER) performance in the physical media dependent (PMD) layer of the TIC-TOC system. Figure 6(asolid )'s filled symbols depict the measured back-to-back BER performances of the upstream and downstream signals, which have an ER of 8 dB and a PRBS of 231-1 length. After 20 kilometres of downstream and upstream signal transmission, measured BER performances are shown by hollow empty symbols. Due to O-band transmission's ability to tolerate chromatic dispersion, there are never any noticeable power penalties after transmission across a distance of 20 km. A measured optical eye diagram of back-to-back and that after being transmitted over 20 kilometres are shown in the insets of Fig. 6(a). There was no discernible distinction between the eye diagrams. Due to the OLT transmitter's restricted output power, a forward error correction (FEC) must be used in the PCS layer in order to archive BER of 10–12 after passing via ODN (20 km SMF, 64 splitter, and WM). It was chosen to use FEC with RS (255, 223) coding to archive BER 10–12 at 25 Gb/s downstream and 10 Gb/s BM upstream. Since a launched power at OLT was 3 dBm for each wavelength, the minimum received power at ONU3 (25G), which has the longest transmission length of 20 km among the ONUs, was -23.0 dBm. Using FEC, we can transmit packets without making any mistakes. Fig. 6 displays a measured optical waveform for the BM 10 Gb/s upstream signal (b). After confirming that the preamble pattern was broadcast clearly within 10 ns of the laser being turned on, we measured the output power of the laser.




(a)




(b)

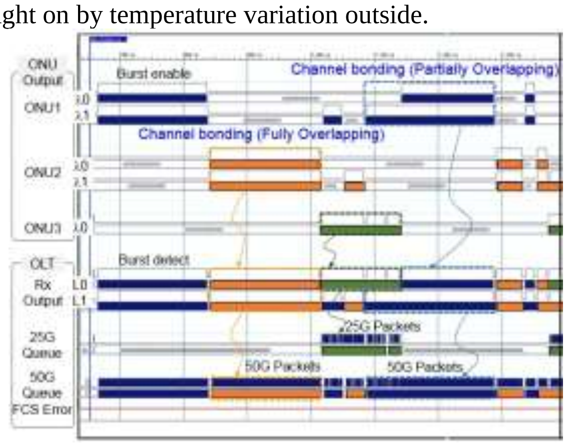



(c)

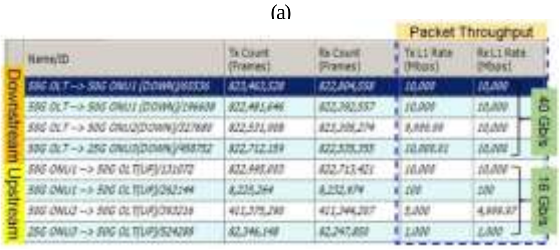
**Fig. 6. Measured BER and eye diagrams (a) performances of 2 x 25 Gb/s downstream and 2 x 10 Gb/s upstream (b) waveform of burst-mode upstream signal with 10 ns of laser turn on time (c) eye diagram of upstream signal at 55 °C (i) without temperature compensation (ii) with temperature compensation.**

As a result, the amount of BM overhead in an upstream packet can be decreased.

Because ONUs are frequently operated in settings that are out of our control, the ONU transceiver must be able to work stably at high temperatures. We investigated the optical output performance of a distributed feedback (DFB) transmitter operating at high temperatures in an ONU transceiver. The laser bias voltage and amplitude voltage, two operational factors of the uncooled DFB transmitter, were first optimised at room temperature. As shown in Fig. 6, when operating temperature is increased from room temperature to 55 °C, an eye diagram is no longer dependable due to rising jitter and overshooting (c-i). We created an automatic parameter control method for the DFB transmitter using the PON transceiver's processor to get around the output performance degradation brought on by temperature variation outside.




(a)



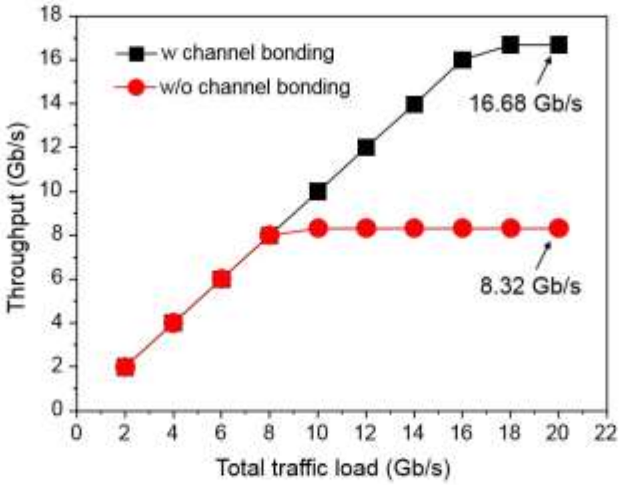

(b)

**Fig. 7. Real-time packet transmission with channel-bonding (a) simulation result of channel bonding through Xilinx Vivado (b) packet throughput measured in both downstream and upstream directions.**

When the observed temperature varies, the optical transceiver's -processor adjusts the DFB transmitter using a lookup table. An optical diagram that was measured using the automatic parameter control method at 55°C is shown in Fig. 6(c-ii). When the optical transceiver's -processor regulates the operating parameters of the DFB transmitter based on a lookup table, a clear eye diagram of the upstream signal is visible. The BER performance at high temperatures with adjustment was comparable to that at ambient temperatures without compensation.

B. Real-time 50 Gb/s Packet Transmission
The functional simulation result of the BM transmission using upstream channel bonding is shown in Figure 7(a). According to the simulation results, each ONU broadcasts BM data and a burst enable signal for the duration specified by an OLT. We further demonstrate that, depending on the time allotted to each lane, 50G ONUs (ONU1, ONU2) transmit BM data with totally or partially overlapping channel bonding. As shown in Fig. 7, 50G ONUs only transfer BM data via lane 1 (1) when 25G ONU (ONU3) transmits BM data to lane 0 (0). (a). As a result, each ONU's bandwidth can be allocated by the DBA in an effective manner. As a result, many speed ONUs can coexist in a single ODNThe receiver at the OLT picks up BM data from every lane and categorises it as 25G ONUs or 50G ONUs using LLID. In other words, when BM data with the same LLID is received over two lanes, channel bonding is carried out.




(a)


(b)

**Fig. 8. Channel bonding performance measured at upstream direction (a) packet throughput with and without channel bonding (b) packet throughput measured at packet analyzer.**

Channel bonding confirmed that the packets transmitted from each ONU may be reliably and error-free retrieved. Real-time packet transmission performance was assessed using HDL channel-bonding in FPGA-based OLT and ONUs, as illustrated in Fig. 7. (b). We produced the packets with a set length of 1,518 bytes to assess the packet throughput. In the downstream route, traffic loads of 20 Gb/s were sent to ONU1, and in the experimental arrangement, traffic loads of 10 Gb/s were also transmitted to ONU2 and ONU3. On the other side, ONU1 was connected to a traffic load of 10.1 Gb/s. ONU2 and ONU3 received traffic loads of 6 Gb/s and 1 Gb/s, respectively.

As a function of input traffic load, Fig. 8 depicts measured upstream packet throughput with and without channel bonding. Without channel bonding, we can see that lane 0 is the only way to transmit packets at a rate of roughly 8.32 Gb/s. In contrast, channel bonding enabled two-lane packet throughput of up to 16.68 Gb/s. A snapshot of the packet rate in the packet analyzer is shown in Fig. 8(b). We may assume that channel bonding will provide support for 16.68 Gb/s packet rate in the upstream direction with a single MAC.

*C. Low latency operation*
Through a real-time traffic transmission test, the latency of LOPS-based DBA was assessed. The packets returned to the packet generator and analyzer are timed to determine the latency as a round trip delay. Three ONUs' input traffic conditions are displayed in Table I.

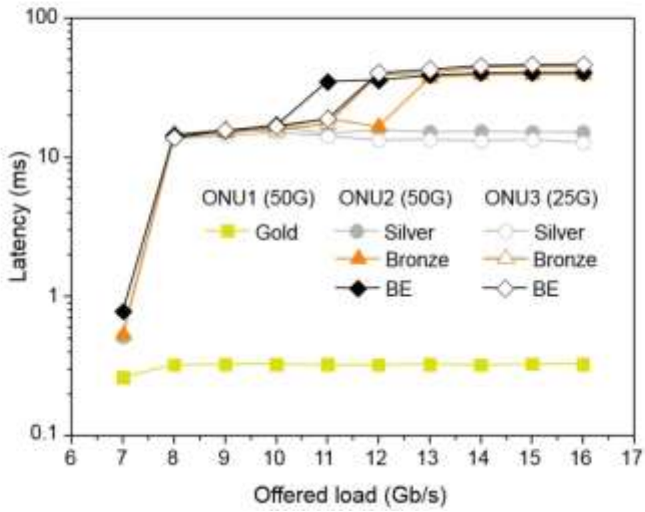


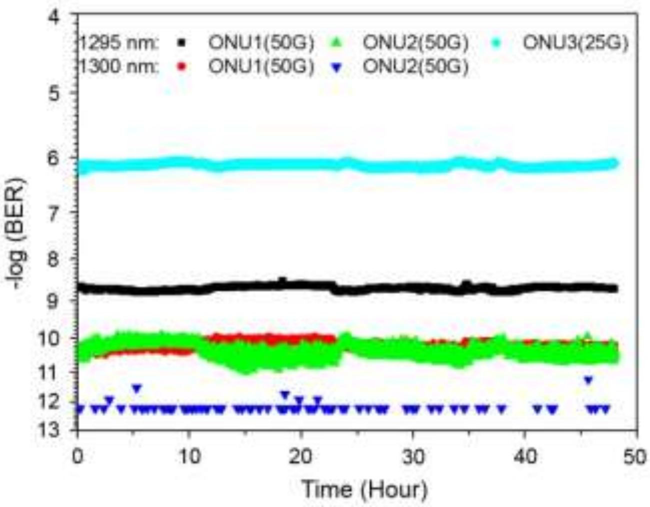

**Fig. 9. Measured latency in gold, silver, bronze, and best effort class as a function of offered load**

While ONU2 and ONU3 are configured in the silver, bronze, and BE queues, ONU1 is only configured in the gold queue. The total uplink bandwidth is 16 Gb/s, and the cycle period is set to 250 s. In an ONU, each class queue has a size of 8 MB. While the provided load to ONU2 and ONU3 fluctuates from 1 Gb/s to 10 Gb/s, the offered load to ONU1 is set at a constant rate of 6 Gb/s. The input packets to ONU2 and ONU3 are divided equally across the three class queues. The maximum delay is calculated using packets that are 1,518 bytes long. Since packets in the ONU were handled using the store-and-forwarding approach, the latency will often grow as the length of the packet increases. We utilised Ethernet packets that were the longest possible. For a priority policy, the weights of silver, bronze, and BE in the WFQ algorithm are set to 2:1:1. ONU1 has been given a static bandwidth allocation of 6.2 Gb/s. the observed delay under the condition that the provided loads to ONU2 and ONU3 are consecutively raised by 1 Gb/s.

A test result of the observed delay is shown in Fig. 9. The vertical axis displays observed delay, while the horizontal axis displays the provided load to all ONUs. Even if the traffic load grows, the latency of the gold class is guaranteed to be less than 400 s. As gold traffic grows, more time is provided for it to be sent, which decreases latency. On the other side, the delay increases as gold traffic volume decreases. If there was only a little amount of gold flow, the latency would be close to its maximum value. Equation (2) estimates the latency (latency hmax) of ONU1 to be 481 s (500 s - 250 6/16 s + 75 s), where Fdelay is close to 75 s. (15 km). Better than estimated latency is measured latency. In the worst-case scenario, the latency

would be close to the estimated latency if more ONUs were connected. Owing to priority scheduling, the latency of the silver class is practically kept constant at traffic loads greater than 8 Gb/s, but the latency of the bronze and the BE rises due to packet loss.

*D. Long-term Stability*




(a)

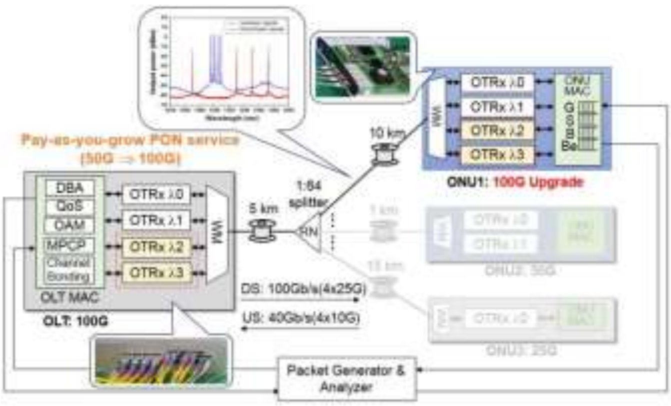

(b)

**Fig. 10. Real-time long-term performance with 48-hour (a) BER (b) screenshot of packet transmission measured with multi-speed ONUs using the packet generator (Spirent N4U).**

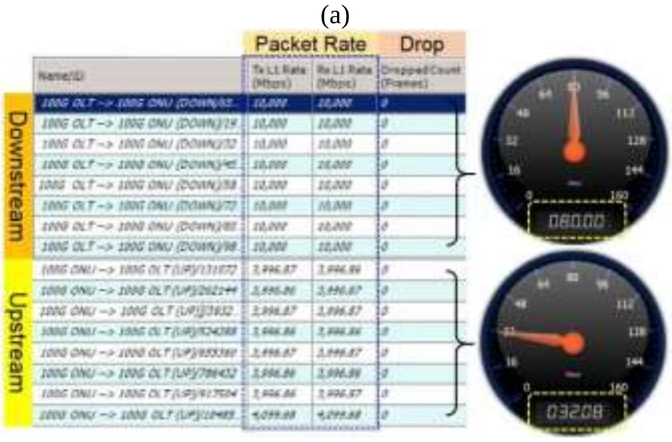
The results of the 48-hour BER and packet loss ratio (PLR) measurements are shown in Fig. 10. All ONUs utilised a wavelength of 1295 nm, while only 50G ONUs used a wavelength of 1300 nm (ONU1 and ONU2). We verified in Fig. 10(a) that ONU3 at a distance of 20 km maintains a continuous proximity to a BER of 10-6 for 48 hours. A 1.5 dB increase over 1295 nm wavelength was found in the receiver input power at 1300 nm. As a consequence, each wavelength band of ONU1 has its BER of 10-11 and BER of 10-8 measured. The BER of 10-13 and 10-10 are also assessed in ONU2. We can see that TIC-TOC system maintains at least BER of $10^{-6}$ at the distance of 20 km and 64-way split. This means that it is possible to provide error-free service using simple RS-based FEC.

**Table I: Input Traffic Condition To Verity The Lops Algorithm.**

| ONU | Total Offered Load (Gb/s) | Uplink BW (Gb/s) | Offered Service | | | Weight |
|---|---|---|---|---|---|---|
| | | | Type | Service Ratios (%) | Mode | |
| ONU1 (50G) | 6 | Total 16 | Gold | 100 | Static | - |
| ONU2 (50G) | 1 ~ 10 | | Silver<br>Bronze<br>BE | 33<br>33<br>33 | Dynamic | 2<br>1<br>1 |
| ONU3 (25G) | | | Silver<br>Bronze<br>BE | 33<br>33<br>33 | | 2<br>1<br>1 |




(a)




(b)

**Fig. 11. Real-time 100 Gb/s network performance (a) experimental setup (b) screenshot of layer 1 packet rate measured with 100 Gb/s ONU.**

The outcome of real-time packet transmission during a 48-hour period is shown in Fig. 10(b). We conducted a packet transmission test using random packets with lengths ranging from 64 to 1,518 bytes that were created by utilising a commercially available router tester in order to assess the real-time system stability at the packet level (Spirent N4U). As seen in Fig. 10(b), we delivered packets to ONU1 in the downstream and upstream directions at rates of 20 Gb/s and 10 Gb/s, respectively, under the premise of 5G small cell service. Finally, we sent the packets at the rates of 10 Gb/s and 1 Gb/s to ONU3 for next-generation residential service. We also allocated the packet rates of 10 Gb/s and 5 Gb/s to ONU2 for business service consideration. As seen in Fig. 10(b), we send packets totaling approximately 1.59 1012 and 6.42 1011 in both directions during the course of 48 hours, respectively. As a result, we may say that every packet is received through an FEC without error counters. We may thus anticipate that the TIC-

TOC system will use low-latency DBA and channel bonding to achieve steady transmission performance.

*E. Capacity upgrade to 100 Gb/s*

Each ONU's capacity may be increased by including additional wavelengths. In the same experimental setup as shown in Fig. 11, a single 100 Gb/s ONU is used to illustrate the real-time functioning of a transmission service at 100 Gb/s over four wavelengths (a). OLT and ONU1 were upgraded to 100 Gb/s in order to achieve this, and two more downstream wavelengths of 1304 nm and 1309 nm were added. Additionally, ONU1 received two upstream wavelengths of 1350 nm and 1370 nm. The channel bonding has also been expanded to four lanes in the 100 Gb/s capacity OLT and ONU1. We anticipate that ONU1 will be able to dynamically attain an instantaneous transmission rate ranging from 50 Gb/s to 100 Gb/s in this trial. The real-time packet throughput as measured by the router tester is shown in Fig. 11(b). Using four lanes of channel bonding, the TIC-TOC system can handle packet rates of 80 Gb/s in the downstream and 33 Gb/s in the upstream, as illustrated in Fig. 11(b). This shows that the system can be simply upgraded to support 100 Gb/s line rate via an FPGA-based OLT/ONU MAC update.

## 5. SUMMARY

With the use of time-controlled-tactile optical access technology, which provides channel bonding and low-latency DBA for 5G mobile, corporate, and residential applications, we were able to effectively demonstrate high-speed and low-latency PON. The guaranteed bandwidth of the optical connection between OLT and ONU was shown using multilane channel bonding. The experimental findings demonstrated that transmission speeds of up to 100 Gb/s could be achieved utilising four lanes, and that channel bonding might enable several speed ONUs to coexist on a single ODN.

We were able to accomplish safe BER and real-time packet transmission of 50 Gb/s in 64-way power split across 20 km of SMF for 48 hours using an FPGA-based OLT and ONU prototype. In order to demonstrate bandwidth growth up to 100 Gb/s, channel bonding was also utilised. Low latency DBA was further shown through the use of low latency driven packet scheduling in TDM-PON for 5G mobile services (LOPS). Regardless of traffic conditions, the gold class was assured to have a latency of less than 400 s. The 25 Gb/s based multi-wavelength PON might enable bandwidth-intensive and low-latency services for the 5G mobile network, according to all these studies.

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