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Self-protected time-division-multiplexed passive access networks in tree and ring topology architectures

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Abstract In this investigation we propose and experimentally demonstrate the self-protected and survivable time-division-multiplexed passive optical networks (PONs) in tree and ring topology architectures against fiber fault. Here, the feasible protection access architectures for the tree- and ring-based PONs are studied and discussed. Furthermore, different scenarios of fault locations, such as in the feeder fiber and distribution fiber, are also studied in the optical distributed networks.

Keywords Passive optical network (PON) · Fiber fault · Self-healing · TDM · Ring topology · Tree topology

1 Introduction

Recently, passive optical networks (PONs) have emerged as a promising technique to provide the high capacity and broadband services to the end-users [1–4]. In the traditional PON networks, the multiservices are supplied from the optical line terminal (OLT) at central office (CO) and carried along an feeder fiber having about 10–15 km long, before launching into multiple distribution fibers via an optical splitter (OS) located at remote node (RN). Then the downstream services will be sent to the optical network unit (ONU) via the distribution fiber, which is usually less than 5 km long. Both the RN and the ONUs are kept as simple as possible to reduce the cost. PONs could be a promising solution in overcoming the last mile bottleneck in present copper-based access networks due to the benefits of great-capacity, high flexibility and cost-effectiveness [5,6]. PONs can also meet the growing demand of bandwidth in the near future [7,8].

Nowadays, the time-division-multiplexed (TDM) PONs have been thoroughly explored and standardized, and they are the first point-to-multipoint solutions moving into the field. Some commercial products in the PON standards already exist, such as the BPON [9], EPON [10] and GPON [11]; 1310-nm wavelength (λ_{up}) is used for the upstream, and 1490-nm wavelength (λ_{down}) is used for the downstream in TDM-PONs. And the video service employs the 1550-nm wavelength. The bandwidths of the present TDM-PONs might not be large enough to satisfy the extensive bandwidth requirements of the future multiple-play services for end-users, and thus, the present TDM-PONs should be upgraded. Recently, the standardization of the next generation 10-Gb/s TDM-PONs, including 10G-EPON and 10G-GPON, has been discussed for providing the upcoming enormous bandwidth requirements [12–14]. As the demands of bandwidth and reliability by end-users are increasing, the issue of network survivability and protection has aroused more attention [15,16].

For the current TDM-PON systems, equipment failure at the OLT or ONU is relatively easy to solve by using a backup. However, for the fiber fault, it would take a long time for repairing. As a result, the self-protection

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network architectures to enhance the fiber network survivability against fiber fault are desirable [17–23].

In this paper, we propose and design several reliable and survivable network architectures in ring- and tree-based TDM-PONs against fiber fault. Here, the new proposed OLT module, ONU module and fiber distributive networks are used simultaneously to produce the fault protection in two network topologies of tree and ring. Besides, the system performances are also measured and discussed in the proposed network architectures.

2 Self-protected tree topologies

Generally, there were two topologies of PON system, namely tree- and ring topologies. According to the TDM-PON standards [9–11], the wavelengths of 1490 and 1310 nm were employed to serve as the downstream and upstream channels. And, the 1550-nm wavelength was used to broadcast the video service, such as CATV, IP-TV and HD-TV etc. Besides, defined by these standards, the conventional PONs were currently operating at nominal line rates of 1.25 Gb/s for EPON and 2.5 Gb/s for GPON, respectively. In the general tree-based PON, the downstream signal sent from OLT was split at RN and transmitted to each ONU via the distribution fiber, as shown in Fig. 1. Generally, the 1 × N optical splitter (OS) was used in the RN for broadcasting the downstream signal to the N ONUs. Hence, there were two occurrences of fiber faults possibly at the feeder fiber or distribution fiber. If a fiber cut was at feeder fiber, as shown in Fig. 1, the N ONUs would be out of service. Besides, when a fault occurred between ONU$_1$ and RN, the ONU$_1$ would be affected. Thus, to verify and provide fiber network protection, the basic idea of using alternative protection paths could be used and implemented.

First, according to the PON standard [11], we could use two feeder fibers to protect the traffic of PONs against fiber fault, as illustrated in Fig. 2. In front of the optical transceiver (TRx), a 1 × 2 optical switch (OSW) was added to connect to two feeder fibers, namely working fiber (solid line) and protecting fiber (dash line), as shown in Fig. 2. In RN, a 2 × N OS was employed to deliver the broadcasting traffic. And, the two feeder fibers were connected to 2 × N OS from the OLT. In Fig. 2, the OSW could be controlled by medium access control (MAC) of OLT. In normal traffic, the OSW was connected to working fiber for the entire network traffic. If a fiber fault occurred at working fiber, the OLT would not receive the entire upstream signals. As this moment, the MAC could be used to switch the OSW to connect to protecting fiber for reconnecting the signal traffic. Furthermore, if a fault was occurring between RN and ONU$_1$, the data connection will be broken. Thus, to provide the fiber fault protection in feeder, distribution fibers were very important for the end-subscribers.

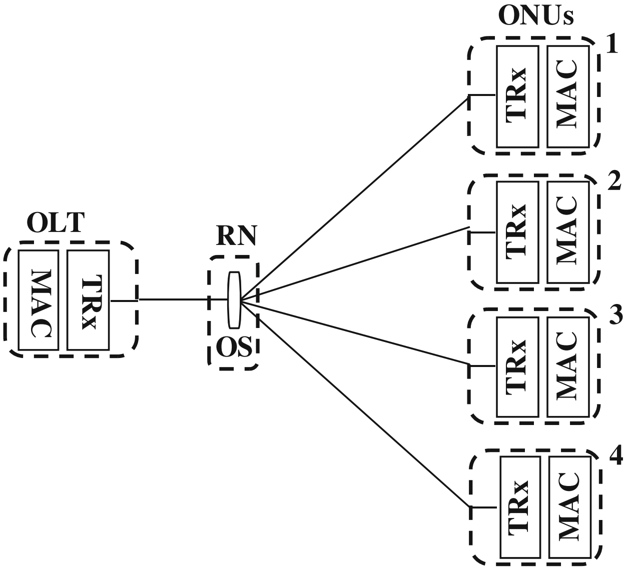

Fig. 1 Conventional tree topology TDM-PON architecture

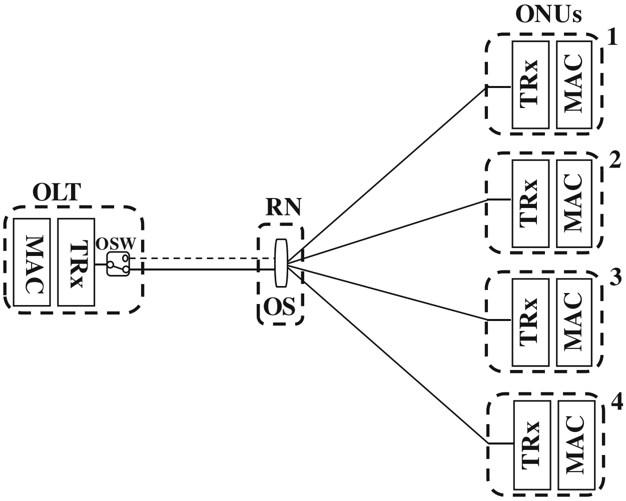

Fig. 2 Feeder fiber protection tree topology TDM-PON architecture

In this study, we proposed a new network architecture to protect fiber fault and TRx failure simultaneously. Hence, the proposed architecture was as follows: We used two TRxs (TRx$_1$ and TRx$_2$) in OLT to avoid the failure on equipment, as illustrated in Fig. 3. The TRx$_2$ was a backup element to prevent the failure on TRx$_1$. In the OLT, a 2 × 2 OSW was used to connect to two TRxs and two feeder fibers which were the working and the protecting paths, respectively. The two feeder fibers connected to a 2 × N OS, which was located at RN, as also seen in Fig. 3 and N distribution fibers were used for the N ONUs. In this design, two adjacent ONUs were regarded as a group and connected together by two protecting fibers (dash lines), as shown in Fig. 3. Besides, each

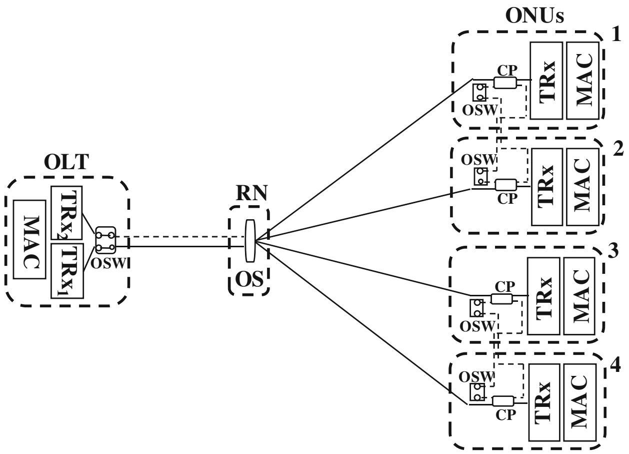

Fig. 3 Self-protection and restoration architecture in tree topology TDM-PON system

ONU added a 2 × 2 CP and a 1 × 1 OSW in front of TRx to produce the protecting mechanism, as also seen in Fig. 3. Initially, the 2 × 2 OSW of OLT and 1 × 1 OSW of each ONU were located at "bar" and "off" status, respectively, for the downstream and upstream data connections. Moreover, the direction of OSW was also controlled by MAC to reduce the network complexity.

While a fiber cut occurred at the feeder fiber (working path), the OLT would not receive any upstream signal of each ONU. Immediately, the MAC of OLT would switch the OSW to "cross" status for reconnecting the upstream traffic via protecting fiber, as shown in Fig. 3. When the fault was revived, the OSW did not need to change the switching status until this fiber had an occurrence of fault. That was to say, this protecting fiber could be regarded as working fiber after switching the OSW. Furthermore, the fault occurrence of TRx also could be monitored by the MAC layer in our proposed scheme. If a failure occurred at TRx_1 module, the TRx_2 would be turned on by MAC to take of place of TRx_1 for data traffic reconnecting at the same time.

In Fig. 4, the upstream channel from TRx of each ONU could pass through the 2 × 2 CP and 1 × 1 OSW simultaneously. In normal transmission, the OSW of each ONU was "off". Hence, the upstream signals could transmit via its corresponding branched fibers due to the high isolation of OSW. If a fault occurred between RN and ONU_2, the ONU_2 would not receive the downstream signal. At this moment, the MAC of ONU_2 would turn on the OSW for data reconnecting. So, the downstream and upstream traffic could be reconnected by the protecting fiber via ONU_1. While the fiber fault was restored, the ONU_2 would receive the downstream signal by working and protecting fibers simultaneously. It could produce downstream channel collision. The Rx of ONU_2 also cannot obtain the current data traffic. The MAC could turn off the OSW for reconnecting again. Identically, when a fault was between RN and ONU_1, the data traffic could reconnect by the protecting fiber via ONU_2. As a result, the proposed PON system not only could avoid the TRx failure of OLT, but also could protect fiber fault in this network.

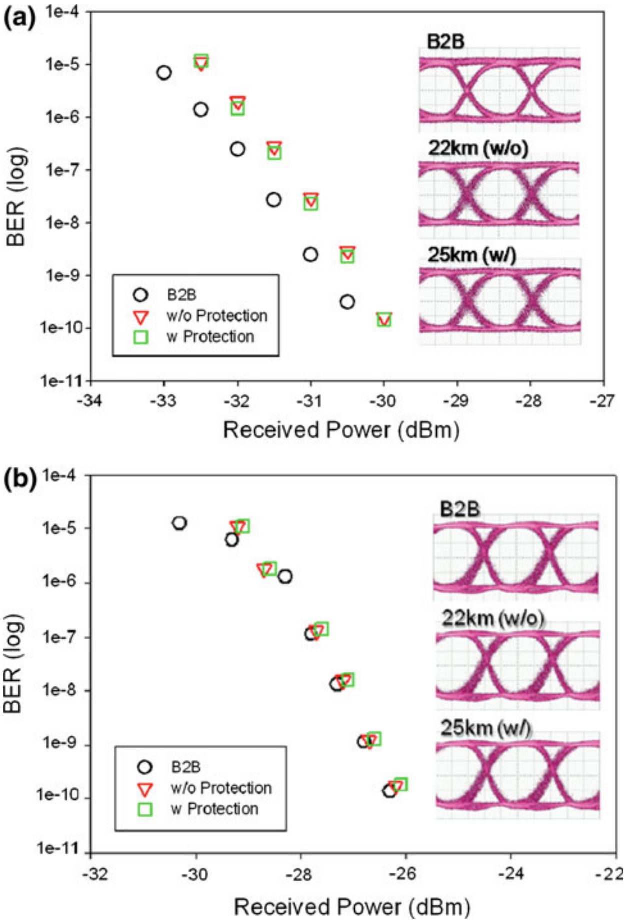

Fig. 4 BER performances of **a** downstream and **b** upstream traffic in the proposed PON architecture of Fig. 4. The inserts are corresponding eye diagrams at BER of 10^{-9}

To realize the performance of the proposed self-protected tree-type TDM-PON of Fig. 3, a bit error rate (BER) measurement was carried out. Figure 4 showed the experimental setup in the self-protected architecture for serving eight OUNs. In the experiment, a fiber transmission distance between OLT and each ONU was set at 22 km. Besides, the fiber length between two adjacent ONUs was 3 km long. In this measurement, we used the 1490-nm distributed feedback (DFB) and 1310-nm Fabry-Perot (FP) lasers acting as the downstream and upstream signals according to current PON standards. Based on the standards [9–11], the downstream and upstream signals were direct modulated at 2.5 and 1.25 Gb/s with on/off keying (OOK) format for data traffic. And the output powers of 1490- and 1310-nm wavelengths are 2.0 and 1.4 dBm respectively. Moreover, in regard to the power budget of protection PON system in Fig. 3, the traffic signal will traverse a 2 × 2 OSW (∼1 dB), a 2 × 8 OS (∼9 dB), an 1 × 1 OSW (∼1 dB), a 2 × 2 CP (∼3 dB) and about 25-km single-mode fiber (SMF) (∼5 dB), thus the total loss budget was nearly 19 dB. In the proposed system, the protection and restoration time could be measured within 7 ms according to the two OSWs used in our experimental setup. Here, the BER performances are measured by using a 2.5 and 1.25 Gb/s non-return-to-zero (NRZ) pseudo-random binary sequence (PRBS) with a pattern length of $2^{31} - 1$ for the downstream and upstream traffic without and with protection when fiber fault occurs on the feeder or distributed fibers. Figure 4 shows the BER performance of (a) downstream and (b) upstream traffic at 2.5 and 1.25 Gb/s OOK modulation format via the working and protecting fiber paths without and with protection, respectively. The received powers are measured at -30.8 and -26.8 dBm at the BER of 10^{-9} for downstream and upstream signals, respectively. And the inserts of Fig. 4a and b are the corresponding eye diagrams at the BER of 10^{-9}. The eyes are clear and widely open after 22- and 25-km transmission. Besides, the observed optical power penalties of Fig. 4a and b are smaller than 0.5 and 0.2 dB when the BER is 10^{-9}.

3 Self-protected ring topologies

In the ring-type PON, the OLT was connected to multiple access nodes (ANs) via single fiber. Each AN comprises an optical 1 × 2 power splitter (or CP), to which multiple ONUs were further connected, in either a star or ring topology, as shown in Fig. 5. However, if a fiber fault occurred in the trunk fiber between ONU_1 and ONU_2, the data traffic would be unreachable behind this fault point. That was to say, the OLT could not link the upstream signals from ONU_2 to ONU_N. Therefore, the PON system must have the self-protection function for data traffic to overcome the fiber fault problem.

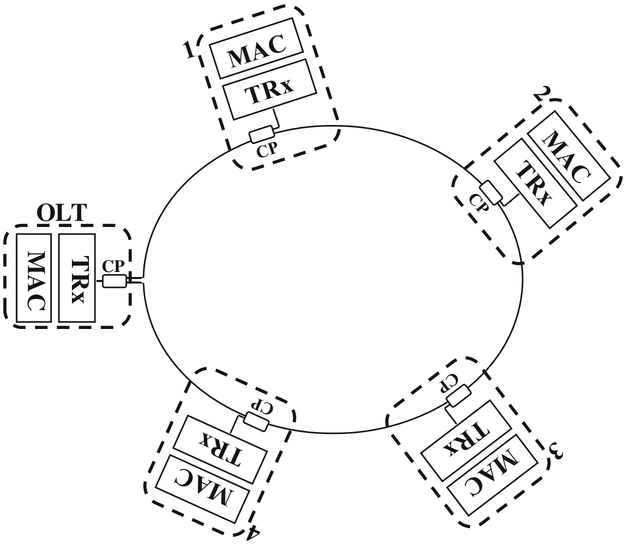

Fig. 5 Conventional ring-topology TDM-PON architecture in single fiber

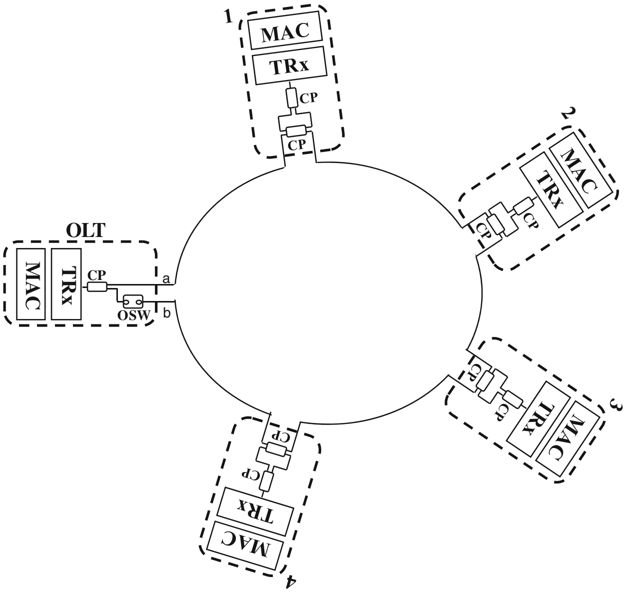

Fig. 6 New proposed bidirectional ring topology self-restored TDM-PON system

To achieve the desired network survivability, different protection schemes were recommended. The post protection method with double transceivers at both ends and two individual fiber paths for the ring-based TDM-PONs has also been reported [24–26]. Hence, we proposed and investigated a new architecture for ring topology PON network against fiber fault with simple scheme, as illustrated in Fig. 6. For this architecture, we designed a new OLT and AN to complete the fiber protection. In OLT side, we added a 1 × 2 CP and a 1 × 1 OSW in front of TRx. Initially, the OSW was "off" status. Based on the design, the OLT could determine two different transmission paths for data traffic by using the additional components. And the on/off switching of OSW was also controlled by the MAC. In the normal state, the OSW was "off" state for the downstream signal passing through the "a" path [in clockwise (CW) direction]. Moreover, in ONU side, we proposed a bidirectional element to access the data traffic connections. It was consisted of a 2 × 2 CP and a 1 × 2 CP to produce a bidirectional path, as shown in Fig. 6. When the network has not fault, the entire upstream traffic could be transmitted through "a" path [in counterclockwise (CCW) direction]. For example, when a fault occurred between ONU_2 and ONU_3 in the network, behind the fault point, the data traffic would not connect to OLT. Thus, the OLT could not receive the remainder upstream signals behind ONU_2 and the OSW would switch to "on" state by MAC promptly. Then, the downstream signal could be separated to pass through the "a" and "b" paths simultaneously for downlink traffic, when the OSW turned on as shown in Fig. 6. As a result, the data traffic from OLT to ONU_1 and ONU_2 were routed through the “a” path (in CW), and the remainder ONUs (behind ONU_2) were routed through the “b” path (in CCW). When the fiber failure was restored, then the operation mechanism of the PON system would be restored. Hence, according to the proposed operating mechanism, the OLT would determine the transmitted direction of downstream signal in “a” and “b” paths. When the access network was without any failure, the downstream signal was only passed through the “a” path. However, while a fiber cut occurred on the major fiber path, OLT was no longer possible to receive the upstream signals behind a fault point. The downlink signal would be split via the “a” and “b” paths simultaneously by switching the OSW to “on” state at this time.

Besides, we also measure the BER performance of the proposed PON, as shown in Fig. 6. In the experiment, four ONUs are used in the ring-based PON system. The fiber distance between OLT and ONU_4 is 20 km through “a” fiber path (without protection). Furthermore, the distance from OLT to ONU_4 is 5 km when downlink signal through the “b” path.

BER performance was measured by using NRZ-PRBS with a pattern length of $2^{31} - 1$ for the downlink (1490 nm) and uplink (1310 nm) traffic with 2.5 and 1.25 Gb/s directly modulation, respectively, from the OLT to ONU_4. And, the output power of 1490- and 1310-nm wavelength was 2.1 and 1.3 dBm, respectively. In addition, the 1490- and 1310-nm signals would traverse six 3 dB CPs (∼18 dB) and about 20-km single-mode fiber (∼5 dB) via “a” path; thus, the loss budget was about 23 dB in normal state while the data traffic between OLT and ONU_4 was link. In the ring network, we assumed a fiber fault happens between the ONU_3 and ONU_4. In accordance with the issues, when the fault occurred, the proposed self-protected operation needed to start for the PON restoration. The received powers were measured at −29.9 and −26.7 dBm at the BER of 10^{-9} for downstream and upstream signals, respectively. Hence, the scalability of the proposed ring network was nearly 28.8 dB due to the losses of fiber and other components. Thus, Fig. 7a and b shows the measured BER performances of downstream and upstream traffic when the ring-based network was with and without protection between OLT to ONU_4. The inserts of Fig. 7a and b were the corresponding eye diagrams at the BER of 10^{-9}. The eyes were clear and widely open without and with protecting operation. The observed optical power penalties of downlink and uplink traffic were very small at the BER of 10^{-9}, in the proposed architecture.

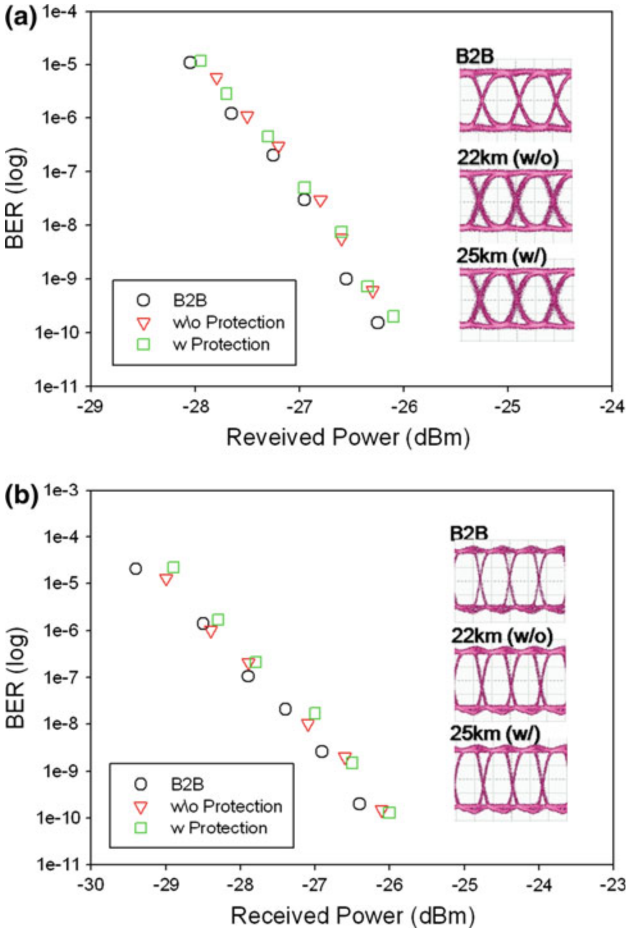

Fig. 7 BER performances of **a** downstream and **b** upstream traffic in the proposed PON architecture of Fig. 6. The inserts are corresponding eye diagrams at BER of 10^{-9}

4 Conclusion

In summary, due to the requirement of large bandwidth in the last mile access networks, the availability and survivability of PON were highly desirable to provide the self-protection mechanism against fiber fault in network management. In this paper, we have proposed and experimentally demonstrated the self-protected and survivable TDM-PON systems against fiber fault in tree topology and ring topology. The feasible protection apparatus and architectures for automatic traffic restoration upon any fiber faults were studied and discussed. In the measurements of the paper, the system restoring time is measured within 7 ms depending on the OSW used in the proposed PON systems. In addition, the network performances of proposed protection PONs have also been discussed and analyzed.

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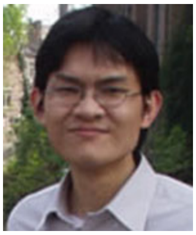

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