Logical optical line terminal technologies towards flexible and highly reliable metro and access integrated networks

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ABSTRACT

In this paper, flexible and highly reliable metro and access integrated networks with network virtualization and software defined networking technologies will be presented. Logical optical line terminal (L-OLT) technologies and active optical distribution networks (ODNs) are the key to introduce flexibility and high reliability into the metro and access integrated networks. In the Elastic Lambda Aggregation Network (EλAN) project which was started in 2012, a concept of the programmable optical line terminal (P-OLT) has been proposed. A role of the P-OLT is providing multiple network services that have different protocols and quality of service requirements by single OLT box. Accommodated services will be Internet access, mobile front-haul/back-haul, data-center access, and leased line. L-OLTs are configured within the P-OLT box to support the functions required for each network service. Multiple P-OLTs and programmable optical network units (P-ONUs) are connected by the active ODN. Optical access paths which have flexible capacity are set on the ODN to provide network services from L-OLT to logical ONUs (L-ONUs). The L-OLT to L-ONU path on the active ODN provides a logical connection. Therefore, introducing virtualization technologies becomes possible. One example is moving an L-OLT from one P-OLT to another P-OLT like a virtual machine. This movement is called L-OLT migration. The L-OLT migration provides flexible and reliable network functions such as energy saving by aggregating L-OLTs to a limited number of P-OLTs, and network wide optical access path restoration. Other L-OLT virtualization technologies and experimental results will be also discussed in the paper.

Keywords: Logical optical line terminal, active optical distribution network, optical access path, migration, virtualization technologies, elastic lambda aggregation network

1. INTRODUCTION

The amount of world-wide network traffic volume continues to increase exponentially due to the popularization of bandwidth-hungry applications such as video streaming and cloud services. People are now accessing network applications by not only wired access systems such as fiber to the home (FTTH), but also with high-speed wireless access system such as Long Term Evolution (LTE) and Worldwide Interoperability for Microwave Access (WiMAX). This increases network traffic capacity. An expansion of network transmission capacity leads to an increase in power consumption of network components1. Therefore, network operators have to achieve both network capacity enhancement and power reduction. The power consumption of the current IP network is estimated and the result shows that about 60%–80% of power is consumed in the access network area2, 3. Passive optical network (PON) systems are widely deployed as a cost-efficient FTTH solution today since a single optical line terminal (OLT) is shared by multiple (32 to 64) optical network units (ONUs) by using passive optical splitters4, 5. PON systems are also applied to wireless infrastructure as a mobile front-haul network and a mobile back-haul network. Currently, these different network services such as Internet access, leased line, data-center access, and mobile radio access network are provided over different access and aggregation network systems due to the differences in protocols and quality of service (QoS) requirements. Therefore, capital expenditure (CAPEX) and operation expenditure (OPEX) are increasing.

From this background, a next-generation access and aggregation integrated network, named “Elastic Lambda Aggregation Network (EλAN)”, has been proposed6, 7 and studied8-16. In the EλAN, OLTs become programmable to provide multiple network services that have different QoS requirements or transport protocols. A programmable OLT (P-OLT) provides logical OLTs (L-OLTs) and a programmable ONU (P-ONU) provides logical ONUs (L-ONUs). L-OLTs and L-ONUs are configured to support the functions required for each network service17. Multiple P-OLTs and P-ONUs are connected by the active (or switched) optical distribution network (ODN). Optical access paths that have flexible capacities are set on the ODN dynamically to provide network services from L-OLTs to L-ONUs. The programmability of OLTs and ONUs and the reconfigurability of ODN have a potential of providing a virtual FTTH service over metro
and access integrated network, flexible networking function to realize energy efficient network operation, and a highly reliable metro and access integrated network. The OLT/ONU programmability includes wide range of implementation levels such as parameter configuration of the hardware, reconfiguration of the field programmable gate array (FPGA), firmware replacement, and software-defined OLT data plane. In the ELaAN project, some members try to develop adaptive forward error correction (FEC) controllable 40 Gbps (10 Gbps x 4 wavelengths) OLT/ONU by the parameter configuration approach\textsuperscript{13}, and Keio University tries to develop software-based OLT prototype system\textsuperscript{9-11, 15} from 2012. Recently, software-based OLTS are developing from carriers such as virtual OLT (vOLT) called “CORD”\textsuperscript{18, 19} from AT&T and Open Networking Lab., and Flexible Access System Architecture (FASA)-based OLT\textsuperscript{20, 21} from NTT have been announced. These software-based OLTS will provide the same function of the L-OLT in ELaAN.

In this paper, we will discuss possible OLT virtualization technologies and experimental results. One example is moving an L-OLT from one P-OLT to another P-OLT like a virtual machine (VM). This movement is called “L-OLT migration”. The L-OLT migration provides flexible and reliable network functions such as energy saving by aggregating L-OLTS to a limited number of P-OLTS, and network wide optical access path restoration. Second example is OLT sharing to improve disaster tolerance. Last example is a software-based P-OLT as an edge computing platform.

2. OVERVIEW OF ELaAN

2.1 Architecture

Figure 1 shows the architecture of the ELaAN. ELaAN integrates the current access network and metro/aggregation network into a single network. In ELaAN, L-OLTS, L-ONUs, and an active ODN using all optical devices, such as a bandwidth variable wavelength selective switch (BV-WSS) and an optical splitter, provide flexibility to accommodate a variety of services and provide reconfigurability to the network. An access path is defined between an L-OLT and an L-ONU on the active ODN. By providing flexible access paths in response to service requests, ELaAN increases the accommodation efficiency of the entire network.

![Figure 1. The ELaAN architecture.](image)

The active ODN connects L-OLTS and L-ONUs. Orthogonal frequency division multiplexing (OFDM) technology is adopted to increase the number of independent access paths (logical links). The system changes the modulation level, the number of subcarriers, and the symbol rate according to the service requirements and the condition of the active ODN. Target transmission distance (or access path length) between the L-OLT and the L-ONU is designed more than 40 km. A
single L-OLT, which is configured in the P-OLT and can be constructed with multiple optical subscriber units (OSUs), can accommodate more than 256 L-ONUs. Traffic from L-OLTs to core networks is aggregated in the P-OLT by the virtual and/or real layer2 switch (L2SW). P-OLTs are located in central offices (COs) and connected to core networks via a virtual layer2 network, which is constructed with distributed virtual and/or real L2SWs. The L2SWs in the P-OLT and the virtual layer2 network provide a single virtual layer2 switch (VL2SW). VL2SW transmits traffic between the core networks and P-OLTs and also traffic between P-OLTs. The core networks are constructed for each service. Each service has its own L-OLTs and L-ONUs. Therefore, ELAN provides a virtual FTTH (FTTx) to each service as an access and aggregation integrated network.

The VL2SW, P-OLTs, and the active ODN are controlled by an ELAN network management system (NMS). An L-OLT is initiated by the NMS and configured for the directed service. Each L-OLT provides a media access control (MAC) function and a physical (PHY) function required for each service such as frame processing, time synchronization, multipoint control protocol (MPCP), dynamic bandwidth allocation (DBA), rate adaptation, and FEC coding. The generated L-OLT can be moved to another P-OLT which is located in same CO or other COs. This is called “L-OLT migration”. In Fig.1, a P-OLT in CO#2 does not have an active L-OLT. Therefore, it is possible to sleep the unused P-OLTs and reduce power consumption of CO#2. This is because the active L-OLT in the P-OLT of CO#2 has been migrated to the P-OLT in CO#1. To realize the L-OLT migration, the NMS gives trigger messages to the L-OLT in the P-OLT of CO#2 to migrate to the P-OLT of CO#1, and to the P-OLT in CO#1 to initiate the migrated L-OLT. After initiating the L-OLT, the NMS sends messages to the VL2SW and the active ODN to configure the access path between L-OLTs and L-ONUs. The detailed L-OLT migration procedure is discussed in another paper12.

2.2 P-OLT implementation

2.2.1 P-OLT implementation using FPGA

The specific implementation method of P-OLTs is still under study, but there is a high possibility that P-OLTs will use programmable logic devices i.e. FPGA to process data frames at high speed (10 – 40 Gbps). Figure 2 shows one possible implementation of an FPGA-based P-OLT to realize L-OLTs. A single P-OLT hosts a number of configurable boards (L-OLT configuration board in Fig.2) to realize several L-OLTs. Each L-OLT configuration board has two FPGAs for MAC and PHY. The number of FPGAs is not limited to two but at least two functions should be implemented. These FPGAs are reconfigured to provide the functions shown above. The proof of concept (PoC) version of P-OLT has been demonstrated13. In the same way, P-ONUs will be deployed at subscribers’ premises and support network services by generating L-ONUs. In general, few configuration boards will be provided to the P-ONU.

![Figure 2. P-OLT implementation using FPGAs.](image-url)
2.2.2 P-OLT implementation using software

We have developed a PoC system of the software-based L-OLT. In the PoC L-OLT, a Linux server is used as P-OLT and VMs or containers on the Linux server are used as L-OLTs. Figure 3 shows a P-OLT implementation example. The Linux server provides VMs or containers for L-OLTs and a virtual L2SW. A control process receives/sends a command from the NMS and controls all VMs. In the PON system, a logical link identifier (LLID) is added in the preamble of the PON MAC frame. It is quite difficult to add an LLID in a network interface card (NIC) of the Linux server. Therefore, NTT’s FASA-based OLT has an FPGA board to process an LLID. In our PoC L-OLT and L-ONU systems, a virtual local area network (VLAN) is used for emulating LLID. This means that when S-tag and C-tag are used in the PON system, third VLAN-tag will be added during the transmission between L-OLT and L-ONU. Forth VLAN-tag will be added for emulating Mux/Demux functions in the Linux system.

Figure 3. P-OLT implementation using software.

Figure 4 shows a diagram of the software-based L-OLT with emulated LLID. There are two main components. One is a data plane software component. Another is a control plane and management plane software component. MPCP packets and operation administration and maintenance (OAM) packets will be processed in a user space, on the other hand, data packets will be processed in a kernel space for realizing efficient packet forwarding.

Figure 4. L-OLT function diagram design example with emulated LLID.
In the PoC L-OLT, not all functions shown in Fig. 4 are implemented. Only data plane packet forwarding and MPCP processing (ONU registration function, no DBA) are implemented. This is because our implementation target is for realizing a PoC of virtualization technologies.

3. L-OLT VIRTUALIZATION TECHNOLOGY TRIALS

3.1 L-OLT migration

There are three possible L-OLT migration scenarios. First is P-OLT operating power reduction using the P-OLT sleep mode as shown in Fig. 1. L-OLTs are assigned for minimizing the P-OLT operating power. Second is load balance. L-OLT is moved from high load P-OLT to low load P-OLT. Both L-OLT migration scenarios require as less service down time as possible; i.e. ideally L-OLT live-migration. Third is L-OLT restoration from failure. In this case, the L-OLT live-migration is not required. All scenarios can be applied to both within CO and among COs cases.

3.1.1 VL2SW architecture

The major FTTH service is an Internet access for residential users. To apply L-OLT migration, especially in among COs case, a service continuity is important. To realize the service continuity, continuous use of an IP address should be achieved. Figure 5 shows a service network example for the Internet access service. IP addresses assignment to users from an Internet service provider (ISP) is performed by broadband access servers (BASs) located in each CO. IP datagram from the Internet will be sent through the core router, L2SWs, BAS, L2SWs, L-OLT and L-ONU. Therefore, when an L-OLT in CO#1 will be moved into CO#2, the same BAS should be passed. The VL2SW should provide this mechanism. To realize this, we have proposed the VL2SW logical model shown in Fig. 5. The VL2SW is composed of switching module(s) and line interface (LIF) modules. A link between the switching module and the LIF is provided by a virtual link. Therefore, the virtual link between the L2SW in the P-OLT and the LIF module in the VM/container of the L-OLT maintains connectivity when the L-OLT VM/container moves to other COs.

![Figure 5. IP service on El.AN and VL2SW logical model.](image)
3.1.2 First L-OLT migration demonstration in the 3rd International Symposium on Network Virtualization (Sept. 2013)

We have implemented L-OLTs in CentOS VMs, each VM has one L-OLT and LIF. Figure 6 shows an experimental setup and a picture of the demonstration system. Three VMs are implemented to the P-OLT Linux server machine with six gigabit Ethernet (GbE) interfaces by using KVM (Kernel-based Virtual Machine). Two VMs are used for L-OLTs and one VM which has the open vSwitch (OVS) is used as an L2SW. Two P-OLTs are connected by a GbE L2SW. The GbE L2SW and two OVSs construct a VL2SW. An Ethernet over GRE (Generic Routing Encapsulation) technology, e.g. “gretap” in Linux, is adopted for providing a virtual link between an OVS and an L-OLT. An endpoint of the gretap tunnel in the L-OLT provides a LIF function. A file server machine and a video server are connected to the VL2SW for providing Internet services to users.

Before the L-OLT migration, the video receiver #1 (IPv4 address 60.60.60.24) receives a video stream from the video server using VLAN 200. In the P-OLT#1, a gretap tunnel named gretap10 is set between the OVS VM and the L-OLT VM (L-OLT#1). Two users (user A and B) get files from the file server using VLAN 100. Two gretap tunnels gretap11 and gretap21 are used for transmitting VLAN 100 data.

In case of the L-OLT migration, L-OLT#1 in P-OLT#1 is moved to P-OLT#2. In this experiment, a VM live-migration technology is used to realize the L-OLT migration. VM live-migration traffic is sent through P-OLT#1, L2SW, and P-OLT#2. A trigger of L-OLT migration is sent from the NMS to P-OLTs.

After the L-OLT migration, gretap10 is rerouted to connect the OVS in P-OLT#1 and the L-OLT#1 in P-OLT#2 via the L2SW. Therefore, VLAN 200 is also rerouted to the video receiver #1. In this experiment, two video receivers which have the same IPv4 address are used. They have different MAC addresses. Therefore, learned MAC address of IPv4 address 60.60.60.24 should be refreshed. To refresh the MAC address, an IP router which flashes its address resolution protocol (ARP) table periodically (1 s cycle) is implemented. This IP router is not required when the same video receiver is used both before and after the migration.

In this experiment, L-OLT migration time (from VM live-migration trigger to receiver #1 down) is nearly 8 s and service down time (from receiver #1 down to receiver #2 up) is nearly 1 s. 1 s is not so large time, the dominant processing time is re-establishment of the gretap tunnel.

3.1.3 L-OLT migration with active ODN reconfiguration

To optimize the traffic route in the VL2SW, a VLAN path reroute technology using the OpenFlow is applied. To realize the L-OLT migration, the optical access path between an L-OLT and an L-ONU on the active ODN also should be
reconfigured. To realize the active ODN reconfiguration, the OpenFlow protocol is also applied for the control protocol to the ODN. As a result, in EλAN, reconfiguration of the VL2SW and the active ODN can be controlled with unified OpenFlow protocol.

We have constructed a prototype active ODN using a single optical space division switch with an OpenFlow protocol adaptor (ADP). GbE media converters are inserted for converting from electrical GbE signals to optical GbE signals and vice versa. NMS controls L-OLTs, P-OLTs, VL2SW, and active ODN.

We evaluated the service down time of this system. As a result the service down time becomes nearly 10 s. This large service down time is caused by asynchronous procedure of VM live-migration and active ODN reconfiguration. To reduce the service down time, synchronous procedure between notification of the end of the L-OLT VM migration and the start of the ODN reconfiguration is required.

To solve this problem, process migration instead of the VM live-migration is applied. Before starting the L-OLT migration, a VM in a target P-OLT has been booted. NMS tries to transfer status and setting parameters from the original L-OLT process to the target L-OLT process. The NMS easily recognizes the end of L-OLT migration and easily performs synchronized path setup in the VL2SW and the active ODN. As a result, 4.5 s averaged L-OLT migration time and 0.79 s averaged service down time are achieved. This experiment has been done in laboratory level. Therefore, transmission distance between NMS and all equipment, two P-OLTs, and P-OLT and P-ONU, etc. are physically separated in few meters. More time will be required in the actual environment that is separated in few 10s km. And in case of the active ODN constructed by BV-WSSs, few seconds are required in reconfiguration.

3.1.4 L-OLT migration time estimation in the actual environment

How long time is required for the L-OLT migration is an important issue to apply the L-OLT migration to the actual service environment. To evaluate this, we made an experiment of the L-OLT migration on the wide area network conditions.

We performed an L-OLT migration experiment between P-OLTs with different physical distances to measure the required time. Figure 7 shows the constructed wide area EλAN experimental network.

Figure 7. Wide area L-OLT migration experimental network structure.

Domain#1 is located in Koganei (Tokyo, Japan). Domain#2 is located in Koganei, Yokohama (Kanagawa, Japan), and Naha (Okinawa, Japan) in order. The distance between Domain#1 and Domain#2 is defined as X. The L-OLT migration is performed between P-OLT#1 in Domain#1 and P-OLT#2 in Domain#2 by changing the distance X. As a result, three patterns of X between P-OLT#1 and P-OLT#2 are set. In the first pattern, both P-OLT#1 and #2 are located in Koganei.
Therefore, the distance between P-OLT#1 and P-OLT#2 is 0 km (less than 20 m). In the second pattern, P-OLT#2 is moved to Yokohama. The distance between P-OLT#1 and P-OLT#2 is 23 km in a straight line. In the third pattern, P-OLT#2 is moved to Naha. The distance between P-OLT#1 and P-OLT#2 is 1,543 km in a straight line. Figure 8 shows geographic locations of Koganei, Yokohama, and Naha. Domain#1 is composed of P-OLT#1, an L2SW, an L2SW OpenFlow ADP for controlling L2SW, a traffic generator, and a video server. Domain#2 is composed of P-OLT#2, a layer-1 switch (L1SW) which emulates the active ODN, an L1SW ADP, P-ONUs, and NMS. Two domains are connected by Ethernet VLANs provided by JGN-X. In the first pattern (Koganei – Koganei), two domains were not connected on JGN-X.

Figure 8. Geographic location arrangement.

In EλAN, the actual target of L-OLT migration distance is up to 40 km. Therefore, evaluation of 1,500 km is not necessary in practical ways. However, it is necessary to evaluate how L-OLT migration time changes according to distance.

First measurement is round trip times (RTTs) from the NMS in domain#2 to OVSs in each P-OLT and ADPs. Average of 10 pings’ RTTs from the NMS to each device (OVS#1, OVS#2, L2SW ADP, L1SW ADP) are 0.313 ms, 0.421 ms, 0.248 ms, 0.190 ms in the first pattern (0 km), 5.545 ms, 0.421 ms, 5.517 ms, 0.190 ms in the second pattern (23 km), and 42.111 ms, 0.225 ms, 41.944 ms, 0.256 ms in the third pattern (1,543 km). Next, L-OLT migration time is measured. L-OLT migration time is determined as an average of the three measured L-OLT migration times. As a result, the L-OLT migration time between Koganei – Yokohama is 77.035 s, and between Koganei – Naha is 79.118 s. The process that spent much of the L-OLT migration time is VLAN configuration at the L2SW. Used L2SW device in this experiment is different in experiments described in 3.1.2 and 3.1.3. This configuration time is device-dependent and nearly 70 s is required for VLAN setting and ports setting in this experiment. The migration time of the first pattern can be reduced to 4.5 s as indicated in 3.1.3.

L-OLT migration time can be divided into two parts. One is a distance-dependent part such as message transmission time from the NMS to each device. Another is a distance-independent part such as device configuration time. Therefore, L-OLT migration time is estimated using Eq. (1):

\[ t = \alpha \times X + t_{init} \]  

(1)

In Eq. (1), \( t \) [s] is L-OLT migration time, \( \alpha \) [s/km] is the proportionality constant, \( X \) is a distance of L-OLT migration, and \( t_{init} \) is a distance-independent device configuration time. From the experimental results, we can estimate that \( \alpha \) is 0.0014 [s/km]. This value is varied according to the information amount of L-OLT and transmission rate at control plane network. However, since the information amount of L-OLT is relatively small, \( \alpha \) can be treated as constant value. \( t_{init} \) is the sum of VL2SW configuration time and active ODN configuration time. This leads a service down time. 2 s – 3 s is a target of the BV-WSS based ODN environment.
3.2 OLT sharing to improve disaster tolerance

In the FTTH system, a failure in a trunk fiber leads service interruption in multi-lines (ONUs). In order to solve this problem, a PON protection method that sets up a backup system and duplicates the route is standardized in ITU-T G.983.5. However, the PON protection is not good enough to recover the failure. For example, in March 2011, by the Great East Japan Earthquake, many COs were collapsed by tsunami and redundant fiber routes were broken. Therefore, a new disaster recovery method that provides higher availability than the protection method is required. In EoAN, the active ODN provides multi-routes between an OLT and ONUs. Therefore, restoration method can be applied to recovery from failure. The L-OLT migration between two COs also provides restoration among multiple COs. However, only 256 L-ONUs can be accommodated into a single L-OLT. When the number of surviving P-OLTs is very limited, other L-ONUs cannot be accommodated even if many P-ONUs are available. To solve this problem, we have proposed a time division multiple access (TDMA) OLT sharing based ONU recovery method to improve disaster tolerance. A basic idea is L-OLT virtualization using TDMA. Multiple virtualized L-OLTs (vL-OLTs) are generated in a single L-OLT. By applying the virtualization, a single L-OLT resource can handle multiple ONU groups. Therefore, a single L-OLT can accommodate more than 256 L-ONUs.

Figure 9 shows a conceptual model of the proposed method. It assumes that CO#A is collapsed and P-OLT in CO#B accommodates P-ONUs under CO#A’s control. In Fig.9, L-ONUs are divided into two ONU groups (ONU group #1 and #2). The number of L-ONUs in each group is smaller than 256. A single L-OLT will support 2 or 4 ONU groups using virtualized 2 or 4 L-OLTs via TDMA manner.

TDMA operation of an L-OLT is as follows. First, the L-OLT activates vL-OLT#1 for ONU group #1. The active ODN is also configured for ONU group #1. Ranging and registration operation will be done in this period and parameters for ONU group #1 are stored in vL-OLT#1. Second, the L-OLT activates vL-OLT#2 for ONU group #2. The ODN is also reconfigured. Ranging and registration operation will be done in this period and parameters for ONU group #2 are stored in vL-OLT#2. Finally, the L-OLT periodically exchanges vL-OLT#1 and #2 with data transfer operation using MPCP. The vL-OLT sends a HOLDOVER message to L-ONUs before the L-OLT switches ONU groups. The HOLDOVER message is to maintain a logical link even if an L-OLU detects optical signal loss. L-ONUs which receive a HOLDOVER(start) message stop communication to the vL-OLT. The vL-OLT sends a HOLDOVER(end) message to L-ONUs and then L-ONUs resume communication. It is assumed that the switching time of vL-OLTs takes less than 50 ms and few seconds transfer operation time will be assigned to each group. This means that in first transfer operation time, vL-OLT#1 accommodates ONU group #1 without registration process and transfers the data from buffer to ONU group #1 and receives data from ONU group #1. In the last MPCP operation, 0 byte is assigned to stop data sending from
ONU group #1. During this period, downstream data to the ONU group #2 may be lost or buffered. After 50 ms of vL-OLT switching operation, vL-OLT#2 works.

The proposed TDMA-based L-OLT sharing method should take into consideration an overhead time of switching among ONU groups. It is required to reduce the number of switching ONU groups as much as possible in order to increase the communication efficiency. To increase the number of restorable subscribers, the number of groups should be as large as possible. Therefore, it is necessary to increase the service time to accommodate ONU groups. However, this will affect the service quality especially in the voice communication since the communication interval is increased due to a long service time. To solve this problem, we have proposed a proxy insertion between the P-OLT and the core network. A proxy server will be inserted between a virtual L2SW network and the core network using network function virtualization (NFV) and service function chaining (SFC) techniques. The proxy server has three main functions. First, the proxy buffers data from the core network. When the vL-OLT accommodates a group, it cannot buffer the data of other groups. Therefore, the proxy will buffer the data to the L-OLT and transfer them in synchronization with group exchange of the L-OLT. Second, the proxy controls the transmission timing of the periodical burst data to L-OLTs and works as a TCP proxy to the TCP/IP traffics. In case of large buffer environment, TCP packet retransmission and throughput degradation will occur by seconds-ordered data buffering. To prevent retransmission by time-out, the proxy terminates a TCP session and creates a new TCP communication between the proxy server and the subscriber. Third, the proxy provides traffic shaping of burst traffic from the L-OLT and transfers it to the core network. The proxy controls the packet intervals using a traffic shaping in order to eliminate the interruption of the voice communication and improves the service quality.

We evaluated the TCP throughput and the UDP packet loss rate with proxy and without proxy environments. A simplified test network is configured as shown in Fig. 10. One 1 Gbps link is set between a client host and a server host. Delay between the server and the proxy is set as 10 ms one-way. Delay between the client and the proxy is ignored because it is relatively small (40 μs). L-OLT's transmission time is divided into 32 timeslots in order to emulate 32 L-ONUs. In EλAN, it is assumed that 10 Gbps link is set and L-OLT accommodates 256 L-ONUs. However, in this experiment, L-OLT accommodates only 32 L-ONUs because of the 1 Gbps link. The number of ONU group is set to 2, 3, and 4. Switching time between ONU groups is set to 50 ms. 1 s is assigned to each ONU group for transfer operation. The vL-OLT#x (x=2, 3 and 4) sends data 1 s and waits for 1.05 s × (the number of the ONU group – 1). Measurement time is set to 1 minute.

![Experiment network and picture of the test network.](image_url)

Figure 11(a) shows the packet loss rate at the time of performing the UDP communication. When the proxy does not buffer (without-proxy), packet loss rate of the two ONU groups case is 52%, and the four ONU groups case is 77%. In
case of using the proxy (with-proxy), no packet loss is observed in this experiment. Figure 11(b) shows the TCP throughput evaluation results. In the without proxy case, few Mbps throughput is observed. On the other hand, in the with-proxy case, over 10 Mbps is observed in the two ONU groups case. The proxy can enhance the throughput. Few Mbps throughput of the without-proxy case will be drastically reduced as increasing the distance between the server host and the client host. On the other hand, in the with-proxy case, the TCP proxy function will keep the throughput.

![Graphs showing packet loss rate and TCP throughput](image)

Figure 11. Experimental results. (a) UDP packet loss rate. (b) TCP throughput.

Figure 12 shows the traffic shaping effect of the proxy in the four ONU groups case. Upper graph shows the without-proxy case and lower graph shows the with-proxy case. It founds that in the without-proxy case, more than 4 s burst interval, nearly 40 ms burst peak, and nearly 80 ms burst transmission time are observed. This will cause voice packet interruption. On the other hand, in the with-proxy case, no burst traffic is observed. A theoretical burst transmission time is 31.25 ms (= 1/32 s). The burst peak time matches with the theoretical value. 80 ms burst transmission time may be caused by traffic shaping in the Linux kernel.

![Graph showing traffic shaping effect](image)

Figure 12. Experimental results of traffic shaping effect (4 ONU groups, UDP traffic).

In the actual active ODN environment, ONU group switching time in the active ODN becomes few seconds order. In our experiment, 50 ms switching time and 1 s data transmission time are assumed. If switching time will be 2 s, transmission time may be 5 s or more. In this case, TDMA cycle becomes 28 s (5 s transfer operation and 23 s waiting time). Therefore, real time UDP and TCP application may not be usable. A delay tolerant networking (DTN) application can be applicable.
3.3 P-OLT as NFV and edge computing platform

As shown in 3.1 and 3.2, Linux servers can become a P-OLT platform. The software-based OLT of FASA also uses general-purpose servers as a platform25. Multiple VMs can be run on the Linux server. As shown in Figs. 6 and 7, L-OLT VM instances and an OVS VM instance can be run on the P-OLT. This means that the server-based P-OLT platform can become an NFV platform and a computing resource platform. The L-OLT VM instance can access the computing resource VM instance in the same P-OLT platform. This feature is very important in an edge computing environment. This is because a transmission delay between a user device and an edge computing node should be as small as possible. To provide a PoC, distributed industrial robot control with software defined transport network (SDTN) operation has been demonstrated26, 27. The distributed robot control is an example of the cloud and edge cooperation computing application.

Current industrial robot applications have been designed for repetitive and high-volume tasks. Manufacturers do not have viable solutions for handling a variety of compute-intensive unstructured tasks. The cloud robotics28 will become a possible solution. In the cloud robotics, robots are connected to the cloud and can leverage the virtually unlimited compute and communication resources in the cloud to carry out the unstructured tasks. Time-constrained unstructured tasks require data sets of considerable size to be exchanged between the robot production floor and the cloud. Therefore, flexibly interconnect the production floor to the cloud/edge sites are essential. The demonstration has been aimed to indicate the applicability of SDTN and cloud/edge computing technologies to supporting the cloud robotics.

Figure 13 shows the demonstration system architecture for remote control of an industrial robot with SDTN and cloud/edge compute nodes. For the network configuration, a data center (cloud) and an edge compute node (NFV/P-OLT platform) located at the network edge are interconnected through a number of network domains. Each network domain, the data center and the edge compute node are controlled by a domain-specific network controller and a cloud/edge controller, respectively. A holistic network orchestration is introduced for end-to-end flow provisioning as well as setting up VMs on the cloud/edge resources. The industrial robot system consists of a robot arm and a controller based on the robot operating system (ROS) framework29. The ROS control functions are separated into two parts. One is a main control function, which is implemented in the cloud in order to assist and interact with a robot operator. Another is a sub-control function, which is implemented at the edge compute node to assist and interact with the robot in order to reduce latency and traffic volume across the network. The robotic application chosen for the demonstration is the “surface blending” of a metal piece. The metal piece is securely placed on a bench, next to the robot arm. The task of the robot is twofold. It first scans the piece with a 3D sensor and sending the collected 3D raw data to the sub-control function. The sub-control function processes the raw data to reconstruct a digital image of the surface that needs to be blended. The digital image of the surface is then transmitted to a main control function defined as the sequence of movements that the robot has to execute in order to blend the surface with a grinding tool attached to the robot. The main control function makes use of an appropriate set of algorithms to compute the blending path for the robot. Finally, the blending path is sent to the robot to be executed. A status of the robots or log data will be directly sent from the robot to the main function.

Figure 13. The demonstration architecture for remote control of an industrial robot.
Figure 14 shows the testbed configuration. The data planes of the testbed are implemented at National Institute of Information and Communications Technology (NICT) in Tokyo, Japan and at the University of Texas at Dallas (UTD) in Dallas, TX, USA. The testbed in Japan consists of three different network domains: a 100 Gbps core network domain, a 10 Gbps metro network domain, and a 1 Gbps access (EλAN) domain. The metro network domain provides transmission pipes for the attached edge compute node controlled by an OpenStack controller and the P-OLT of the EλAN. The sub-control function to control the industrial robot for surface detection and motion planner is implemented at the edge compute node. The robot arm is simulated by a computer connected to the EλAN. In the control plane, the network orchestrator is connected to all SDTN controllers and the OpenStack controller. As a southbound interface (SBI) of the network orchestrator, a RESTful interface is utilized. The network orchestrator is based on the OdenOS architecture and each domain is orchestrated by the orchestrator located at the KDDI R&D Labs. in Saitama, Japan connected by using a virtual private network (VPN). The testbed in the USA consists of a datacenter emulated by a server located at UTD. The main robot control function is implemented on the server and is controlled by the robot operator. The network connection between Japan and USA is established using a VPN.

Figure 14. Testbed configuration.

A demonstration flow is as following. First, the robot operator requests to the orchestrator for setting up the server to start ROS functions. In the initial phase, both main and sub control functions are initiated in the cloud server. Next, the robot operator requests for setting up the network between the robot and the control functions. After starting the robot operation, the operator realizes too large delay. Then the operator requests for setting up another VM to separate controllers and reconfigure the network. The VM setup request is submitted to the OpenStack controller, while the interconnection network setup requests among the datacenter, the VM at the edge compute node, and the simulated robot are submitted to each of the domain specific controller for execution. After the reconfiguration, smooth operation becomes possible.

Geographically unconstrained remote control of an industrial robot performing surface blending was achieved and demonstrated. It showed the possibility of providing the software-based P-OLT and NFV platform as the edge computing platform.

4. CONCLUSION

In this paper, three OLT virtualization technologies and experimental results in the elastic lambda aggregation network (EλAN) were discussed. EλAN provides programmability and reconfigurability to an OLT, an ONU, and an active ODN. The possible programmable OLT (P-OLT) implementations were using FPGA and software. As a proof of concept
(PoC) of the software-based P-OLT, a virtual machine (VM) based logical OLT (L-OLT) was implemented and three OLT virtualization technologies were demonstrated. First was the L-OLT migration, second was the OLT sharing with TDMA-based L-OLT virtualization, and third was P-OLT as an edge computing platform. Software-based OLTs are now developing in some carriers. Therefore, other OLT virtualization technologies will be developed and deployed in the future networks.

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