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Using Optical-Approaches to Raise Energy Efficiency of Future Central and/or Linked Distributed Data Center Network Services

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Abstract

Novel optical network architectures are proposed for creating future network services. The first architecture is a centralized approach for higher energy efficiency; it yields a data center-centric metro/access optical aggregation network based on wavelength/time-slot multiplexing. Not only higher application layer functions but also all layer-3 or upper traffic are transferred through the simple metro/access optical aggregation network and switched in a huge centralized giant router at the data center. Its simple optical switching is 200 times more energy efficient and only one electrical router is needed, so power consumption of the network can be reduced ten or twenty fold compared to the existing Internet. The second is service mash-up by linked data through a network that uses broadband optical wire for the IoT era. All service contents, hardware, and software programs are defined as service parts. Optical wire interconnects some service parts and creates new mash-up services in the network. That creates deep network functionality in combination with network and processing functions. Both two approaches are quite simple and energy efficient in comparison to existing Internet, so they can be applicable future data center network architecture.

Keywords: Photonic network, Access network, Energy efficient, Metro network, Future network, Data center

1 Introduction

The Internet is an extremely convenient network and has become the key infrastructure of daily life; today's multi-media network services are implemented on it. Data traffic, which includes real-time traffic and routing traffic, now exceeds 15 Tbps [14]. Internet traffic consists of Peer-to-Peer (P2P) traffic such as file exchange, Voice over IP (VoIP), Video over IP, etc. or Client-to-Datacenter (C2D) traffic for server-client communication including Web access, content download, and data file download. P2P is being replaced as the dominant traffic by C2D [14].

The first problem is that the network structure of today's Internet does not suit "centralization onto data centers". Instead, we need the "data center centric" architecture [34]. The Internet is basically a flat structure network consisting of interconnected autonomous systems (ASs); it is scalable and plug-and-play and so suits changes in traffic demand. One of its key problems is the rapid increase in its power consumption. This is being exacerbated by the Internet of things (IoT). IoT involves adding a huge number of sensors, terminals and processing/server functions to the network. This paper expands the definition of IoT to include "Service Part (SP)". SP includes not only hardware but also contents data or software functions. IPv6 addresses are assigned to all SPs and SPs can interconnect with each other. This architecture suits distributed and linked data (Figure 1) [34]. For the data center centric architecture, we emphasize the technologies and background.

The dominant Internet service providers (ISPs) and content delivery network (CDN) providers are called the hyper-giants. The top 30 hyper-giants (Google, Yahoo, Amazon, Akamai, etc.) generate more than 30 % of all Internet traffic [14]. This dominancy will increase in the near future. Unfortunately, the worldwide power consumption of network devices has been increasing over 12% every year. In 2008, it was 25 GW, and in 2020 it will quadruple to reach 97 GW [22]. The power consumption of the Internet has been increasing rapidly due to the adoption of rich data services as well as the increasing number of users.

Fiber to the home (FTTH) service has grown rapidly, and the passive optical network (PON) [8] is a global major access network technology. The enhancement of its bandwidth contributed to the current increase in total broadband traffic [9, 11]. Optical systems have been greatly improved by advanced technologies such as wavelength division multiplexing (WDM), high-speed optical switching, digital coherent transmission, and optical orthogonal frequency division multiplexing (OFDM). Optical systems are extremely useful given their wide bandwidth and low power consumption. The Long-Reach PON (LR-PON) is being researched to determine capital expenditure (CAPEX) and operational expenditure (OPEX) in access/metro network areas [1, 24] when accommodating large numbers of users in wide coverage areas.

Given the above background, this paper proposes two network architectures; the Data Center Centric Architecture is realized by a metro/access optical aggregation network while the Distributed Linked Network Architecture uses optical wire interconnects. The Data Center Centric Architecture is for metro/access integrated optical networks. The architecture provides wide bandwidth to a centralized data center having giant layer-3 (L3) routers through a wide optical time slot with WDM aggregation network. In other words, all user data is gathered and transferred to a giant centralized L3 router through the metro/access optical aggregation network transparently. The metro/access optical aggregation network supports massive subscriber aggregation via its combination of time slot switching and WDM. The metro/access optical aggregation network realizes transparent switching. Therefore, each time slot flexibly supports various kinds of services, such as residential services, small data centers, business users, small office home office (SOHO) users, and mobile backhaul. Each time slot transfers data between the customer premises equipment (CPE) and the centralized giant L3-router via a simple multiplexer/de-multiplexer. Since the proposed network architecture has no complicated electrical switching functions, the optical metro/access aggregation network becomes the center of the network which dramatically reduces the network power consumption twenty-fold compared to the current Internet [25, 26].

On the other hands, IoT such as sensor network is distributed components. Optical interconnection can connect two things without large delay or bandwidth restriction. In other words, it is not necessary to correct all functions into one physical data center. That means distributed parts can be interconnected by optical wire. So opposite way to realize new network service is the linked-data network as described as approach 2. For this, we have been proposing the service mash-up network named E^3-DCN [18, 21]. All contents (picture, movie, sensor data, etc.), hardware (CPU, memory, storage, display, video camera, etc.), and software programs (game, application software, etc.) are defined as SPs. SPs are dynamically interconnected by optical wires to produce new mash-up services. In the paper, Section 2 describes two different architectures in general, Section 3 describes detail about Data center centric approach and its merit for energy efficient and prototype system results. Section 4 shows, on the other hand, distributed linked function network in detail. Finally, in Section 5 shows the conclusion of the paper.

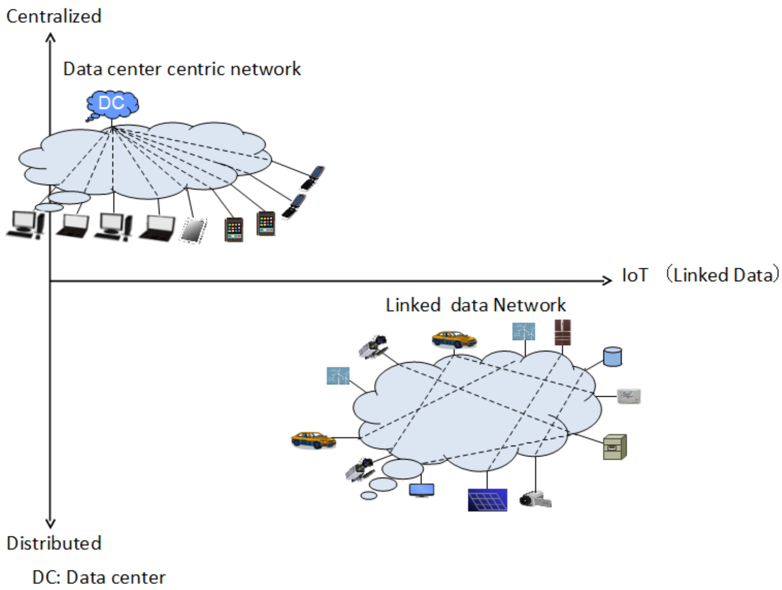

Figure 1: Two images of network enhancement.

2 Future network architecture

2.1 1st proposal: Data Center Centric Architecture (Centralized Architecture)

Major Internet application services, such as social network service (SNS) or YouTube, are migrating to C2D service. In addition, the optical access service will include not only residential services such as Internet access service or VoIP, but also SOHO/business or mobile backhaul service. This migration to C2D service indicates that the whole network structure needs to be restructured, not just the access network. Figure 2(a) shows the baisc Internet network structure; multiple autonomous systems (ASs) are interconnected.

This network structure is easy to expand to meet traffic demand, and scale to meet greater numbers of Internet users. Plug-and-play is also possible for ASs/routers/hosts. However, the Internet structure in Figure 2(a) does not suit C2D traffic. This is because of traffic from users toward the data center of the hyper-giants occupies more than 40% of all Internet traffic. In other words, this multi-ASs network structure is not energy efficient. Our metro/access optical aggregation network architecture is the solution as shown in Figure 2(b) [25, 26]. The network consists of a simple transparent aggregation network realized by optical circuit switches, wavelength-converters, and wavelength-multiplexer/de-multiplexers, and a massive centralized power-scalable L3-router in the data center. In the proposed architecture, the metro/access optical aggregation network has a simple multiplexing function and so is very energy efficient.

2.2 2nd proposal: Distributed Linked Network Architecture (Distributed Architecture)

Our other proposal is the distributed linked network architecture. In the future network, billions of sensors, content processing functions, and also terminals, will be assigned IPv6 addresses and widely dispersed. The optical Internet provides flexible and systematic connections among them with enough bandwidth.

In the distributed linked network architecture, contents, hardware, programs, and functions are named “Service Parts” and are interconnected by optical wires. An optical wire provides a logical connection or path to an SP that offers huge point-to-point bandwidth, security, and minimal delay. Each SP has a meta-data table. The linked data network exchanges meta-data and SPs are connected by extract key matching such as location, function, capability, etc. The combination of network functions, such as named data search, linked data matching, and optical wire, and SPs creates new mash-up services. Figure 3 shows an example. The network provides 3 functions (A, B, and C). The contents are transferred from source to destination via A, B, and C. Functions A, B, and C customize the input content. The source SP provides an ISO image data, function A SP provides DVD player software and MPEG2 data output, function B SP provides video enhancement, and function C SP provides digital rights management (DRM), finally, a DRM protected enhanced video image is generated as a customized content. This architecture allows the virtual creation of highly functional networks. This is discussed later.

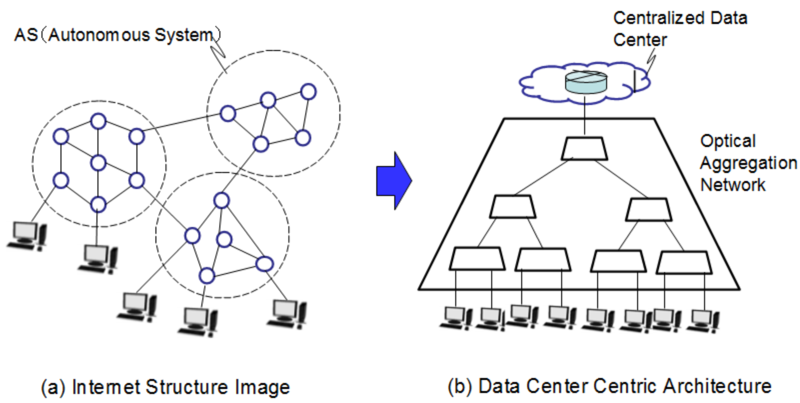

Figure 2: Future data center-centric network architecture.

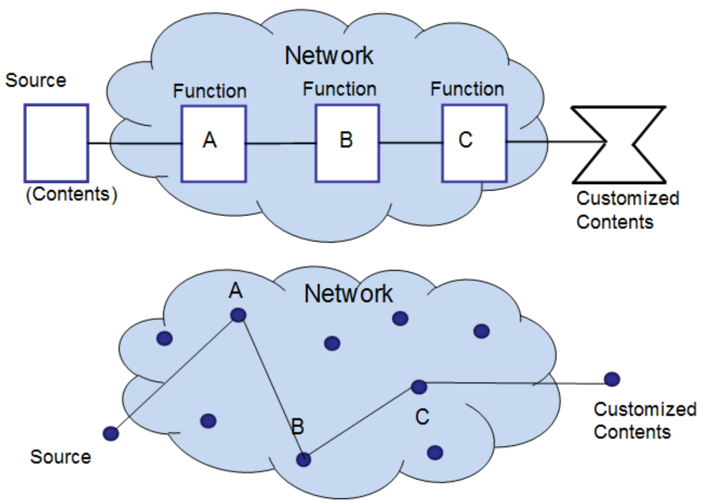

Figure 3: An example of a mash-up service on the distributed linked network architecture.

3 Metro/access optical aggregation network for data center centric architecture

Figure 4(a) shows the conventional metro/access network, and Figure 4(b) shows the proposed metro/access aggregation network [25, 26]. The proposed metro/access optical aggregation network can accommodate a large number of users and enable long distance transmission between users to central data centers; it accommodates the various kinds of services provided by the data centers. Data for services are transparently transferred to users through the metro/access optical aggregation network. The metro/access optical aggregation network decreases power consumption by reducing the number of electrical devices; electrical technology is replaced by optical technology. The average number of routing hops in the conventional Internet is nearly twelve in Asia, Europe, and the USA [29], whereas the proposed one has only 1 hop at the data center. All traffic is aggregated and transferred to the giant centralized L3-router in the data center. This router is power scalable to traffic demands, i.e. active switching capacity is proportional to the amount of traffic, and it offers huge statistical multiplexing gain. Of course, it is necessary that redundancy to achieve high reliability is needed. Data center approach is always need to prepare for single point failure.

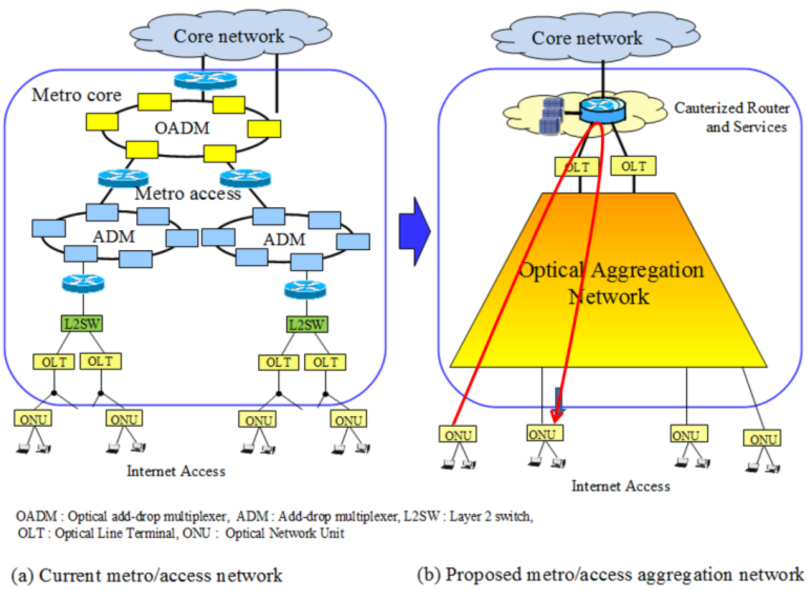

Figure 4: Detailed structure of today's and the future's data center access.

3.1 Energy efficiency

We introduce two important background issues. The first one is router power consumption. Figure 5 shows the relationship between consumption and throughput [10, 29]. Equation (1) is taken from the literature.

$$P = A \cdot C^{2/3}. \tag{1}$$

Where P [watt] is router power consumption, C is router throughput [Mbps], and A [watt·Mbps$^{-2/3}$] is a constant. The value of A is 1.0 in Eq. (1).

This equation indicates that increasing electrical router throughput improves the energy efficiency; power consumption per-bit decreases as router throughput increases. Accordingly, the proposed metro/access aggregation network architecture utilizes extremely large capacity electrical routers. We introduce a second important background issue; the power consumption characteristic of

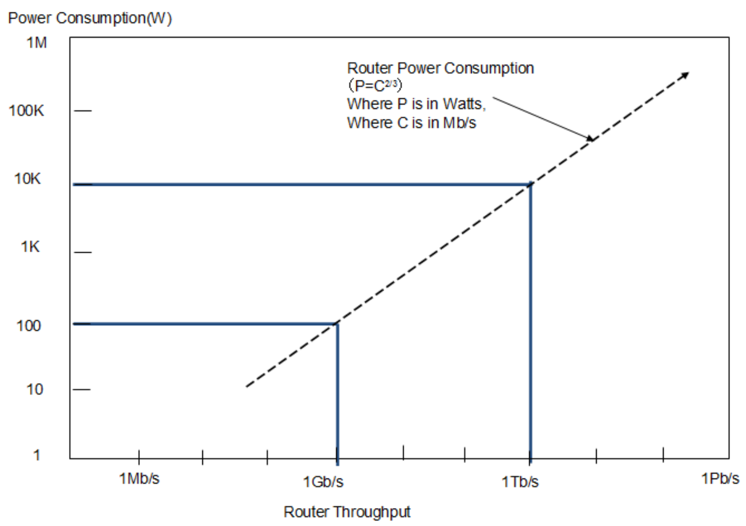

Figure 5: Router power consumption which is proportional to $C^{2/3}$ where C is router throughput [10, 29].

switches. References [10] and [4] describe power consumption issues in future high-capacity switching systems, and examine different architecture implementations both all-electronic and all-optical as shown in Figure 6.

Figure 6 plots the power consumption of an electrical switch node and an optical switch node; upper line plots power consumption of an electrical packet-switched node, lower lines plot power consumption of an optical circuit-switched node built as micro-electric-mechanical (MEMS) switches. This graph shows that optical-switched node significantly reduces the power consumption of the switching function. Of course this comparison is not fare, because packet switch and circuit switch have different switching function. However, this graph shows that circuit switching is higher energy efficient than packet switching. So this is because electrical L3 functions are extremely complicated compared to the optical circuit switched functions under different functions but some switching throughput. MEMS-based circuit switched nodes without wavelength-converters can reduce the power consumption 500 times compared to the electric packet switched node. Therefore, we adopt optical circuit switching to realize the metro/access optical aggregation network [25, 26, 35].

For transition to realize data center centric network, long reach PON and L2 aggregation are introduced. L2 switch network is lower performance than optical L1 aggregation, however, number of L3 routers can be reduced.

3.2 Proof of Concept

We used very high-speed (less than 10ns switching) (Pb,La)(Zr,Ti)O3 (PLZT) optical switches [17, 27] to implement a prototype system, see Figure 7. This prototype includes a newly proposed automatic ranging function [28] that can handle more than 128 optical network units (ONUs) with 40 km length links, a significant enhancement over the conventional limit of 32 ONUs at 20 km [30].

PLZT switches offer extremely high-speed switching (nano-second order), and can greatly decrease the optical power loss compared to the optical splitters used in current PON systems. In case of upstream data, the metro/access optical aggregation network offers a simple data multiplexing function. For downstream data, pre-fixed slot distribution switching with source routing is applied. Because there is no complicated header processing or store-and-forward queues in the metro/access optical aggregation network, it is a simple and buffer-less optical network. These features greatly enhance energy savings. Details are discussed in [5].

An 1x128 optical switch is composed of 1x2 switch elements, all of which must be controlled

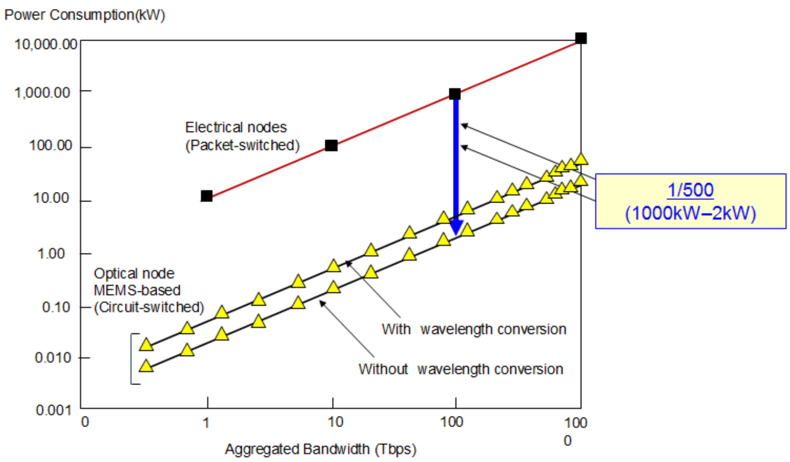

Figure 6: Power consumption of both all-electrical and all-optical switches [4, 10].

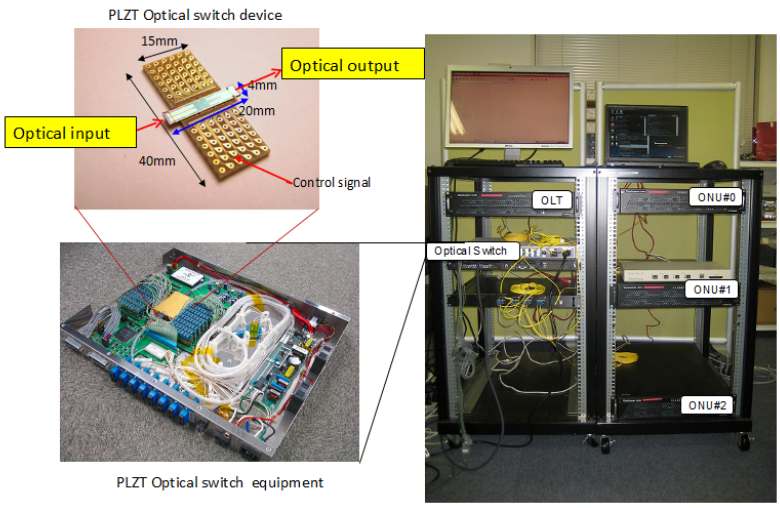

Figure 7: Prototype of optical slot aggregation switch network.

synchronously to minimize the guard time. We set the skew of triggers in the switch driver circuits to be zero, and also designed equal-length wiring between the switch driver circuit and all 1x2 switch elements. We verified that control triggers for two 1x2 switch elements reached the switches simultaneously, so we confirmed that 1x2 switch elements could be controlled synchronously [30].

In a demonstration, high-quality video data and Internet access data were transferred through optical timeslots.

3.3 Energy reduction by data centric architecture

To feed the data center the proposed metro/access optical aggregation network is realized by optical WDM/slot aggregation technologies. The traffic data are aggregated and transferred through the optical lower layer; layer-2/3 or high layers are realized only within the data center node. In other words, this simple optical aggregation network realizes a one hop L3 network. Figure 8 shows the power consumption of an IP network implemented by the current Internet and by the proposed metro/access optical aggregation network. The proposed network architecture reduces the power consumption to 20 times compared to the current Internet.

This evaluation uses the power consumption of network components as shown in Table 1.

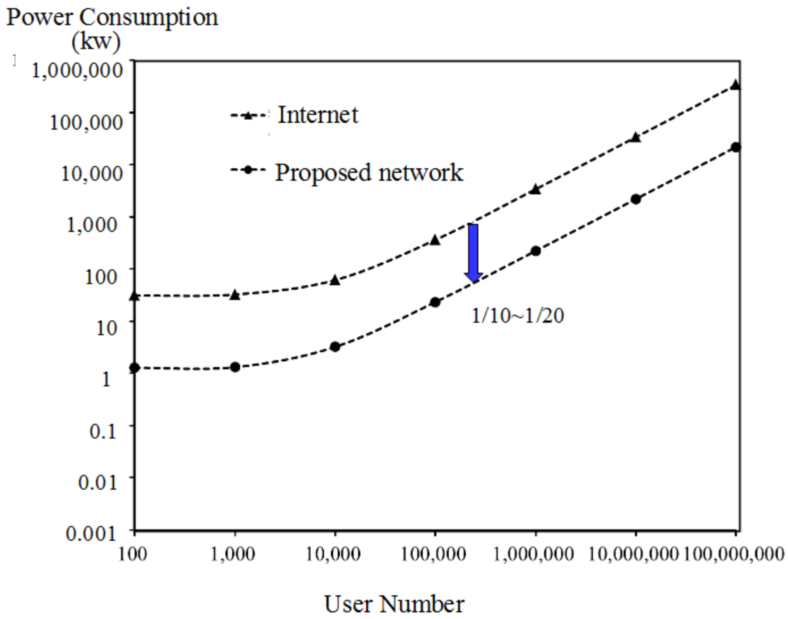

Figure 8: Power consumption reduction by the proposed architecture.

Table 1: Typical power consumption data of network components

	Component	Capaciy	Power consumption
Internet	SONET ADM	95 Gbps	1,200 W [37]
	OADM	N/A	450 W [37]
	EDFA (Erbium-Doped optical Fiber Amplifier)	N/A	8 W [37]
	Access first stage router	51.2 Gbps	1,380 W [25]
	Access Second stage router	256 Gbps	4,030 W [25]
	Access third stage router	320Gbps	4,680 W [25]
Proposed network	PLZT switch (including driver)	1x16 switch 1x8 switch	2.4 W 2.4 W
	EDFA	N/A	8 W [37]
	3R(Re-amplifying, Re-Shaping, and Re-timing)	N/A	2.79 W [4]
	WC(Wavelength Converter)	N/A	1.65 W [4]
	Controller	N/A	150 W [4]

4 Optical wired mash-up service network for distribution linked network architecture

The second proposal is the distributed data/hardware /function linked network architecture. The optical technologies provide “Optical Wires” that offer huge bandwidth. Optical wire can provide over 100 Gbps/user big-fat-pipe to link everything in the world. In addition, high-speed switching (switching times shorter than several nano-second are possible) of the optical wires creates a dynamic provisioning service. The ubiquitous grid networking environment (uGrid) [3, 12, 20] has been proposed as a new service concept. uGrid defines not only hardware such as central processing units (CPUs), graphics processing units (GPUs), memories, storages, personal computer peripherals, displays, video cameras, game machines, and smart phones but also software programs as "Service Parts (SPs)" as shown in Figure 9. This is called "Everything as a Service Part". Linking SPs by optical wires creates new mash-up services. uGrid can be realized Today's Internet connectivity. However, optical wire can reduce delay time and bandwidth restriction. The optical wire, which is provided by optical interconnection technology at the local area network (LAN) scale or a dynamic optical switched path at the wide area network (WAN) scale, provides a huge bandwidth and delay tolerant link among SPs. Therefore, SP combinations can be formed without regard to location (and owner if possible) to create an optical wired network mash-up service. In other words, any SP (if open access is possible) can be used by any user in a dynamic manner.

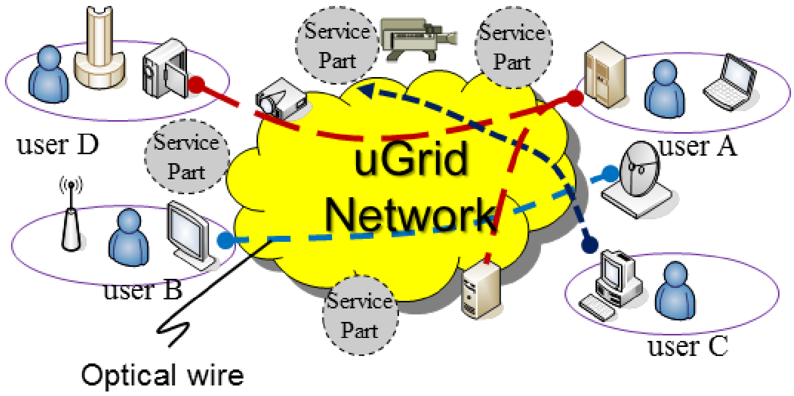

Figure 9: Ubiquitous grid networking environment (uGrid) concept of "Everything will be linked to each other via optical wire"

Figure 10 shows a trial example of the uGrid service [12]. Video streaming data is processing in the uGrid network. Four SPs, the video camera (SP A), the face detection function (SP B), the image enhancement function (SP C), and the video monitor (SP D) are logically connected by three virtual cables. The virtual cable is actually provided by optical wire. An end-to-end service path consisting of the three reserved SPs and four optical wires is set to create the service.

The optical wire between SPs can set by using generalized multi-protocol label switching (GMPLS) protocols in the transport network layer. In case of the virtual full high definition multimedia interface (HDMI) cable emulation, a 10 Gbps optical wire is needed.

The service path is also set by extended GMPLS resource reservation protocol for traffic engineering (RSVP-TE) protocol which reserves SPs and optical wires from the uGrid network resource pool. The signaling protocol for controlling the service path is called "Service Signaling"[12].

The uGrid concept can be applied to yield information-centric networking (ICN) [2] and the content-centric network (CCN) [13]. CCN is one of the most promising technological targets of the new generation network (NwGN) in Japan or the Future Networks in EU/USA. CCN mainly transfers large content sets as transport units in the service network layer. CCN can act as a content delivery network, while uGrid can acts as a content generating network. The E^3-DCN concept [18, 21] unites CCN and uGrid in the network virtualization environment and applies an energy aware routing method to both networks. Two energy-aware routing strategies are applicable to E^3-DCN.

The first strategy is "Dynamic Network Reconfiguration". Two approaches have proposed to realize dynamic network reconfiguration. One is applying energy efficient TE methods [19, 6, 36]. In this approach, the traffic flow is concentrated on a limited number of links and nodes to make vacant links. Next, unused links and nodes are shut-down (or pushed into sleep mode) to reduce operating power consumption. To realize operation power savings in the virtual network environment, cooperation between the tenant network and the network virtualization platform using a network application programming interface (API) is required [18]. Another approach is "Service-Copy" [23].

The processing function of a Service-Part, i.e. software, can be easily copied from one computer system to other computer systems. Examples of the service-copy are remote shell, remote procedure call, virtual machine copy, and virtual machine migration. To copy service to another location needs energy but distance between SPs can be decreased. So optimizing total power reduction is possible.

The second strategy is "Optical Circuit Switching Bypass". Optical wire can be constructed on both packet switching and circuit (or path) switching networks. This is because the optical wire is a logical path, i.e. a kind of label switched path. In general, packet switching networks have lower data transport costs than circuit switching networks. This is because it allows small traffic flows to share the bandwidth by statistical multiplexing. However, if statistical multiplexing is not permitted or does not work effectively this is not true. As a small number of flows share the whole bandwidth and strict QoS preservation is required, the circuit switching network is more preferable than the packet switching network. In [7], it was shown that the switching energy of an optical circuit switch is 0.5 nJ/bit while that of an electrical packet switch such as an Ethernet switch and IP router is 10 nJ/bit. Setting optical wires on a packet switching network raises the energy consumption, but the transport cost is cheaper. The circuit switching alternative requires less energy consumption but higher cost. The service path route decision algorithm must determine optical wire implementation given the content size, content transfer duration, and transport energy/bit. The required physical network parameters such as number of switches along the optical wire, interface speed, and occupied bandwidth by other users can be accessed via the network API.

E^3-DCN and uGrid provide an in-network processing feature. This means that the end-to-end service path is not transparent and data conversion within the network is possible. The network provides not only transportation but also the content creation service. As a result, future energy efficient mash-up services allow users to dispense with the need to own hardware or even complicated software functions; the network provides the user with the desired customized service. This concept expands to the "Inter-cloud network architecture" [31, 32, 33], a most attractive approach for future cloud service as shown in Figure 11.

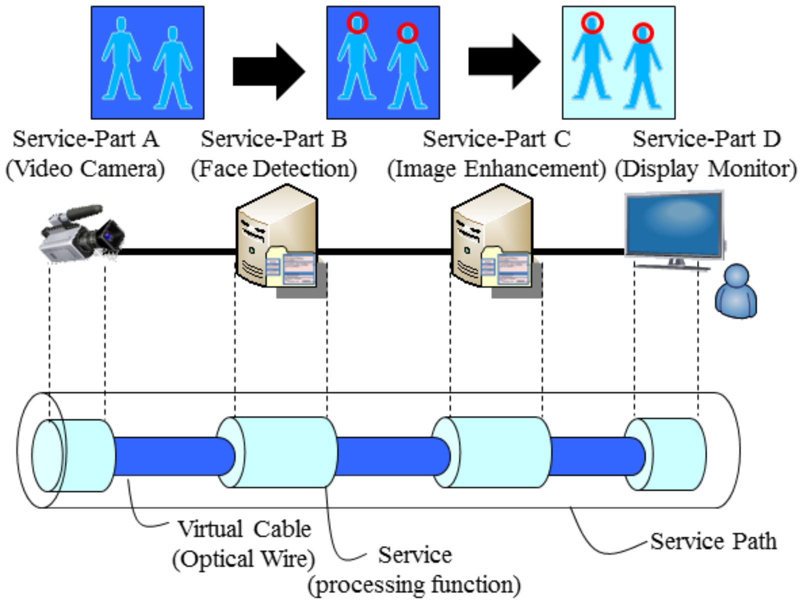

Figure 10: Service path in the service signaling.

Today's cloud service is realized by one central data center (both centralized type data center and distributed type data center) and by one cloud service provider such as Google or Amazon. In the future, however, we will need to combine cloud functions such as software as a service (SaaS), platform as a service (PaaS) or infrastructure as a service (IaaS) to create the virtual service cloud that supports dynamic use and cloud resource access. In the inter-cloud environment, each real or virtual cloud can be defined as a “Service Part” (Cloud as a Service) and the optical wire can connect real cloud data centers. Software defined networking (SDN), which provides the virtual service network on virtualized computing and networking resource pools and network functions virtualization (NFV), will be highlighted for this generalized optical wired mash-up service approach. The SDN is a deeply programmable network (DPN) [15, 16].

In the DPN environment, the ser can define own virtual node function and virtual link function. A service application on the DPN will access network functions via the Service Network Interface (SNI). The SNI can be defined as one of the northbound API in the SDN. Service creators, such as cloud business providers, system integrators, educational institutions, and government, do not own the network facilities but operate their own virtual cloud as their application platform. This is the key to creating the inter-cloud business model.

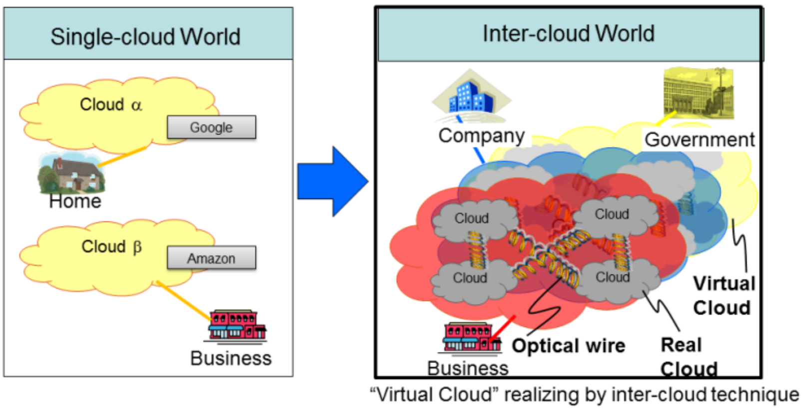

Figure 11: Inter-cloud provides virtual cloud services using uGrid approach.

5 Conclusion

This paper proposed two attractive optical network architectures. One is the Data Center Centric Architecture realized by a new metro/access optical aggregation network for the next generation network. The architecture consists of giant L3 routers and a metro/access optical aggregation network. Internet traffic data are aggregated and transferred to data centers, within which giant L3 routers switch the traffic. The current Internet creates a large number of hops but the proposed network architecture needs only one. The optical metro/access aggregation network can realize simple metro/ access networks without complicated L3 interconnection functions. This architecture reduces CAPEX and power consumption. The proposed metro/access optical aggregation network dramatically reduces the network power consumption up to 20 times compared to the current Internet. This is because reducing number of router hops and L1 optical switch has small power consumption than L3 electrical router. Tests on a prototype based on PLZT optical switches (switching times under 10 ns) confirmed the feasibility of the proposed architecture. The proposed architecture and system can realize future metro/access networks.

The second alternate proposed architecture, the service mash-up network named uGrid, uses dynamic optical wires. These huge bandwidth dynamic optical interconnections can create location-free mash-up services. The service part in the uGrid network encompasses not only hardware components but also software. This idea can be extended to yield the inter-cloud network architecture. Both the aggregation network and the mash-up service network can be applied to establish future optical network services.

6 Acknowledgment

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