Creating Future Energy Efficient Network Services through Optical Technologies
— Data center-centric and/or linked distribution data —

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Abstract— Two newly-structured optical network architecture alternatives are proposed for creating new network services. The first target is an energy efficiency network; a data center-centric optical aggregation network based on wavelength/time-slot multiplexing. Not only application layer functions but also all layer-3 or upper traffic are transferred through the optical aggregation network and switched in the huge centralized router at the data center. Power consumption of the network can be reduced ten or twenty fold compared to the existing Internet. The second is a service mash-up network that uses broadband optical wire under the IoT generations. All service contents, hardware, and software programs are defined as a service part. 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.

Index Terms— Photonic network, Access network, Energy efficient, Metro network, Future network, Data center

I. INTRODUCTION

The Internet is the infrastructure for today’s multi-media network services. Statistical traffic data including real-time traffic and routing flows now exceed 15 Tbps [1]. Internet traffic consists of Peer-to-Peer (P2P) traffic such as file exchange, Voice over IP (VoIP), etc. or Client-to-Datacenter (C2D) traffic for server-client communication including Web access, data download, and content download. The current traffic king, P2P traffic, is being dethroned by C2D traffic [1].

The first problem is that today’s Internet network structure does not fit with “centralization onto data centers”. We call this the “data center-centric” architecture [2]. Because the Internet is basically a clustered structure of autonomous systems (ASs) with an interconnection network, it is scalable and plug-and-play to match changes in the traffic demand. Second is the rapid increase in the power consumption of the Internet. On the other hand, the Internet of things (IoT) is creating a huge number of sensors, terminals and processing/server functions in the network. We have defined such expansion of IoT as “Service Part (SP)” in this paper. The SP includes not only hardware but also contents or software functions. All of them are assigned IPv6 addresses and interconnected with each other. This architecture is distributed and linked-data (Fig.1) [2]. For the first architecture, named the data center-centric network, following background and technologies are highlighted.

The dominant large content providers, large consumer networks, large content delivery network (CDN) providers are called the hyper-giants. The top 30 hyper-giants (Google, Yahoo, Amazon, etc.) generate 30% of all Internet traffic [1]. This number may increase in the near future. Unfortunately, the power consumption of worldwide network equipment has been increasing over 12% every year and will reach 97 GW in 2020, about 4 times that of 2008 [3]. The power consumption of the Internet has been increasing rapidly with the expansion of rich data services as well as usage.

The passive optical network (PON) [4] is used as a global basic network access and goes by the name of fiber to the home (FTTH). Its bandwidth enhancement contributed to the current increase in total broadband traffic [5], [6]. Optical technology has been greatly improved by advanced technologies such as wavelength division multiplexing (WDM), high-speed optical switching, digital coherent detection, and optical orthogonal frequency division multiplexing (OFDM). The optical technology is very attractive with its huge bandwidth and low power consumption. The Long-Reach PON (LR-PON) is being researched to decrease capital expenditure (CAPEX) and operational expenditure (OPEX) in access / metro areas [7], [8] to support large numbers of users, and create huge coverage areas.

Given the above background, this paper first proposes the optical aggregation network as a new metro / access integrated optical network architecture. The architecture uses a huge optical time slot division with WDM aggregation network to provide access to a centralized data center having large layer-3 (L3) routers. In other words, all local traffic is gathered to a large centralized L3 router via an optical aggregation network without any complicated protocol. The optical aggregation network offers large-scale subscriber aggregation through its combination of WDM and time slot switching. The optical aggregation network uses transparent switching, so multi-services, such as residential service, business users, small office home office (SOHO) users, and mobile backhaul are integrated on each time slot. Note that each time-slot is transparently transferred between the customer premises equipment (CPE) and the centralized L3 router, there are only
multiplexer functions between them. 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 decreases the network power consumption by 90-95% [9], [10].

Our second idea is the linked data network. For this, we proposed the service mash-up network named E3-DCN [11], [12]. All contents, hardware and software programs are defined as SPs. Any SPs are interconnected by optical dynamic wires and new mash-up services are created.

II. FUTURE NETWORK ARCHITECTURES

A. 1st option: Centralized Architecture (Data Center-Centric)

Internet application services such as social network service (SNS) or YouTube are moving toward the C2D service. In addition, the optical access service will encompass not only residential services such as VoIP or Internet access service, but also business/SOHO or mobile backhaul service. This suggests that the whole network architecture needs to be reconstructed, not just the access network. Fig. 2 (a) shows the basic Internet architecture; multiple autonomous systems (ASs) are interconnected to each other. This architecture is easy to expand and scales to meet increase in Internet user numbers. Plug-and-play is also possible for ASs/routers/hosts. However, it does not suit C2D traffic where more than 40% of traffic is access toward the data center of the hyper-giants. In other words, this multi-ASs network is not energy efficient. To meet this background, we propose the optical aggregation network shown in Fig. 2 (b) [9], [10]. The network consists of a simple transparent aggregation network and a centralized L3 router in the data center. In the proposed architecture, the optical aggregation network has simple multiplexing function and so is very energy efficient. Details are discussed later.

B. 2nd option: Distributed Linked Network Architecture

Our other network architecture is the distributed linked network architecture. In the future network, billions of sensors, content processing functions, and also terminals are widely dispersed but assigned IPv6 addresses. 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. The optical wire provides logical connection or path to the SP that offer 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, the function A SP provides DVD player software and MPEG2 data output, the function B SP provides video enhancement, and the 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 also discussed later.
III. OPTICAL AGGREGATION NETWORK

The conventional metro / access network and the proposed metro / access aggregation network are shown in Fig. 4 (a) and (b) [9], [10]. The proposed network can accommodate a large number of users and enable long reach transmission; it supports the various kinds of services realized by the data center. Data for services are transported to users through the optical aggregation network. The optical aggregation network reduces power consumption by cutting the number of electrical devices and using optical technology instead of electrical technology.

Today’s Internet uses, on average, 12 hops in routing whereas the proposed one has only 1 hop at the data center. All traffic is transferred to the large centralized L3 router at the data center. This router is scalable to traffic demands and realizes huge statistical multiplexing gain.

Fig. 4. Detailed structure of today’s and the future’s data center access.

A. Energy efficiency

We would like to introduce two important background issues. First, Fig. 5 shows the relationship between router throughput and power consumption [13], [14]. The power consumption of routers is given by the following equation in the literature noted.

\[ P = A \cdot C^{2/3} \]

Where \( P \) [watt] is power consumption, \( C \) is router throughput [Mbps], and \( A \) [watt \cdot Mbps^{-2/3}] is a constant value. Note that it can be defined as 1.0 in Eq. (1).

This equation indicates that power consumption per bit decreases as router throughput increases. In other words, larger capacity electrical routers raise the energy efficiency. According to these results, a new network architecture that utilizes large capacity electrical routers is proposed.

We would like to introduce another distinguishing characteristic. References [14] and [15] address power consumption issues in future high-capacity switching systems and examines different architecture designs by either all-electronic or all-optical implementation as shown in Fig. 6.

As shown in Fig. 6, upper line plots electric packet switching performance, lower line plots optical circuit switching performance realized by micro-electric-mechanical system (MEMS) switch. This graph shows that optical switching can significantly reduce the power consumption of switching equipment. Because electrical L3 functions are extremely complicated compared to the WDM circuit switch under some switching throughput, a MEMS-based circuit switch without wavelength-converters can reduce power consumption by a factor of 500 compared to the electric packet switch. Therefore, we utilize the optical circuit switch to realize the optical aggregation network. This suits traffic centralization and reduces power consumption [9], [10], [16].

Fig. 5. Router power consumption which is proportional to \( C^{2/3} \) where \( C \) is router throughput [13],[14]

Fig. 6. Power consumption of both electrical and optical switches [14], [15].
B. Proof of Concept

A proof-of-concept prototype system that uses very high-speed (10 ns switching) (Pb,La)(Zr,Ti)O3 (PLZT) optical switches [17], [18] has been demonstrated. The experimental set up is shown in Fig. 7. The prototype system includes a newly proposed automatic ranging function [19] that can handle more than 128 optical network units (ONUs) with 40 km links unlike today's limit of 32 ONUs at 20 km [20].

PLZT switches offer nano-second order high-speed switching, and can greatly reduce the optical power loss compared to the optical splitters used in current PON systems. The optical aggregation network has the simple function of signal multiplexing only the upstream signal. On the other hand, pre-fixed slot distribution switching with source routing is applied for the downstream signals. Because there is no complicated header processing or store-and-forward queues in the network, simple, and buffer-less optical aggregation networks can be realized. This greatly enhances energy saving in the optical aggregation network. Details are discussed in [21].

All 1x2 switch elements forming an 1x128 optical switch must be controlled synchronously to shorten guard time. We designed the skew of triggers at switch driver circuits to be zero, and also homogenize electric wiring between switch driver circuit and all 1x2 switch elements. Triggers for two 1x2 switch elements arrive simultaneously, so we confirmed that 1x2 switch elements could be controlled synchronously [20].

In a demonstration, high-quality video signaling and Internet access were realized via optical slots.

C. Energy reduction by proposed network

The proposed optical aggregation network is used as the optical WDM/slot aggregation network to feed the data center. The traffic flows are aggregated in the optical lower layer and layer-2/3 or high layers are realized only within the center node. In other words, an one hop L3 network with a simple optical aggregation network. Figure 8 shows the power consumption of an IP network realized by the conventional Internet and the proposed optical metro / access network. The proposed network architecture reduces the power consumption by 90 to 95% compared to the existing Internet.

IV. OPTICAL WIRED MASH-UP SERVICE NETWORK

The alternative approach is the distributed data/hardware/function linked network architecture. The optical technology provides optical wires with huge bandwidth. In addition, high-speed switching of the optical wires creates a dynamic provisioning service. The uGrid (ubiquitous grid networking environment) [22], [23] is a new service concept. uGrid defines not only hardware such as CPU, memory, storage, displays, video cameras, game machines, and smart phones but also software programs as “Service parts (SPs)” as shown in Fig 9. The combination of SPs linked optical wire creates new mash-up services. The optical wire, which is provided by an optical interconnection technology or a dynamic optical switched path, provides a huge bandwidth and delay tolerant link among SPs. Therefore, SP combinations without regard to location create an optical wired network mash-up service. In other words, any SP can be used by any user in a dynamic manner.

Figure 10 shows a trial example of the uGrid service [23]. Video streaming data is processing in the uGrid network. Four SPs, the video camera, the face detection function, the image enhancement function, and the video monitor are logically
connected by optical wires. An end-to-end service path consisting of reserved SPs and optical wires is set to create the service. The optical wire between SPs can be set by using generalized multi-protocol label switch (GMPLS) protocols in the transport network layer. 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 uGrid concept can be applied to yield a content-centric network (CCN) [24]. The CCN is one of the most promising technological targets of the next generation network (NwGN) or the Future Networks. The CCN mainly transfers large content as transport units. The CCN acts as a CDN, and the uGrid network acts as a content generating network. The E3-DCN concept [11], [12] unites CCN and uGrid in the network virtualization environment and applies an energy aware routing method to both networks. We apply two energy aware routing strategies to E3-DCN.

The first strategy is “Dynamic Network Reconfiguration”. We propose two approaches. One approach is applying energy efficient TE methods [25], [26]. In this approach, the traffic is concentrated on a limited number of links and nodes and then unused links and nodes are shutdown to reduce operating power consumption. To realize the operation power saving from the virtual network environment, co-operation between the tenant network and the network virtualization platform using a network application programming interface (API) is required [12]. The other approach is “Service-Copy” [27]. The processing function of an SP, i.e. software, can be easily copied from one computer to other computers. Virtual machine copy / migration are examples of Service-Copy. While SP copying requires additional power, there are some total power reduction possibilities.

The second strategy is “Optical Circuit Switching Bypass”. The optical wire can be constructed on both packet switching and circuit/path switching networks. This is because the optical wire is a logical path. In general, packet switching networks have lower data transport costs than circuit switching networks. This is because small traffic flows can share the bandwidth by statistical multiplexing in the packet switching network. However, if statistical multiplexing is not permitted, a small number of flows share the whole bandwidth and strict QoS preservation is required, circuit switching networks are preferred. Setting the optical wire on a packet switching network consumes more energy, but offers more flexibility and cheaper transport cost. The circuit switching alternative requires less energy consumption but higher cost. The network API must determine which type of optical wire is preferable as a function of content size, content transfer duration, and transport energy/bit.

E3-DCN and uGrid provide in-network processing. That means the end-to-end service path is not transparent and data conversion in the network is possible. As a result, in future energy efficient mash-up services, users do not 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 [28-30], a most attractive approach for future cloud service as shown in Fig. 11.

Today’s cloud service is realized by one central data center and by one cloud service provider such as Google or Amazon. But in future, the combination of cloud functions such as software as a service (SaaS), platform as a service (PaaS) or infrastructure as a service (IaaS) is important to create the virtual service cloud with dynamic use and cloud resource access. In the Inter-cloud environment, each cloud can be defined as a “Service Part” and optical wire can connect cloud data centers. Software defined networking (SDN), which provides virtual service network on virtualized computing and networking resources and network functions virtualization (NFV), will be highlighted for this generalized optical wired mash-up service approach.

Fig. 10. Network service path in service signaling.

V. CONCLUSION
This paper proposed two attractive future optical network architectures. One is a new metro / access optical aggregation network architecture for the next generation network. The architecture consists of a large L3 router and an optical aggregation network. Internet traffic flows are transferred to data centers, within which large L3 routers switch the traffic. The conventional Internet employs many hops but this architecture needs only one. The optical metro / access aggregation network can realize simple metro/ access networks without complicated L3 interconnection capabilities. This reduces CAPEX and power consumption. The resulting optical aggregation network has much lower electrical power
consumption than the current electrical router configuration; power reductions of the order to 90-95% are possible. Tests on an experimental system using 10 ns switching PLZT optical switches confirmed the feasibility of the proposed architecture. The proposed architecture and system can be applied to realize future metro/access networks.

The second proposed architecture, the service mash-up network named uGrid, uses dynamic optical wires. The huge bandwidth dynamic optical interconnections can create location restriction free mash-up services. Our definition of service part encompasses not only hardware components but also software. This idea can be extend 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.

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