Highly Energy Efficient Layer-3 Network Architecture Based on Service Cloud and Optical Aggregation Network

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SUMMARY The Internet is an extremely convenient network and has become one of the key infrastructures for daily life. However, it suffers from three serious problems; its structure does not suit traffic centralization, its power consumption is rapidly increasing, and its round-trip time (RTT) and delay jitter are large. This paper proposes an extremely energy efficient layer-3 network architecture for the future Internet. It combines the Service Cloud with the Cloud Router and application servers, with the Optical Aggregation Network realized by optical circuit switches, wavelength-conversing, and wavelength-multiplexing/demultiplexing. User IP packets are aggregated and transferred through the Optical Aggregation Network to Cloud transparently. The proposed network scheme realizes a network structure well suited to traffic centralization, reduces the power consumption to 1/20–1/30 compared to the existing Internet, reduces the RTT and delay jitter due to its simplicity, and offers easy migration from the existing Internet.

key words: power consumption, service cloud, optical aggregation, cloud router, future network

1. Introduction

The Internet is an extremely convenient network and has become the key infrastructure of life. People can get various kinds of information through the Internet immediately as well as disseminating information. Internet user numbers have been increasing 16% every year, and at the end of June 2010, reached 1967 million user [1]. Statistical traffic data indicates that real-time traffic and routing flows now total almost 14 Tbps [2]. Internet traffic consists of Peer-to-Peer (P2P) traffic for mutual communication (file exchange, VoIP, etc) and Client-to-Datacenter (C2D) traffic with data centers for server-client communication (Web access, data download, content download, etc). The current traffic champion, P2P traffic, is being dethroned by C2D traffic.

Given the existing situation, the Internet is suffering from three big problems. The first problem is that the standard network structure of the Internet does not well support traffic centralization onto data centers. Second is the rapid increase in the power consumption of the Internet. The last problem is excessive round trip times (RTT), and delay and delay jitter. The traffic of the Internet is becoming more centralized onto data centers, which is a deviation from the original goal of the Internet. There are two reasons, one is that P2P traffic is being overwhelmed by C2D traffic, and download traffic has been increasing rapidly due to the adoption of cloud computing. The dominant Internet service providers (ISPs) and content delivery network (CDN) providers are called the hyper-giants. The top 30 hyper-giants (Google, Yahoo, Akamai, etc.) occupy 30% of all Internet traffic [2]. However, the network structure of the Internet has not been drastically changed to suit this traffic centralization. The worldwide power consumption of 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 in accordance with the expansion of the Internet. Internet Engineering Task Force (IETF) started discussing the power consumption problem in December 2007 [4].

The large number of hops encountered by user packets through routers increases the RTT, delay, and delay jitter. The RTT, delay and delay jitter depend on the distance to the destination, bandwidth, and congestion on the path. Distance is the fixed component of the RTT, while delay and delay jitter depend on the number of hops, which is the number of routers between the source and destination. Router delay depends on Layer-3 processing (such as forwarding lookup, queuing, and other processes). The average number of hops is nearly twelve in Asia, Europe, and the USA [5]. The average RTT with 12 hops is about 300 ms (probability of 90%) [6]. The long RTT degrades interactive communication service, and large delay jitter degrades the quality of streaming services, VoIP, Tele-conferencing, and movies. It is necessary to migrate smoothly from the existing Internet to the future Internet, because the existing Internet is already a huge infrastructure, and additional capital investments must be minimized.

Requirements for the future Internet are as follows; it should suit traffic centralization onto data centers, realize a highly energy efficient layer-3 network, realize a simple network structure to minimize the number of hops, and realize easy migration from the existing Internet.

This paper proposes a highly energy efficient layer-3 network architecture for the future Internet. The proposed network combines the Service Cloud with the Opt-
tical Aggregation Network. The Service Cloud consists of the power-scaling Cloud Router and application servers, while the Optical Aggregation Network consists of multiplexers/demultiplexers with optical circuit switches, wavelength-converters, and wavelength-multiplexers/demultiplexers. Routers and servers are integrated in the power-scaling Cloud Router and application servers. In case of the fiber to the home (FTTH), user IP packets are aggregated and transferred through the Optical Aggregation Network to the Cloud Router transparently. This realizes a simple one-hop network. Consequently, the proposed network realizes the four above requirements since its network structure suits traffic centralization, reduces the power consumption to 1/20–1/30 compared to the existing Internet, reduces the RTT and delay jitter by reducing the number of hops, and offers easy migration by keeping the same interface in the existing Internet. The rest of the paper is organized as follows. In Sect. 2, we describe the requirements for the future Internet. Section 3 summarizes the power consumption trends of routers and switches. In Sect. 4, we propose a network architecture based on the Service Cloud and the Aggregation Network. In Sect. 5, we evaluate the proposed architecture against the four requirements. Finally, In Sect. 6, we summarize this paper.

2. The Requirements for the Future Internet

The future Internet has four main requirements, the first requirement is that its network structure should suit traffic centralization onto data centers, the second is the realization of a highly energy efficient layer-3 network, the third is the realization of a simple network structure to minimize the number of hops, and the last is easy migration from the existing Internet.

2.1 Support of Traffic Centralization

Internet traffic is increasingly being centralized onto data centers. One key factor is the rapid increase in download traffic generated by cloud computing. P2P traffic constituted 30% of the packets in 2002 [7] P2P but declined to just 1% in 2009; it dropped by nearly 2% from 2007 to 2009 [2]. C2D traffic occupied 52% in 2009 and increased 10% from 2007 to 2009. Prior to 2007, the hyper-giants connected through Tier1 and Tier2 providers. Now, however, they use peer-to-peer mutual connections and connections through Tier2/Regional providers, thus dispensing with Tier1 providers [2]. Cloud computing with Infrastructure as a Service (IaaS), Platform as a Service (PaaS) and Software as a Service (SaaS) have become far more widely adopted, so traffic is becoming centralized onto the data centers of the hyper-giants.

2.2 Highly Energy Efficient Network

The total power consumption of Information and Communication Technology (ICT) and network equipment has been increasing rapidly. In 2008, ICT power consumption grew to 168 GW, and in 2020, it will reach 430 GW (nearly 2.6 times) [3]. The power consumption of network equipment has been increasing nearly 12% per year, which is 4% larger than the 8% of ICT. In 2008, it was 25 GW, and in 2020 it will reach 97 GW (nearly 4 times) [3]. In Japan, the power consumption of routers is expected to reach 13 million kWh in 2010 [8]. We cannot drastically reduce the power consumption of the existing Internet by reducing the power consumption of switching equipment, because the power consumption of the existing Internet depends on the network structure.

The rapid increase in Internet power consumption is due to its redundant network structure. The Internet started as a flat cluster structure suitable for data communication, and data could reach its destination by rerouting to avoid router trouble. The Internet can be seen as a one large packet switch containing many additional switches and routers. The Internet then morphed into realizing various kinds of services to a large number of Autonomous Systems (ASs). In response, IETF started to discuss the power consumption problem in December 2007 [4], while Cisco held the Cisco Green Research Symposium in March 2008 [9]. Since the redundant network structure of the Internet ties its power consumption to the volume of traffic carried, the future Internet should realize a highly energy efficient layer-3 network.

2.3 Realization of Simple Network Structure to Minimize the Number of Hops

Increasing the number of hops increases both RTT and delay jitter. The average RTT of 12 hops is nearly 300 ms (90% probability), while the average RTT is nearly 600 ms (90% probability) for 14 to 19 hops [6]. Increasing the RTT degrades the quality of interactive communication services. Generally speaking, RTT values over 300–400 ms make natural conversation difficult. Large delay jitter degrades the quality of streaming services, VoIP, Tele-conferencing, and movies. Excessive delay jitter triggers memory buffer overflow and packet-loss, so original voice and picture become corrupted. Accordingly, future Internet should realize simple network structure to minimize the number of hops.

2.4 Migration from the Internet

The future Internet should realize easy migration from the existing Internet, while minimizing the investment needed for migration and maintaining service continuity. The keys are to simplify the network structure and retain the existing interface points of the Internet.

3. Power Consumption of Routers and Switches

3.1 Power Consumption of Routers

Figure 1 shows the relationship between router throughput...
and power consumption [5], [10]. This relationship was developed from source data [11]. The power consumption of routers is given by the following equation [5], [10].

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

where \( P \) [watt] is power consumption, \( C \) is router switch-capacity [Mbps], and \( A \) [watt \cdot Mbps \(^{-2/3}\)] is a proportion constant. The value of \( A \) is 1.0 in Eq. (1).

This equation indicates that power consumption per bit decreases as switching capacity is increased. For the capacity of 1 Tbps, we need 1000 systems using 1 Gbps-routers and the total power consumption is 100 KW as shown by Eq. (2). When we use one system with a 1 Tbps-router, power consumption is 10 KW as shown by Eq. (3). Thus the 1 Tbps-router can reduce the power consumption by 90% compared to the 1 Gbps-router.

For the case of 1 Gbps-router:

\[ \text{Power consumption} = 100 \text{ W} \times 1000 \text{ sys} = 100 \text{ KW} \quad (2) \]

For the case of 1 Tbps-router:

\[ \text{Power consumption} = 10 \text{ KW} \times 1 \text{ sys} = 10 \text{ KW} \quad (3) \]

Therefore, to reduce power consumption in the same switching router capacity, large capacity router is very efficient.

### 3.2 Power Consumption of Switches

Figure 2 shows the relation between switch-capacity and power consumption [12], [13]. Upper lines plot electric switching performance (Electric Router and electric circuit switch), lower lines plot optical switching performance (semiconductor optical amplifier (SOA) switch and micro-electrical mechanical systems (MEMS) switch). This graph shows that optical switching can significantly reduce the power consumption of switching equipment. For a 100 Tbps-switch, the MEMS-based circuit switch without wavelength-converters has a power consumption of 2 KW while the power consumption of the equivalent electric packet switch is 1000 KW. Thus a MEMS-based circuit switch without wavelength-converters can reduce power consumption nearly 1/500 compared to the electric packet switch.

### 4. Proposed Network

This paper proposes a highly energy efficient layer-3 network architecture for the future Internet as shown in Fig. 3. Routers and servers, physically part of the backbone network, are integrated in the Service Cloud. All IP traffic is transparently transferred through the Optical Aggregation Network to the Service Cloud. The Service Cloud consists of the power-scaling Cloud Router and application servers. The Optical Aggregation Network consists of optical circuit switches, wavelength Converters, and wavelength-multiplexers/demultiplexers. Together they create a simple one-hop network.

#### 4.1 Proposed Network Architecture

Figure 3 shows the proposed network architecture. The left side (a) is the Internet and the right side (b) is our proposal, a highly energy efficient layer-3 network architecture for the future Internet. The proposed network consists of two parts: the Service Cloud and the Optical Aggregation Network. In this paper, we mainly discuss the Optical Aggregation Network. The Service Cloud will be discussed in detail in another paper. Service Cloud and Aggregation Network are constructed by regional access providers. The Service Cloud, installed on the backbone network, consists of the powers-scaling Cloud Router and application servers. Routers and servers in the Internet are integrated into the Cloud Router and application servers in the Service Cloud. The Optical Aggregation Network consists of optical circuit switches and wavelength Converters and wavelength-multiplexers/demultiplexers. All IP traffic is transferred through the Optical Aggregation Network to the Service Cloud transparently. This realizes a simple one-hop network. The main discussion point is the Optical Aggregation Network using optical time slots and wavelength, which implement layer 2 and 1.

Figure 4 shows the architecture of the proposed network in more detail. Routers are integrated to the
Cloud Router, so we can reduce the total routing capacity needed. Moreover, the Cloud Router is power-scaling, i.e. active switching capacity is proportional to the amount of traffic. Since active switching capacity depends on the traffic amount, and power consumption of the Cloud Router is determined by active switching capacity, the proposed network can minimize the power consumption needed for routing. The Optical Aggregation Network consists of multiplexers/demultiplexers with optical circuit switches and wavelength-converters and wavelength-multiplexers/demultiplexers, and transfers user IP packets transparently. This means that, as shown in Fig. 4, point A logically extends to point B, so point A and point B are the same entity. Source user IP packets are transferred to the Cloud Router through the Optical Aggregation Network and layer-3 switching is always executed by the Cloud Router, and transferred to destination user through the Optical Aggregation Network. Thus the proposed network, a simple one-hop network based on optical techniques, can reduce the power consumption.

One Service Cloud is connected with other Service Clouds through Dynamic Optical Circuit Switch (DOCS) [21] as shown in Fig. 5. DOCS is also connected with international networks. One Service Cloud communicate with international networks through DOCS. When a Cloud Router receives an IP packet, Cloud Router transfer it to its own Optical Aggregation Network, its own application server, or a different Service Cloud or an international network through DOCS, based on the IP destination address.

Figure 6 shows one example of the Optical Aggregation Network structure: the serial combination of optical time slot multiplexers/demultiplexers, wavelength-converters, and wavelength-multiplexers/demultiplexers. In the case of upstream traffic, source user IP packets in optical time slots are simply multiplexed by an optical circuit switch and wavelength-multiplexers/demultiplexers, while in the case of downstream traffic, source routing is executed by demultiplexers using optical time slots and wavelength-demultiplexers.

The Cloud Router is power-scaling such that active switching capacity is proportional to the amount of traffic. It consists of line interface units, switch fabric units (consist of sub-switch fabric units), and controller unit (consists of sub-controller units). The units are widely distributed, and power consumption is remote-controlled. The amount of
traffic determines which units are activated. There are three modes: power on, off and sleep. In the case of high traffic loads, all units are active; in the case of low traffic loads, several sub-switch fabric units and sub-controller units are powered down or sleep mode, and some of the line interface cards are power down mode. This realizes power-scaling routing.

4.2 Migration from the Internet

This paper describes how the proposed network offers smooth migration from the Internet. Previous work presented in [14] showed that the proposed network can reduce the power consumption to 1/1000 compared to the existing Internet [14]. However, it is difficult to migrate the existing Internet to the proposed network directly, because the Optical Aggregation Network is all optical, and so it is necessary to replace the Internet by the proposed network. Our solution starts from the understanding that access networks are the major part of the existing Internet, and we define the interface point between the existing Internet and the proposed network. Our proposal is to place the interface point between the regional access provider and the local access provider, see Fig. 7. The Internet was originally designed as a flat cluster structure for data communication services. The recent addition of different kinds of services means that the network structure has been changed gradually. We verified the Internet structure using the trace-route command from campus network (KEIO University), CATV network (Jcom), and FTTH network (FLET'S), and created the network model shown in Fig. 7. The interface point for migration is set between the regional access provider and the local access provider.

4.3 One Example for Smooth Migration

Figure 8 shows one example of smooth migration from the existing Internet to the proposed network architecture for the case of a broadband user in Japan. The Optical Aggregation Network is the serial combination of optical time slot multiplexers/demultiplexers (Mux/Dmux) and wavelength-multiplexers/demultiplexers as shown in Fig. 8. To realize the easy migration from the existing Internet, we set aggregation equipment and keep the interface between the regional access provider and local access provider.

Figure 9 shows the Optical Aggregation Network structure for Fig. 8. We have a lot of experience in utilizing PLZT optical switches [15], and implementing control protocols for optical slot-based access networks [16], [17], so the Optical Aggregation Network is assumed to employ PLZT optical switches. We realize an optical time slot Mux/Dmux by...
a PLZT optical switch module (16 × 1, 8 × 1) [18] and wavelength Mux/Dmux is realized by Array Waveguide Gratings (AWGs). Optical line speed is 40 Gbps, the degree of wavelength-multiplexer/de-multiplexer is 40. The aggregation equipment converts Ne Gigabit-Ethernet-interfaces into one optical time slot. The optical highway consists of frames structured as equal width optical time slots and the 40 Gbps optical highway is divided into Ns optical time slots. The aggregation equipment cross-links Ethernet and optical time slot interfaces. It also has queuing buffer memory to wait for the insertion of each IP packet in an optical time slot (for upstream) and to extract the IP packet from optical time slots and transfer it to the Ethernet interface (downstream). Figure 10 shows a block diagram of the Aggregation equipment. Ne is the degree of the multiplexer/de-multiplexer.

5. Evaluation and Discussion

5.1 Power Consumption Model

5.1.1 Traffic Conditions

To evaluate the basic characteristic of the proposed network architecture, we assumed the same traffic rate for each user as follows. Table 1 shows broadband traffic per user at the end of 2009 in Japan [19]. Over one-third of the upload traffic is transferred to international networks and twice that traffic is returned as download traffic from international networks [19], [20]. Peak average of upload traffic is 42 kbps and peak average of download traffic is 64 kbps. Peak average traffic is calculated as the total amount of traffic transferred in the busiest two-hour period divided by the number of broadband users [19]. We assume that the traffic flow bandwidths follow a Poisson distribution, and define the bandwidth so as to minimize the probability that the defined bandwidth will be exceeded. The probability that the bandwidth exceeds twice the average Poisson distribution is less than 10^{-12}, which is extremely low. Accordingly, we define the bandwidth in this evaluation as twice the peak average traffic, upload-traffic is 84 kbps and download-traffic is 128 kbps per user.

Table 1  Broadband traffic/user in Japan (2009).

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<thead>
<tr>
<th></th>
<th>Average</th>
<th>Peak Average</th>
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<tbody>
<tr>
<td>Upstream</td>
<td>29.9 kbps</td>
<td>41.6 kbps</td>
</tr>
<tr>
<td>Downstream</td>
<td>43.2 kbps</td>
<td>63.9 kbps</td>
</tr>
<tr>
<td>Total</td>
<td>73.1 kbps</td>
<td>105.5 kbps</td>
</tr>
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</table>

5.1.2 Network Model

Model A, Nationwide existing network: Figure 11 shows the existing Internet network model as model A. We define the network structure, shown in Fig. 7, and define various parameters to replicate the broadband traffic condition in Japan. The average upload traffic is 84 kbps and the average download traffic is 128 kbps per user. Router switching capacity is defined with reference to vendor catalogues.

Model B, proposed network: We define the traffic in the evaluation as twice the peak average traffic. Each link has enough bandwidth to support the defined traffic, and optical slot allocation is static. Upload bandwidth per user ranges between 84 kbps and 768 Mbps, and download bandwidth per user ranges between 128 kbps and 768 Mbps at the user network interface (UNI), see Fig. 7. We define the proposed network model and parameters as shown in Fig. 8. Parameter Ne is 60, and Ns is 50 corresponding to twice the peak average traffic bandwidth. The aggregation equipment converts 60 Gigabit-Ethernet-interfaces into 1 optical time slot of 40 Gbps optical highway. 40 Gbps optical highway is divided into 50 optical time slots. The number of users accommodated by the Optical Aggregation Network, N, is given by the following equation.

\[ N = n \times Ne \times Ns \times m \times f. \]  \hspace{1cm} (4)

where n is the aggregated user number per Gigabit-Ethernet -interface in the aggregation equipment in Fig. 10, Ne is the number of Gigabit-Ethernet-interfaces per aggregation equipment unit, Ns is the number of slots in the 40 Gbps optical highway, m is the number of wavelength Mux/Dmuxs for each fiber, f is the number of fibers connected to the Cloud Router. When n = 100, Ne = 60, Ns = 50, m = 40, f = 10, then, \( N = 120 \times 10^6 \); that is, the maximum number of users accommodated by the Aggregation Network is 120 million. The Optical Aggregation Network can scale to support optical interface speeds beyond 40 Gbps and numbers of wavelength Mux/Dmuxs beyond 40.

The power consumption of the Cloud Router is calculated by Eq. (1). Table 2 shows the details of the power consumption of the function blocks. We calculated these consumption values with reference to a packet router’s line card with 40 Gbps port [12], and LSI vendor catalogues.

5.2 Evaluation and Discussion about Requirements for Future Internet

We evaluate four items associated with the requirements. The first is to investigate if the proposed network well supports traffic centralization onto data centers. The second is
to investigate if the power consumption is reduced, compared to the existing Internet, by the proposed highly energy efficient layer-3 network. The third is to investigate if the number of hops is reduced. The last is to evaluate if easy migration is achieved from the existing Internet.

### 5.2.1 Traffic Centralization

The proposed network employs a network structure that is suitable for C2D traffic. We evaluate how much the proposed network structure reduces cost compared to the Internet. Figure 12 shows the network cost comparison models. The Internet network structure model is a five layer-3-switching-equipment (router) stage structure as shown in Fig. 12(a), and the proposed network structure is a four Layer-2-switching-equipment stage structure and one router as shown in Fig. 12(b). We simply assume that the network cost is the sum of the costs of network elements, which includes the interface costs. The cost of each network element, which has either layer-3 or layer-2 switching function, is assumed to be proportional to the traffic volume passing through the element. We also assume that C2D traffic volume is five times that of P2P traffic.

Figure 13 investigates the dependency of network cost of the two models on the traffic. We focus only on the comparison of the capital expenditures, and do not consider the migration cost. The centralization ratio, \( c \), is introduced for this purpose. \( c \) is a ratio of the C2D traffic volume to the total traffic volume which includes both C2D and P2P. The C2D traffic goes to the server, while the P2P traffic flows are equally distributed among the access nodes. The costs of the proposed network structure model are normalized by those of the existing Internet network structure model with the same conditions. Normalized cost is defined as the sum of the proposed network structure model cost divided by the sum of the existing internet structure model cost with traffic centralized ratio, \( c \), as the parameter. If the normalized cost is less than 1, the proposed network structure model is less expensive than the existing Internet network structure model.

The normalized network cost decreases as the centralization ratio increases. It also decreases as the ratio of layer-2 switching equipment cost to layer-3 switching equipment (router) cost decreases. When the centralization ratio be-
5.2.2 Power Consumption

Figure 14 shows the results of the power consumption evaluation. Model A has a power consumption of 46 KW for 100 K users and 22 MW for 100 M users. Model B has a power consumption of 2 KW for 100 K users and 960 KW for 100 M users. Thus the proposed network can reduce the power consumption to $1/20$–$1/30$ compared to the existing Internet.

Figure 15 shows the power consumption breakdown for the components of model B. This graph shows the aggregation equipment, which are signal converters between Ethernet interface and optical time slots interface, the major power consumers in the proposed network beyond 100 K broadband users. The power consumption ratio of the Optical Aggregation Network is extremely low, while that of the Cloud Router is not so high.

5.2.3 Reduction of Hops

The distribution of the number of hops as given by the Cooperative Association for Internet Data Analysis (CIDA) measurement data is shown in Fig. 16(a) [6]. The average number of hops between source and destination addresses is 13.1, (includes multiple provider networks). Figure 16(b) shows the proposed network application for CIDA measurement data. If one regional access provider network is replaced by the proposed network, the nearly seven hops required by the regional access network is, on average, replaced by one hop. Therefore, the total average number of hops is reduced from 13.1 to 7.4.

The reduction of the number of hops decreases both RTT and jitter. In the proposed network, the delay reduction effect is as follows. Layer-3 processing time is reduced by the elimination of six hops. Layer-2 processing time at the aggregation equipment is both upstream and downstream is increased. The former effect is larger than that of the latter. Thus, RTT is the proposed network is reduced in total compared to the existing network.

6. Conclusion

This paper proposes a highly energy efficient layer-3 network architecture for the future Internet, which consists of the Optical Aggregation Network and the Service Cloud with the power-scaling Cloud Router and application servers. All traffic is transparently aggregated to the Cloud Router through the Optical Aggregation Network. The proposed scheme satisfies the four main requirements imposed on the future Internet; suitable for traffic concentration onto data centers, high energy efficiency, simple network structure to minimize the number of hops, and easy migration...
from the Internet. The proposed network well supports traffic concentration onto data centers by accommodating and processing all layer-3 packets at the Cloud Router in the Service Cloud. The proposed architecture realizes easy migration from the existing Internet, because the proposed network and the existing Internet can coexist. Evaluations show that the proposed scheme can reduce the power consumption to 1/20–1/30 compare to the existing Internet, and drastically reduce the number of hops to one hop. The proposed network is expected to become the foundation of the future Internet that offers high capacity and high energy-efficiency.

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