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Review paper

The road towards future Internet

WU Jianping, LIU Lili, LI Dan

Tsinghua National Laboratory for Information Science and Technology, Beijing 100084, China

Abstract: Given the emerging problems of today's Internet, many new Internet architectures have been proposed by the networking community. In general, the new approaches can be categorized into two types: evolutionary approaches and clean-slate approaches. The representative evolutionary solution is IPv6, while representative clean-slate approaches are NDN (Named Data Networking), MobilityFirst, NEBULA, XIA (Expressive Internet Architecture), and SDN (Software-Defined Networking). A comprehensive survey of these approaches is presented. Additionally, a novel network architecture that we recently proposed: ADN (Address-Driven Networking) is described, which intends to address the challenges faced by today's Internet via the flexible and innovative utilization of IP addresses.

Key words: future internet architecture, address-driven network, IPv6, routing, forwarding, IP address

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1 Introduction

In the last half-century, the scale of the Internet has grown from a small research network connecting several US universities to the worldwide information communication network it is today.

The Internet has become an indispensable and important part of our infrastructure, as well as a key to social production, public life, and international communication. The success of today's Internet is dependent not only on the huge demand for information sharing and interaction in modern society, but also the technology rationale behind TCP/IP architecture. IP allows the network layer to not only support a variety of different underlying network technologies, but also considerable up-layer network applications, ensuring the ubiquity of Internet connection and the vitality of innovation. Using TCP, the transport layer successfully coordinates the conflict between the users ever-increasing demand for network bandwidth resources and the limited availability of these resources.

Internet development has encountered great challenges in recent years. The first challenge is the scalability of the Internet. As the number of users and access diversity (desktop, laptop, tablet, mobile phone, etc.) increase, the space of traditional IPv4 addresses is far outstripped by demand; as of February 2011, IPv4 addresses have been exhausted. Although the promotion of CIDR (Classless Inter-Domain Routing)[1] and NAT (Network Address Translation)[2] has al-

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leviated the problem of address deprivation temporarily, it cannot fundamentally solve this problem. Meanwhile, the introduction of technologies such as NAT has violated the end-to-end principle of Internet design. Broad consensus has been obtained for deploying IPv6 networks on a large scale and smoothly transferring IP protocol from IPv4 to IPv6. The Internet is entering the era of IPv6.

The second challenge facing the Internet is security. Current Internet routing protocols do not validate source addresses, and source spoofing[3] has caused security problems such as DDoS (Distributed Denial of Service) attacks, spam, and worms. With the exponential growth of the Internet's scale, it has suffered heavy losses from direct and indirect network attacks. There are now more than 4 000 DoS attacks in China per week. A fundamental cause of DoS attacks lies in routers forwarding packets based only on their destination address, without validating the source address. Because we are incapable of tracking the attack's source, many security strategies aimed at curbing these network attacks fail; resulting in more common source spoofing attacks.

The third challenge is the problem of mobility. With the successful combination of mobile phones and online applications, a large quantity of mobile devices have been connected to the Internet, and the mobile Internet is currently a hot topic of research. One problem that must be solved is that of assigning addresses for these devices. As IPv4 addresses run out, allocating IPv6 addresses for mobile devices may be the most direct solution. Nevertheless, mobile devices have their own issues, such as access network switching and mobile device identity problems. Current IP addresses are used as both the host's identity and location, interrupting TCP connection and negatively influencing user experience when changing the host location and IP address when moving. The ability to design an addressing plan suitable for mobile devices using the characteristics of huge IPv6 addresses is a vital challenge of future Internet architecture.

The fourth challenge is quality of service and traffic engineering. As Internet applications are increasingly diversified, different network businesses have differing demands for the quality of their services, such as real-time requirements from video applications. Therefore, strict control on network traffic is a demand. The present traffic engineering strategy mainly adopts MPLS[4], requiring complex control and management technology support. However, today's Internet merely uses destination address as the forwarding condition, which makes the network layer treat different business flows fairly and cannot guarantee the quality of service in a prioritized way. Therefore, it remains a challenge to ensure real-time capability and quality of service on connectionless IP networks.

To overcome the problems above, the networking research community has proposed many new architectures for the future Internet. In general, these approaches can be categorized into two types: evolutionary and clean-slate. The main idea of the evolutionary approach is to transite to the future Internet without breaking current Internet architecture and applications. The evolutionary approaches usually adopt targeted and patched methods to fix the problems of today's Internet. Once the weaknesses and faults of the current Internet are found, researchers can improve the problems immediately. The advantages of this patched way lie in easy deployment and implementation, with the intention of protecting the existing investment of today's Internet. However, its disadvantage is that it can only solve partial problems on a small scale. Additionally, repairs may introduce new problems, as NAT has. The clean-slate approach is based on a different idea: abandoning existing Internet architecture and designing a brand-new Internet architecture to accomplish a variety of design goals. The advantages of this approach include: 1) getting rid of the bondage of TCP/IP architecture and removing the constraints and framework to solve the legacy problems of the architecture for years; and 2) redesigning the Internet comprehensively to solve all the problems we understand today. The problem is that it cannot coexist with today's Internet and thus is problematic for transition. This is the reason why technologies such as IP multicast[5], IntServ[6], and DiffServ[7] have not been widely implemented in recent decades.

The rest of this paper is organized as follows: Sections 2 and 3 introduce the evolutionary and clean-slate future Internet proposals, respectively. Section 4 introduces current future Internet architecture research in China. Section 5 describes a novel future Internet architecture called Address-Driven Networking. Section 6 concludes the paper.

2 Evolutionary approach

The representative solution of evolutionary future Internet architecture is IPv6. In this section, we describe the basic improvements of IPv6 over IPv4, work on IPv6 in the IETF (Internet Engineering Task Force), and experimental IPv6 networks around the world.

2.1 IPv6

The main purpose of IPv6 is to replace IPv4 and increase the ad-dress space of the Internet. IPv6 adopts a new network-layer packet header. Compared with IPv4, IPv6 makes the following innovations: 1) IPv6 extends IP addresses from 32 bit to 128 bit, which guarantees that the IP address space will be sufficient in the future, even considering the connections that will be made by smart objects. 2) IPv6 better supports multicast by making multicast a requirement, instead of an option as in IPv4; 3) IPv6 better supports network-layer security with IPsec (Internet Protocol Security)[8]; 4) IPv6 better supports mobility by enabling Mobile IPv6; and 5) IPv6 supports a better quality of service by using protocols such as IntServ[6] and DiffServ[7].

2.2 Current works of IETF

As the authoritative standards organization for Internet protocols, the IETF is actively working on protocol standards for IPv6 (starting with RFC 1883). The primary working groups are 6bone, IP Next Generation (ipng), ipv6, ipv6mib, Site Multihoming in IPv6 (multi6), IPv6 Operations (v6ops), softwire, and savi. 6bone is a workgroup focusing on IPv6 backbone research for the IETF IPng project, creating the IPv6 protocols that will eventually replace IPv4. Another workgroup is ipng, which proposes specifications for the core functionality of SIPP (Simple Internet Protocol Plus) and its extensions. The IPv6 (IP Version 6) workgroup is responsible for the specification and standardization of IPv6, implementing the recommendations of RFC1752 and related standardizations. IPv6 MIB is focused on identifying potential changes to existing MIBs and studying new and additional MIBs. Multi6 mainly considers the problems of multihoming in IPv6 and IPv6 site multihoming architectures. The v6ops workgroup is dedicated to developing guidelines for the operation and the deployment of IPv6 networks. The softwire workgroup studies the transition from IPv4 to IPv6 networks. The savi workshop concentrates on source address validation in IPv6 network.

2.3 IPv6 experimental network

There are many experimental IPv6 networks around the world doing testbed experiments in IPv6 networks and applications, including Internet 2 and its backbone network, Abilene, in America; the backbone network GEANT2 of the Second Pan-European Research & Education Network; the APAN (Asia Pacific Advanced Network Society) and its backbone network; the TEIN2 (Trans-Eurasia Information Network) and its backbone network; CNGI (China's Next Generation Internet) and its backbone network; the second-generation academic network SUPER SINET in Japan; and the new generation academic network CAnet4 in Canada.

There were 34 American universities jointly sponsored to construct Internet 2 in 1996. They then united more than 100 American universities to establish the non-profit organization, UCAID (University Corporation for Advanced Internet Development), focusing on the research plan for Internet 2. Their main purpose is to establish and maintain a technology-leading network infrastructure, and to develop advanced future Internet network applications for universities and research organizations in United States. At present, the membership of Internet 2 mainly consists of more than 300 universities and research organizations in United States, a number of interested companies offering financial funding, and some international academic network partners. The backbone network, Abilene, of Internet 2 adopts a dual-stack of IPv4 and IPv6, with 32 core nodes. Among these are 11 core switch nodes. The backbone network's bandwidth is 10 Gbit/s, with more than 300 universities and research units accessed. In 2006, Internet 2 announced the upgrade of the backbone network bandwidth to 100 Gbit/s to support faster future Internet technology and applications. In addition, organizations such as the United States NSF (National Science Foundation) have funded the construction of a number of high-speed interconnections and exchange centers to connect international academic networks and future experimental networks with Abilene.

APAN[9] was founded in 1997 as a cooperation between multiple academic networks in various countries of the Asian-Pacific region, aimed at planning, constructing and running a connected academic network in Asian-Pacific counties; and cooperating to research future Internet experimental networks and their applications with other parts of the world. APAN currently has 39 members, including academic research networks from various countries in Asian-Pacific region, future Internet research organizations, and some sponsors. Among them, countries and regions such as Japan, Korea, China, Australia, and Singapore have played a significant role in APAN.

TEIN2[10] is an international cooperation program to promote high-speed interconnections between Eurasian networks with the sixth framework plan. The project aims to build a high-speed inter-connection between the future European academic network's high-speed backbone network GEANT2 and the main Asian academic network, providing advanced information infrastructure for technology and education cooperation between the two continents. The backbone network of TEIN2 started in December 2005; its core nodes include Beijing, Hong Kong, and Singapore. It has realized high-speed interconnection between Beijing and Singapore in Asia, and Copenhagen and Frankfurt in Europe. Meanwhile TEIN2 has realized an interconnection to North America via Tokyo, with a 10 Gbit/s bandwidth. TEIN2 adopts dual-stack technology of IPv4 and IPv6, implementing the interconnection through 4 core nodes from the TEIN2 backbone network to 6 benefit countries, including China, Vietnam, Thailand, Malaysia, Indonesia, and the Philippines; and 4 non-benefit countries, including Korea, Japan, Singapore, and Australia. TEIN2 has become the only future Internet backbone network with unified operation and management in the Asia-Pacific region. The operation of TEIN2 greatly improves the information transmission speed of the academic Internet between various countries in Europe and Asia, promoting technological cooperation among these countries.

After the developments of the last ten years, the backbone networks of Internet 2 and its interconnections, including the GEANT2 backbone network, and the APAN and TEIN2 backbone network, have not only realized the high-speed interconnection of national academic networks around the world, but also formed the main body of international large-scale IPv6 future Internet experimental networks. This situation is very similar to the international IPv4 Internet, which connected national academic networks around the world in the early 1990s.

As one of the largest pure IPv6 networks around the world, CNGI-CERNET2 connects more than 20 cities and more than 100 university campuses in China, providing a 100 bit/s core network speed. CNGI-CERNET2 deploys many new IPv6 technologies, such as 4 over 6 and Sava, as well as many IPv6 websites, promoting the popularization of IPv6.

3 Clean-slate approaches

The representative clean-slate approaches to future Internet architecture include NDN, MobilityFirst, NEBULA, XIA, and SDN. In this section, we present the basic idea of each of these approaches.

3.1 NDN

The main design of the current Internet was formed in the 1960s and 1970s. Telephones were used widely at that time, so Internet architecture was designed based on the concept of the telephone, and also retains some characteristics of telephone communication systems. It adopts end-to-end communication, interacting between two designated end-hosts. Just as telephone systems could not satisfy the requirements of modern media, as Internet applications became popular, their communication method based on host destination could not meet the abundant requirements either. Meanwhile, the Internet has encountered severe scalability and security problems. NDN[11] tries to solve these problems by changing the design that uses IP as the narrow waist in the traditional hourglass network structure. NDN uses named data as the narrow waist of the new network structure. The naming method, similar to URL structure, has many characteristics of IP, including hierarchy and unique assignment.

NDN completes communication via active request by the recipients[12]. The interest packet initiating the request contains the name of requested data. The router forwards the request based on the interface of the corresponding name (or the longest prefix match) in the forwarding table. Once the requested content has been found, the content message is returned along the forwarding path. In order to improve efficiency, the router would maintain a list of recently forwarded requests and a forwarded data cache. If the received request exists in the request list, the router would not forward the repeated request, but instead would send data after the initial request gets a response.

Compared to traditional address-based network architecture, NDN has many remarkable advantages. First, named data improves the efficiency of the application layer. Most current network applications, especially downloading and streaming media services, use the Internet to get data service, not caring from where the content is obtained. NDN bypasses the limitation of host addresses and gets the content based on name directly. This method cannot only locate position information more accurately, but also implements a router cache for frequently accessed content and improves the utilization efficiency of high bandwidth. In addition, the data namespace is theoretically infinite, simultaneously solving the scalability problem of IP address space. Finally, name identification based on transmitted data could more flexibly achieve data integrity and secure authentication.

3.2 Mobility first

The motivation of the MobilityFirst[13] project is that, with the development of future Internet applications, mobile platforms will become the main application mode, instead of fixed endhost/server applications.

Mobile application mode will be more comprehensively developed, from the present situation of mobile phones and laptops to the future situation of mobile sensors and mobile vehicle-mounted devices. Therefore, the design of future Internet architecture must take mobility as it first-tier criterion. Under the premise of satisfying all the performance requirements of coverage ratio, service stability, and reliability, MobilityFirst summarizes the unsolved problems of mobile Internet architecture into six points: end-host and network mobility, not requiring a basis on some fixed trusted root node, conforming to the requirements of transmission strategy, Byzantine robustness, address traceability of online content, and compatibility with possible new applications. The MobilityFirst project tries to use delay-tolerant routing to replace the end-to-end connection in today's Internet; routers store data in case the final destination is moving and cannot be reached at a certain time.

3.3 NEBULA

The idea of cloud computing was put forward as early as 1965, with the goals of: always being online, as the telephone system; meeting a variety of service demands; keeping pace with the times; and adapting to all possible new applications. Large-scale distributed computing systems, composed of multiple large-scale data centers offering a variety of service patterns, have currently realized this idea. However, cloud computing still lacks an effective network architecture to support it. This new network architecture should not only solve the problems of the security and mobility of network architecture, but also satisfy the features of data center networks, such as high bandwidth and low latency.

NEBULA[14] was proposed to meet the requirement of such a network architecture. It considers the security, flexibility, and extensibility of the new architecture. Future cloud computing systems should be able to cope with current and upcoming network threats, support continuously-updated applications, and take all the features of technical feasibility, economic benefits, and other rules and regulations into account. NEBULA consists of three parts: network layer protocol (NDP), extensible control strategy (NVENT), and high-speed core router (NCore). The NDP header adds all the information needed in routing, using an MPLS-like structure to provide multiple alternative paths. When the end-host needs to start a session, NDP will send both the path query requirements and parameters to NVENT. Afterwards, NVENT will find one or multiple feasible paths, based on topology, negotiate a strategy via a protocol similar to BGP, then return to NDP with an authorized certificate of the pass-through domain. In this way, when going through each domain, NVENT can verify the legitimacy of the passing flow.

3.4 XIA

Considerable research indicates that the design of future network architecture still needs to follow an hourglass structure, but with new elements as the core. Many designs take element-like content, service, or users as the core of new architectures instead of IP, using the aforementioned NDN as an example. These architectures can achieve high efficiency on their own model-oriented applications, but face difficulties in other applications. Hence, there are not enough advantages to replace other architectures as the master architecture of the Internet. The main purpose of XIA[15] is to load and transition to architectures designed for different centeroriented architectures, like the present Internet architecture based on IP perfectively, to adapt to different applications, and to overcome the scalability and security problems in traditional network architecture. XIA defines a factor from a broader level as the core of the whole network structure to achieve this goal. Thus, practical applications can specify the factor as one or multiple specific instances based on their own demand, such as content, services, etc. As long as these instances conform to the three requirements of expressiveness, extensibility, and security, network protocol support of different center architectures would be realized. In terms of routing, XIA uses expressive Internet routing protocol XIP to replace current IP routing protocol, defining the format of the packet header and the operation of the instance specified by users. XIA supports multiple instances in the same network. Each route node selects a routing path based on the instance information from the user description.

The most prominent feature of XIA is that it provides a network layer solution describing user requirements specifically. Traditional IP network architecture does not provide more route information beyond the destination address for users, while the instances put forward by a variety of new structures are too unified. XIA combines the merits of different architectures successfully, considering the effect of each factor comprehensively when routing. This brings the users powerful self-defined function: the more detailed and comprehensive the application's description of the instances, the more optimized and compliant the service the user will receive. XIA efficiently ensures the scalability and security of network structure for each instance request.

3.5 SDN

SDN[16] aims to separate the control plane and data plane through a centralized controller running the routing protocols and algorithms. The representative data plane abstract is the OpenFlow protocol[17]. OpenFlow can provide a programmable open virtual platform on routers and switches, to achieve the test of network architecture independently in a physical network environment. In traditional network architecture, when a packet arrives at a switch, the programmed firmware will forward the packet from the specified interface based on the destination address and forwarding table. Meanwhile, the operators have no more control rights (although a distributed routing protocoldoes run). While in a network running OpenFlow protocol, OpenFlow enables the operators to have more control rights and can thus define finer paths for packets.

The architecture of OpenFlow mainly contains three components: a controller, a router/switch forwarding layer, and a communication scheme between the controller and router/switch. SDN/OpenFlow separates the control layer from the traditional router to more flexibly configure and control the route for researchers and operators, reduces the complexity and cost of routers, and opens network function to upper-layer applications. In essence, SDN/OpenFlow is a new network implementation architecture instead of a new network architecture itself.

4 Current researches in China

With the emerging research of the future Internet, Chinese researchers have conducted research in SDN/NFV, 5G networks architecture, IUNs (Identifier-based Universal Networks), SINETs (Smart Identifier Networks), SOFIAs (Service-Oriented Future Internet Archi- tectures), etc.

4.1 SDN/NFV research in China

The combination of SDN and NFV introduces significant change and challenge to the current Internet. Researchers indicate that the Internet will transform to SDN and NFV architecture in the future. There are several research projects addressing SDN and NFV in China now. Several world-class educational programs, featuring global leaders from multiple renowned Chinese universities and research institutes, organized two Chinese SDN/NFV Conferences, where a considerable quantity of SDN and NFV research, integration, software, equipment, and standards discussed.

Furthermore, many industries and companies have been dedicated to SDN/NFV for several years, including China Telecom, Huawei Technologies and ZTE, the China Mobile Research Institute, and China Unicom. China Unicom released a white paper titled New-Generation Network CUBE-Net 2.0, which gave insight into a decoupled and intensive network architecture. Based on this white paper, ZTE and China Unicom started a project to improve the development of SDN and NFV technologies. In addition, China Mobile has cooperated with Huawei to launch a new NFV lab early last year. In addition, China Telecom decided to develop a Proof of Concept for SmartPipes with Programmable Forwarding based on NFV with Intel, which would be China's first IP intelligent edge service chaining solution. Moreover, the China Mobile Research Institute has been focused on Open Platform for NFV (OP-NFV) for quite a long time.

4.2 5G network architecture

With current 4G technology being insufficient to satisfy the high requirements of users, the research and development of 5G have attracted world-wide attention. There are multiple projects focusing on 5G technology in China, involving several research institutes and enterprises. Huawei has developed a radical new version and concept network architecture to meet the future application demands of 5G networks, invested in RG for 5G since 2009, and promoted multiple workgroups of the IETF on 5G. ZTE has been dedicated to multiple 5G techniques for several years[18]. Furthermore, the MOST (Ministry of Science and Technology) in China set up The National High Technology Research and Development Program of China (863 Program) in 5G. The China Mobile Research Institute and Ericsson decided to cooperate on 5G to accelerate the development of 5G initiatives and focus on network architecture evolution.

4.3 IUN (Identifier-based Universal Network)

IUN architecture is proposed to address problems and challenges of scalability, mobility and security as a future Internet architecture, led by a research group at Beijing Jiaotong University in May 2007. The research team has achieved multiple successes in this architecture, having built a prototype to demonstrate the feasibility of IUN. The IUN architecture comprises a Pervasive Service Layer and a Switching and Routing Layer. Furthermore, some enterprises and institutes have employed and deployed IUN in China[19].

4.4 SINET (Smart Identifier Network)

SINET[20], another clean-slate future Internet architecture, is proposed to establish an information-centric network architecture, adapted to reallocate network resources and separate the control and data planes to make the current Internet flexible[21]. Its main idea is based on the basic SINET framework, with three layers and two domains. The design of SINET conveniently perceives real-time traffic matrices to solve load balancing, traffic engineering and routing problems more easily, leading to a more effective congestion control scheme[22].

4.5 SOFIA (Service-Oriented Future Internet Architecture)

SOFIA, another clean-slate network architecture, is proposed to solve the multiple problems that the current Internet is facing to improve the efficiency of service transmission[23]. An additional service layer is introduced as the waist of the Internet protocol stack,

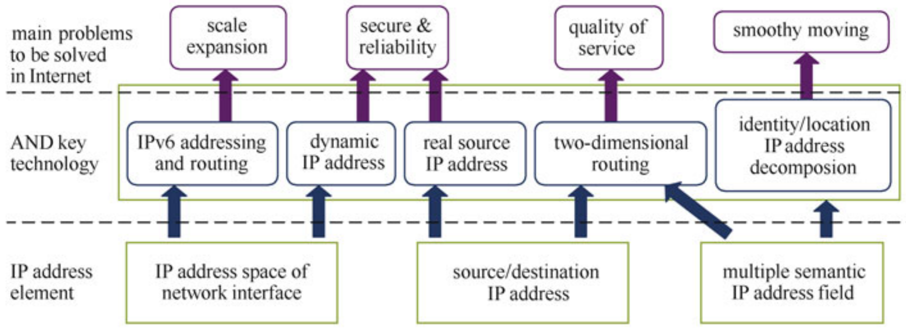

Figure 1 ADN architecture

including some new techniques for service migration, identity/location separation, and service authentication. The design of SOFIA improves network mobility support and guarantees service security. Implementation and deployment of SOFIA demonstrate that it could improve service efficiency and user experience significantly[24].

5 Address-driven network

We put forward a novel Internet architecture called ADN (Address-Driven Networking)[25], as shown in Fig.1. The basic idea of ADN is to push the development of Internet architecture forward with the innovative usage of IP addresses.

5.1 The attributes of addresses

IP address has multiple attributes, including the length attribute, the logic attribute, the topology attribute, the space attribute, the time attribute, as well as the owner attribute.

The length attribute is the simplest. It refers to the bit length of an IP address, which represents the total number of objects the IP address space can host. For instance, IPv4 address has 32 bit while IPv6 address has 128 bit.

The logic attribute is the logical indication of the IP address. Generally speaking, IP addresses represent the location of a network interface in network space. In today's TCP protocol, IP addresses are also used to indicate the identity of an end-host, i.e., the connection entity in the transport layer. In multicast communication, IP addresses are also used to identify a multicast session, i.e., a multicast group. In fact, we can use IP addresses in a more flexible way and support richer logical semantics.

The topology attribute is the hierarchical location of a network interface in network space. Since the Internet's topology is hierarchically organized, every IP address has its position. This location also determines the routing path, routing hops, and transmission delay between any two network interfaces.

The space attribute is the geographical position of a network interface in the physical world. We can also use latitude and longitude to represent the space attribute of an IP address. This attribute can provide support for many location-aware applications, for instance, location-aware advertisement, weather forecasts, etc. There are also proposals about geographical routing.

The time attribute is the effective time of an IP address. The IP address is allocated by ICANN. An IP address becomes effective when it is allocated, but is seldom recycled in practice. For a certain host, if its IP address is obtained by DHCP, its lifetime is just the period its allocation and when it disconnects.

The owner attribute is the owner of an IP address. The Internet is a huge globally distributed system, run by many different operators. When an IP address is allocated, its administrative owner is fixed, either to an ISP, organization, or end user.

5.2 Address-driven network

We argue that today's Internet does not fully exploit the multiple attributes of IP addresses. Specifically, we make use of the topology attribute for routing IP addresses, but do not have enough preparation for the length of IP addresses (now we propose IPv6 to solve the problem). We use the logic attribute of IP address to some extent (multicast group addresses), but do not make enough use of the owner, space, and time attributes of IP addresses. Fully utilizing the multiple attributes of IP addresses remains a key challenge in the design of the future Internet.

The core idea of ADN is to try to address the challenges of today's Internet by flexible utilization of IP addresses attributes, as shown in Fig.2. ADN does not change the layered architecture of today's Internet, but enhances the usage of IP addresses in the network layer. IPv6 serves as the basis of ADN. More specifically, ADN has the following key technologies.

First, ADN separates the IP address space into a location IP address and an identity IP address. IPv6 provides an IP address space as large as $2^1$28. In the near future, IP address space is much larger than the number of objects that can use it. Therefore, we do not need to worry about IP address space. However, we need to think about how to make better usage of long IP addresses. For instance, we can use the first 64 bit of an IP address to represent the location of a network interface, while using the second 64 bit of an IP address to represent the identity of the network interface. It can thus provide better support for the mobility of nodes. This technology uses the logic attribute and location attribute of IP addresses.

Second, ADN guarantees the validity of an IP address. We can use the source IP address as the responsible entity for every packet on the Internet. When there is a network attack or some security issue, we can use IP addresses to trace the responsible entity of a packet. By combining the source IP address and the physical network ports when assigning the address, we can avoid source spoofing and guarantee the validity of an IP address. Between ISPs, we can use a trust union to filter the packets with invalid IP address. This technology mainly uses the owner attributes of IP addresses.

Third, ADN uses two-dimensional forwarding based on the destination and source IP address simultaneously. When a router forwards a packet, it uses not only the destination address but also the source address. Therefore, traffic to the same destination IP address can be spread to different paths. It not only makes better use of the link bandwidth resource of the network, but also provides opportunities for finer adjustment based on other attributes of the IP address. Two-dimensional forwarding can also serve as a major

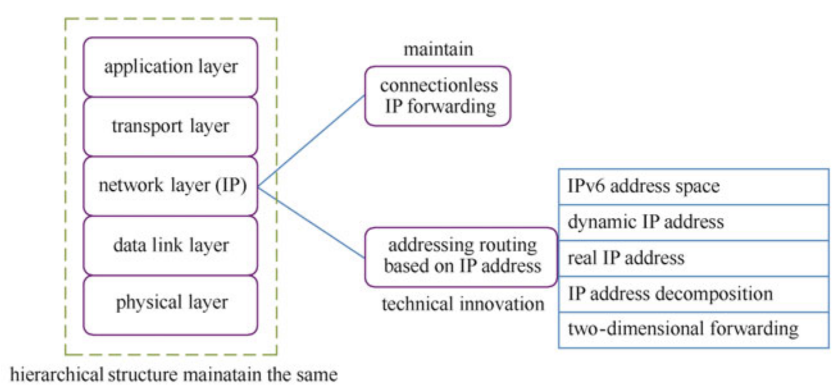

Figure 2 ADN key technology

solution for network virtualization. This technol- ogy mainly uses the topology attribute and owner attribute of IP addresses.

Fourth, ADN enables dynamical network addresses. Every router and every host can change its IP address from the address space of $2^6$4. The purpose of IP address dynamics is to anonymize the IP address and reduces the attack risk of a host. In most cases, a host will drop a packet destined to an irrelevant address. However, we need to guarantee normal communication during the address switching period. This technology uses the time attribute and owner attribute of IP addresses.

Finally, ADN explores location-based service on top of IP addresses. Internet services based on geographical locations are more and more popular. Although many cell phones use GPS for localization, it has two drawbacks: 1), not all devices have GPS; 2) GPS cannot locate objects indoors. Using IP address to locate an object is an important complement. This technology mainly uses the space attribute of IP addresses.

5.3 The differences between ADN and other future internet architecture

There are currently many other newly-proposed future Internet architectures, such as Locator/Identity Separation architecture and architectures supporting source routing. Locator/Identity Separation architectures, including LSIP[26], Ivip[27], and Six/One Router[28], divide a single IP address into location space and identity space. Location space is allocated by network topology and is provided by an Internet service provider, while identity space does not rely on network topology and can be used in both the transport and application layers. Architectures supporting source routing, including NIRA[29] and Pathlet Routing[30], mainly aim at solving routing scalability and supporting source and multipath routing. ADN extracts the advantages of these architectures and focuses on the address. Addresses, as the key part of ADN, play a significant role and realize multiple functions, as discussed in the previous section.

6 Conclusion

In this paper, we present the recent research on future Internet architecture, including both evolutionary approaches and cleanslate approaches. The representative solution to the evolutionary approach is IPv6. The IETF is actively working on IPv6 standards and there are many experimental IPv6 networks around the world. The representative solutions to the clean-slate approach include NDN, MobilityFirst, NEBULA, XIA and SDN. These solutions abandon the constraints of today's Internet and aim to design a wholly new Internet architecture. In addition, we describe a novel network architecture that we recently proposed: ADN (Address Driven Networking). ADN intends to address the challenges faced by today's Internet with the flexible and innovative utilization of IP addresses. Its key technology includes separating the IP address space, guaranteeing the validity of IP addresses, using two-dimensional forwarding, enabling dynamic network addresses, and exploring location-based services in concurrence with IP addresses.

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About the authors

WU Jianping received the master and doctoral degrees in computer science from Tsinghua University, Beijing, China, in 1997. He is now a Full Professor with the Computer Science Department, Tsinghua University. In the research areas of the network architecture, high-performance routing and switching, protocol testing, and formal methods, he has published more than 200 technical papers in academic journals and proceedings of international conferences. (Email: jianping@cernet.edu.cn)

LIU Lili received the B.S. degree from Department of Communication Engineering, Xidian University, Xi’an, Shaanxi, China, in 2012, and is currently pursuing the Ph.D. degree in computer science at Tsinghua University. Her research interests include Internet architecture and protocol designing, routing strategy designing, and data center network. (Email: liu-ll12@mails.tsinghua.edu.cn)

LI Dan [corresponding author] received the Ph.D. degree in computer science from Tsinghua University, Beijing, China, in 2007. He is an Associate Professor with the Computer Science Department, Tsinghua University. He lead the NASP (Network Architecture, System and Protocols) research group, which is part of the networking research lab. His current research interests include Future Internet architecture, data center networking, software defined networking and cloud computing systems. He has published more than 50 technical papers in referred conferences and journals, including ACM SIGCOMM, IEEE ICNP, IEEE INFOCOM, IEEE/ACM Transactions on Networking, IEEE Transactions on Computers, IEEE Transactions on Parallel and Distributed Systems, etc. (Email: tolidan@tsinghua.edu.cn)