An Open Unified Addressing System for 6G Communication Networks

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ABSTRACT

With the rapid and continuous development of the Internet, it is foreseeable that current addressing schemes and fixed-length IP addresses would create further bottlenecks and limitations in realizing future 6G networking requirements, such as massive connections, resource-constrained communication, and heterogeneous hyper interconnections and guaranteeing agreement-based services and KPIs. Moreover, the locator-based addressing semantic is unsuitable for mobile and content-oriented networks. Thus, this paper proposes the Open Unified Addressing (OUA) system, a novel, flexible, multi-semantic and hierarchical addressing architecture that better supports the flexibility and extensibility of the Internet protocol framework in the context of 6G Communications. The OUA addresses several limitations in the current IP protocol and improves communication efficiency. According to the evaluation with two typical forwarding models, the results show that the OUA system has almost no impact on forwarding delay. Moreover, it can provide scalable addressing spaces and shorten the route convergence time.

I. INTRODUCTION

Full architecture specifications for public networks in the year beyond are presented in [1]. Part of such future networking is 6G communications that focus on the technical developments for providing (ultra-broadband and ultra-low latency) hyper-scale connectivity and full support for a wide range of precision services. As such, 6G would realize requirements and innovation [2] in the undelaying IP layer in terms of significant reengineering capable of overcoming today's bottlenecks and limitations. Target innovations are in the multi-form addressing, facilitating guaranteed agreement-based services and KPIs, and related to payloads in the IP that better support the flexibility and extensibility. Part of these 6G requirements and expected innovations are explicitly addressed in this paper, enabling a wide range of addressing schemes of various address structures, multi-semantics, and variable lengths.

The scope of the Internet has continuously expanded from an experimental and local area network (ARPANET) to a global net, work including many networks (ManyNets), such as the Internet of Things networks (IoT), satellite networks, cellular networks and manufacturing networks, etc. Meanwhile, the number of devices connected to the Internet has increased dramatically since the Internet's birth. It is estimated to have more than 1 trillion devices on the Internet in the year 2035 [3]. Furthermore, thanks to the maturing virtualization technologies, virtual entities, such as contents, services, virtual identities, computation resources, etc., have become independent communication end-points that can interconnect with a human ing, physical objects, and themselves. It is demarking entities addressable directly to increase desirable's communication efficiency and effectiveness. In that case, both physical and cyber objects can seamlessly communicate, eventually consuming a larger addressing space than expected.

Meanwhile, the available address space of IPv4 seems insufficient to identify devices and objects. Although the 128-bit IPv6 contains much bigger address spaces, it will run out in the future with the ever-rapid-increasing requirement on the address space. The flat structure and non-extensibility of the current IPv4/IPv6 addresses cause the IPv4/IPv6 address space's perceived exhaustion. Secondly, the new version might not be compatible with the old ones. The migration can take quite a long time, as we observed in the transition from IPv4 to IPv6. Since the invention of IPv6 more than 20 years ago, only two network devices have adopted IPv6. Finally, the extended address length is a pain point for networks (e.g. IoT networks) where hosts only send small packets. Although the IETF working group IPv6 over Networks of Resource-constrained Nodes (6lo) [4] has proposed an IPv6 header compression method for resource-constrained devices, it has to use a protocol conversion gateway with high processing cost to support interconnection and communication with the Internet.

Moreover, the IP was designed initially with a locator-based addressing scheme for peer-to-peer communication, which poorly supports mobility and service-oriented routing. Since the host's identity is bound to a fixed IP address, making the mobile use case is complicated as the host is moving its location. The system needs to translate the requested content name into the destination IP address by querying Domain Name System (DNS) servers, bringing unnecessary overheads and latency. MobilityFirst [5] and Named Data Network (NDN) [6] were developed based on Information-Centric Network (ICN) technologies. By naming contents uniquely, MobilityFirst and NDN'ss communication focus on retrieving content instead of connecting to the host. Therefore, the connection issue caused by mobility could be solved naturally.

Moreover, with the rapid development of satellite networks, new addressing technologies like geographic addressing are emerging to eliminate the impact on the routing caused by satellites" mobility. With the topology-based addressing method, geographic routing allows the packet to be forwarded based on the destination's geographic location. This emerging non-locator-based addressing scheme clearly shows advantages in many networks. However, the new addressing schemes only work in specific networks. So far, there is no unified address scheme capable of supporting all features and compatible with all possible routing methods in heterogeneous networks.

With the above motivations, we propose a new addressing system called Open Unified Address (OUA) system, a hierarchical structure that enables efficient interconnection among heterogeneous networks. The core concept of OUA is to allow the same communication entity to bind with multiple addresses for different routing domains with a hierarchical addressing structure. To better support various addresses" coexistence, the proposed addressing system also enables two additional key features: (1) variable-length IP address to support cross-network communication seamlessly; (2) multi-semantic (e.g., locator, topology, identity, etc.) addressing scheme supporting various routing methods without the need of network address translation or gateway. With these features, the OUA system can solve the limitation of the addressing space and simplify global routing by reducing the top-level entries and improving communication efficiency.

The remainder of this paper is structured as follows. Section 2 reviews the existing technologies to achieve variable-length and multi-semantic addressing. Then we introduce the definition of name, address, and namespace to analyze the current Internets problems. With the naming and addressing of the theoretical model, we propose the OUA's design principles and explain how to support variable-length and multi-semantic addressing. To achieve interconnection among heterogeneous networks, we also define the Network Index Address for top-level namespace routing. In section 4, there are evaluations of the scalability and performance of the proposed addressing system. We conclude this paper with future work in section 5.

II. STATE OF THE ART

This section introduces various technologies, 6lo, variable length addressing and NDN, which try to realize the variable length and the multi-semantic addressing.

Short Address for IoT

As mentioned above, 6lo is one of the most popular IPv6 header compression mechanisms for IoT devices. The header compression reduces power consumption in communication at the expense of requesting more computation resources due to the complexity of implementation [7]. From 2004 to 2012, IPv6 over Low power WPAN (6LoWPAN) working group finished designing the adaptation mechanism to support IPv6 over IEEE 802.15.4. However, with the rapid development of IoT, the 6LoWPAN mechanism cannot be flexibly adapted to new link-layer technologies (e.g., ITU-T G.9959 and Bluetooth). Although the 6lo working group was established to adopt IPv6 to various types of IoT nodes through header compression, there is, unfortunately, no general 6lo mechanism applicable over heterogeneous link layer protocols due to the IP protocol's fixed-length nature. As a result, 6lo published a few RFCs, each supporting a different type of wireless access technology. Due to the lack of a unified header compression method for layer-2 protocols, each forwarding node has to restore the complete header before routing, which costs extra processing overheads.

[19] describes various benefits of using shorter addresses, including energy savings in low-bitrate networks.

Variable Length Addressing

Some variable Length Addressing schemes were analyzed in [8], [9], [10] and [11]. The work [8] proposed a variable-length addressing scheme for 6LoPAN to enhance the scalability. However, since this coding scheme won't fully utilize all the binary combinations, the waste of address space could be an issue, especially for the energy-constraint IoT devices. The authors of [9] defined a fixed-length subnet mask pattern to utilize better IPv4 address spaces, which only applies to IP addresses of class C. In [10], a hardware design is introduced to switch variable-length IP packets. The work [11] explores a possible way of variable-length addressing. The Type-Length-Value (TLV) is modified in [11] to combine the T and L to reduce a packet header's length. However, it increases packet header resolution complexity, thus impacting the forwarding speed of routers and switches. NGP (Next Generation Protocol) ETSI's project analyzed the problem of the current TCP/IP-based communication protocols for the Internet. It also proposed next-generation protocols for key performance indicators (KPIs) [16], [17].

Name-Based Routing

Name Data Networking (NDN) [6] is a proposed *network architecture* that aims to request and forward packets with the name of the required content or service. The motivation of NDN is that the original IP routing, designed for end-to-end communication, is not suitable for current network content distribution. Therefore, NDN proposes to change the semantics of addressing and routing from the locator to the content name to meet current and future user application demands. However, irregular content names lead to a large number of hard-to-converge routing entries and complex name-based routing. Thus, it is essential to have multi-semantic namespaces which support both name-based routing and aggregable routing entries.

III. OPEN UNIFIED ADDRESSING SYSTEM

This section defines a few terms like name, address, and namespace used in the novel OUA scheme. The OUA scheme is designed to incorporate multiple namespaces and overcome the current IP addressing scheme's limitation. Besides, it supports ManyNets interconnection with a hierarchical addressing structure.

Since J. F. Shoch [12] first presented the explicit definitions of name, address, and route in 1978, there have been a few evolutions in theoretical studies about network addressing and routing. According to Shoch's work, the IP address could be considered a communication object, and the name is a kind of label. The namespace is a set of object labels, like IPv4 namespace and IPv6 namespace.

There are two key attributes of the name: assignment and binding/unbinding. The assignment defines the length, semantics, and scope of names in a specific namespace. For example, each object in the IPv6 namespace has a 128-bit topological name for local or global networks. If two objects want to communicate, they should be bound to names in the same namespace.

Although the 6LoWPAN and NDN were introduced to solve specific network problems, it is difficult for communication objects in heterogeneous networks to interconnect directly because they are bound to different namespaces. Thus, we propose the Open Unified Addressing system to solve the problem by allowing multiple namespaces to coexist. Each network can use its namespace, use the original namespace, or even use various namespaces simultaneously.

The design principles of OUA are as follows:

1) Names in a namespace identifies a physical or virtual object (a group of logical objects in the same namespace).

2) Different virtual objects are addressed in independent namespaces. Similarly, one namespace's address identifies an object or a group of objects, which is not restricted by the upper-layer namespace (there is no dependency relationship) and can be named as required. Therefore, the number of upper-layer namespaces is unlimited.

3) New namespaces can be added to the addressing system freely for its openness. Objects in different namespaces can communicate with each other.

4) New namespaces can be added as either peer-to-peer or hierarchical architectures.

In the OUA, an object's address can be expressed as a name in a namespace *NS*.

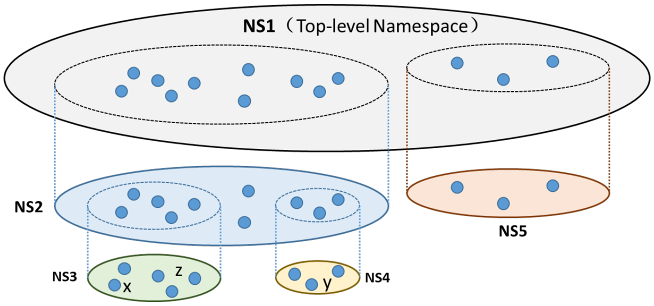


Fig. 1 A Paradigm of Open Unified Address system

A paradigm of the OUA system is illustrated in Fig. 1. In this case, there are five namespaces named as *NS1, NS2, NS3, NS4,* and *NS5*. The namespace *NS3* and *NS4* are subsets of *NS2*, and *NS2* and *NS5* are subsets of the top-level namespace *NS1*.

The object's address is composed of its local name and the label of the namespace where it belongs in a hierarchical way. The local name is defined as the unique name of one object in the smallest upper-layer namespace to which it belongs [80] describes various benefits of using shorter addresses in- cluding energy savings in low-bitrate networks.. Therefore, combined with the labels of the object's upper-layer namespaces, the object can be uniquely addressed.

For example, the object x wants to communicate with object z. As they both belong to the same namespace *NS3*, they can reach each other by using their local names x and z as addresses. If the object x would like to communicate with the object y, they should use their hierarchical addresses. In this case, the address of *x* is composed of not only its local name *x but also the namespace label NS3*. The address of the object y contains its local name y and the label *NS4*. Since the *NS3* and the *NS4* are subsets of *NS2*, it is not necessary to add the label *NS2* to the addresses for the communication between these 2 objects. In this way, the global addressing and interworking of multiple namespaces are implemented. Moreover, the addressable range includes the current namespace and its lower-layer namespace.

The OUA can easily support variable-length addressing with more flexible namespaces. The length of a name can be set on demand. For example, a namespace for a local sensor network could have only 8 bits, thus 256 addresses. Each node in this network can communicate via a short address for energy-saving purposes.

The OUA system also supports multi-semantic addressing and routing by decoupling the communication object from its namespace. The available semantics of address is categorized into locator and IDentifier (ID). Locator is the topology dependent name, while an ID is a topology independent name. Locator represents not only the topological network location but also other location information. For instance, the geographical location namespace applies to satellite networks, and the object is a satellite. The namespace of ID comprises many kinds of namespaces with different semantics, such as user ID and service ID. The user ID is unique for each node in the network, and the service ID may be shared among many nodes for service provision.

Inspired by the design of Concise Binary Object Representation (CBOR) [13] and with an update from our previous work in [14] the following depicts the proposed structure for the packet headers in support of the OUA: The Type-Length-Value (TLV) is adopted as a basic unit for the packet header. The first octet is the type of the following field, which indicates the meaning of the value, such as source address or next header. The second octet is the length of the value, and the last octet is the value itself. The compound attribute, such as segments of an address, can be expressed by nested TLVs. Optional information, such as security-related information; functions that an end-user expects the network to perform on the packet (e.g., Function ID - FID, Metadata Index - MDI and Metadata - MD fields to enable user-definable networking), can be added to the packet header dynamically. The TLV is modularized, which is easy to process by the parser.

IV. NETWORK INDEX ADDRESS (NIA)

In the existing IP network addressing system, all network prefixes need to be advertised to the backbone network. However, the number of core network prefixes reaches nearly 1 million, leading to minutes or even hours for the routing convergence, which is impractical for the future Internet in the context of 6G Communications. On the other hand, although the AS number is a better namespace for route aggregation than BGP route entries, it cannot be used for packet forwarding directly. Also, if the number of BGP routers keeps increasing, as we observed, the existing addressing space and the memory usage will soon reach the physical limitation.

For example, if 50 destinations are located within an autonomous system (AS) calledAs1As1's'sAs1As1's'ss *As2* will have to add 50 entries to its routing table. The Fig. 2 derived from [15] indicates the faster increase of the BGP routes, limiting the Internet's scalability and increasing the routing convergence time.

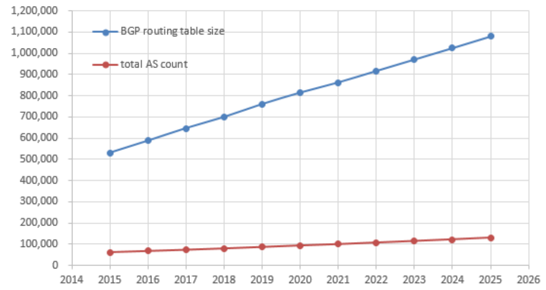


Fig. 2. BGP routing table size vs. total AS count from 2015

However, an ideal way would be to aggregate these entries into one AS number, as the AS number is already in use won't create any confusion. Therefore, the OUA system defines the Network Index Address (NIA) using the AS numbers as the top-level namespace to identify networks allocated and advertised in a decentralized way. The introduction of NIA by leveraging the AS numbers can reduce the number of Internet routes and reduce the route convergence time.

When an object wants to communicate with others, it can bind itself to the corresponding namespace to obtain a reachable address. Since each network's namespace (or sub-network) is independent, a hierarchical address structure is used for routing among different namespaces. For example, as illustrated in Fig. 3, the Campus Network obtains NIA=100 as its top-level address and advertises it to other top-level networks via BGP (extending the path attribute *MP_REACH_NLRI*). Thus, a communication entity in different networks (such as Satellite Network) can find the routes to the Campus Network via searching for NIA=100.

The hierarchical global address of a communication entity in the Campus Network can be expressed as <100, 10.32> where the 10.32 is the identity's' local address. The hierarchical global address can be extended downward to denote multi-layer subnets. For instance, an n-level hierarchical address can be constructed as <NIA, 1st level network address, 2nd level network address, …, nth level network address>.

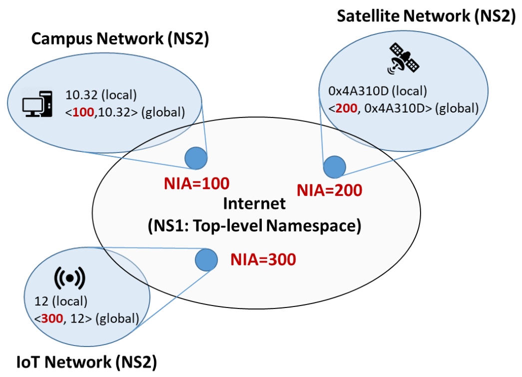


Fig. 3. An example of the interconnection of heterogeneous networks with hierarchical addresses

V. IMPLEMENTATION IN ROUTER

The forwarding models can be categorized into two types: Pipeline and Run To Completion (RTC). In the Pipeline model, packet processing is divided into several stages. Each stage has an independent memory for a single function, such as querying Forwarding Information Base (FIB) and matching Access Control List (ACL). Meanwhile, the RTC model uses shared memories in all stages to achieve a more flexible function composition. The comparison between the above two forwarding models is illustrated in Fig 4.

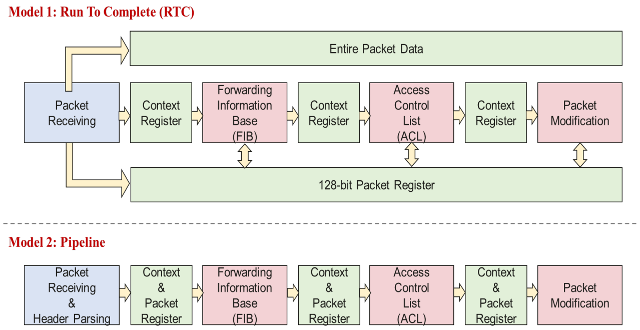


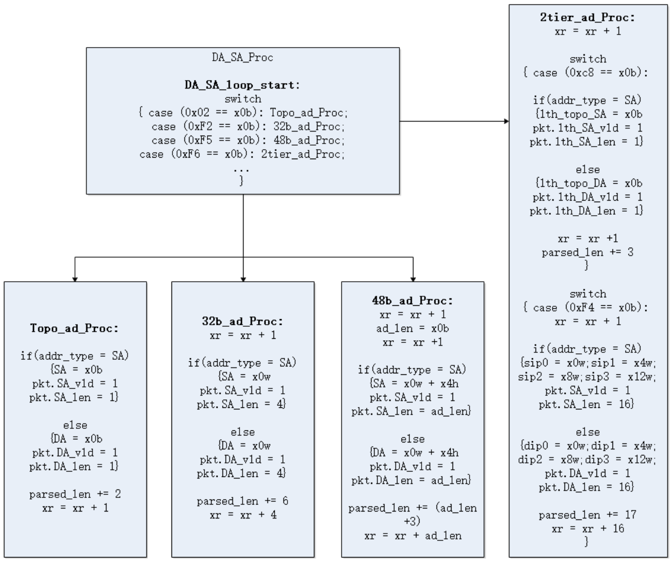
Fig. 4. The comparison between Pipeline and Run To Complete (RTC) forwarding models

In the Pipeline model, there is a specific parser to process fields in packet headers. Thus, the forwarding delay can be divided into the parsing delay and the packet processing delay. Only the parsing delay is affected by the design of the new OUA system.

The parser is composed of three main modules: header identification, field extraction and the field buffer. The header identification module can identify the packet type and tell the field extraction module its target header field locations. Then the field extraction module extracts each header fields separately and sends them to the field buffer module. All header fields stored in the field buffer module are used for Forwarding Information Base (FIB) lookups.

Based on our previous work [14], the OUA header parser design is composed of a primary header and destination and source address. The necessary header fields include the next header, time to live (TTL), header length and total length. Once an OUA-format packet is received, the parser reads the destination address firstly and matches it with the FIB.

Four typical OUA addressing structures were implemented during this evaluation: a) 8-bit short address for IoT devices; b) 32-bit address for IPv4 compatibility; c) 48-bit address for unique scenarios; and d) 2-tier hierarchical address, as illustrated in Fig. 5. Since the OU address' first octet may indicate the length or level information, the parser differentiates addressing structures by the first octet of the destination address. Then, there are distinguish parsing processes for various kinds of destination addresses. Especially for the 2-tier hierarchical address, the parser will iteratively process different level addresses.



```
DA_SA_Proc

DA_SA_loop_start:
switch
{ case (0x02 == x0b): Topo_ad_Proc;
  case (0xF2 == x0b): 32b_ad_Proc;
  case (0xF5 == x0b): 48b_ad_Proc;
case (0xF6 == x0b): 2tier_ad_Proc;
...
}
```

```
Topo_ad_Proc:

if(addr_type = SA)
{SA = x0b
pkt.SA_vld = 1
pkt.SA_len = 1}

else
{DA = x0b
pkt.DA_vld = 1
pkt.DA_len = 1}

parsed_len += 2
xr = xr + 1
```

```
32b_ad_Proc:
xr = xr + 1

if(addr_type = SA)
{SA = x0w
pkt.SA_vld = 1
pkt.SA_len = 4}

else
{DA = x0w
pkt.DA_vld = 1
pkt.DA_len = 4}

parsed_len += 6
xr = xr + 4
```

```
48b_ad_Proc:
xr = xr + 1
ad_len = x0b
xr = xr +1

if(addr_type = SA)
{SA = x0w + x4h
pkt.SA_vld = 1
pkt.SA_len = ad_len}

else
{DA = x0w + x4h
pkt.DA_vld = 1
pkt.DA_len = ad_len}

parsed_len += (ad_len
+3)
xr = xr + ad_len
```

```
2tier_ad_Proc:
xr = xr + 1

switch
{ case (0xc8 == x0b):

if(addr_type = SA)
{1th_topo_SA = x0b
pkt.1th_SA_vld = 1
pkt.1th_SA_len = 1}

else
{1th_topo_DA = x0b
pkt.1th_DA_vld = 1
pkt.1th_DA_len = 1}

xr = xr +1
parsed_len += 3
}

switch
{ case (0xF4 == x0b):
xr = xr + 1

if(addr_type = SA)
{sip0 = x0w;sip1 = x4w;
sip2 = x8w;sip3 = x12w;
pkt.SA_vld = 1
pkt.SA_len = 16}

else
{dip0 = x0w;dip1 = x4w;
dip2 = x8w;dip3 = x12w;
pkt.DA_vld = 1
pkt.DA_len = 16}

parsed_len += 17
xr = xr + 16
}
```

Fig. 5. Four addressing structures in the OUA header

VI. Evaluation and Analysis

In the pipeline mode, the proposed OUA header format has almost no impact on the parsing delay. According to the existing switch ASICs' performance, the OUA header's parsing delay is about 70 ns per packet, fast enough to support the switch to run at line-rate.

In the RTC model, the codes to support different headers and their performances are shown in Table 1.

Type	Microprogram size	Throughput
IPv4	520 lines	180 Mpps
IPV4 with ACL	610 lines	155 Mpps
OUA	624 lines	150 Mpps
OUA with ACL	770 lines	120 Mpps

Table 1. The microprogram performance.

As a result, with the current RTC-based forwarding chip, the proposed OUA header parser's code size is about 624 lines with a throughput of 150 Mpps (packet per second). Compared with traditional Ipv4 forwarding, the throughput of OUA forwarding is decreased by 16.7%. If the ACL process is incorporated, the code size is increased to 770 lines, while the throughput will be reduced to 120 Mpps, a reduction of 22.6%. The root cause of performance reduction is the hardware limitation of the current RTC-based forwarding chip, not the design of OUA. If we implement a specific parser for the OUA header, which supports variable-length and multi-semantic addressing, there will be no apparent additional parsing delay.

This experiment shows that the flexible addressing scheme introduced by the OUA system has a small (in case of implementation on existing forwarding chips) or no impact (in case of designing new ASICs) on the parsing delay. Moreover, the introduction of NIA significantly reduces the routing convergence time, thus improving the routing efficiency.

VI. CONCLUSION

In this paper, we propose the OUA system – a new addressing space that is extendable in a hierarchical fashion to meet future 6G communication networks, such as IoT, satellite communication, and service-oriented connection with guaranteed KPIs. The proposed OUA system enables two key features: (1) variable address in length to seamlessly support cross-network communication; (2) multi-semantic addressing scheme to support various routing methods without network address translation or gateway. The OUA system increases flexibility by resolving the existing addressing limitation, which is beneficial for heterogeneous interconnection in 6G. Moreover, the NIA is introduced as the top-level namespace to identify networks and reduce the inter-domain routing convergence time. With the design of NIA, the hierarchical OUA structure can improve the scalability of the future Internet. Finally, the evaluation shows that the OUA system has little or almost no impact on the forwarding delay in both Pipeline and RTC forwarding models.

In the future, we will further evaluate the OUA system in a large-scale testbed in the 6G networks. Moreover, there are further challenges in assessing the OUA system in different multi-semantic routing scenarios, such as service-oriented routing and geographic routing. The compatibility and alignment with the traditional IP address and network management of the OUA system will also be considered in the next steps. The OUA system could enable customized functions to be performed on data packets, including functions to program the header. Additional benefit evaluation will be performed to enable safe, flexible user-definable networking and energy savings in 6G networks.

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BIOGRAPHIES

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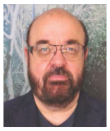

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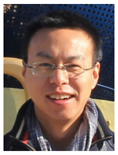

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