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Experimental Verification of SDN/NFV in Integrated mmWave Access and Mesh Backhaul Networks

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SUMMARY In this paper, a Proof-of-Concept (PoC) architecture is constructed, and the effectiveness of mmWave overlay heterogeneous network (HetNet) with mesh backhaul utilizing route-multiplexing and Multi-access Edge Computing (MEC) utilizing prefetching algorithm is verified by measuring the throughput and the download time of real contents. The architecture can cope with the intensive mobile data traffic since data delivery utilizes multiple backhaul routes based on the mesh topology, i.e. route-multiplexing mechanism. On the other hand, MEC deploys the network edge contents requested in advance by nearby User Equipment (UE) based on pre-registered context information such as location, destination, demand application, etc. to the network edge, which is called prefetching algorithm. Therefore, mmWave access can be fully exploited even with capacity-limited backhaul networks by introducing the proposed algorithm. These technologies solve the problems in conventional mmWave HetNet to reduce mobile data traffic on backhaul networks to cloud networks. In addition, the proposed architecture is realized by introducing wireless Software Defined Network (SDN) and Network Function Virtualization (NFV). In our architecture, the network is dynamically controlled via wide-coverage microwave band links by which UE's context information is collected for optimizing the network resources and controlling network infrastructures to establish backhaul routes and MEC servers. In this paper, we develop the hardware equipment and middleware systems, and introduce these algorithms which are used as a driver of IEEE802.11ad and open source software. For 5G and beyond, the architecture integrated in mmWave backhaul, MEC and SDN/NFV will support some scenarios and use cases.
key words: *5G, mmWave, HetNet, testbed, PoC, SDN, NFV, MEC, mesh backhaul, route-multiplexing, prefetching algorithm, orchestration*

1. Introduction

Mobile traffic is increasing drastically at the rate of about 47% per year [1] due to the spread of mobile terminals such as smartphones, tablets, etc. Moreover, this rate of increase is estimated to continue. Therefore, enhanced mobile broadband (eMBB) targeting 20 Gbps peak throughput is considered as one of the main use cases of the 5th generation cellular networks (5G) [2]. As an architecture for realizing this requirement, millimeter-wave (mmWave) heterogeneous network (HetNet) [3], [4] in which a lot of wide-band small-coverage [5] mmWave small cell (SC) base stations (BSs) are deployed over the conventional wide-coverage macro cell (MC) BS, has been proposed. In fact, many countries introducing 5G (will) support 28/39 GHz for SC-BS [6], [7], for realizing eMBB. Furthermore, MC-BS employing conventional micro-wave band can be utilized as a robust control plane (C-plane) between User Equipment (UE) and BS for constructing a flexible network. Since the micro-wave band has wide coverage at the expense of low communication capacity, it is more useful as a C-plane for control connection and sharing of context information (e.g. global positioning system (GPS) information), rather than as a data plane (U-plane) for transferring application data. This mechanism, called C/U Plane Separation [3], [8], is an important technology for realizing mmWave HetNet.

Although the architecture provides tremendous improvements in access data rates owing to the introduction of mmWave SC-BSs, the system throughput can only be improved if high-speed backhaul links, e.g. optical fibers connecting SC-BSs to the core networks, are installed. However, the optical fiber penetration rate worldwide is still low, which prevents the system rate improvement even when mmWave overlaid HetNet is introduced [9]. For example, although the penetration rate of optical fiber exceeds 90% in Japan and Korea, it is still at a low value of about 38% in the Organisation for Economic Co-operation and Development (OECD) areas [10]. Furthermore, the Capital Expenditure (CAPEX) for introducing high-speed optical fiber is very high, and thus it is not easy to renew or replace all conventional backhaul links by fiber technology. In order to solve this problem, there are two complimentary solutions. One is mmWave backhaul [11], and the other Multi-access Edge Computing (MEC) [12]. These functions are implemented by Software Defined Network (SDN)/Network Function Virtualization (NFV) based platform which are network virtualization technologies.

In this paper, we apply these technologies to access links and mobile backhaul to solve the problems of the conventional technologies as shown in Fig. 1. These technologies are also important factors in mmWave HetNet embedded with mmWave backhaul and MEC technologies. The proposed architecture in this paper attempts to address 5G requirements especially focusing on system rate, latency

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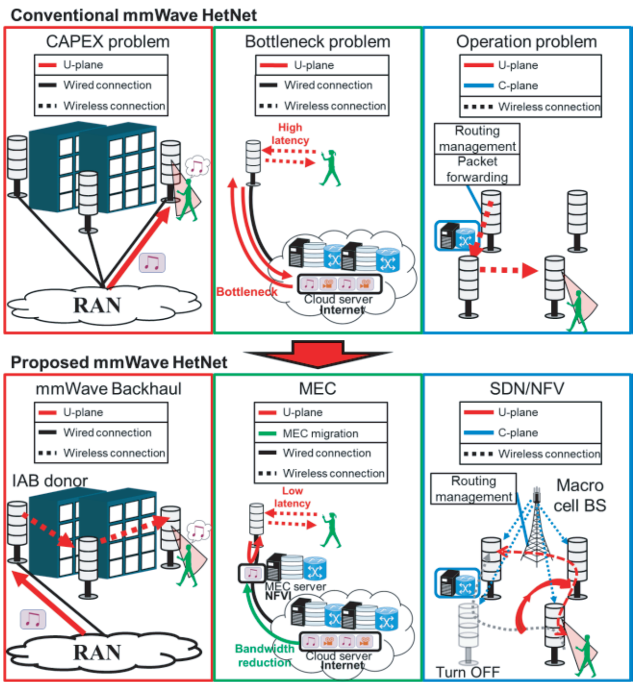


Fig. 1 Proposed approaches for SDN-based mmWave networks.

and cost points of view. In conventional architecture, the target of system rate can be achieved owing to high density SC-BSs deployment, at the expense of increasing fiber-backhauling cost while stringent latency requirement is still not fulfilled if application servers are not deployed at the edge but the cloud. Our proposed architecture can alleviate such issues by introducing both mmWave backhaul and MEC technologies, that the former helps avoiding expensive wired backhauling and the latter helps reducing latency owing to the deployment of application server at the edge of the network. However, the drawback of the wireless backhaul compared to conventional wired backhaul is limited capacity. To overcome this issue, our architecture furthermore introduces prefetching mechanism over the proposed mmWave HetNet with MEC. In sum, since a single system of combined technologies, i.e., mmWave backhauling, MEC and prefetching, is required to fulfill 5G requirements, this paper is the first attempting to implement and evaluate such system as a whole.

In the architecture proposed in our previous research [13], the mmWave backhaul routing is controlled by wireless SDN using C-plane over micro-wave band based on the UE's context information such as requested application, GPS information, etc. Due to managing SC-BSs using out-band C-plane, it is possible to introduce power control of SC-BSs, which is called Dynamic ON/OFF in [13], that properly turns off the power of SC-BSs with a small number of assigned UEs. This manner realizes the reduction of energy consumption of not only the deactivated access links but also the unnecessary backhaul links connecting to the deactivated SC-BSs. Because BSs occupy a large proportion of energy consumption in mobile networks, SDN control via out-band C-plane relates to OPEX reduction. Furthermore, in our conventional work in [14], the packet forwarding and MEC server functions of each SC-BS are implemented by SDN/NFV using the virtual switch and network containers, and the application on the MEC server is migrated according to the UE's context information. The architecture realizes Information-Centric Networking (ICN) [15]/Content Delivery Network (CDN) [16] based on these functions. In summary, this paper implements SDN/NFV, which enables economic and efficient network construction, into mmWave access and mesh backhaul, and realizes virtualization on the access side instead of core side. Compared with our previous work in [14], experimental verification of the approaches including not only prefetching algorithm but also route-multiplexing is investigated more thoroughly.

Table 1 Difference between previous researches and this paper.

	This paper	[13]	[14]
Server location in route-multiplexing	Container	Node	Node
MEC migration	Following UE	NA	Static
How to measure throughput of MEC	FTP	iPerf	iPerf3
UE	Real	Virtual	Real
Locations of agent functions	SC-BS and UE	SC-BS (Only routing)	SC-BS and UE
C-plane	WiMAX	Wi-Fi	WiMAX

Table 1 shows the differences between our previous works and this paper. The architecture in this paper not only integrates those of [13] and [14], but adds some novel functions as well. In [13], evaluation was performed using virtual users generated locally at evaluation nodes. In other words, the experiment did not have actual UEs like mobile terminals or PC tablets. Inversely, the access links in this paper are implemented with both real access point (AP) and UEs (PC). In addition, different from [14], the generated MEC container automatically follows the UE to verify the feasibility of ICN/CDN in mmWave HetNet using actual devices. As one of novel functions compared to [14], each UE can automatically send response messages after obtaining request messages from SDN controller, since the novel architecture adds Container Agent API server to each SC-BS and UE Agent API server to each UE.

In [11], 3GPP Release 16 defines mmWave backhaul under the terminology of Integrated Access and Backhaul (IAB), as a promising technology in 5G and 5G Beyond. Moreover, Facebook is running a project called Terragraph [17], [18], in which unlicensed 60GHz-band mmWave backhaul links are established in urban area for providing ubiquitous internet/Wi-Fi connection environment. In addition, experimental results in [19] proved that mmWave backhaul could achieve a maximum throughput of 4.7 Gbps over a distance of even 200 m. European Telecommunications Standards Institute (ETSI) has proposed an architecture that implements MEC functions as software/middleware on Mobile Edge Host (MEH), which are operated by Application Programming Interface (API) from the controller. Similarly, several organizations have been established, e.g., Open

Fog Consortium (OFC) [20], Open Edge Computing Initiative (OECI) [21], Automotive Edge Computing Consortium (AECC) [22], etc., to investigate and develop the architecture and the related technologies. In addition, experimental results in [23] confirmed the effectiveness of MEC mechanism in improving not only response time but energy consumption as well when MEC is introduced into the network edge. With SDN/NFV technologies, the network become cost-efficient and time saving for innovation of network architecture, so it is expected to proliferate the newest networks at low cost for coping with rapidly increasing mobile traffic [24]. In addition, [25] worked on virtualization of core network using SDN/NFV, and experimented on latency reduction through their developed Proof-of-Concept (PoC) system. However, although these studies mentioned about access links and mobile backhaul virtualization, the PoC is only about core backhaul virtualization. Up to the authors' knowledge, this paper is the world-first to develop PoC for integrated mmWave access and mesh backhaul with the introduction of novel technologies like MEC, SDN/NFV and demonstrate the effectiveness of the proposed system e.g. throughput and latency improvement via experimental results.

This paper is organized as follows. Section 2 describes the outline of the proposed mmWave HetNet architecture and the advantages of the considered approaches, i.e., MEC migration with prefetching algorithm and route-multiplexing. Section 3 explains how to implement these technologies from both hardware and middleware perspectives. Section 4 explains the evaluation methods, results and considerations. Finally, Sect. 5 concludes the paper.

2. Scenario of mmWave Edge Cloud

This section describes the scenarios and the architecture of the PoC of our developed SDN/NFV in the integrated mmWave access and mesh backhaul networks, which is called mmWave Edge Cloud. Besides, we recapture the concept of the proposed approaches based on our previous works.

2.1 Overall Architecture

This sub-section describes the overall architecture of the testbed shown in Fig. 2. In [4], the demand of mobile traffic in 2020s, in hotspots, is estimated to become 1000 times that in 2010s. In order to cope with the demand, [4] proposed high density deployment of mmWave SC-BSs. In addition, when UEs move between hotspots where UEs download large volume data such as 4K video at, and download small volume data while moving, [27] indicated that the networks can cope with the demand in 2020s owing to the introduction of prefetching algorithm even if existing capacity-limited backhauling is used. Based on [4] and [27], the system architecture considered in this paper is shown in Fig. 2. Each mmWave SC-BS has mmWave mesh backhaul and MEC functions, which are operated by an orchestrator

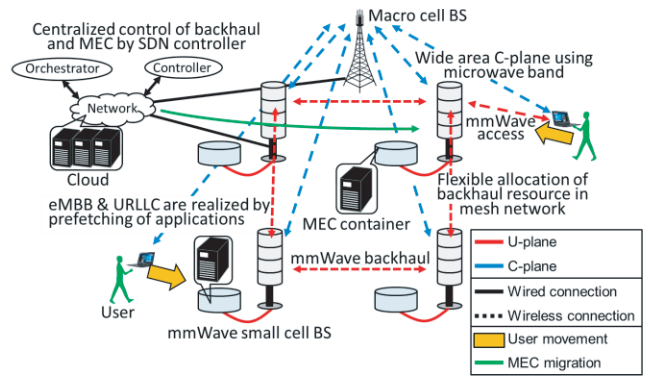


Fig. 2 SDN/NFV-based mmWave edge cloud.

and a SDN controller. The orchestrator collects UE's context information via C-plane for optimizing backhaul routing, etc., using the SDN controller. U-plane uses mmWave band for both access links and backhaul links. Each SC-BS is embedded with multi-sector antennas to realize a mesh topology backhaul network. The architecture realizes eMBB and Ultra-Reliable and Low Latency Communications (URLLC) by pre-sending (prefetching) applications to each SC-BS. For simplification without loss of generality, our PoC assumes only downlink contents e.g. video data, browsing internet, and etc. The effectiveness of our PoC is thus verified for downlink but the proposed architecture is general for both uplink and downlink.

2.2 Advantage of mmWave Edge Cloud

This sub-section describes the proposed approaches of the testbed. Route-multiplexing is one of the technologies, which helps coping with intensive mobile traffic by data delivery using multiple backhaul routes. Prefetching algorithm is another technology, which helps using mmWave access efficiently without updating the existing capacity-limited backhaul with optical fibers.

2.2.1 Route-Multiplexing

It is necessary to fully utilize mmWave access at a SC-BS if it experiences intense mobile traffic. However, only one single backhaul route may not provide sufficient throughput compared with access links e.g. when throughput of mmWave access link is larger than that of one sector of backhaul links. In that case, the network can deal with this issue by delivering data via multiple mmWave backhaul sectors based on space division multiple access realized by the introduction of high directivity mmWave antennas. Therefore, it is possible to supply traffic as many as the number of backhaul sectors. The system rate can be maintained by adopting route-multiplexing [13] even when intensive traffic occurs at a distance away from mmWave SC-BS gateway (GW), which is equipped with high-speed wired backhauling. Figure 3 shows the flow diagram. First, we assume that several UEs in Fig. 3(a) use the backhaul route. Next, the

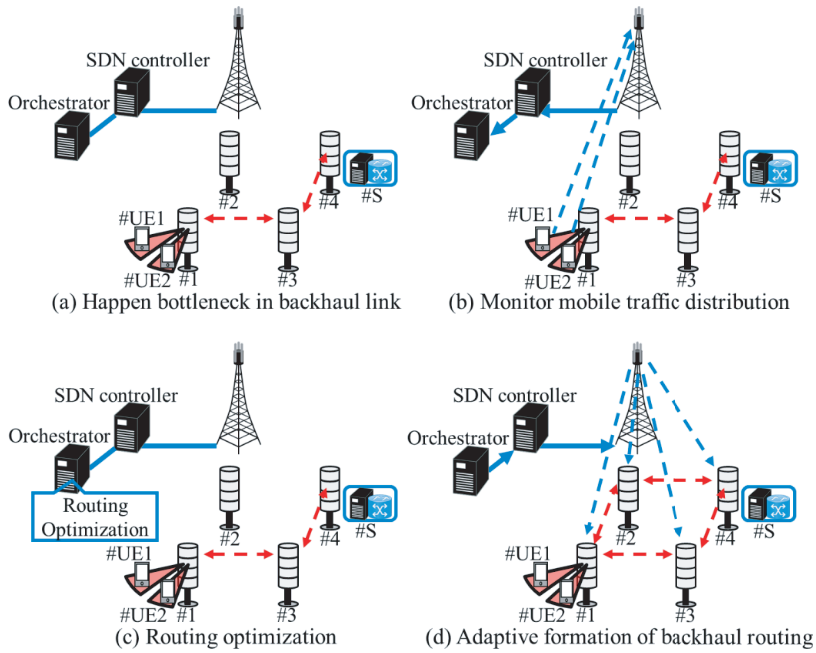


Fig. 3 Flow diagram of route-multiplexing.

UEs periodically transmit their own context information to the SDN controller in Fig. 3(b). In Fig. 3(c), the orchestrator calculates the routing optimization based on the collected information. Finally, the routing change request is transmitted to each SC-BSs from MC-BS. After rewriting the flow table based on the request, each SC-BS acknowledges to the SDN controller. As a result, route-multiplexing is performed as shown in Fig. 3(d). This paper will verify the effectiveness of the route-multiplexing algorithm via our developed PoC.

2.2.2 Prefetching

Even when MEC server is deployed on the nearest SC-BS from UE, if the contents requested by UE are not stored in the MEC server, UE has to access to a cloud application server. Moreover, the 5G networks are designed to introduce mmWave access so that throughput of access links might be much larger than that of the existing capacity-limited backhaul links. Therefore, the system throughput becomes further degraded when bottleneck happens at backhaul links to cloud server. Therefore, prefetching algorithm should be introduced to utilize MEC server and mmWave access efficiently.

The algorithm is a mechanism which pre-sends applications to MEC servers in advance by utilizing UEs context information. In order to conduct this mechanism, [26] shows how to predict and pre-allocate network resources through an orchestrator via gathered information of mobile traffic. Numerical results in [27] have confirmed that the system rate can be greatly improved even with 1 Gbps Ethernet (GbE) backhaul links when introducing the prefetching algorithm assuming that the capacity of the wired backhaul does not exceed the long-term average value of the total download amount of all UEs, and achieve almost equivalent performance of 10 GbE backhaul without prefetching. In other words, the algorithm is effective in an environment where the time variation of mobile traffic is large and the time dependency of mobile traffic is large. This paper will verify through our developed PoC the effectiveness of the proposed prefetching algorithm, under an ideal assumption that the requested application is known in advance without prediction.

Figure 4 shows migration process using container-typed virtualization technology. Container exports image file for server configuration. Recently, there are two types, i.e. a VM (Virtual Machine) type and a container type, when establishing a virtual environment. The container type is superior to the other one, when comparing them in terms of light data size and startup time. The image described in this paper refers to the latter container, and one container has only one content. If any SC-BS has the image file, the SC-BS can build the same container regardless of which SC-BS. Moreover, it is possible to migrate applications by transporting the image file following user movements. Figure 5 shows the flow diagram. Container migration is executed based on registered UE's context information such as destination, requested application, etc. via C-plane before UE arrives at the destination. First, the UE periodically sends its own context information to the SDN controller in Fig. 5(a). Next, container migration request is transmitted to each SC-BS based on the context information in Fig. 5(b). Based on the request, a source SC-BS exports process to a container. At the same time, each SC-BS updates these flow tables in order to transmit the container to a destination SC-BS. After that, the destination SC-BS imports and restarts it to realize the migration. When the migration is completed, the

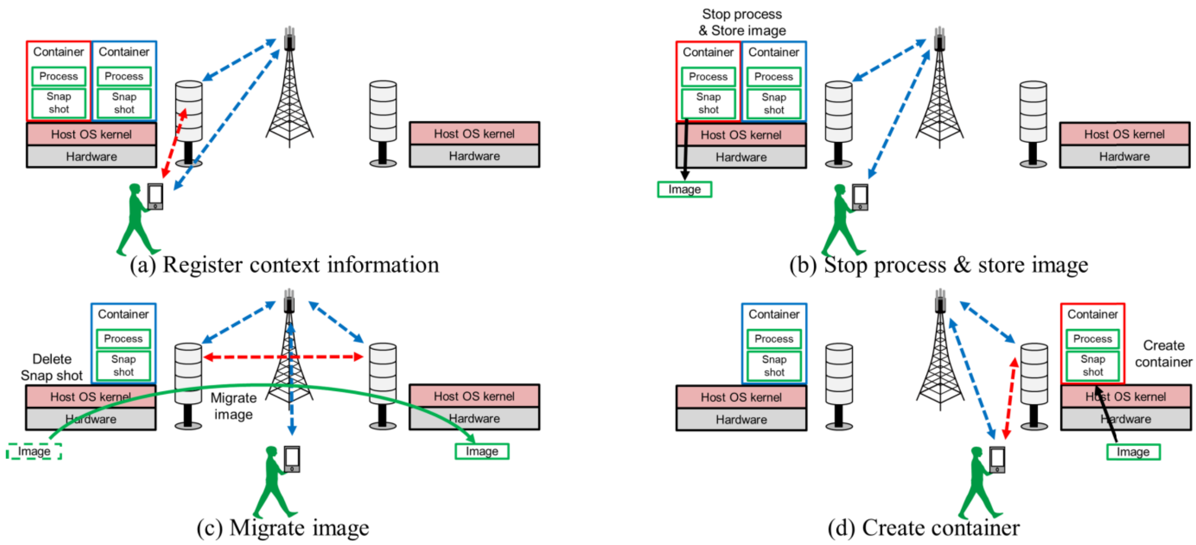


Fig. 4 Migration container process between MECs.

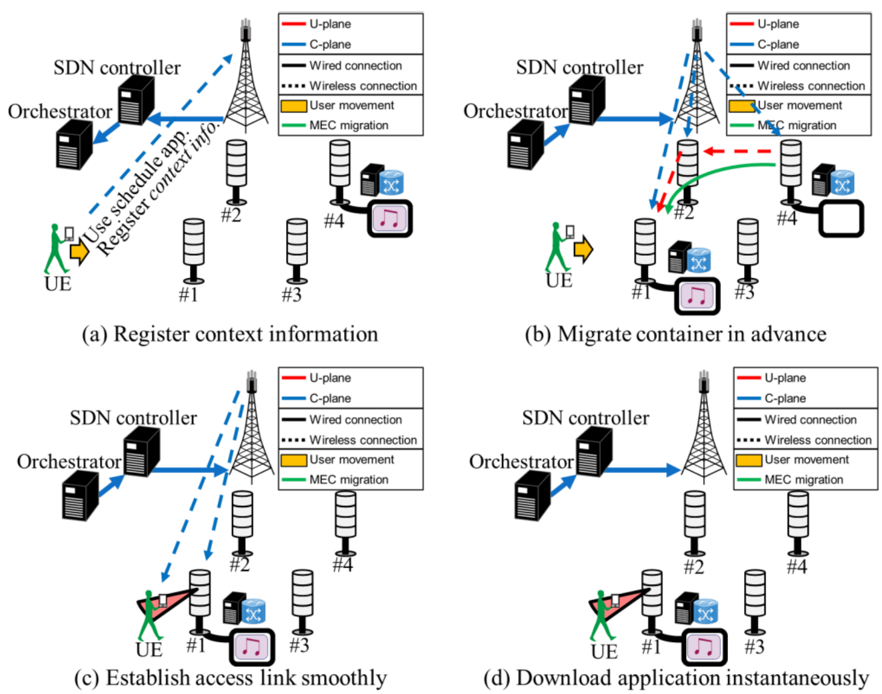


Fig. 5 Flow diagram of prefetching algorithm.

source SC-BS removes container to release the resources. SDN controller commands to establish a link between the container server in the SC-BS and the UE in Fig. 5(c), and the UE starts to download an application in Fig. 5(d). In addition, this paper assumes cloud- typed file storage applications such as Dropbox, Google Drive, OneDrive, etc.

3. Experimental System

This section describes the hardware equipment and middleware system of the PoC.

3.1 Hardware Equipment

This sub-section describes the hardware architecture of the testbed. Figure 6 shows the connection of physical interfaces at each SC-BS. In addition, Fig. 7 shows the overall of hardware architecture.

3.1.1 Control PC at Each mmWave SC-BS

"GBBKi7HA-7500" [28] made by Gigabyte is used as a control PC at each mmWave SC-BS. "Open vSwitch version 2.7.0" [29], [30] is used as a software switch, and "Docker"

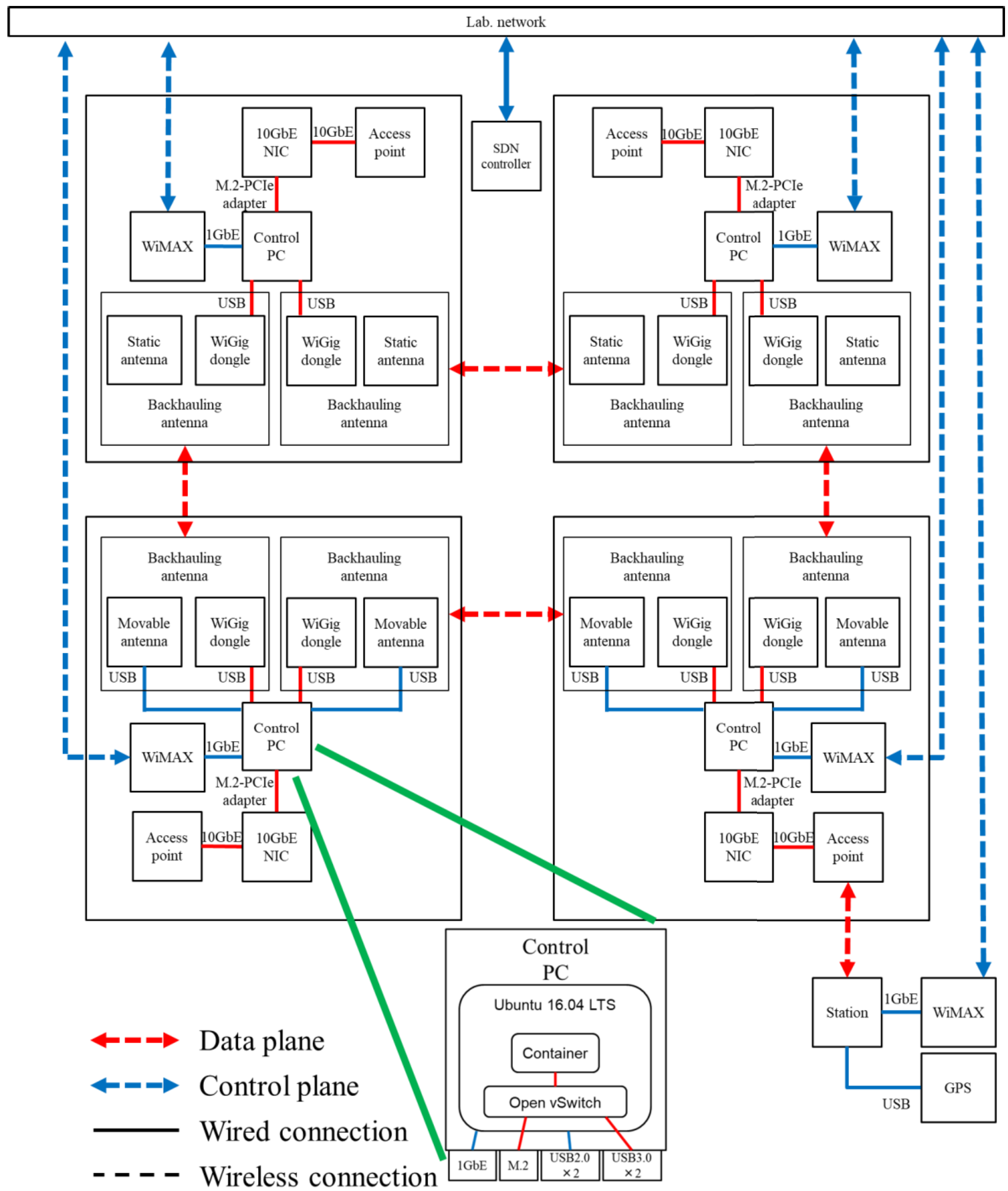


Fig. 6 Connection of physical interfaces.

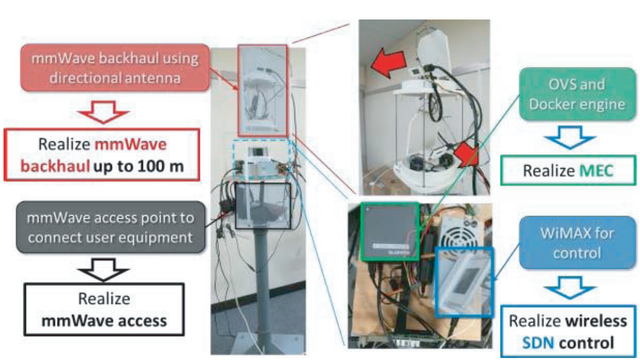
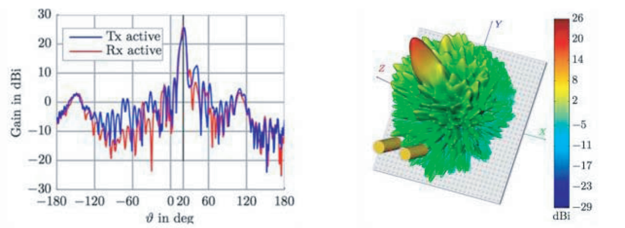


Fig. 7 Overview of hardware architecture.

[31] is used as MEC server. Ubuntu 16.04 LTS server is used as OS, which is implemented with the SDN controllable packet forwarding function and MEC function. In order to connect mmWave APs with 10GbE, the SFP+ port for 10GbE is extended using M.2 SSD slot.

3.1.2 WiMAX for C-Plane

“WX03” [32] made by NEC is used as C-plane. In regard to the performance of the device, the downlink of C-plane achieves a maximum throughput of 440 Mbps, and this paper assumes that there is no bottleneck problem in C-plane which conveys context information. In addition, the C-plane is possible to connect between an external PC used as e.g. SDN controller with mmWave SC-BSs via a port forwarding function with fixed global IP address. The port forwarding function makes it possible to translate the received packet’s destination IP address from WiMAX’s Wide Area



(a) 2 dimension antenna radiation pattern (b) 3dimension antenna radiation pattern

Fig. 8 Antenna radiation pattern [34].

(WAN)-side interface to the control PC's interface. Therefore, the architecture enables outdoor wireless SDN control using micro-wave band communication.

3.1.3 Reflector Antenna for mmWave Backhaul

In order to establish mmWave backhaul links, a reflector antenna is attached to the WiGig chip to extend coverage. The antenna reflects the radio wave emitted from the WiGig chip by changing the phase of radio wave, so that the electric field strength increases in a specific direction. In addition, the WiGig chip is connected to a control PC via USB3.0, and the chip achieves more than maximum throughput of 1.0 Gbps measured by *iperf3* with corresponding modulation coding scheme (MCS) up to 9 [33]. Physical (PHY) layer data rate using MCS9 achieves up to 2.5 Gbps, while that of TCP layer is about a half. In this experiment, the antenna's half power beam widths (HPBW) are 6 deg and 10 deg in azimuth and elevation angles respectively and the directivity gain is approximately 26 dBi [34] as shown in Fig. 8.

3.1.4 mmWave AP and UE

"Nighthawk X10" [35], [36] made by NETGEAR is used as mmWave AP at each mmWave SC-BS, and "TravelMate P648" [36] made by ACER is used as UE. In order to realize Gbps communication, "wil6210" [37] is used as a driver of IEEE802.11ad standard and "QCA9500" [38] made by Qualcomm is used as a WiGig chip. The mmWave AP has a 10 GbE SFP+ port, which is exploited to connect the AP with a control PC via 10 GbE cable. The WiGig chip used in the AP supports MCS up to 12, and achieves the maximum throughput of about 2.0 Gbps when measured by *iperf3*. PHY layer data rate using MCS12 achieves up to 4.6 Gbps. In addition, the maximum coverage is about 30 m and a connection is established for about 90 deg in azimuth domain.

3.2 Middleware System

This sub-section describes the middleware architecture of the testbed. Figure 9 shows the overall architecture of middleware system.

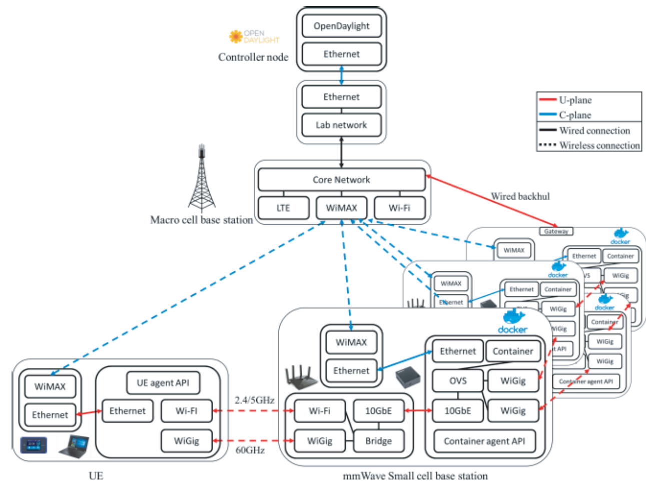


Fig. 9 The overall architecture of middleware system.

3.2.1 OVS for Packet Forwarding

Open vSwitch(OVS) is one of the OpenFlow (OF) switches that can be connected to the OF controller, and that is an open source software (OSS). OF is a protocol that separates the packet forwarding function and the routing management function, and the routing table can be updated immediately by the controller. This routing table is called a flow table, and functionalities such as packet forwarding, rewriting, etc. based on OVS follow this flow table. In addition, the containers can be connected to the network by using the ovs-docker [39] framework.

3.2.2 Docker for MEC Server

Docker is used as MEC server, and it is an OSS which provides a virtualization environment called containers. It is the world's leading software container platform. It can be run by installing the docker on the control PC of each mmWave SC-BS. Docker images on which the container is based store the file system, directories and the setting of containers. Docker container can be built to run the docker image on the docker engine. Container migration in this paper is realized by a process of shutting down the container at a certain node, migrating the image from that node to another one and reactivating the container at the destination node. Because this migration includes stopping and restarting the process, live migration is not possible in this manner. However, high-speed downloads using mmWave access links enable the download time shorter than conventional access links, so stopping and restarting the process does not yield any problems on the UE side, even in this case of non-live migration.

3.2.3 ODL for SDN Controller

OpenDaylight (ODL) is an OSS which provides functionalities of a SDN controller for building programmable networks [40], [41]. ODL can collect context information from the entire network, and implement additional functions such as changing MCS in mmWave mesh backhaul networks, ovs-docker control for MEC, etc. It is mainly implemented using Java language, and typical protocols are NETCONF, OVSDB, RESTCONF, etc. Figure 10 shows the architecture of ODL extended in this paper. The controller is provided with Northbound API that receives/processes instructions from an external PC and Southbound API that operates each SC-BS and UE. Therefore, the setting of each mmWave SC-BS can be optimized automatically through Southbound API by commands to add/delete/update the network configuration through Northbound API from the orchestrator. In addition, it is possible to migrate containers, establish connection between SC-BS and UE, etc. by only extending some functions properly.

This paper adopts the manner to input SDN commands through RESTful (REST: Representational State Transfer) API based on a scheduler which registers all application schedule in advance by a UE (the orchestrator in this paper). For our scenario, we assume that the UE specifies a destination or a desired application in advance. It means that a daily life pattern such as commuting route, commuting time and using application/service is pre-registered by such a scheduler.

In addition, the scheduler can be replaced with an orchestrator-oriented GUI such as Node-RED, which is an OSS operable by running Node.js. The operation of collecting data from GPS navigator, calendar, etc. and outputting the processing results can be implemented by this GUI. Additionally, it provides REST API interfaces, etc. for SDN controller. It also provides user interface (UI) to develop a Node-RED dashboard. Container migration process is executed based on a schedule pre-registered by UE. The experiment assumes that container migration is completed before UE arrives at its target SC-BS.

In this paper, in order to verify the feasibility of this architecture through the developed PoC system, we assume that context information is registered in the scheduler in advance. However, the system also prepares RESTful API to input commands to the SDN controller, that enables our future works such that the orchestrator will generate RESTful API commands by using results of network optimization based on UE's context information.

4. Experiment Environment and Results

This section describes experiment methods, parameters and performance evaluation results. The parameters are shown in Table 2 and experimental environment is shown in Fig. 11 [42].

4.1 Route-Multiplexing

4.1.1 Measurement Method

Figure 12 shows two UEs are connected to mmWave SC-BS and MEC servers corresponding to two UEs orchestrated by SDN controller through REST API interface. After that, backhaul links between two UEs and the MEC server are established adaptively. First, the throughput is measured using *iperf3* when the same backhaul link is used for two flows. Second, the route of one of the two backhaul links is switched by SDN control such that the two backhaul links

Table 2 Specifications of the testbed.

Parameter		Value
Carrier frequency	(Access)	60.48 GHz
	(Backhaul)	62.64 GHz
Bandwidth	(Access & Backhaul)	2.16 GHz
Maximum data rate	(Access)	4.620 Gbps
	(Backhaul)	2.502 Gbps
Number of sectors	(Backhaul)	2
Antenna gain	(Backhaul)	26 dBi
Carrier frequency	(C-plane)	2.6 GHz
Bandwidth	(C-plane)	20 MHz
Maximum data rate	(C-plane)	Down : 440 Mbps Up : 30 Mbps

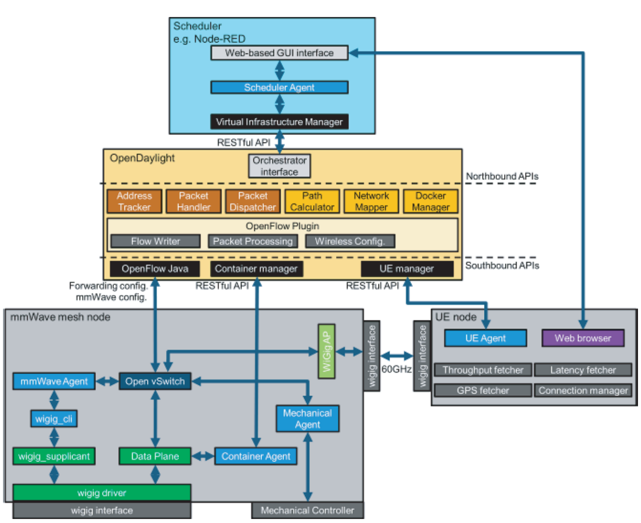
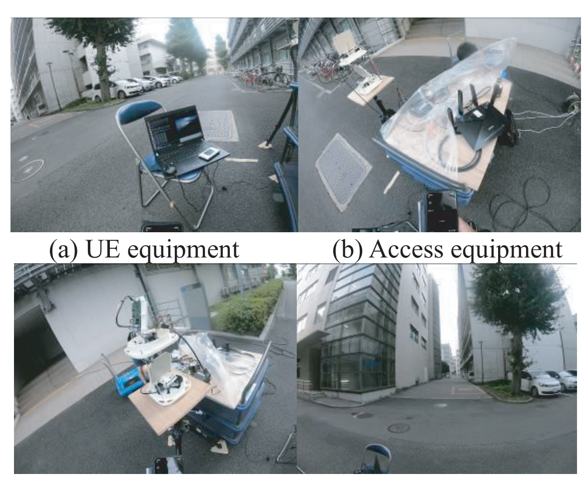


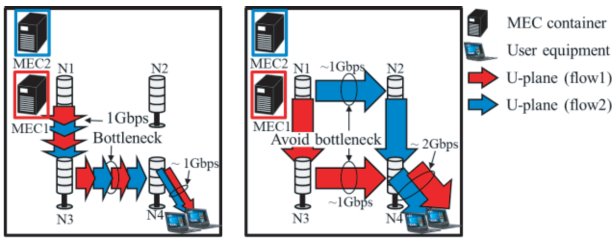
Fig. 10 Architecture of developed SDN controller.



(a) UE equipment (b) Access equipment

(c) Backhaul equipment (d) LOS environment

Fig. 11 Experimental environment of backhauling.



(a) w/o route-multiplexing (b) w/ route-multiplexing

Fig. 12 Experimental environment of backhauling.

Table 3 Result of route-multiplexing.

Method	Flow	Throughput Mean	Throughput Standard deviation	Total throughput Mean	Total throughput Standard deviation
w/o route-multiplexing	1 (Red) 2 (Blue)	441 Mbps 486 Mbps	39.8 Mbps 41.4 Mbps	927 Mbps	8.13 Mbps
w/ route-multiplexing	1 (Red) 2 (Blue)	851 Mbps 848 Mbps	40.6 Mbps 45.4 Mbps	1.70 Gbps	85.6 Mbps

are used for different flows, i.e. route-multiplexing, a mechanism to mitigate backhauling bottleneck. Theoretically, the achievable network throughput must be doubled when introducing route-multiplexing. It is noted that the throughput of mmWave access link is twice that of the mmWave backhaul link as a fact of device constraints.

4.1.2 Performance Evaluation Result

The performance evaluation result is shown in Table 3 when measuring 10 times. The throughput is measured for 10 seconds using Transmission Control Protocol (TCP). Since TCP is a protocol used for communication with general Web applications, it is synonymous with the throughput when application downloading is actually performed. When route-multiplexing is used, it is confirmed that the system rate is improved even when actual UE device is used. In fact, the result with route-multiplexing was 1.83 times higher than that without it. The value of standard deviation with route-multiplexing is larger than that without route-multiplexing because of higher probability of contention of mmWave access [36]. In the future, we will implement an orchestrator that predicts the traffic distribution based on UE's GPS information, requested application, connection destination, etc., and automatically allocates multi-backhaul links to cope with intensive traffic.

4.2 Prefetching Algorithm

4.2.1 Measurement Method and Parameters

The performance of prefetching algorithm is evaluated via download time of real traffic data. Container migration was realized automatically by commanding REST API to SDN controller at the set time, which is based on the scheduler registered in advance by UE. The scheduler is determined based on user's moving speed, normal throughput of access and backhaul, container start-up time, etc. which are shown in Table 3.

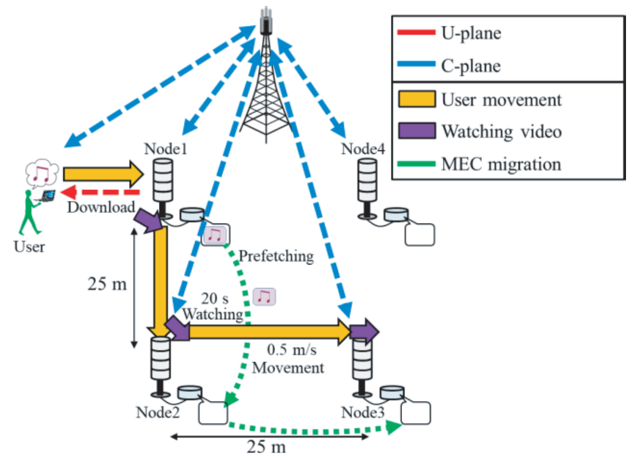


Fig. 13 Experimental environment of prefetching.

All SC-BS and UE receive REST API commands from SDN controller to implement the prefetching algorithm based on the scheduler. The experiment environments and schedule of prefetching algorithm are shown Figs. 13 and 14 respectively. At first, UE stays at Node1 and connects to the nearby SC-BS using mmWave access. After UE finished downloading 4K video, UE waits a few seconds for watching the video.

At the same time, each node starts container migration, which includes processes of stopping container, transferring container image among the SC-BSs and starting up container at another SC-BS. After watching the video, UE starts moving from the source node to the destination node. The testbed was designed to finish container migration just before UE arrives at the next node.

The time schedule is calculated by the following equations, and the parameters of which are summarized in Table 4. Generally, walking speed is about 1.0 m/s, but the experimental environment is more densely arranged than realistic BS interval, therefore the walking speed is scaled down to 0.5 m/s in our scenario. Additionally, we assume that the watching time of the downloaded content is about 20 seconds, so UE stays for 20 seconds in each BS before moving to the next one. The container migration time can be calculated from Table 4 and the formula in this paper, and the mmWave backhaul route reconfiguration time can also be derived from [43]. Therefore, it is possible to deploy mmWave SC-BS embedded with container migration function even in capacity-limited backhaul environment like Ethernet, if the systems are carefully designed in advance as in Fig. 14. In addition, the scheduler will not need to consider migration time if live migration function, considered as the paper's future works, is introduced.

In this paper, for the evaluation of the developed PoC, we assume perfect knowledge about the UE's destination and the required content, although context information prediction as dealt in [44] is out of scope of this paper.

$$\text{Download [s]} = \frac{8 \times \text{Data size [Byte]}}{\text{Throughput of Access [bps]}}$$

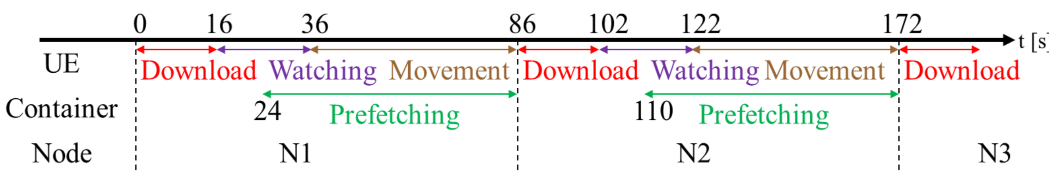


Fig. 14 Scheduler of prefetching algorithm.

Table 4 Parameters for creating scheduler.

Parameter	Value
Throughput of Access	1Gbps
Throughput of Backhaul	700Mbps
Data size of image	2GByte
User speed	0.5 m/s
Inter-site distance	25 m
Container start-up time	40 s
Waiting time for watching video	20 s

Table 5 Result of prefetching algorithm.

Method	Download time [s]					
	@node1		@node2		@node3	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
w/o prefetching	106	0.73	200	0.41	191	0.31
w/ prefetching	110	0.16	102	0.68	100	0.50

$$\text{Prefetching [s]} = \frac{8 \times \text{Data size [Byte]}}{\text{Throughput of Backhaul [bps]}} + \text{Container start up time [s]}$$

$$\text{Movement [s]} = \frac{\text{Inter site distance [m]}}{\text{User speed [m/s]}}$$

$$\text{s.t. Prefetching [s]} \leq \text{Waiting [s]} + \text{Movement [s]}$$

First, download, prefetching and user movement time is calculated. Second, we set waiting time for watching video, and determine whether prefetching is possible or not. Final, if prefetching time is shorter than the sum of waiting time and moving time, the orchestrator decides to conduct container migration.

4.2.2 Performance Evaluation Result

As this paper focuses on the evaluation of the proposed context-based orchestration mechanism, we performed experiments with only one UE, however the system can be easily generalized to more complicated scenarios of multiple UEs. Also, the performance evaluation on C-plane side has not been conducted, which will be considered in our future works.

Table 5 shows the result averaging over 10 times repeated measurements. The video data size is about 2 Gbyte, and UE downloads it using File Transfer Protocol (FTP). FTP command's protocol is based on TCP. Therefore, the result shows download time when the application uses TCP. In case of container migration utilizing prefetching algorithm, it is confirmed that the download time of 4K video does not change significantly because the location of the container of the UE is changed automatically by SDN control via C-plane in accordance with the schedule even if the UE moves among different target nodes. On the other hand, download time increases as the number of hops increases when the container server is fixedly deployed on Node 1, in other words, w/o MEC (and migration) case. It can be deduced that packet error rate increased due to multi-hop relay which incurs the increase of re-transmission requests might be the reason for the worsen phenomenon, and there are bottlenecks in backhaul links. In addition, standard deviation was less than 1 second, that reveals the stability of the developed system.

5. Conclusion

Based on the previous works proposing the prefetching/orchestration algorithm and route-multiplexing with numerical analysis, this paper evaluated these algorithms using the developed testbed for ICN/CDN system, enabled by SDN/NFV technologies. The architecture of the PoC implements these technologies from both hardware and middleware perspectives. Docker is used as MEC server, and OpenDaylight is used as SDN controller. In the route-multiplexing experiment, the result was 1.83 times higher than that without it even when actual UE is used. In the prefetching experiment, it is confirmed that the download time does not change because the location of MEC application is migrated automatically by SDN control via C-plane in accordance to the schedule even when the UE moves among different target nodes. We evaluated a single system of combined technologies, i.e., mmWave backhaul route-multiplexing and MEC with prefetching algorithm, of which the former helps avoiding expensive wired backhauling and the latter helps reducing latency owing to the deployment of application server at the edge of the network. This paper revealed that the proposed architecture can fully meet 5G requirements in terms of system rate, latency and cost.

In the future works, the testbed will be upgraded with other functionalities and more experiments will be conducted on extended use cases, e.g., from video streaming in this paper to multi-sensor fusion in V2X (Vehicle-to-Everything) scenario.

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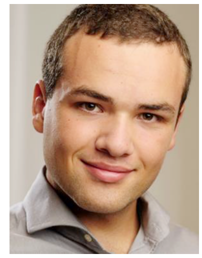

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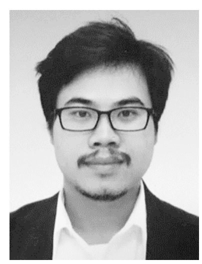

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