HomeCloud: An Edge Cloud Framework and Testbed for New Application Delivery

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Abstract— Conventional centralized cloud computing is a success for benefits such as on-demand, elasticity, and high colocation of data and computation. However, the paradigm shift towards "Internet of things" (IoT) will pose some unavoidable challenges: (1) massive data volume impossible for centralized datacenters to handle; (2) high latency between edge "things" and centralized datacenters; (3) monopoly, inhibition of innovations, and non-portable applications due to the proprietary application delivery in centralized cloud. The emergence of edge cloud gives hope to address these challenges. In this paper, we propose a new framework called "HomeCloud" focusing on an open and efficient new application delivery in edge cloud integrating two complementary technologies: Network Function Virtualization (NFV) and Software-Defined Networking (SDN). We also present a preliminary proof-of-concept testbed demonstrating the whole process of delivering a simple multi-party chatting application in the edge cloud. In the future, the HomeCloud framework can be further extended to support other use cases that demand portability, cost-efficiency, scalability, flexibility, and manageability. To the best of our knowledge, this framework is the first effort aiming at facilitating new application delivery in such a new edge cloud context.

Keywords—Cloud Computing; Edge Cloud; HomeCloud; Internet of Things; Network Function Virtualization (NFV); Software-Defined Networking (SDN)

I. Introduction

Conventional centralized cloud computing proved to be a huge success for benefits such as on demand, elasticity, and high colocation of data and computation. The economics of such highly centralized cloud computing strongly favor centralized infrastructure with a few large data centers. It was broadly adopted by many corporations. Facing the future, however, there are several unavoidable challenges for such centralized cloud model. **Firstly**, the Internet is experiencing a paradigm shift toward the "Internet of Things" (IoT), which will potentially network billions (even trillions) of devices. Current application delivery highly depends on the giant companies' proprietary overlays, and data from the edge devices generally have to be transferred to the remote data centers, which will not be possible considering the massive and ever-increasing amount of data in the future. **Secondly**, conventionally centralized cloud model also means that the edge devices (often mobile) are usually far away from the remote data centers. High latency can be a tremendous challenge for quite a number of applications involving end-to-end communications. Typical examples include real-time video monitoring, face recognition, and augmented reality applications. **Thirdly**, applications are usually not portable across platforms. Expensive centralized clouds often use proprietary protocols. Customers are stuck to some specific infrastructure and the cost of switching to other infrastructure could be dreadful. Such lack of openness could lead to monopoly and ossification of the Internet, which further inhibits innovations, especially for those small and medium-sized vendors or Application Service Providers (ASPs) who are the most active and innovative groups for the Internet community.

To address the above challenges, an open edge cloud framework seems inevitable and necessary to break monopoly and embrace the IoT paradigm shift. Edge cloud is drawing increasing attention from both academia and industry whose importance was reflected when three "Looking beyond the Internet" workshops of National Science Foundation (NSF) were held at the beginning of year 2016. Two example efforts are Cloudlet and Fog Computing [1, 2]. However, for now, it is still in a very early stage and there are a lot of challenges ahead. Specifically, edge cloud orchestration and application delivery approaches and mechanisms are important necessities to enable edge cloud. Thus, in this paper, we propose a new HomeCloud framework for the edge cloud to efficiently deliver future new portable applications over a shared edge infrastructure. To do that, it aims to coherently integrate two emerging and complementary technologies: Network Function Virtualization (NFV) and Software-Defined Networking (SDN). Using NFV in the edge, local computing, storage, and networking are available and close to edge mobile devices for those applications that generate massive volume of data and require low latency. SDN, on the other hand, is very suitable to work with NFV to network, configure, control, and manage the Virtualized Network Functions (VNFs) created in the edge cloud. Organically integrating NFV and SDN in edge cloud potentially opens a new door for innovative, fast and cost-efficient applications delivery and deployment.

The major contributions of this paper are summarized as follows:

(1) We present the HomeCloud orchestration and application delivery framework in edge cloud, which is significantly different from the application delivery mechanism in traditionally centralized cloud. To the best of our knowledge, our effort is the first about facilitating new application delivery in such a new edge cloud context.

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(2) The HomeCloud framework integrates NFV and SDN. It facilitates NFV and SDN coherence in the edge cloud, which includes the general framework, functional components, coordinate interfaces, and interactions between them. HomeCloud is designed to be open to break monopoly and nurture innovations from especially those small and medium-sized application providers.

(3) We discuss two use cases and scenarios that can be delivered over the HomeCloud framework. Although it takes time before the real "killer applications" emerge for edge cloud, it is important to envision such use cases and scenarios that could be turned into realities in the future.

(4) We build a unique HomeCloud proof-of-concept testbed and demonstrate the whole process of the cloud orchestration and application delivery of a simple multi-party chatting application.

Note that the results discussed in this paper represent the latest progress of our ongoing research project. The rest of this paper is organized as follows. Section II presents the detailed HomeCloud framework and designs. Section III describes example HomeCloud use cases and scenarios. In Section IV, we discuss a proof-of-concept testbed we build. Section V is the related work. Section VI is conclusions.

II. HOMECLOUD FRAMEWORK AND DESIGN

This section is about the general HomeCloud framework and designs.

A. *HomeCloud Framework, Components and Interactions*

The central idea of HomeCloud is built on top of the integration of NFV and SDN. The research on development, application and standardization of NFV and SDN are all early stage and they are being carried out by different organizations. Under such context, one of the major challenges is how we could enable NFV and SDN to coexist and coherently work together to realize our overall vision. Such coherence mechanism would help the research community deepen understanding of NFV and SDN respectively and synergistically, even though both of them are evolving rapidly and separately. HomeCloud represents such an effort.

Particularly, in Fig. 1, we provide an illustration of the NFV and SDN ecosystem. We divide it into two correlated domains: technical domain and stakeholders' domain. The right-hand side technical domain denotes the interaction and synergy between NFV and SDN, and the customers' new application delivery can be facilitated with automated orchestration and management capabilities. The left-hand side is the stakeholder's domain, and it requires the Internet Service Provider (ISPs) and ASPs to work together to mutually benefit from the new architecture for healthy evolution. Also, ISPs and ASPs have strong motivations to protect their existing investments and the coexistence and transition mechanism are of importance. The intersections of the two domains are the technologies coherently connecting them. Specifically, they are virtualization provided by NFV and centralized control/configuration/programmability provided by SDN.

Fig. 2 illustrates the framework and building blocks and their interactions in more details. Lower layers of the NFV infrastructure consist of virtualized compute, network and storage that interact with the hardware resources via a hypervisor. In this framework, NFV needs to provide networking capabilities to the VNFs to form virtual networks for specific new applications. The virtualized overlay network works exactly like the physical network but with more flexibility, scalability, and re-programmability. The SDN side is organized as three major planes: application, control, and data planes. The VNFs on the NFV side correspond to the Network Elements on the SDN side. Particularly, the SDN controller is in charge of the control, configuration, monitoring, and programming of these VNFs. On top of the SDN controller are various new applications to be deployed.

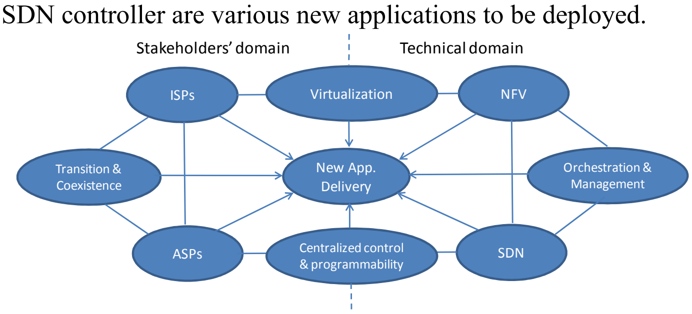

Fig. 1. An illustration of the new NFV and SDN ecosystem

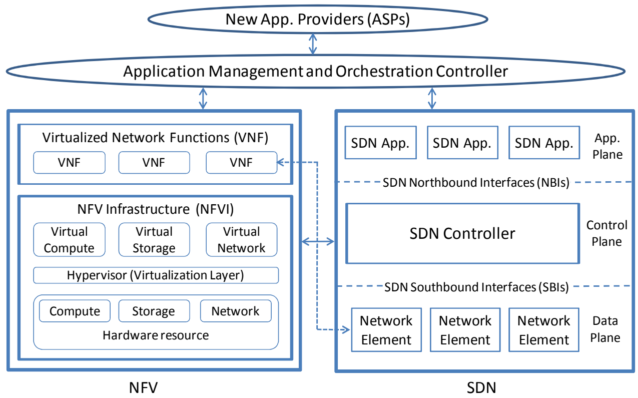

Fig. 2. HomeCloud framework, building blocks and their interactions

Between the application plane and control plane are the SDN Northbound Interfaces (NBIs), and the SDN Southbound Interfaces (SBIs) stand between the control plane and data plane. The application management and orchestration controller manages the whole platform. It turns the new ASPs' Service Level Agreements (SLAs) into executable schemes for the new application and achieves abstraction and further application portability.

B. *Efficient Orchestration and Application Delivery*

Conventional centralized cloud is proprietary and the cloud owners and providers are generally giant corporations. Facing the incoming edge cloud "game changer", in our HomeCloud framework, we aim to create an open and coherent platform to break monopoly and promote innovations by small and medium-sized vendors. For edge cloud application orchestration and delivery, a northbound approach is needed to turn the high-level objectives from SLAs into the real deployment of the application, which is significantly different from those in the conventional centralized cloud. We illustrate an example network scenario for HomeCloud application delivery in Fig. 3. In this scenario, the edge has various applications. The edge clouds run NFV and virtualize the compute, network, and storage resources. There will be at least one Virtualized Application Server (VAS) at the edge for each of the new applications (more than for applications such as virtual reality that need intensive data, computation, or coordination).

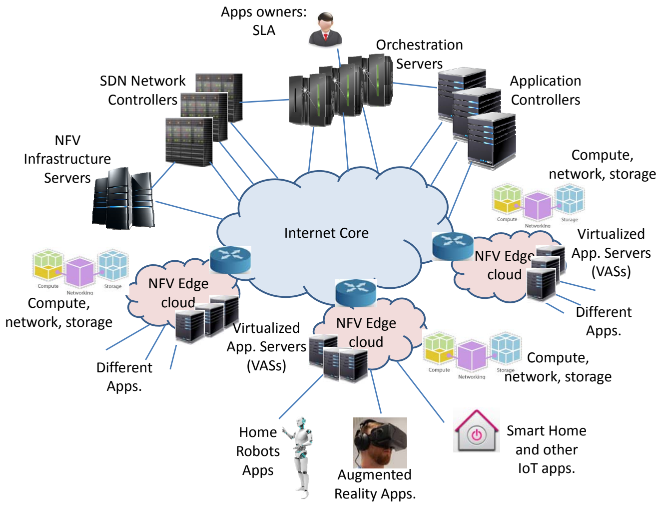

Fig. 3. Example network scenario in HomeCloud

The VASs are typically VNFs launched by the NFV infrastructure and they act as the entry servers to the application users. The VASs also access virtualized compute, network, and storage in that edge cloud. The NFV infrastructure consists of a series of separate logical functioning units such as controller node, network node, and a series of computing nodes. The VASs are launched and are usually close to the application users. The top parts in Fig. 3 are various HomeCloud controllers and servers. Particularly, orchestration servers sit between application owners and the real technical application delivery process to meet the demands from the application owners.

After the VASs are launched, the SDN controllers are responsible for the monitoring, configuration, control, and maintenance of the VASs. We use OpenFlow for the SDN controllers. The final set is the application controllers. Their typical functions are to maintain application-level topologies, and monitor and control application-level functional entities.

We further illustrate the internal logical interactions and the interfaces between the functional components in Fig. 4. Some of the fundamental components and their major functions and purposes are listed and briefly discussed:

(1) **Providers of the new applications**. They are usually various ASPs that have full knowledge about the customers' demands that the to-be-delivered application plans to achieve.

(2) **Application orchestration servers**. They turn the ASPs' demands into scripts allocating and managing specific resources by coordinating with other controllers and servers.

(3) **Application controllers**. They track, monitor, and manage the application-level entities and topology. Typical application-level entities include various VASs.

(4) **NFV infrastructure servers**. They are virtualization controllers that directly allocate and manage the compute, network, and storage resources over the edge cloud and they dynamically launch VASs.

(5) **SDN controllers**. They are responsible for the control, configuration, monitoring, and programming of the launched VASs to form a workable overlay network for a particular application. They interface with the VASs through network control interfaces and a typical protocol example is OpenFlow.

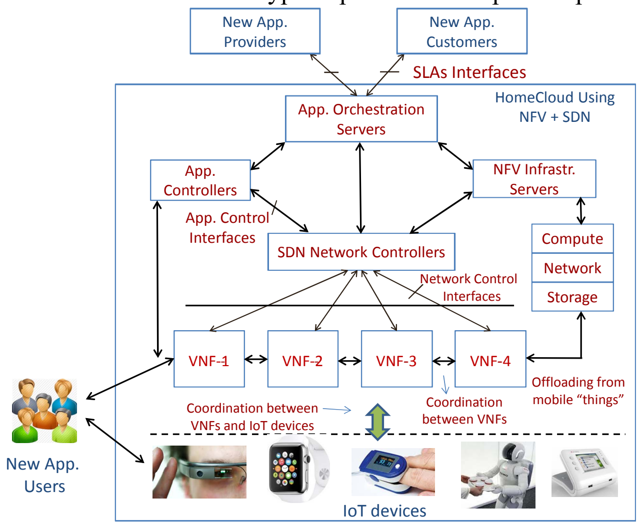

Fig. 4. NFV and SDN Logical building blocks and their interactions in HomeCloud

Fig. 4 shows that multiple interfaces standing between different categories of servers for functional coordination and interactions. From top to bottom, they are SLA interfaces, Applications Control interfaces, and Network Control interfaces. The SLAs interfaces define the mechanisms translating application owners and customers' high-level demands into recognizable and executable scripts to the application orchestration servers. The Application Control interfaces are essentially SDN Northbound Interfaces (NBIs). The Network Control interfaces at the bottom define SDN Southbound Interfaces (SBIs). NFV infrastructure servers manage the virtual network, and launch and configure the VASs that work for the application users. These interfaces and their interaction mechanisms are usually defined by an Infrastructure-as-a-Service (IaaS) cloud platform (e.g., Openstack). These VASs of edge-cloud application routers can be flexibly launched close to the users to achieve best performance matching the SLAs between ISPs and ASPs. The management and orchestration servers work with application controllers and SDN controllers to accomplish multiple tasks to ensure a successful new application delivery.

To deliver a specific new edge-cloud application, a typical process can be approximately described as the following steps:

(1) **Reading Demands**. The demand specifications of the application are presented to the orchestration servers. They include the basic descriptions, expectations, scales, parameters, and the required resources. Such specifications are sent through the SLAs interfaces as a machine-understandable scheme.

(2) **Sending Coordination Requests**. The application orchestration servers check the demands from the descriptive scripts and send out coordination requests to the other functional servers such as application controllers and NFV infrastructure servers.

(3) **Resources Allocation and Provision**. The NFV infrastructure servers receive coordination requests and check available resource in compute, network and storage pools. If enough resource is available and policies permit, they will allocate corresponding resource and launch VASs.

(4) **Configuring and Managing VASs**. The launched VASs are configured and managed by the SDN controllers which allow virtual overlay networks to be created to serve for a specific new application. The SDN controllers pass the application-specific information to the application controllers.

(5) **Application-level Monitoring, Control, and Management**. The application controllers collect all the application-level information for the virtualized overlay networks. Typically, they will maintain the application-level topology and status, which are used and managed by application administrators.

After the above 5 steps are finished, the new application requests are turned into the real implementation and the application is successfully delivered.

With HomeCloud, if enough physical resources are available in the edge cloud, when additional new applications need be delivered, they do not need to buy and deploy new physical equipment. Instead, all they need to do is to provide a new application demand scheme and HomeCloud would go through the above steps and build a customized virtualized overlay network serving for the new application without any significant additional costs.

III. Example HomeCloud Use Cases

Edge cloud will be an intensive place for future application and potentially there will be tons of use cases in such environments. In this section, we will discuss two example use cases that can be delivered in the HomeCloud framework.

A. Heterogeneous Home Robots Work in a Human-centric Mode

For the first use case, we envision home robots with networking capability. We consider the use case of putting networked home robots as the center of a smart home. Such home robots can provide health care, elder care, interactive entertainment, communication, cleaning, and home security services. Right now, if you purchase a home robot such as an iRobot, it is a standalone device and may not be equipped with advanced networking services. Such service is not available in our real life yet. In HomeCloud we have NFV and SDN enabled edge data center. Suppose a small ASP wants to deploy a new portable application that integrates multiple home robot types from different vendors into a human-centric application in which multiple home robots work around an elder or home owner in a coordinated manner. With HomeCloud, this ASP can create a new application that launches multiple virtualized servers in the HomeCloud data center using NFV. One or more such virtual instances serve one type of home robot and multiple virtualized servers can network and create interactions to serve a common purpose, for example, working around and reporting to the target elder or home owner. Through such integration and coordination, we essentially enable a much more powerful use case. Moreover, some of these home robots are designed to provide video monitoring, face recognition, speech recognition, and augmented reality services which may require intensive computation, large storage or low networking latency. The tasks can be offloaded from the resource-poor home robots to the HomeCloud elastic virtual instances which can be created dynamically to match the specific demands. In terms of the complete application orchestration and delivery process, we need to prepare a portable and abstract specification describing the demands from this particular application. Then this specification is parsed into detailed resource allocations in HomeCloud edge data center. The virtual servers (VASs) are launched, and one or more such virtual servers work coherently with a robot or a type of robots. Using SDN, these virtualized servers are networked and they are put into the same private group to deliver services for the elder or home owner. More security specific virtualized instances can be launched to work as a firewall or access controller to the private home robot network for the new application. Then the whole process of the new application orchestration and delivery is finished.

B. Augmented reality and 3D shopping mall navigation.

The second use case we envision represents a series of potential applications related to virtual reality (VR) or augmented reality (AR) for multiple applications including 3D navigation in all kinds of places. The "Oculus Rift" helmets are a typical example. We consider the use case of putting multiple wearable augmented reality devices into a virtual space and they can interact with each other. Supposedly they are all in a single smart home served by a HomeCloud data center. Such service is not available in our real life yet. Now suppose a specific small or medium-sized ASP wants to provide this new application in a home. First of all, such individual helmets need intensive computation assistance in the edge cloud and we could launch virtual servers to help the helmets offload the computationally intensive tasks. In reality, multiple such virtual servers could be launched to achieve the task. If multiple persons wearing these helmets need to interact, then apparently the virtual servers serving different persons need to be networked and exchange information in very high speed for best user experience. Similar to the home robots use case, to deliver such new applications, the ASP needs to prepare a portable abstract specification describing the requirements for this particular application. Then the objectives are parsed into detailed resource allocations and the new application is orchestrated and realized in the HomeCloud platform. More advanced security-related virtual instances can also be added. Again, everything is elastic due to the usage of NFV and SDN.

IV. Proof-of-Concept Testbed

In this section, we discuss a proof-of-concept testbed and show the process of delivering a simple multi-party chatting application.

Through this testbed and experimentations, our goals are to demonstrate that: (1) new applications can be launched dynamically and flexibly on the testbed, (2) NFV and SDN can be integrated coherently in the edge cloud.

A. Testbed Descriptions

In the testbed we use Openstack for NFV and OpenFlow for SDN, due to the openness of these platforms and our previous research experience on these two platforms. The example application scenario is the CCNx [12] chatting service which is a typical Information-Centric Networking (ICN) application. However, note that many more other future applications such as IoT and smart-home applications can also be delivered over the shared HomeCloud environment with appropriate isolation. The conceptual structure of the testbed is shown in Fig. 5.

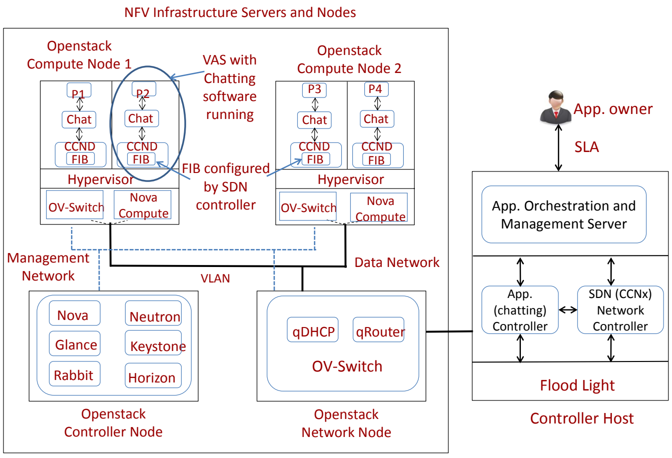

Fig. 5. HomeCloud application delivery proof-of-concept testbed

The left-hand side of the figure is the NFV Infrastructure based on Openstack in which we use 2 compute nodes, 1 controller node, and 1 network node. For the testbed, each of the nodes is presented as a real physical server. To launch the new chatting application, the first thing is that the edge cloud orchestrator turns the application owner's requirements into resource allocation and assignment scripts which further turns into the detailed configuration in the OpenStack and launches appropriate number of Virtual Machines (VMs) to act as chatting service "routers" which act as the service entry points. These chatting service "routers" are also called Virtualized Application Servers (VASs) and are launched into the compute nodes as VMs with load balancing capability. In the future real production deployment, these VASs will be only application servers and the chatting client software will be installed only in the users' own machines. After the VASs are launched correctly, the SDN controller configures the FIBs in each of these VASs to setup overlay network connections for the new chatting applications. The right-hand side of Fig. 5 is the controller host; we integrate three servers' function into the controller host for simplification but their logical functions are separate and should be implemented individually in the real production. The three servers run on OpenFlow to communicate, configure and monitor the application VAS launched in the Openstack compute nodes. The more specific deployment scenario of the NFV module is shown in Fig. 6.

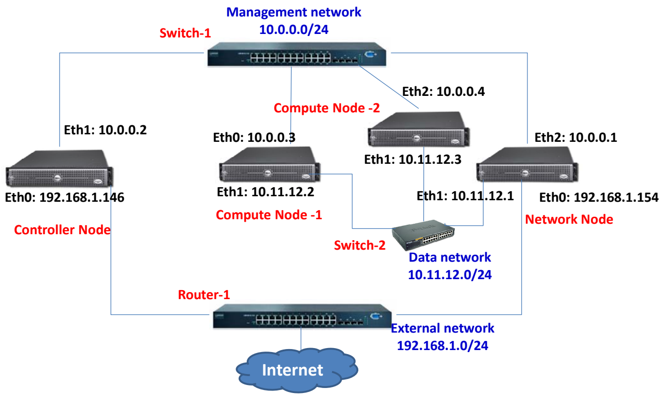

Fig. 6. Detailed deployment scenario in the testbed

Worth noting that in this deployment, it consists of three networks: management network, data network and external network. Basically it is for traffic isolation and security purposes. The management network is for the internal communications among the controller, compute, and network nodes. Data network is for the actual production traffic from the VNFs which is acting as the application entry point for the users.

B. Testbed Experiments and Results

The implementation and test results show the success and effectiveness of HomeCloud framework. After the testbed is setup and configured appropriately, we are able to launch the VASs into any of the two compute nodes with load balancing configurations. The CCNx chatting software is installed all the VASs and the SDN controller monitors the status of the chatting software run in the VASs. The application controller also talks to the SDN controller monitoring application servers' (VASs) topology and tracking the application-level users' activities and status. The Forwarding Information Bases (FIBs) in each of the VASs is configured by the SDN controllers to be able to forward the data packet and find each other. The application orchestration and management server turns the application owners' demands into real resource allocation scenario and reserve compute, network, and storage resources accordingly. The specific number of VASs will be launched by the NFV platform to match the application owner's demands. After the FIBs are configured appropriately by the SDN controller, the normal CCNx-based chatting application is delivered. Fig.7 shows that the two CCN chat clients (top and bottom) were running in the launched VASs located in two separate VASs and they are configured by SDN controllers and after the flow rules are configured appropriately in the two

VASs, they are able to see each other and the two chatting clients are also able to talk to each other.

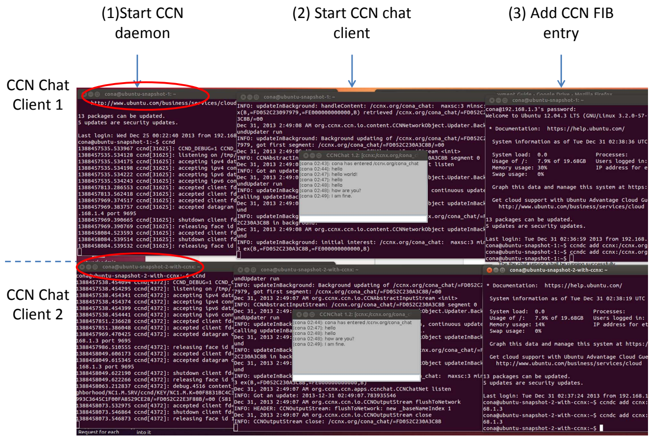

Fig. 7. Two CCN chat clients successfully talk to each other in the launched applications in HomeCloud

Moreover, this deployment can be changed, rescaled, and failover on the fly, which is a great flexibility provided by HomeCloud. Also, the policy configurations of these VASs can be done very efficiently.

V. Related Work

We did a broad literature survey on comprehensive topics related to the work of this paper. However, limited by the length, we will not enumerate all the contributions here. Overall, the number of state-of-the-art research directly comparable to ours is strictly limited since it is a relative new area. Some of our previous works that are directly related have been published [3, 4]. A SDN ICN edge service [5] focuses on implementing ICN applications in edge routers using SDN. Regarding edge cloud and edge computing, some recent years' related papers include the cloud orchestration scheme in NSDI 12' [6] and SOCC'11 [7]. Numerous other important related work about concepts of edge computing are in form of "cloudlet" [1] from Carnegie Mellon University group, FemtoClouds [8] from Georgia Tech group, Nebula [9] from University of Minnesota, and fog computing [2] concept from Cisco. Europe has initiated a "Mobile-Edge Computing Initiative" (MEC) [10]. One of the important traits of the MEC strategies is that it puts a lot of focuses on the 3G/4G/LTE mobile edge computing infrastructure. Open Networking Foundation (ONF) started a northbound interfaces working group that is working on specifying an intent-based interface to the SDN controllers which can potentially facilitate cloud orchestration. OpenDaylight is a typical vendor-driven group defining northbound interfaces for SDNs. In academia, there are also some other related papers on a northbound approach [11]. But so far, none of them provide comparable solutions and ideas in edge cloud as in our proposed project. There are also related works on NFV and SDN respectively. For example, NFV Research Group (NFVRG), SDN Research Group (SDNRG) and ONF are three representative organizations.

VI. Conclusions and Future Work

Conventional centralized cloud computing faces challenges when facing the IoT paradigm shift where huge volume of data and low latency requirements are normal for many applications. Edge cloud seems to be a viable and emerging direction. In this paper, we proposed an open HomeCloud framework to facilitate new application delivery in the edge cloud. We adopted an integrated NFV and SDN design and illustrated how they can coordinate to achieve the design goals. HomeCloud aimed to break monopoly and allow small and medium-sized ASPs to innovate in edge cloud with less expense and more flexibility. We also discussed some typical use cases and built a proof-of-concept testbed to validate the whole delivery process of a simple multi-party chatting application. The results discussed in this paper represent the latest progress of our ongoing research project. Our future work includes a northbound approach to achieve application portability across platforms in edge clouds. Further new findings and results will be presented in our future publications.

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