

A SOFTWAREZARIZED PARADIGM FOR MOBILE VIRTUAL NETWORKS

Overcoming a Lack of Access Infrastructure

Nhu-Ngoc Dao, Umar Sa'ad, Viet Cuong Vu, Quang Dieu Tran, Eun-Seok Ryu, and Sungrae Cho

Market analysis reports suggest that the mobile virtual network operator (MVNO) market will experience subscriber growth at a compound annual growth rate (CAGR) of 10.7% from 2014 to 2020. This optimistic news presents great opportunities as well as many challenges. The major issue lies in the MVNOs' lack of spectrum allocation and an end-to-end network infrastructure, which means they must rely on mobile network operators (MNOs) for wireless access network connectivity to service their customers. In this article, we propose an approach that provides alternative wireless access methods to enable MVNOs to minimize their dependency on MNO networks. This leverages the fifth-generation (5G) softwarezation technologies to provide selective multipath device-to-infrastructure (D2I) connections and service assortments. Supervised by software-defined networking (SDN)-based edge controllers, the multipath D2I connections provide flexible user data delivery over available communication resources without strict consideration of the MNO's infrastructure

restraints. Additionally, a priority-based classification policy is applied to user data providing service assortments before it reaches the network infrastructure. Multiple pilot scenarios are implemented to verify the feasibility and performance tradeoff between the communication metrics of the proposed approach.

Emergence of Mobile Service Providers

In recent years, a new group of mobile service providers known as *MVNOs* has emerged to provide differentiated services, such as in-vehicle infotainment, retail, and roaming services to customers in niche markets. These operators have neither spectrum allocation nor complete mobile network resources, especially in access infrastructures. Therefore, they usually depend on the wireless communication infrastructure provided by MNOs to service their customers. As a result, this dependency on MNOs limits their ability to introduce innovative services in a timely manner.

Additionally, some MVNOs focus primarily on marketing and sales or cooperate with MVN enablers and aggregators (jointly referred to as *MVNE* for the remainder of this article) to reduce capital expenditure (CAPEX)

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for revenue maximization. Figure 1 shows a comparison of full MVNO, light MVNO, and MVNE, with respect to MNO. The MNOs own and provide end-to-end wireless communication infrastructure and services, including radio spectrum allocation, wireless access and backhaul infrastructure, and billing and customer services. Conversely, the full MVNOs provide all services except the wireless network infrastructure, while the light MVNOs mainly focus on marketing operations, customer relations, and, optionally, billing systems and subscriber management. Finally, the MVNEs provide core network, billing, and subscriber management systems to aggregate and facilitate light MVNOs with corresponding features. Even though the respective MVNO types have different capabilities and business interests, they both lack a wireless network infrastructure.

Fortunately, the rapid development and convergence of 5G network softwarization technologies, including SDN, network function virtualization (NFV), and fog/cloud computing, present great opportunities for MVNOs. These technologies provide a harmonized and elastic infrastructure that is required for emerging applications and services such as the social Internet of Things (SIoT), machine-to-machine (M2M) communications, over-the-top (OTT) services, and ubiquitous data mining [1], [2]. This fits perfectly into the strategy of next-generation MVNOs, focusing on social services rather than traditional cost-oriented ones. As a result, global MVNO subscribers are expected to exceed 300 million by 2020, which represents a CAGR of 10.7% from 2014 to 2020 [3]. Unfortunately, the scarcity of technological and infrastructural knowledge, the dependency on the MNO infrastructure, and the associated contract constraints are issues that must be resolved prior to benefiting from such opportunities. It is therefore necessary to find innovative ways to enable MVNOs to interact directly and control services on user equipment (UE) to successfully provide an increasing number of new services.

Most existing research aims primarily at exploiting cooperative solutions that share radio resources between MNOs and MVNOs. For instance, the MNO might lease out its free mobile channels to the MVNOs based on timing duration or specific services (e.g., voice and virtual private networking services). Such approaches are inspired by concepts from areas like game theory, cognitive wireless access methodology, and femtocell utilization [4], [5]. Although this provides the MVNO with some management and control of the access network

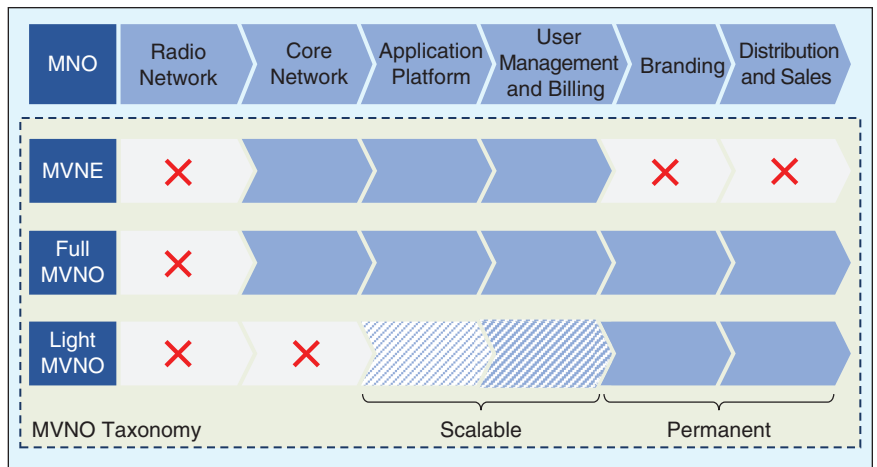


FIGURE 1 The MVNE, full MVNO, and light MVNO versus the MNO.

infrastructure, in almost all cases, it also makes CAPEX and the network complexity increase proportionally. Moreover, there are no guarantees regarding business profits because the MVNO must balance the pros and cons of physical infrastructure investment.

In this article, we propose a feasible approach that provides alternative access methods for MVNOs. Based on 5G softwarization technologies, the proposed approach provides selective multipath D2I connections between UEs and the network as well as service assortments. The selective multipath D2I connections flexibly choose appropriate communication resources for data delivery without a strict consideration of the MVN's infrastructure restraints. The connections are configured following user networking policies supervised by SDN-based edge controllers. Provisioning data, which contains configurable policies and user information, is synchronized among devices owned by individual users. Additionally, user services are classified with respect to predefined priorities before reaching the network. As a result, the MVNOs can minimize the dependency on the MNO's infrastructure within service management (SM) by cooperatively utilizing public infrastructures such as wireless Internet and device-to-device connections when applicable.

Opportunities and Challenges

In this section, we highlight the opportunities brought about by the convergence of 5G softwarization technologies and the technical challenges that MVNOs currently face.

Opportunities

A key enabler of 5G network softwarization is cloudization. Cloudization comprises three technologies: NFV, SDN, and ubiquitous fog/cloud computing [6]. Ubiquitous fog/cloud computing is a distributed resource architecture that provides an infrastructure for big data mining from multiple applications to deliver

actionable intelligence to users and businesses. SDN decouples control functions from network components, enabling the applications and network services to operate on top of a logical, programmable, and centralized framework and underlying vendor agnostic hardware. Complementing SDN and fog/cloud computing, NFV transforms the network functions from dedicated, proprietary appliances into software platforms running on general purpose infrastructure to provide automated service delivery and orchestration [7]. Together, these three technologies provide a perfect environment for enabling a full MVNO deployment at a reasonable scale with acceptable costs.

In 5G communication networks, the access tier consists of heterogeneous technologies working together in a seamless and autonomous manner to provide a unified access network model, referred to as *HetNet+* [7], which consists of both wireless and wireline access technologies and operates in both licensed and unlicensed environments. Although the service quality provided by these technologies can differ, satisfactory service levels can be achieved by nearly all technologies [8]. Therefore, this provides multiple access methods for user devices to access MVNO networks, resulting in better service delivery.

Consequently, the pervasiveness of these technologies brings about new services, including social services such as SIoT, M2M, OTT, and ubiquitous data mining, as well as rich content services, e.g., high-resolution multimedia, real-time and virtual reality services. The trend toward social services may create opportunities for MVNOs to develop a variety of new customer segments. However, to realize these opportunities, MVNOs must address the accompanying challenges described in the next section.

Challenges

The fundamental problem faced by MVNOs is the lack of a wireless access infrastructure because they do not possess any spectrum allocation [9], [10]. Additionally, since their focus is on niche market segments, it is necessary to minimize investment in the network infrastructure and management to significantly reduce expenses and maximize returns. Therefore, to serve its customers, the MVNO must utilize an MNO's wireless infrastructure by leasing bundled access to volumes of voice and data services. This dependency restrains the ability of the MVNO to develop new services and increases direct competition with MNOs in traditional market segments. Moreover, the dimension of MVNO networks is scaled to be very small in comparison to the MNO networks.

Furthermore, customer segmentation becomes even more difficult because of their rapidly changing requirements as well as the desire for multiple high-quality, feature-rich, and low-cost services. For instance, retail

customers interested in M2M services not only want a low price but also require enhanced services like ubiquitous data mining and location tracking. In the discount segment, customers usually focus on data services but may sometimes want high-quality voice and other real-time applications. If the user requirements are not satisfied, they are likely to move to other providers without concern for whether they are MVNOs or MNOs.

Although MVNOs are faced with increasingly complex requirements from customers, the MVNOs must consider the tradeoff between minimizing the cost by reducing investment in network infrastructure and ensuring end-to-end quality of service (QoS). This creates a catch-22 situation, because without full network management and control, QoS is very hard to guarantee. Therefore, the survival of MVNOs requires a new approach and development of a dynamic network model.

System Architecture

In this section, we discuss how to utilize opportunities presented by 5G network softwarization technologies to address the challenges of the MVNO. We begin with a brief introduction of SDN technology and how it can help resolve such challenges. We also propose a novel SDN-based approach for D2I management and service assortment and describe the detailed functions of the supplemented network components.

Our Approach

Most MVNO limitations arise from the lack of an end-to-end wireless network infrastructure because of cost and management constraints. Fortunately, these limitations can be addressed by developing a dynamic and flexible network model to support various new services through advanced 5G network softwarization technologies, such as SDN. As a modern networking architecture, SDN employs a standard-based abstraction protocol (e.g., OpenFlow) between a centralized network controller and the underlying data-forwarding components (i.e., switches). This abstraction enables drastic improvements in network agility and management, and eliminates vendor dependency, which was previously not possible. The network controller facilitates customization of the network operations through a set of application programming interfaces. This helps with the deployment of tailor-made applications that enable the execution of specific network functions. The network operation is controllable, programmable, and automatic.

Therefore, by utilizing the advantages of SDN technology, we propose a novel solution that helps the MVNO network overcome the limitations of lacking access infrastructure. This solution supports flexible policies (through user service contracts) that reflect the custom service requirements of each user. Users design their own policies based on prespecified service sets. On the

UE side, an SDN-enabled switch component provides direct connections to the MVNO's infrastructure. Based on the selected policy, the user services can be prioritized and processed before leaving the device. If the user connects through an untrusted non-3rd Generation Partnership Project access network, Internet Protocol security (IPSec) connections are used to secure the data and make them transparent during transfer across the access network. To increase flexibility, we suggest integrating a virtual subscriber identity module (VSIM) into the solution to make it possible to switch between MNOs to achieve the best performance.

Proposed SDN-Based Solution

To provide a complete view of a state-of-the-art MVNO, we consider a full MVNO network model that has already been cloudized, as represented by the blue components in Figure 2. Preferably, all typical network functions (e.g., home subscriber server (HSS) and policy and charging rules functions) are maintained and virtualized using NFV technology [11]. The network operations, applications, and contents use cloud computing to improve performance and availability. The core and distribution network switches are controlled and managed by a routing controller entity using SDN technology. This architecture provides the MVNO with optimal performance at a reasonable cost [12], [13]. It is worth noting that these

assumptions do not affect the proposed approach in terms of feasibility and operation.

The access network comes from other providers [e.g., other MNOs or Internet service providers (ISPs)] employing a variety of technologies, including wireless and wireline access methods, trusted and untrusted networks, and licensed and unlicensed mediums, as represented by the orange-colored components in Figure 2. The distinction among access types does not matter because the MVNO has no responsibility for physical access network management.

For these circumstances, we develop an SDN-based solution to provide a controllable D2I connection for the MVNO. The additional components are colored green in Figure 2 and include the following:

- 1) the SDN-enabled switch contains a user profile certification (UPC)
- 2) a service-forwarding function (SFF) integrated into the user equipment
- 3) an optional VSIM.

In the distribution network, the aggregation points contain a user management and control (UMC) component (i.e., an SDN controller) and aggregation routers (ARs) (i.e., SDN switches). An SDN controller-based SM component is in the control plane of the core network, and a user profile data (UPD) component is added into the existing HSS. The SDN-enabled switch establishes connections with the aggregation points as authorized

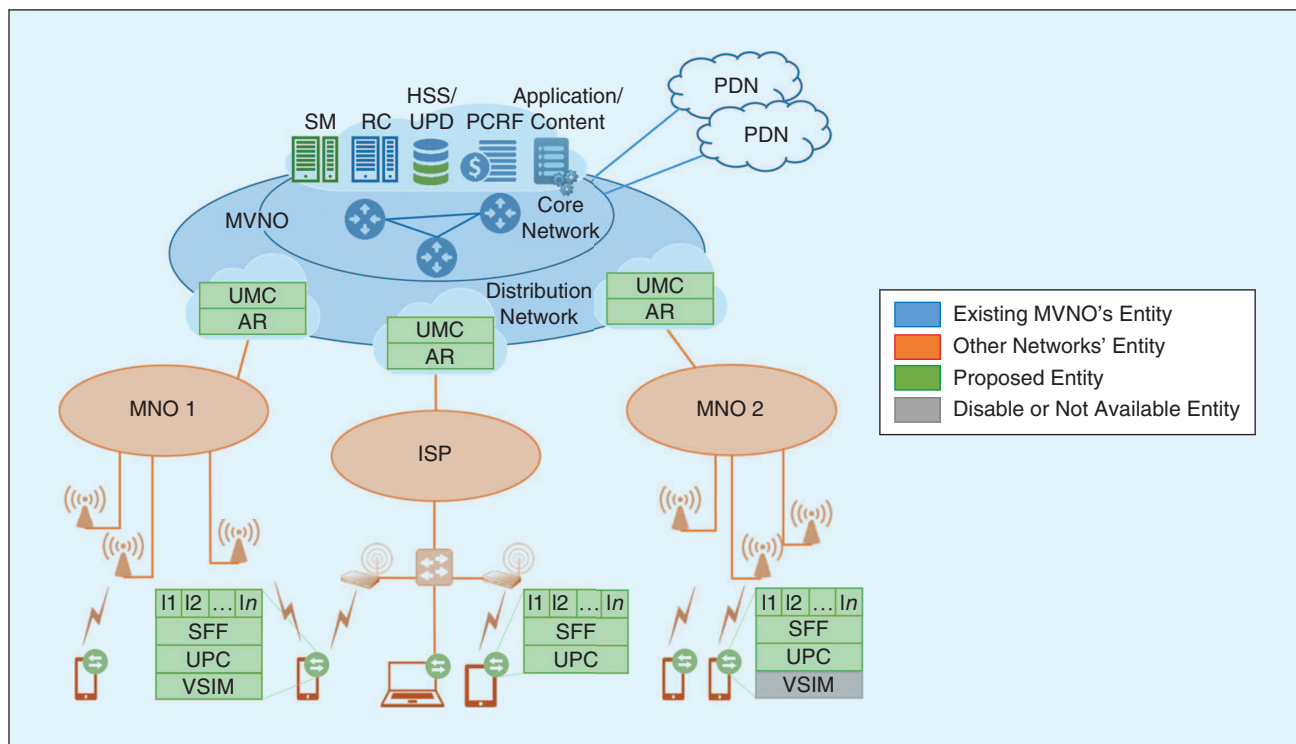


FIGURE 2 The SDN-based D2I approach for mobile virtual networks. D2I: device-to-infrastructure; RC: routing controller; UPD: user profile data; PCRF: policy and charging rules function; PDN: packet data network; UMC: user management and control; AR: aggregation router; In: n th interface; SFF: service forwarding function; UPC: user profile certification.

by the SM. The connections and user services are controlled and managed by the UMCs using the UPD.

The lightweight SDN-enabled switch is integrated into the mobile operating system of the user's device. It allows the for the MVNO to process user data (i.e., prioritizing and routing) as soon as it leaves the applications. These functions are provided through the following modules:

- 1) The UPC is responsible for mutual authentication between the user and the network. Each user has unique identity credentials. Note that this authentication process operates independently from the underlying access network. Moreover, when the VSIM is available, the UPC is responsible for negotiating with the network to deliver provisioning data to the VSIM, and then sends the selected service contract back to the network.
- 2) The VSIM is optional in this solution. It provides for the user to selectively enable provisioning data that supports one of the multiple MNOs stored in the VSIM's internal memory unit to conduct wireless communication [14]. Through the VSIM, the user has more choices regarding access to the network.
- 3) The SFF is a lightweight SDN-enabled switch. The SFF receives flow entries and control messages from the UMC for prioritizing and routing different data packets out of the corresponding interfaces. The actions defined in the flow entries are based on the selected service contracts.

On the MVNO network side, the aggregation point consists of two components: the UMC and the AR. The detailed functions are as follows:

- 1) The UMC operates in the control plane and has four main functions. First, the authentication process identifies the user upon initial participation in the network. Second, the UMC establishes and controls connections from multiple user devices to the AR. For each user device, the UMC assigns a separate set of flow entries corresponding to the selected service contract. If the user data has to be forwarded out of more than one interface due to the selected service contract (i.e., the user data arrive at different ARs), the UMC exchanges this information with the corresponding cooperating UMCs to route the user data correctly. Next, based on the report messages from the AR, the UMC extracts relevant data for billing. In the case of prepaid services, a special flow entry is dispatched to the user device to define a barrier against the user data. And lastly, a lawful interception will be provided upon request from government authorities by issuing the corresponding flow entry into the AR.
- 2) The AR operates in the data plane. Its responsibility is to gather connections from user devices and process user data based on flow entries defined by the UMC.

Moreover, the service-slicing technique [15] can be utilized to classify data traffic and forward it to the core network.

In the core network, the SM server responds to authentication requests from users and manages user service contracts (i.e., issuing, modifying, and deleting service contracts) during the negotiation process. The UPD and service contracts are stored in the UPD database in the HSS server.

SDN-Based D2I Connection and Service Assortment

This section presents the D2I establishment procedures and service assortment in detail. To address security concerns, we propose D2I establishment procedures in two typical scenarios.

D2I Connection

Figure 3 shows the D2I establishment procedure in two typical cases: in Figure 3(a) the VSIM is enabled (i.e., the user device is able to access contracted MNO networks) and in Figure 3(b) the VSIM is disabled (i.e., there are no contracted MNO networks available in this area) or not available (i.e., the user device does not support the VSIM module).

As shown in Figure 3(a), when the VSIM is enabled, the D2I connection is established through three steps:

- 1) *Step 1:* The UPC and UMC initiate a mutual authentication process. Because the VSIM is enabled and the user device is connected to a contracted MNO, the Evolved Packet System-Authentication Key Agreement (EPS-AKA) protocol is used. However, if the underlying access network is untrusted (e.g., an ISP), the EAP-AKA within the Internet key exchange version 2 (IKEv2) protocol is used. The authentication vectors stored in the HSS server are then forwarded from the SM to the UMC.
- 2) *Step 2:* After successful authentication, the service contracts are provided to the UPC. According to their particular requirements, the user selects the preferred contract and sends it back to the UMC. Simultaneously, the UPC forwards the provisioning data to the VSIM to store for the purpose of switching the contracted MNO.
- 3) *Step 3:* Based on the selected service contract, the UMC issues the corresponding flow entries into the SFF and the AR and establishes data connections between them. If the data connection is over the ISP network, an IPsec tunnel is used to secure the user data.

Alternately, Figure 3(b) illustrates the scenario in which the VSIM is disabled or not available. The D2I connection is established through the following three steps:

- 1) *Step 1:* The UPC and UMC initiate mutual authentication using the protected, extensible authentication protocol-transport layer security tunnel within the

IKEv2 protocol, regardless of the kind of underlying access network.

- 2) *Step 2*: The UMC is provided with the default service contract from the SM. Due to the lack of user identity from the VSIM, the user device is restricted from a negotiation process.
- 3) *Step 3*: Based on the default service contract, the UMC issues the corresponding flow entries into the SFF and the AR. Regardless of the kind of underlying access network, IPsec tunnels are used to secure the user data.

Service Assortment

Figure 4 shows an example of the service assortment in SDN-based D2I connections. The user device has two mediums by which to connect to the network: through the contracted MNO infrastructure and over the wireless ISP network. Depending on the pros and cons of each connection, the UMC generates the corresponding flow entries to prioritize and process data packets arriving at the SFF as soon as they leave the applications based on the policy defined in the selected service contract. The service assortment uses the output interfaces and service ports to classify the user data. For example, the voice service requires low throughput but short delay; therefore, it is routed through a cellular interface and assigned a specific service port number for further processing in the AR. For a file transfer, the data are forwarded to the Wi-Fi interface to obtain a high data rate without direct cost since the most important requirement is high throughput.

On the AR side, source IP addresses are used to further classify user data according to service contracts. All policies may be updated through modified flow entries that are managed by the UMC.

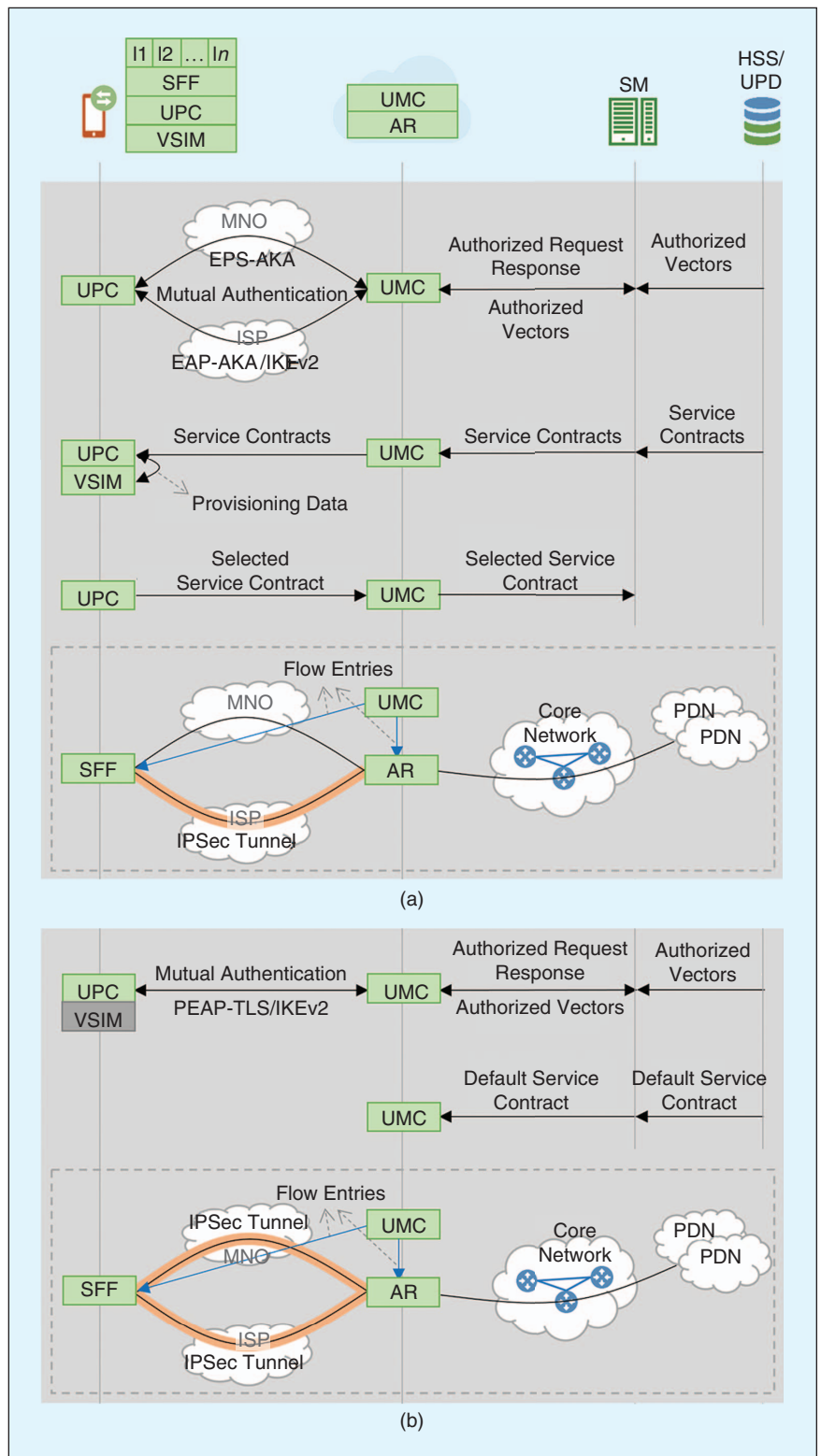


FIGURE 3 The D2I establishment procedure. (a) The VSIM is enabled and (b) the VSIM is disabled or not available. IP: Internet Protocol; PEAP-TLS: Protected Extensible Authentication Protocol-Transport Layer Security.

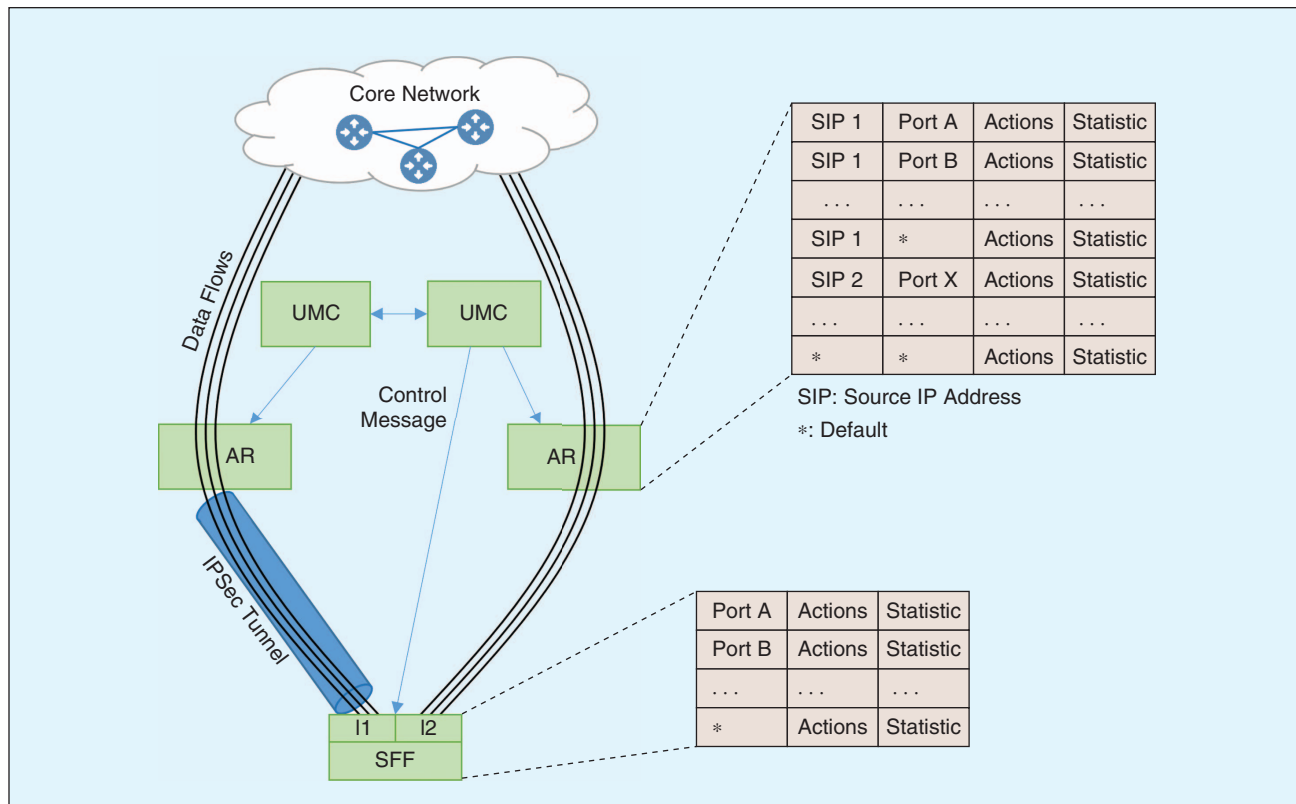


FIGURE 4 An example of the service assortment in a D2I connection. SIP: Source IP.

Feasibility Validation and Benefit

To validate the feasibility of the proposed SDN-based D2I connection and its operations in different scenarios, we develop a pilot network model that consists of both long-term evolution (LTE) and Wi-Fi access networks (see Figure 5). The network model is deployed in two consumer off-the-shelf x86-based servers with an OpenFlow protocol to represent an MNO (LTE connection) and an ISP (Wi-Fi connection). The SFF and ARs are based on Open vSwitch. The secure connection between the SFF and the AR is provided by an additional module. Five Raspberry Pi 2 model B machines are implemented as the user devices, with one server installed to provide voice and data services. The voice data are generated based on session IP transmissions supported by the 3CX SIP software. Meanwhile, data are also generated by File Transfer Protocol (FTP) and Hypertext Transfer Protocol transmissions via FTP and web servers as well. Additional system parameters are provided in Table 1.

The experimental scenarios are built based on different user service contracts. For simplicity, we divide the user data into two categories: voice and data. The user chooses either quality or cost as the priority for voice and data service contracts as follows:

- contract 1: voice > quality; data > quality
- contract 2: voice > cost; data > cost
- contract 3: voice > quality; data > cost.

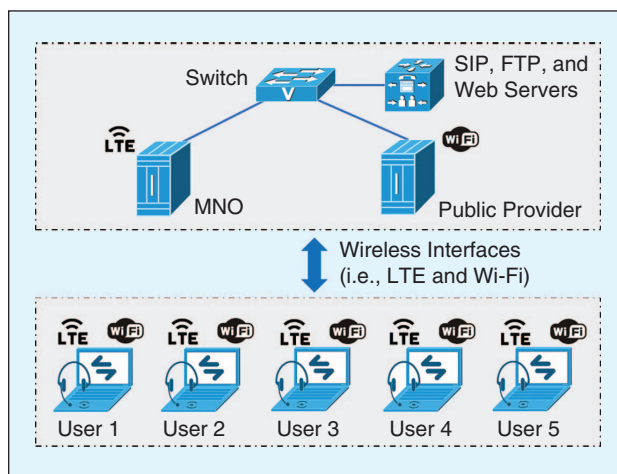


FIGURE 5 The pilot network model.

To ensure fairness in the performance comparison, we only consider value-added services (e.g., SIP calls, FTP transfers, and website accesses) provided by the MVNO since data services might be transferred to public Wi-Fi connections beyond the MVNO's control or management whenever it is available. For performance evaluation, 500 sessions of Monte Carlo voice and file transfer experiments are performed for each service contract in five user devices.

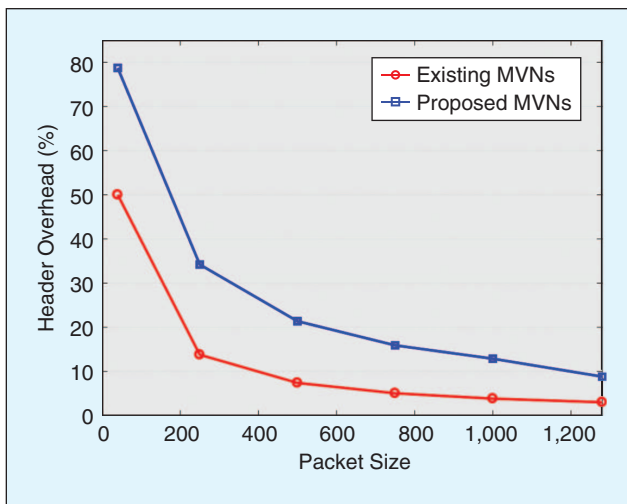
Figure 6 shows the overhead increase due to IPsec encapsulation in the proposed solution compared to

TABLE 1 The system parameters.

Parameters	Value
Bandwidth	10 MHz
Frequency	2.4 GHz
Transmit power	15 dBm
Receiver sensitivity	-100 dBm
Service cost	Three unit/MB (LTE) One unit/MB (Wi-Fi)

existing MVNs [15], which provides a slicing technique to prioritize different applications at the access network. Note that both evaluated MVNs share the same architecture elements in the access and core networks, but with distinguished logical functions depending on their own schemes. The proposed MVNs introduce two new elements (e.g., the SFF and UPC) in user devices compared to the existing MVNs. The results show that the difference in overhead decreases from 28.72 to 6.8% when the packet size increases from 40 B (e.g., voice packet) to 1,280 B (e.g., data packet). This means that the effect of the extra overhead becomes insignificant as the packet size grows (i.e., nearly all data services are acceptable). Meanwhile, although small communications might suffer from encapsulation overheads, the light traffic volume results in insignificant overhead compared to the data services.

In Figure 7, the box-plot representation illustrates the communication latency depending on service contracts in two stages: the initial stage and the session connection stage. The statistical results reveal that the average communication latencies of the initial stage and the connection stage when using service contracts 1, 2, and 3 are 8.55 and 1.71; 15.13 and 3.08, and 12.58 and 2.45 ms,

**FIGURE 6** The header overhead comparison between the existing MVNs and the proposed MVNs.

respectively. The diversity of communication latency is close between service contract 2 and service contract 3 since service contract 3 flexibly manages data services within a Wi-Fi connection instead of the LTE interface. Meanwhile, service contract 1 truly provides the lowest average latency due to its LTE usage. In spite of the existing difference, the communication latency results of the three experimental service contracts are within the acceptable limits of 5G services [16].

Table 2 shows a performance comparison between the proposed MVNs (via three contracts) and the existing MVNs (via LTE or Wi-Fi connections). The proposed MVNs demonstrate an impressive performance of service prioritization in terms of latency. Because the proposed MVNs support service assortment from the user device as well as at the AR, voice service is processed with a higher priority. The average voice latency in contracts 1 and 3 is lower than that of the existing LTE-based MVN by approximately 0.65 ms, while the difference between contract 2 and the existing Wi-Fi-based MVN is approximately 0.93 ms. Since the data services are considered to be latency tolerant, they are assigned lower priority than that of the voice services. The average latency differential between the voice and data services shows that contract 3 provides the best performance in prioritizing user services (a higher differential is better). In other words, multiple time-sensitive IoT applications in the 5G era can be effectively served by the proposed MVNs, along with traditional data applications.

For the service-cost comparison, we considered two pricing policies: 1) a volume-based policy for both LTE/Wi-Fi connections and 2) a volume-based LTE pricing policy as well as a fixed-rate Wi-Fi pricing policy. The volume-based pricing policy is adopted by operators for service delivery to the users, e.g., 3 unit/MB for the LTE connection and 1 unit/MB for the Wi-Fi connection [4].

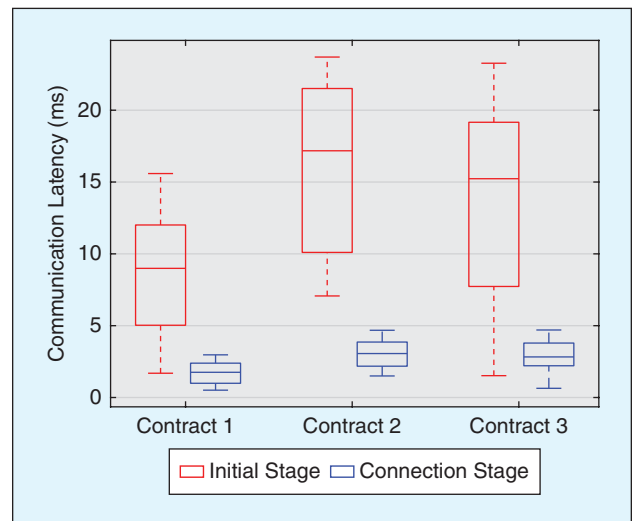
**FIGURE 7** The communication latency depending on the type of service contracts.

TABLE 2 The performance comparisons.

Parameters	Existing MVNs		Proposed MVNs		
	LTE	Wi-Fi	Contract 1	Contract 2	Contract 3
Average voice latency (ms)	1.508	2.677	0.852	1.747	0.858
Average data latency (ms)	1.692	2.911	1.904	3.338	2.915
Average latency differential (ms)	0.184	0.234	1.052	1.591	2.057
Additional cost with fixed-rate Wi-Fi pricing (unit/s)	+165.194	0	+170.884	0	+17.833
Average cost with volume-based Wi-Fi pricing (unit/s)	165.194	61.78	170.884	65.618	83.451
Average goodput (b/s)	49,257,236	43,903,188	47,616,970	41,334,852	43,335,937
Energy consumption (J/s)	3.442	3.861	3.56	4.101	3.91

TABLE 3 The new features and benefits for the MVNO and customers.

New Features	Existing MVNs	Proposed MVNs	MVNO	Customer
Multuser profiles	No	Yes	Extend the logical coverage area	Have more choices to access the network
Controllable D2I connection	No	Yes	Reduce the dependency on MNO access infrastructure	Improve security for user connections
Service assortment	Limited (in core network [15])	Enhanced (from the user devices)	Sort outgoing data regarding service priorities	Satisfy different service requirements
Value-added and OTT services' support	Limited	Enhanced	Exploit more new customer segments	Reduce the communication service expense and have more available services

Within the assumption of fixed-rate Wi-Fi pricing, contract 1 pays a 3.44% cost increase for data encapsulation and control overheads to obtain a good latency differential compared to that of the existing LTE-based MVN. On the other hand, contract 3 is reduced to a 89.56% cost by using a Wi-Fi connection; however, it still achieves approximately the best latency performance, similar to that obtained by contract 1. In case the volume-based policy is applied for both LTE and Wi-Fi connections, contracts 2 and 3 have a lower cost than the existing LTE-based MVNs by 60.28 and 49.48%, respectively, due to their Wi-Fi utilization. Contract 1 is the most expensive in terms of service cost, while the existing Wi-Fi-based MVN is the least expensive.

Despite introducing great performances in terms of service prioritization and QoS cost balance, the proposed MVNs have IPSec encapsulation and control overheads on the D2I connections from the UMCs and ARs to the SFFs. These overheads lead to an average goodput decrease and an average energy consumption increase, both by approximately 6%. Note that the goodput has been monitored in time-varying wireless channel conditions due to environmental factors and user mobility.

In summary, the proposed SDN-based D2I connection solution introduces some new features and capabilities, including multiple access methods via multiple user profiles, controllable D2I connections and user service

assortments based on SDN-supported protocols, value-added and OTT services support, and so on. As a result, the MVNO is able to overcome the limitations of lacking a physical wireless access infrastructure to provide diverse services to its customers. Furthermore, the customer requirements with respect to quality and cost are better satisfied because of the D2I management capability of the MVNO. The detailed benefits for the MVNO and the customers are presented in Table 3.

Conclusions

One of the biggest factors that negatively impacts the development of MVNOs is the lack of access infrastructure. In this article, exploiting the supportive 5G network softwareization, we proposed a novel SDN-based D2I connection to overcome this limitation. This approach provides selective multipath D2I connections and a service assortment for the users. The user services are classified with respect to their priorities before reaching the networking infrastructure. The feasibility and performance of the proposed approach have been validated through three typical experimental scenarios. The results show that the proposed approach provides new features in the network as well as additional benefits to both MVNOs and their customers. In particular, the service assortment prioritizes user services throughout the D2I connection. Therefore, it promotes time-sensitive 5G

applications to be served by the MVNOs. Although the proposed approach provides significant advantages, it also has some limitations. In most cases, the D2I connection utilizes an IPSec tunnel for data transfer between user devices and the network. This usually requires users to install a new application on their devices, which may be impossible for certain low-end devices. These limitations may be the focus of future research.

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