Survey on PMIPv6-based Mobility Management Architectures for Software-Defined Networking

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Abstract—**Software-Defined Networking (SDN) has changed the network landscape. Meanwhile, IP-based mobility management still evolves, and SDN affects it dramatically. Integrating Proxy Mobile IPv6 (PMIPv6) – a network-based mobility management protocol – with the SDN paradigm has created several promising approaches. This paper will present an extensive survey on the joint research area of PMIPv6 and SDN mobility management by detailing the available SDN-integrated network-based techniques and architectures that intend to accelerate handover and mitigate service disruption of mobility events in softwareized telecommunication networks. The article also provides an overview of where PMIPv6 can be used and how SDN may help reach those ways.**

Index Terms—**PMIPv6, SDN, IP-based mobility management**

I. Introduction

Software-Defined Networking (SDN) [1] [2] introduces a new concept that does not leave any network services and functionalities untouched. SDN separates control and data plane of network traffic. The control plane has been centralized, and a new entity has come to life in the network: SDN Controller. From now, a custom program can run on an SDN Controller, which can direct any traffic. This leads to programable networks where "simple" switches are controlled by a central point dynamically.

IP-based mobility management is also affected by SDN. This paper presents a survey on how Proxy Mobile IPv6 (PMIPv6) [3], a particular case of IP-based mobility management, can be adapted to the new SDN world. Several research papers have started to examine the evolution of PMIPv6 from an SDN point of view.

There are many approaches to implement efficient mobility management in SDN environments. SDN provides scalable and dynamic schema, solving many limitations of legacy architectures related to mobility processes. Using SDN and the protocols like OpenFlow [4], the mobility management processes may become more manageable. One of the expectations of integration with SDN is to solve the Single-Point-of-Failure problem (SPOF). The second is to avoid triangle routing: traffic is not needed to pass through Home Agent/Local Mobility Anchor (HA/LMA). The next one is the initial delay, and handover latency can be decreased thanks to the SDN controller's ability to manage multiple forwarding devices simultaneously and add forwarding rules to them based on the needs. Furthermore, the usage of SDN can eliminate tunnel usage to decrease overhead. Finally, in some cases, the number of control messages can be mitigated [5][6] [7]. The paper will examine all of these aspects while surveying PMIPv6+SDN architecture proposals. Looking at other types of IP-based mobility management schemas with SDN is out of scope in this paper.

The remaining sections are organized as follows. Section II introduces a general overview of IP-based mobility management. An overview of the SDN paradigm and its technological evolution is placed in Section III. The surveyed literature is presented in Section IV. Section V presents details on the future research topics of SDN-PMIPv6 integration. A conclusion has been put in Section VI, while a table summarizing our findings can be found at the end of this paper.

II. Overview of ip-Based mobility management

This section presents how IP-based mobility management has evolved and what approaches have affected the evolution, resulting in the PMIPv6 standard and its extensions.

A. MobileI Pv4 and Mobile IPv6

In the case of host-based mobility management, users are actively involved in their mobility processes. MIPv4 [8] and MIPv6 [9] are the most popular and well standardized host-based mobility protocols operating in the network layer.

MIPv4 is designed to let Mobile Nodes (MN) use two IP addresses. The first identifies the MN's Home Network where a permanent IP address exists, called the Home Address (HoA). Home Agent (HA) is located in Home Network, responsible for tracking users' mobility and providing the globally accessible address for mobile nodes. The second IP address – assigned to an MN – is the Care-of Address (CoA), whose foreign network is the network where MN moves into during its movement. Foreign Agents (FA) are placed in the Foreign Networks, responsible for assigning CoA to MN and notifying HA of the particular MN's new location. In Mobile IP's terminology, Corresponding Node (CN) is considered any node outside the mobility domain and wants to connect with MNs.

The mobility management in MIPv4 works in the following way: if an MN is located in the home network, no additional steps are required than the standard IP communication procedure. The mobility starts when the MN moves to another network (Foreign

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Network): each time an MN moves out from its Home Network, it takes a new CoA from the Foreign Network range. After that, MN registers its CoA by sending a Registration Request message through FA to the HA. When finishing the registration, the packets from the MN to CN are sent directly from the MN through the foreign network. Packets originated at CN and targeted to the MN go through HA. HA tunnels the packets to FA. Finally, FA processes the encapsulated packets and forwards those to the MN. Figure 1 describes the Control flow of MIPv4. Figure 2 depicts the basic architecture of MIPv4.

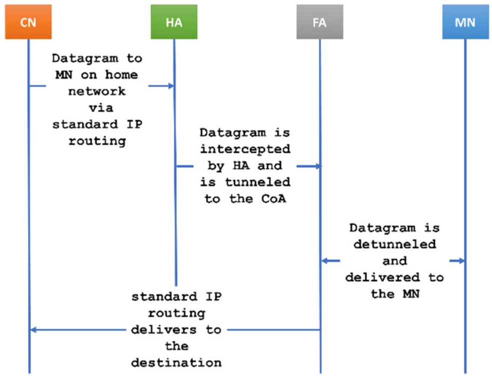

Fig. 1. The standard MIPv4 message flow[8]

The drawbacks of MIPv4 are the triangular routing which adds more latency, single point of failure (SPOF), and consumes bandwidth. In contrast, the traffic does not move directly between the sender and the receiver (CN and MN). Instead, traffic goes through the HA in the middle.

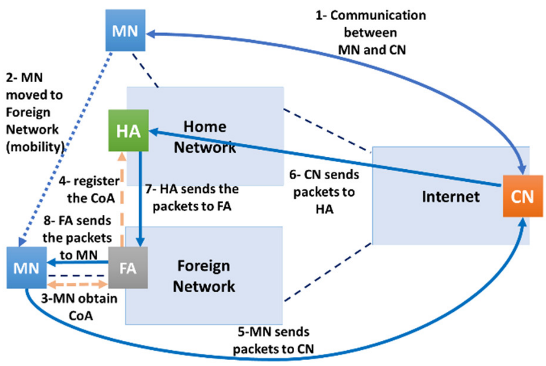

Fig. 2. The basic architecture of MIPv4 [8]

MIPv6 is similar to MIPv4, with enhancements and additional features. MIPv6 uses the Neighbor Discovery Protocol (NDP) of IPv6 [10]. NDP uses Router Solicitation (RS) and Router Advertisement (RA) messages to detect IP network prefix changes. Furthermore, NDP also deals with neighbor reachability. An IPv6 capable access router has replaced the functions of a Foreign Agent in MIPv4. This means FAs are eliminated in the context of MIPv6.

The mobility procedure in MIPv6 works as follows. The communication between MN and CN is addressed by native/ordinary IPv6 routing when MN stays on its Home Link. If the MN moves to Foreign Network, it has a new IP address called the CoA. After that, the MN sends a registration request to the HA (Binding Update) and receives the registration reply (Binding Acknowledgment). Traffic is encapsulated between HA and MN. MN may send a BU to CN to avoid triangle routing in route optimization mode (RO). The detailed message flow of MIPv6 is illustrated in Figure 3 .

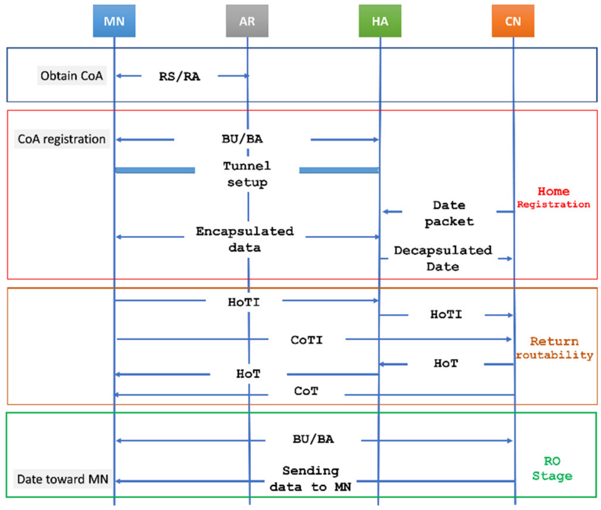

Fig. 3. The standard MIPv6 message flow [9]

Home Test Init (HoTI) and Care-of Test Init (CoTI) messages are part of the return routeability procedure. It is an authorization procedure to enable registration by a cryptographic token exchange. This procedure helps to give some assurance to CN if MN is reachable on that particular CoA. CN can securely accept BU from MN at the end of this procedure and circumvent HA (route optimization).

B. *Proxy Mobile IPv6*

Proxy Mobile IPv6 (PMIPv6) [3] is a network-based mobility management protocol working at the network layer. The network-based mobility management extends the network side and lets the network handle the mobility management instead of modifying the host part. Thus, MNs may not even know they are under any mobility process.

In PMIPv6 (Figure 4), the MN considers the whole PMIPv6 domain as a home network, so the MN uses just a unique HoA and different care-of addresses used by the MAGs. Mobile Access Gateway (MAG) and Local Mobility Anchor (LMA) are introduced in PMIPv6. MAG works as the access router; it detects the MN's movements and does the signaling and tunneling with the LMA, while the LMA works similarly to the HA in MIPv6 but with some additional potentials. LMA preserves accessibility to the MN's address as it travels through PMIPv6 domains. Binding Cache exists in the LMA, which is particularly a database that keeps track of the movement of MNs.

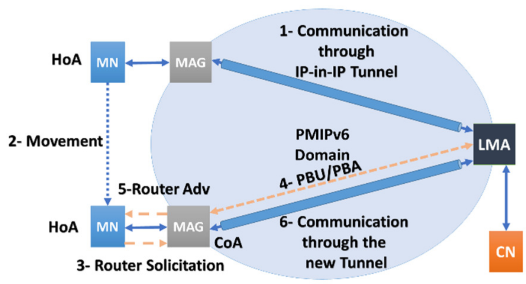

Fig. 4. The basic architecture of PMIPv6 [3]

PMIPv6 operates as follows. The MN attaches to MAG and sends Router Solicitation (RS) messages. Then MAG transmits a Proxy Binding Update (PBU) to the LMA, informing the attachment. LMA replies to the MAG via Proxy Binding Acknowledgment (PBA). MAG answers with Router Advertisement (RA) messages to the MN containing the home prefix of the MN as a reply for RS. Finally, a bidirectional tunnel between LMA and MAG is created to let the MN communicate with the CN, as depicted in Figure 5. When a handover happens (Figure 6), the new MAG detects the MN attachment. PBU/PBA messages are exchanged between the new MAG (nMAG) and LMA containing the latest information. The LMA updates its Binding Cache, and a new bi-directional tunnel will be created between the LMA and the MAG. RS/RA are also sent between MN and MAG. Meanwhile, the previous MAG (pMAG) sends PBU deregistration to the LMA, informing MN detachment. An authentication, authorization, and accounting (AAA) server implementation can supervise and manage network access procedures.

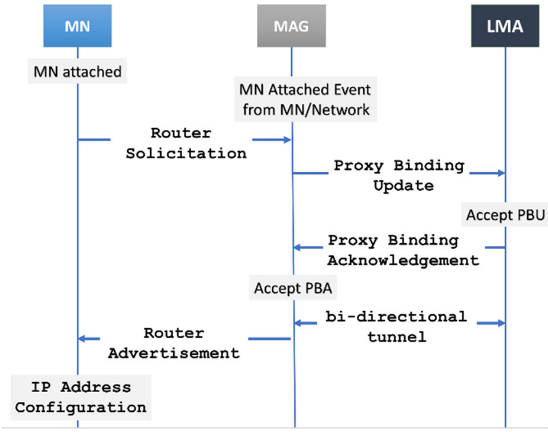

Fig. 5. PMIPv6 attachment control flow [3]

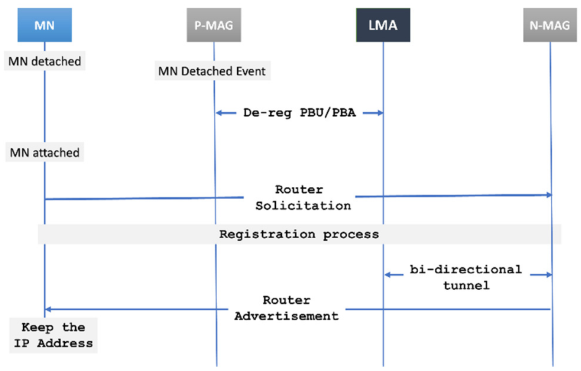

Fig. 6. PMIPv6 handover control flow [3]

PMIPv6 supports IPv4 [11] and IPv6 and doesn't require any MN side modification. The drawbacks of PMIPv6 include the tunneling overhead, the single point of failure, and high throughput in the case of LMA.

Table 2 of [12] shows a detailed comparison between IP-based mobility management protocols. The correspondent sections have been put to this paper as Table 1.

TABLE I
Summary of MIPv4, MIPv6, and PMIPv6 [12]

Category	MIPv4	MIPv6	PMIPv6
Mobility scope	Global	Global	Local
Mobility management	Host-based	Host-based	Network-based
Network architecture	Flat	Flat	Hierarchical
Target network	IP	IP	IP
Operating layer	L3	L3	L3
Required infrastructure	HA & FA	HA	LMA & MAG
MN modification	Yes	Yes	No
Router advertisement	Broadcast	Broadcast	Unicast
Addressing model	Shared-prefix	Shared-prefix	Per-MN-prefix
MN address	HoA	HoA	CoA
Address type	IPv4	IPv6	IPv6
Address length (bits)	32	128	128

C. *Flow Mobility*

A flow is a set of packets matching a certain Traffic Selector (TS [13]), and flow mobility management aims to apply the mobility for each communication flow individually [14] [15]. MN can bind different CoAs (Multiple Care-of Address, MCoA [16]) for each flow to ensure individual handling of a particular flow. One of the benefits of using PMIPv6 is that MN does not have to be modified as MN does not even know that it is under mobility management. However, with PMIPv6 flow mobility extensions, end-user modification is required.

Flow mobility also supports using multiple interfaces for an MN. This leads to the traffic offload and intelligent flow handling topics: based on the interfaces' specific properties; flows can be routed differently even though they originate from the same device. For example, using 4G/5G interface can be costly because of the radio spectrum price, but 3GPP interfaces provide more reliability than ordinary Wi-Fi. Therefore, those flows, like web browsing with lower expectations from the network compared to, e.g., videoconference, can be offloaded to non-3GPP accesses. The procedure to select a suitable interface is out of the scope of this paper, but it can rely on, e.g., QoS metrics, radio resource availability, etc. Section II.H has some connection statements for this section where corresponding references can be found too.

Mobile IPv6 Flow Binding extension has the same signaling and architectural design as “ordinary” MIPv6, depicted in Figure 7, Figure 8. Flow Bindings functions are implemented with a novel Mobility Option called the Flow Identification Mobility Option, attached to the BU and BA messages. This identifies a particular flow (with Traffic Selector sub-option). It is possible to bind multiple flows by the same CoA or different CoAs with multiple interfaces too. The more flows are bound, the more BU/BA signaling messages are needed.

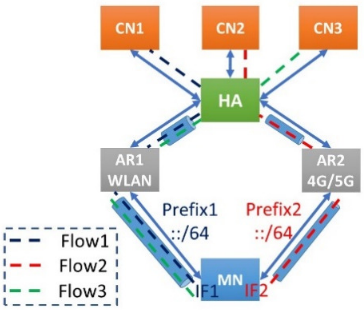

Fig. 7. Mobile IPv6 Flow Bindings architecture

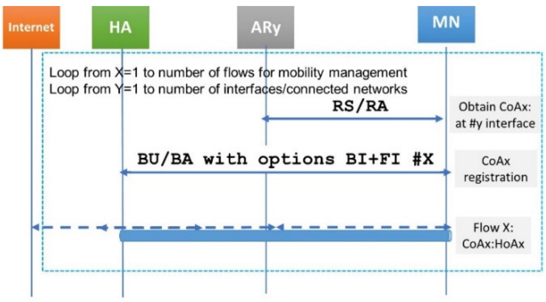

Fig. 8. Mobile IPv6 Flow Bindings signaling flow

Figure 9 and Figure 10 illustrate an example of MN shared prefix across two physical interfaces.

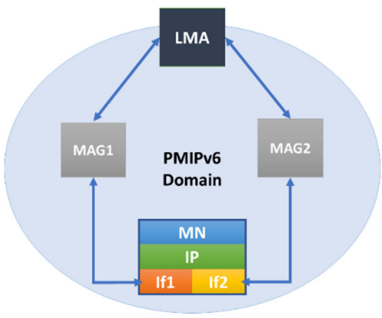

Fig. 9. Shared prefix across physical interfaces in PMIPv6 flow mobility [15]

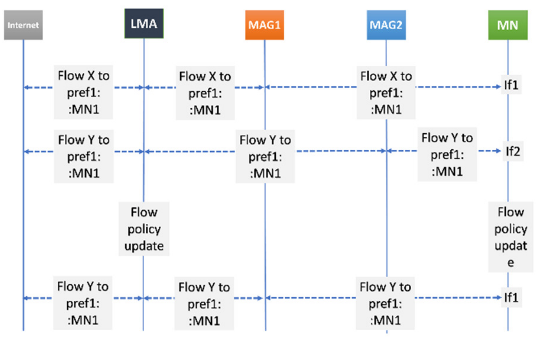

Fig. 10. Flow Mobility Message Sequence with a Common Set of Prefixes [15]

Figure 11 is an example of extended PMIPv6 where flow mobility is enabled. The MN is attached to the network by two interfaces (WLAN interface and 3G interface), and there is a different prefix for each interface. In this case, the LMA is extended to support grouping a set of mobility bindings and refer it to the same MN [17].

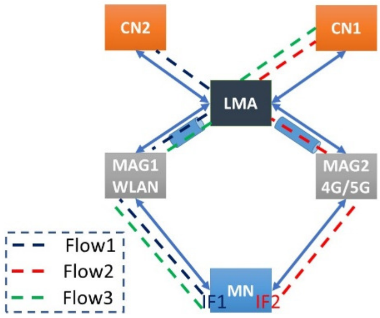

Fig. 11. PMIPv6 flow mobility with 3GPP/non-3GPP offloading

D. Dynamic Mobility Management

Dynamic Mobility Management provides the needed mobility support to a user only when required. This saves resources by reducing unnecessary mobility management signaling overhead and network cost. In the case of IP-based mobility management, e.g., it means avoiding BU/BA message exchange and eliminating tunneling overhead [18][19][20]. This works well when IP-address preservation is not a goal. For those types of traffics, when the change of IP address causes service disruption, this is not a valid path. If the IP address is changed at a VPN service, the VPN itself is broken. But for ordinary web browsing ("surfing"), it does not affect the user experience negatively. Dynamic Mobility Management can be combined with Flow Bindings too. With this combination, the individual dynamicity of particular flows can be realized. Consequently, tunneling overhead can be decreased, too, as the tunnel is not set up if mobility management is not needed.

Figure 12 is an example of dynamic mobility management where the MN moved to a new network, and a new IP (IP2) was assigned to it. Many applications establish connections after the mobility and do not need mobility support. In contrast, the applications that require mobility support forward the traffic with the old IP (IP1) to the AR1 (the AR1 works as HA in this case). To sum up, the system will provide mobility only based on the need [18].

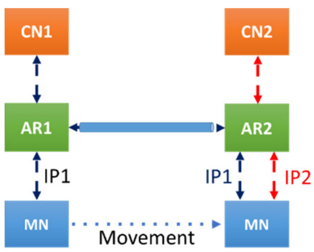

Fig. 12. Dynamic Mobility Management [18]

E. Distributed Mobility Management

Distributed Mobility Management (DMM) refers to the idea of using multiple mobility management functions instead of a centralized one and distributing them over different locations [21]. The nearest mobility function probably serves the MN, as in Figure 13. Distributed Mobility Management could be across different levels: core level, access router level, access level, and host level, and this distribution could be organized partially or fully. By using the distributed mobility management architecture, unnecessarily long routes are avoided, and more scalability is provided to the network. Furthermore, the SPOF issue can be solved, which is one of the biggest problems for HA and LMA to make them carrier-grade.

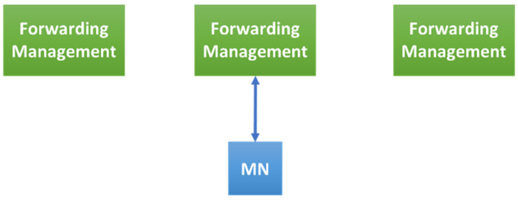

Fig. 13. Distributed mobility management approach [21]

An example of fully distributed PMIPv6 is illustrated in Figure 14. In this case, the standard PMIPv6 signaling messages are used. However, when the CN sends a packet to its MAG, this MAG sends Proxy Binding Query (PBQ) [22] to all MAGs in the domain. Only the MAG that connected the MN will reply with Proxy Binding Query Acknowledgment (PBQA). Then the data packets will be forwarded to the MN through the related MAG.

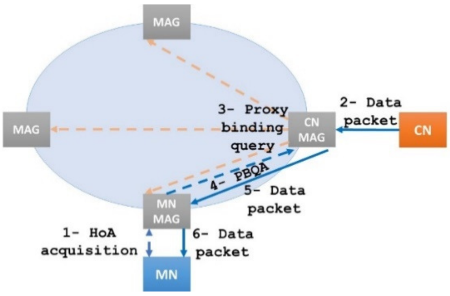

Fig. 14. Distributed PMIPv6 [23]

Dynamic Mobility Management and On-Demand Mobility Management should be differentiated slightly in the context of Distributed Mobility Management. DMM can mean dynamic anchor selection for a particular MN [24]. However, On-Demand Mobility Management pertains to having session continuity requirements [25].

F. Types of Handovers

One of the promises of SDN in the IP-based mobility context is to simplify and/or accelerate handovers. There are several types of handovers related to PMIPv6 [26]:

- Intra-domain handovers: the same MAG is used, but a user switches between different access links. Even the type of access network can be changed.
- Inter-MAG handovers: a user changes its corresponding MAG. In this case, MAG will initialize a new binding (PBU/PBA).
- Inter-LMA handovers: LMA and MAG are changed at the same time. A completely new registration process with their occasional AAA dialog is executed. External routing is also readjusted as the anchor point to the outside world (i.e., the LMA) is changed. So, there is a new path ultimately to reach a particular MN.

The L1 and L2 technology-agnostic design of IP and IP-based mobility management are supporting technologies of inter-technology handovers.

G. Supporting technologies

With the introduction of IP-based mobility management, IP addresses enjoy the separation of identification and locator roles (ID/Loc separation). End-user devices used to be always on the exact location, so a well-defined IP prefix allocation scheme determined the location and identity of nodes. This is where ID/Loc separation comes into the picture. The MIPv6 address family is a good example, but not the only one. The Host Identity Protocol (HIP) [27] introduces a new layer between the IP and the Transport layer for solving the problems mentioned above. A new identifier, Host Identifier (HI), is created to give unique keys to mobile nodes. In the context of MIPv6 and PMIPv6, HIP has been started to get experimented with and standardized [27][28][29][30].

The Media Independent Handover (MIH) [31] was introduced in IEEE 802.21 and aimed to permit handovers between different heterogeneous technologies like Wi-Fi and cellular technologies without disruption of service, leading to enhanced user experience. The MIH defines a set of Service Access Points (SAP) in the link layer that maps to a generic interface between the different link-layer technologies and the upper layers. MIH also provides a group of mobility functions to support the upper layers mobility protocols [31].

H. 3GPP support

PMIPv6 has also been incorporated by the 3GPP standards [32] [33]. There are two basic approaches to use PMIPv6 in 3GPP concepts:

- Relying on the connection of non-3GPP access networks to 3GPP networks: S2 interface family. In most cases, this means connecting a Wi-Fi network to a service provider network (SP-Wi-Fi). There are two subdomains differentiated by the owner of the Wi-Fi network devices. These devices can either belong to an SP or a 3rd party company.
- Using PMIPv6 on S5/S8 interface instead of the GPRS Tunneling Protocol (GTP).

Several papers and standards deal with traffic offloading of mobile networks with the help of Wi-Fi networks and PMIPv6, e.g.: [34][35][36].

III. Overview of Software-Defined Networks and corresponding mobility management

Software-Defined Networking is one of the most popular topics these days in terms of networking technologies. It is considered as the evolution of legacy networking architecture (Figure 15). Before SDN, each networking device is a fix- device with a built-in control plane and data plane. Then SDN came up with the idea of separating the control plane for all networking devices, making it a centralized controlling programable unit "SDN controller" and keeping the data plane inside the networking devices. In other words, the networking devices just forward data based on flow tables, while the SDN controller manages the preferences [1][2][4].

SDN architecture consists of three layers [37]:

- Infrastructure Layer, where the data plane and networking devices work;
- Control Layer, where the network services and the controlling process are kept;

- Application Layer that connects to the Controlling layer via APIs and contains the business applications where policies and rules could be applied to the controller.

SDN commonly uses OpenFlow protocol as a connection channel between the SDN controller and the forwarding devices. Using OpenFlow, SDN controllers can put the flow table entities inside the forwarding devices, and these devices forward the data based on the flow table information.

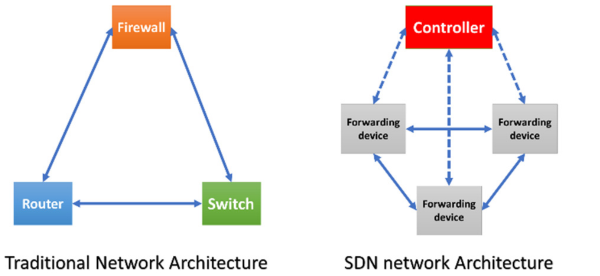

Fig. 15. Overview of traditional and software-defined network architectures

The concept of integrating SDN with mobility management has come up several times in the literature. In this part, we focus on the overall paradigm of mobility management and SDN combination. However, some references deal with IPv6-based mobility management as well.

D Liu et al. [38] present problem statements regarding SDN integration of IP-based mobility management.

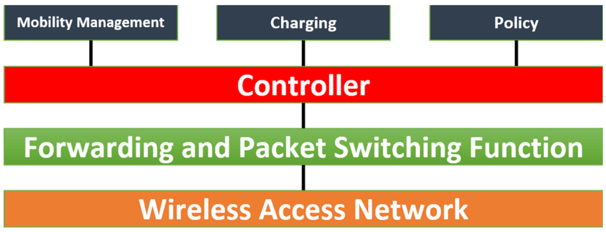

Fig. 16. SDN-based mobile core network [38]

As Figure 16 envisions, they see the mobile network core on SDN-bases, where the SDN controller has networking functions (charging, policy, etc.). Mobility management is also one of the SDN controller-integrated network functions. This approach promises to simplify mobility management in general. As the SDN controller has the full view of the network, it can optimize traffic routing/forwarding and catch mobility events. This leads to Figure 17, which shows an architecture for MIPv4/MIPv6 integration with the SDN controller functions.

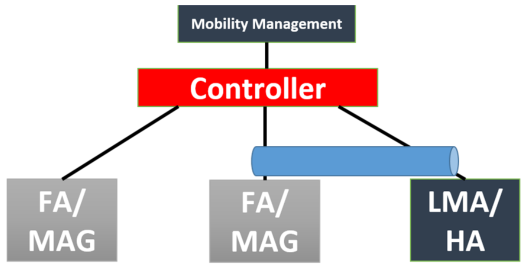

Fig. 17. Enhance SDN to support mobility tunnel processing [38]

Forwarding mechanisms can catch mobility events and notify the Mobility Management application on the top of the SDN controller. Based on the traffic directions, it can calculate optimal routing paths also from MN/HA and CN points of view. This paper does not present detailed architecture proposals and signaling flows on those results; however, it shows and lists open research questions on this topic.

SDN has also influenced Distributed Mobility Management. Hanuel Ko et al. [39] propose an SDN-DMM architecture. They state there are several problems in the context of IP-based mobility management which can be solved or mitigated by using SDN. These identified problems are:

1. lack of dynamic mobility support;
2. suboptimal routing;
3. scalability issues;
4. single-point-of-failure.

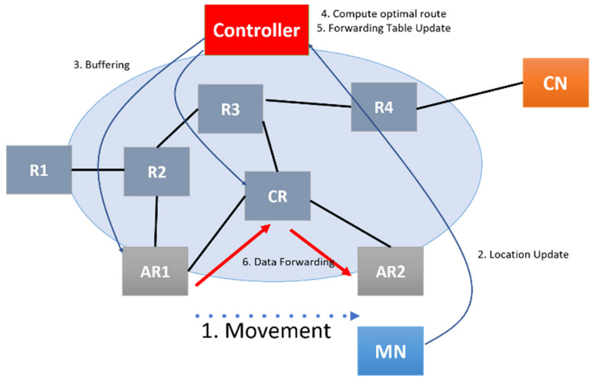

Fig. 18. Distributed Mobility Management with SDN (SDN-DMM) [39]

Figure 18 shows how handover can be executed in the context of SDN-DMM. Their assumption is that there is continuous data traffic between MN and CN. Step 1 pertains to the MN movement where MN changes its attachment point. MN must report its new location (Step 2). At Step 3, the Controller sends Openflow buffering messages to Crossover Router (CR) and Access Router1 (AR1) entities. Meanwhile, in Steps 4 and 5, the Controller computes a new optimal path for the CN-MN traffic through AR2. Buffered traffic is sent to AR2 and MN in Step 6. With this new route calculation, the usage of AR1 is left out, and only AR2 is used. Furthermore, with proper Openflow rules, tunneling may be eliminated.

Tien-Thinh-Nguyen et al. [40] have also dealt with SDN and IP-based mobility management integration. Their proposal's name is S-DMM pertains to SDN and Distributed Mobility Management. They measured that similar performance can be achieved in S-DMM compared to the traditional DMM in terms of handover latency and end-to-end delay. However, the complexity of the overall system control plane is reduced.

In the upcoming sections, we believe the above-introduced SDN concepts can serve as a solid base of understanding for discussing SDN and PMIPv6 integration – a more specific and focused integration case.

IV. The analyzed literature

This section intends to present the studied papers in a timely order. However, at the end of the paper, a summary table (Table 3) indicates the key functional properties of architectural proposals. With the help of Table 3, we believe that the Readers can get a quick but enough broad view and ensure suitable grouping of the most critical aspects of the proposals. Furthermore, this section goes into the details of the SDN-PMIPv6 integration approaches paper-by-paper deeply.

Paper #1 by Seong-Mun Kim et. al (2014 Jan)[41]

Seong-Mun Kim et al. [41] propose a solution where PMIPv6 is integrated with Openflow. Their proposal (OPMIPv6) separates the mobility management functions from PMIPv6 components. Furthermore, this allows the removal of PMIPv6 tunnels with their overheads. The LMA function could be located at the controller; the MAG function could be placed either into the controller or the access switch (Figure 19). There is a case when LMA and MAG are on the same centralized controller node (OPMIP6-C); thus, PMIPv6 signaling should not be used. Openflow is possible to avoid IP tunneling because the data path is set up by Openflow protocol through flow tables in the forwarding devices (switches). Signaling between controller and switches is transferred via a secured channel. In this proposal, the data plane is configured by LMA, located on the controller. It is possible to add multiple controllers to provide redundancy to the system. They proved that OPMIPv6 performs better than PMIPv6 in means of tunneling overhead, the resiliency of failures, and handling capacity.

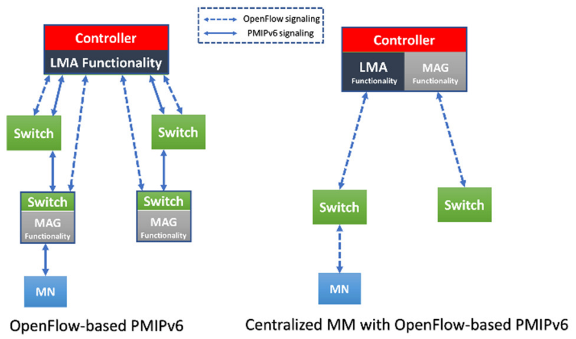

Fig. 19. Seong-Mun Kim et al.'s deployment scenarios[41]

Paper #2 by Kyoung-Hee-Lee (2014 Jan) [42]

Kyoung-Hee Lee [42] extends PMIPv6 with Routeflow to make it SDN-ready. Routeflow[43] is an SDN deployment framework used to handle IP routing protocols (Figure 20). Using a centralized server containing several VMs where each VM represents a programable switch and a routing protocol working between these VMs to create a forwarding information base (FIB), the central server collects the needed data (IP and ARP tables) to build OpenFlow rules. It translates those data to OpenFlow rules installed after processing the forwarding devices. The solution keeps the PMIPv6 signaling and concepts. LMA and MAGs are installed into separate VMs. Each VM carries out the mobility role for a particular mobility node. If an inter-MAG handover happens, standard PMIPv6 messages are exchanged, but the Routeflow server translates the Binding Cache of LMA into Openflow rules. These new Openflow rules are distributed to the switches then. So PMIPv6 Control plane is kept, but the Routeflow server maintains another control channel to manage switches. The routing table of VMs of MAGs is also continuously translated to the underlying Openflow switches by the Routeflow server. In this case, Routeflow is a controller. This scenario suggests some modification on the control message flow of PMIPv6 to fit the underlying SDN architecture.

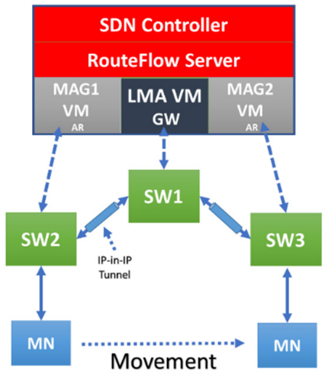

Fig. 20. Kyoung-Hee Lee's proposed architecture [42]

Paper #3 By Syed M. Raza et al. (2014 Jan)[44] [45]

Syed M. Raza et al. [44][45] introduce the OF-PMIPv6 concept as an integration of PMIPv6 and Openflow (Figure 21). In their proposal, the signaling path and the data path are separated. OpenFlow Mobile Access Gateways OMAG entity is introduced, which is only responsible for L2 functionalities and manages the IP tunneling. Meanwhile, L3 (signaling) messages are handled by the controller. PMIPv6 is not modified at all; messages and tunnels are still used in this solution. Their main goal is to decrease handover latency. OMAG communicates with the controller via Openflow.

They introduce three new message types to the Openflow protocol:

- The controller sends Tunnel_init to the next OMAG (nOMAG) to create an IP tunnel from the nOMAG to the anchor.
- S_Report is used for reporting link states of Mobile Nodes to the Controller.
- L_Report is sent by OMAG to report the loss of a Mobile Node to the Controller after a specific time.

This is an extra step of control messaging, but the authors state that it means the minimal effect on handover latency and packet loss based on their performance evaluations.

The OF-PMIPv6 controller communicates with OMAGs and LMAs as well. On the controller, there are three modules proposed:

- OpenFlow Module uses the Controller's built-in functions to communicate the PMIPv6 control and mobility-related messages with OMAG.
- PMIPv6 Module takes responsibility for performing standard PMIPv6 control messages with the anchor and the AAA system.

- Mobility Management Module has a connectivity database (C-DB) that stores the Mobile Nodes' information (MN ID, LMA ID, attached OMAG ID, and MN link-state values from OMAGs).

The C-DB is a kind of Binding Cache. The authors propose two types of handover:

- Reactive: When RS message is received, OMAG forward OF-RS message to controller, not PBU to LMA.
- Proactive: OMAG monitors the link continuously; as soon as the values drop below the lower threshold, it reports it to the controller. Then the C-DB is updated by the controller.

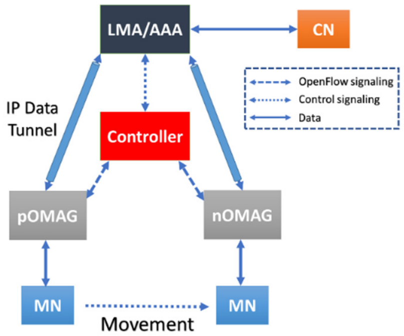

Fig. 21. Syed M. Raza et al.'s architecture proposal[44]

Paper #4 By Hoa Yu (2014 May) [46]

Hao Yu [46] suggests a solution for inter-domain heterogeneous vertical handover in SDN environments using PMIPv6. The SDN controller handles the tunnel creation between MAGs and LMAs from different domains in the proposal. This is required because the original LMA maintains home Network Prefix. If an MN moves to another domain, the traffic is tunneled back to the original LMA to maintain connectivity.

By using SDN, the vertical handover between different domains is possible. When an MN is moved to a new domain, the MAG in the new domain discovers the MN attachment and performs the mobility signaling, depicted in Figure 22. Meanwhile, the old LMA deregisters the MN from the old domain. When the new LMA receives a PBU from the new MAG, it discovers from the PBU that the MN moved from another domain. There is communication between the LMAs from different domains.

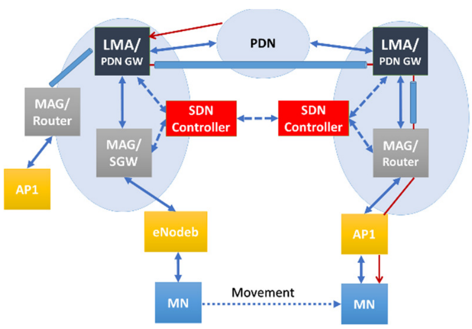

Fig. 22. Hao Yu's architecture proposal [46]

Paper #5 by You Wang et al. (2014 Aug) [47]

You Wang et al. [47] present an Openflow-based architecture for IP-based mobility and discuss how SDN can help evolve mobility management. Their proposal is not a PMIPv6 enchantment and integration to the SDN world. Instead, it is a new mobility approach that behaves similarly to PMIPv6 with taking advantage of SDN. The MN does not own the MN's CoA; the first-hop Openflow switch maintains it. This means MN does not need to take care of address reconfiguring like at PMIPv6. The MN has a non-routable HoA used to look up for MN's current location. One additional role for the controller is to maintain a binding cache that matches the HoA and CoA of the MN.

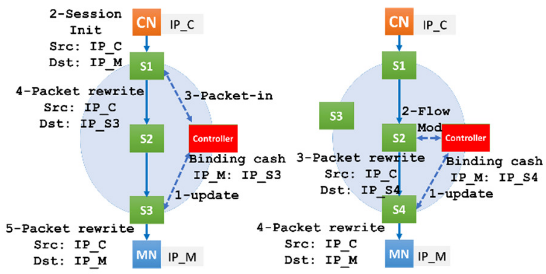

Fig. 23. You Wang et al.'s architecture proposal (left is communication initialization; right is movement handling) [47]

In Figure 23, the IP_M is the HoA, and IP_C is the CN address.

When the first attachment occurs, the switch which detects the MN arrivals (S3) sends a BU to the controller containing IP_M and IP_S3. As the controller has the binding cache locally, it will store the new updates and sends a new rule to the switch to replace all packet's destination addresses to IP_S3 to IP_M.

When CN sends a packet to the HoA of MN (IP_M), the switch (S1) does not know where to forward it, and the switch will ask the controller. The controller checks its local binding cache. Then it will send a flow rule to the first-hop-switch of CN to replace all the packets' destination addresses to IP_S3 from IP_M, which are directed to MN.

During handover, almost the same process happens. The new switch (S4) sends BU to the controller; in this case, the controller sends updates to all switches in the path between CN and MN. This changes all the flow directed to IP_S3 to be IP_S4.

Thus, the network takes care of binding caching, no need to have it on MN, and that's why it is similar to PMIPv6. Also, triangle routing is solved because packets do not need to pass through HA/LMA/Controller. Binding Cache can also be put in several parts of the network. The authors propose an algorithm to find the optimal place. The paper discusses the case of using multiple controllers and Dual mobility.

Paper #6 Yuta Watanabe et al (2015 Jan) [48]

Yuta Watanabe et al. [48] address the problem where LMA is overloaded because every traffic is directed to go through it. With the help of Openflow, they construct a path that avoids LMA to CN. Also, they get rid of tunneling and propose to use only the Openflow toolset without tunneling.

The OpenFlow switch represents the MAG in this solution.

The paper does not include any architecture diagrams, and the messages sequence flow diagram is miss ordered, so we re-created the figure with the corrections we believe represent the target of the paper (Figure 24). The paper concludes that their Openflow-based path optimization has higher throughput than ordinary PMIPv6 or a PMIPv6 route optimization proposal (PRO) [49].

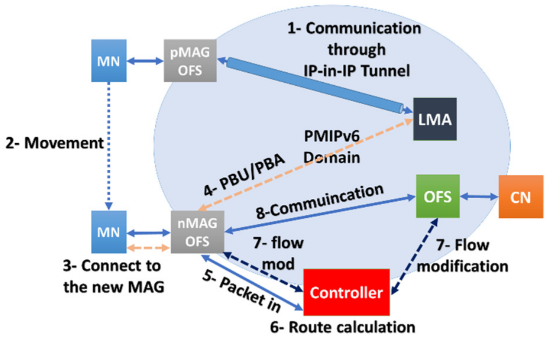

Fig. 24. Yuta et al. 's architecture proposal by the authors of this paper [48]

Paper #7 *Sakshi Chourasia et al. (2015 Apr) [50]*

Sakshi Chourasia et al. [50] present an Openflow-based improvement for EPC networks (Figure 25). They focus on decreasing signaling overhead during handovers (intra-LTE, inter-RAT). They have a logically centralized controller for the EPC control plane to manage mobility, called EPC Controller. SGWs and PGWs are replaced with Openflow switches, controlled by EPC Controller. EPC controller also has connections to eNodeB-s via TCP links. EPC Controller is also responsible for end-user authentication and IP address allocation. Furthermore, it also supports charging procedures. The OpenFlow switches handle the IP mobility and forward the packets based on preferences provided by the controller. They state that tunneling overhead can be eliminated with the usage of Openflow.

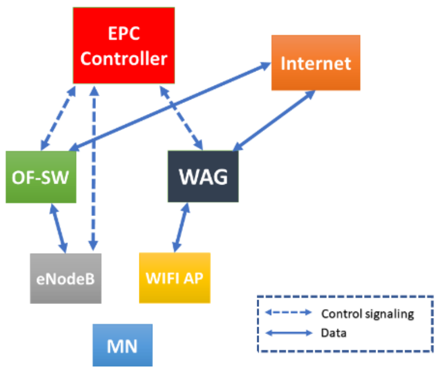

Fig. 25. Sakshi Chourasia et al.'s Openflow integration model to EPC [50]

Paper #8 *Seong-Mun Kim et. al (2015 Apr) [51]*

Seong-Mun Kim et al. [51] have a broader scope in this paper about their previous proposal, already presented at Paper #1. This paper has not given any novel architectural elements compared to the previously presented one because it mainly focused on evaluations. However, a summarized table comparing ordinary PMIPv6 and their OPMIPv6 solution is worth mentioning (Table 2). It is a good basepoint for making architectural conclusions.

TABLE II
COMPARISON OF PMIPV6 AND OPENFLOW-BASED PMIPV6 [51]

	PMIPv6	**OPMIPv6**
LMA	A dedicated router	A normal switch with LMA function and a controller
Multiple LMA	Limited to gateways with LMA functions	Any gateway router connected to the LMA function with a controller
Resilience to failure	Difficult	Easier than PMIPv6 by replicating LMA controller architecture
Flexibility to workload increase	Rigid	Modular installment of the LMA controller is possible
Changing the primary LMA gateway	Not supported	No LMA change is required in a domain; a gateway router can be easily changed
MAG	A dedicated router	A normal IP router with LMA function
Separation of control and data plane	Not supported	Supported
Tunneling	IP-in-IP tunneling	No tunneling with Openflow architecture
Handover delay	PMIPv6 signaling delay	PMIPv6 signaling and flow table setup time for all routers on the flow path
Dual role agent	Not practical	LMA and MAG can be combined into a single mobility management controller

The comparison and the numerical results of the paper show clearly that the cost of tunnel elimination comes with increased handover delay. This is due to the added Openflow signaling (new TCP connections) to the existing PMIPv6 signaling. But Table 2 presents new added features and resiliency by Openflow, which are worth the additional cost from an architectural point of view.

Paper #9 *Abbas Bradai et al. (2015 Jun) [52]*

Abbas Bradai et al. [52] proposed a solution called Software-Defined Mobility Management (SDMM) influenced by the PMIPv6 architecture. In this solution, the mobility management entities are virtual machines (V_LMA and V_MAG) collocated with the SDN controller, depicted in Figure 26. The SDN controller is responsible for creating optimal tunnels for mobility. V_LMA and V_MAG are accountable for receiving control messages (e.g., router solicitation), and they take action of tunnel creation. The tunnel is created between particular Openflow-enabled switches. They eliminate the usage of PBU/PBA. A separate Mobility Database (MD) is connected to the SDN controller, where bindings are tracked. MD has a well-defined interface to the SDN controller, which immediately translates mobility events to Openflow rules for corresponding switches.

V_LMA VM determines the most convenient forwarding entity to work as a mobility anchor point in the network. At the same time, V_MAG is mapped to forwarding functions to make them work as MAGs. After choosing the best anchor point, a tunnel will be created between the LMA and MAG.

They suggest having dynamic anchor entities in the network for each set of flows to achieve the best results in terms of delay and throughput balancing. A study and modeling of choosing the best anchor point are introduced in the paper.

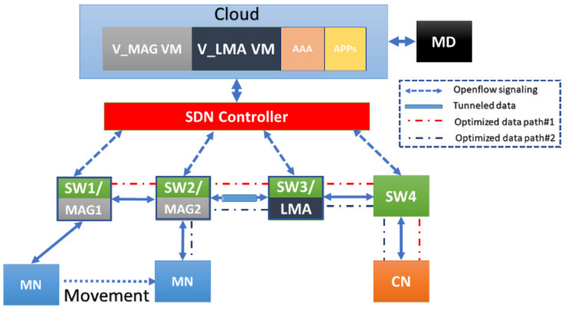

Fig. 26. Abbas Bradai et al. 's Software-Defined Mobility Management architecture [52]

Paper #10 Wen-Kang Jia (2015 Nov) [53]

Wen-Kang Jia [53] has proposed an SDN-based PMIPv6 architecture extension for Evolved Packet Core (EPC). The paper also deals with inter-domain handover with the help of the architecture proposal. Also, route optimization is presented to the CN from MN. The overview of the system architecture is depicted in Figure 27.

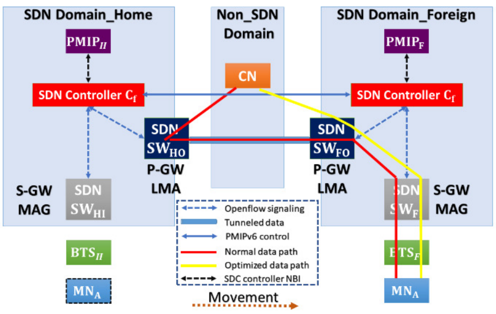

Fig. 27. Wen-Kang Jia's system architecture [53]

MAG is placed to SGW, collocated with an SDN switch (SW home input, SWHI) as an SDN application. LMA is on PGW, which is also collocated with an SDN switch (SW home output, SWHO). There is a central SDN controller (CH) in the domain. When an MN attaches to the radio link (Base Transceiver Station (BTS)), the RS messages go to the central SDN controller forwarded by SWHI. The PMIP function of CH generates the corresponding RA to the MN. It also verifies if that particular MN can join the domain or not. Capabilities also can be set up. A virtual PBU is sent to the LMA function to update its BC on SDN SWHO. Then the SDN Controller updates the forwarding rules of switches via Openflow. Meanwhile, MN acquires its HoA. Attaching to the home network does not use any kind of PBU/PBA message in this architecture proposal.

When the MN visits a foreign network, the foreign SDN controller (CF) should update the home SDN controller (CH) about the MN's attachment. Between controllers, ordinary PBU/PBA is used to exchange information. Data is tunneled back to the home network, but SDN controllers can negotiate route optimization to avoid the home network when reaching a CN from the visited network.

Paper #11 A. Aissioury et al. (2015 Dec) [54]

A. Aissioui et al. [54] extend the Follow-Me-Cloud (FMC) concept with PMIPv6. FMC is about using the available nearest data center to the user. User sessions are always moved to that data center, and VMs in this data center provides the user's services. In this case, not just users move, connected services too. This work assumes that clouds are federated, so there is a control level connection between each cloud. There are two global entities: Inter-Domain Mobility Database (IDMD) and Follow Me Cloud Controller (FMCC). IDMD is responsible for maintaining PMIPv6-related actions (registrations and movement details) while FMCC can select the appreciated data center. Particularly, Binding Cache is outsourced to IDMD. After PMIPv6 registration procedures, FMCC is notified about the movement of MNs. This can be the trigger to relocate service between clouds. FMCC is the SDN controller, and actually IDMD is a supportive database to handle mobility. Service movement decision is made via Decision Making Application Module (DMAM) and Mapping Information Gateway (MIGW). DMAM is responsible for concluding whether service movement is required even while MIGW keeps and maintains the mapping between PMIPv6 entities and the underlying SDN-ready network. The overall architecture can be seen in Figure 28.

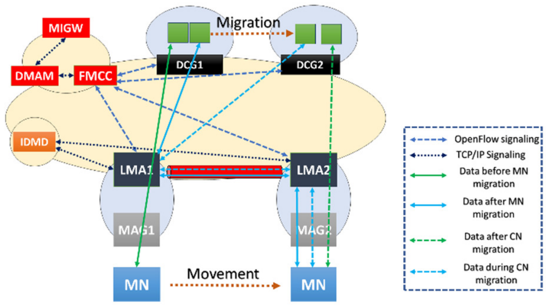

Fig. 28. A. Aissioui et al.'s proposed architecture for PMIPv6-based FMC [54]

Paper #12 Pill-Won Park et al. (2016 Feb) [55]

Pill-Won Park et al. [55] proposed an OpenFlow-Based Mobility Management (OMM) implementation using the PMIPv6 manner to locate mobility management requirements. Their architecture proposal consists of Mobility Management Entity (MME), which existed in the SDN controller and handles all mobility management functions (Figure 29). Three layers of switches are considered:

- Access Switches (ASs),
- Intermediate Switches (ISs),
- Gateway Switches (GWs).

A A A server connects to MME. Binding Cache, Flow Matrix, and GW-HNP mapping table are the relevant data structures of MME for supporting mobility management. GW-HNP mapping table is used for mapping the HNP (Home Network Prefix) with the actual gateway.

Flow Matrix is responsible for saving flow paths of the MNs; also, it saves previous AS, CS, and list of HNPs. The flow paths are saved as pairs of upstream and downstream. After selecting the GW, the MME search for the flow path between this GW and the AS is connected to the MN. When the handover occurs, the flow tables are updated in the switches, as the flow path of the new AS stored in the flow matrix.

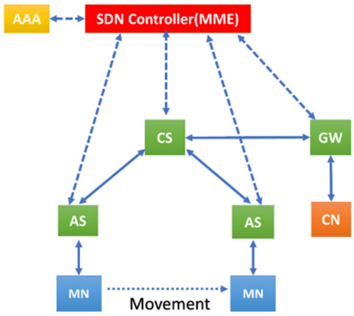

Fig. 29. System Architecture by Pill-Won Park et al. [55]

Paper #13 Kuljaree Tantayakul et. al (2016 Mar) [56]

Kuljaree Tantayakul et al. [56] main goal is to prove mobility management can be done without using PMIPv6 in an SDN-ready network (Figure 30). They propose SDN Mobility Service introducing new SDN signaling-based methods. Only two components are considered: controller and access routers (AR). Consequently, there is no tunnel usage.

Two new SDN operations were introduced: MN registration and MN handover. Both rely on exiting Openflow implementation, and they take the place of the mobility management signaling role.

The performance of PMIPv6 and their SDN-based proposal have been measured in terms of UDP throughput, TCP, and packet loss ratio. In every field, the proposal performed better.

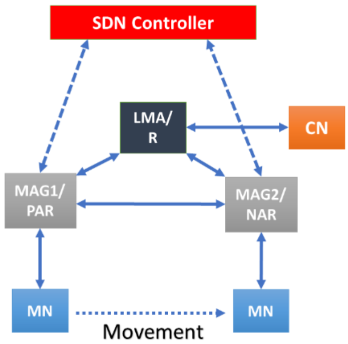

Fig. 30. Kuljaree Tantayakul et al. 's SDN mobility architecture proposal [56]

Paper #14 Ce Chen et al. (2016 Apr) [57]

Ce Chen et al. [57] propose a Mobility SDN scheme (M-SDN) to reduce the handover latency. Their proposal eliminates IP tunneling referred to in the paper by Raza et al., (Paper #3). They introduce the N-casting phase to accelerate handover, a preparation phase of handovers where every possible target is considered and prepared. Besides ordinary Openflow components, they use a Location Server to keep track of users' movements.

They assume that there are two types of handovers based on SDN domains (each domain has its controller, Figure 31):

- intra-domain handover
- inter-domain handover

There is an application called Mobility Application on the controller, which consists of two parts: Core module and REST interface. The Core module handles mobility-related maintenance: location tracing, flow redirection. The REST interface is the bridge between the core module and all other components. New signaling messages have been introduced to take care of mobility management.

One thing to highlight: there is no mention of using IPv6. One of the core components is DHCP. From this, we assume this is an IPv4-based solution, but the underlying ideas come from OF-PMIPv6.

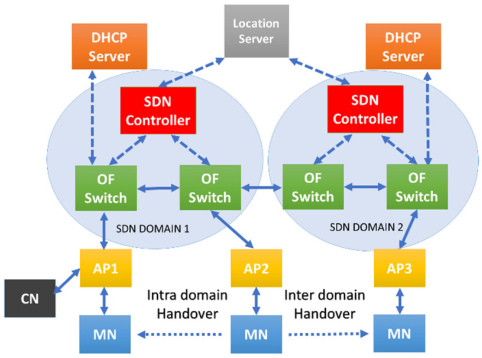

Fig. 31. Ce Chen et al.'s M-SDN proposed architecture [57]

Paper #15 Syed M. Raza et al. (2016 Jun) [58]

Syed M. Raza et al.[58] proposed a solution for inter- domain IP mobility with route optimization using PMIPv6 based on the SDN environment. Their work has a solution to the limitation of serving only one domain in PMIPv6 and SDN-PMIPv6, summarized in Paper #3.

They suggest having a communication channel between the controllers in different domains. When the handover occurs, the new controller checks the MN ID with the other controllers to confirm that this MN is in a new device or attached to another domain before, so the controller can decide to register the MN as a new device or trigger the mobility operation.

The architecture of this proposal is illustrated in Figure 32.

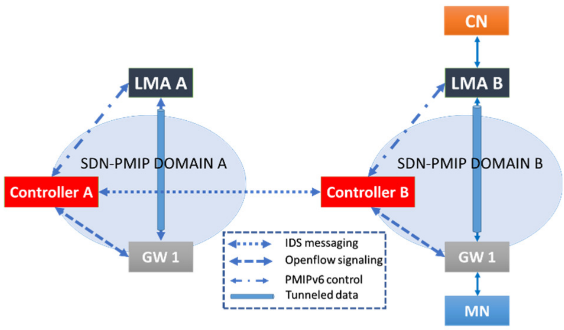

Fig. 32. Syed M. Raza et al.'s architecture [58]

This solution is an extension of Paper #3. They together solve inter-domain handover and addresses triangle routing problems in the context of PMIPv6 and SDN integration. This paper uses the new naming of the solutions: SDN-PMIPv6, instead of OF-PMIPv6 at Paper #3.

Paper #16 Walla F Elsadek et. al (2016 Aug) [59]

Walla F Elsadek et al.[59] aim to propose an LTE- independent inter-domain handover. They utilize the SDN concept inspired by PMIPv6. Their proposal creates a virtual path to the MN's home network with an SDN mobility overlay called "Three Tier Mobility Overlay". They proposed to hide the L3 complexity by using these virtual paths.
SDN controller maintains users' profile data. There is an L4 selective breakout possibility to the Internet to avoid core network overload at this framework. This can be seamlessly integrated into the existing CAPWAP or PMIPv6 deployments. New mobility entities introduced in this paper (Figure 33):

1. Mobility Access Switch Tier (AS): provides the connection between the access aggregation layer and a broadcast domain.
2. Mobility Detector Switch Tier (DS): two types of this switch are introduced. The Foreign DS and this switch work as a foreign agent that provides services to the MN at the foreign network, and Home DS work as the home agent and guarantees security.
3. Mobility Gateway (MG) and Relay Switch (RS) Tier: those entities take care of connecting overlay in intra-domain mobility. The difference between MG and RS is the connected overlay managed by a different or same SDN controller.

Their proposal pushes toward a complete SDN solution for handling mobility management.

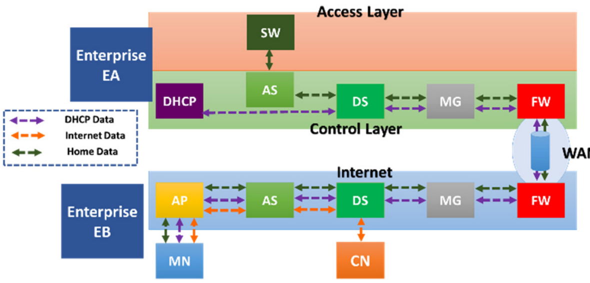

Fig. 33. Walla F Elsadek et al. 's proposed mobility scenario [59]

Paper #17 Syed M Raza et al. (2017 Jan) [60]

Syed M. Raza et al. [60] proposed a solution for inter- domain mobility in the SDN PMIPv6 environment using an on-demand mobility concept: Inter-Domain SDN-PMIP (IDS- PMIP). Using multiple prefixes for the MN makes it possible to have a seamless handover between two domains. The main idea is to keep the old prefix for the already active sessions, and all new sessions will build based on the new prefix. A new field called proxy info is added to the Controller Binding Cache (CBC). This field contains proxy tuples; those proxy tuples have the MNs prefixes and the controllers' addresses, which assign those prefixes. There is a communication (Border Gateway Protocol (BGP) -based) between the controllers from different domains for discovering the previous domain for the MN.

When an MN attaches to an SDN-PMIP domain, it sends RS to the first Openflow-enabled gateway (OGW), depicted in Figure 34. OGW forwards RS to the domain controller, which parses the MN-ID to conclude AAA. If AAA is successful, the controller sends Discovery Request (DISC- REQ) to all the neighboring controllers. Controllers answer with Discover Response (DISC-RESP): if there is a matching entry for the particular MN in their CBC, they respond with that entry (MN-ID, used prefixes). Otherwise, it is left empty. This is also a solution for first-time registration: if the field is empty, it implicitly tells it is not an inter-domain handover. After having this discovery procedure completely, PBU can be sent to the actual LMA, which belongs to the particular domain. When PBA is received from LMA, the controller sets up tunnels between OGW and LMA. This means LMA is not responsible for setting up the tunnel even though one of the tunnel endpoints is LMA.

When inter-domain handover happens (Figure 35), DISC-RESP is not empty. The previous controller (controller A) deregisters the MN from its domain. But two prefixes are assigned at this moment to the MN. The new LMA (domain 2) starts advertising both prefixes after successfully executing the recent PBU/PBA events. New connections are assigned to the new prefix (Prefix B). The usage of double IPv6 prefixes is the method or cost to make handover smother.

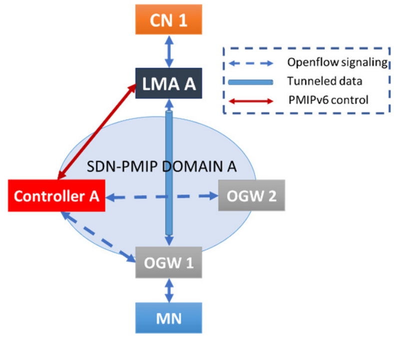

Fig. 34. Mobile Node registration [60]

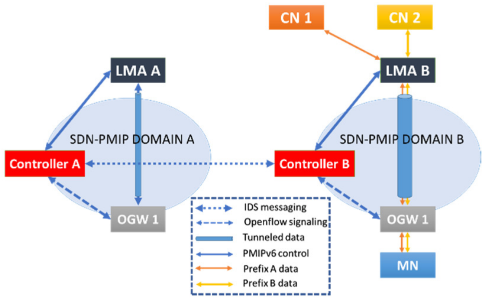

Fig. 35. Inter-domain handover [60]

Paper #18 N. Omheni et al. (2018 Jan) [61]

N. Omheni et al. [61] propose a partially distributed mobility management in the SDN context using PMIPv6.

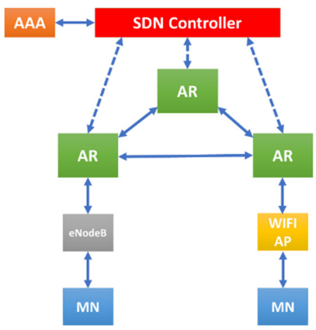

Fig. 36. N. Omheni et al. 's architecture proposal for DMM [61]

They have a three-layer architecture, shown in Figure 36. The first is the access layer where SDN-enable WIFI access points and LTE interfaces are placed, the devices in the access layer can be programmed. Distributed Mobility Management – Access Router (DMM-AR) comes at the second layer, particularly Openflow capable switches that provide connectivity to the access layer and contribute to the mobility management process. The third layer is dedicated to the controller and other management-related entities like AAA. The SDN controller act as PMIPv6 LMA and the DMM-AR Act as the MAG. Their proposal divided the operation into two stages, the preparation and registration Stage and the handover execution stage.

Paper #19 Syed M. Raza et al. (2019 Oct) [62]

Syed M. Raza et al. [62] extended the previously solutions introduced on (Paper #15; Paper #17) with evolved architecture called on-demand inter-domain SDN-PMIPv6 (OIS-PMIPv6). Some advantages came with this solution, like decreased handover latency, improved resources utilization, and added scalability to the system. System architecture can be seen in Figure 37.

New Controller-to-Controller Communication Protocol (C3) was introduced in the paper. It enables session establishment between two controllers to facilitate prefix discovery. Also, a prefix retrieval technique is used to release and return IPs in OnDemand mobility.

The Data Plane Gateway(DP-G) refers to the MAG. CBC mess ages contain new fields to control the mobility in multiple domains; they refer to this field as a "Proxy", including tuples defined as prefix and the home controller of the prefix.

The MN has a new prefix in each domain, and all new sessions establish with this prefix. After inter-domain handover, the IPv6 address with the old prefix remains active in the new domain while the sessions using that IPv6 address stay active while all-new sessions establish with the newly assigned prefix.

The old sessions keep working as follows: the uplink traffic toward CN goes through the new anchor as the destination is the same, while the downlink traffic goes through the old anchor. This uplink/downlink traffic helps in improving the overall delay

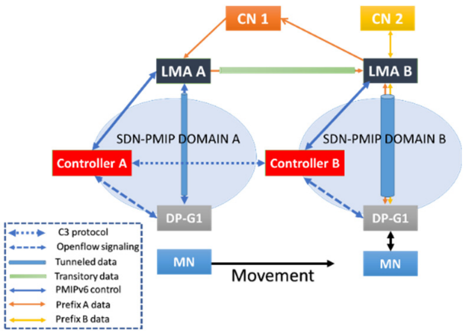

Fig. 37. Syed M. Raza et al.'s testbed for handover tests [62]

V. Outlook on Further Pmipv6 Evolution

PMIPv6 is not just examined in the narrow context of mobile telecommunication. One of the foreseeable future research topics and application possibilities is V ehicular communication (V2X). IPv6 Wireless Access in Vehicular Environment (IPWAVE) [63] [64] is a concept to facilitate vehicular communication in IP networks. Here, communication between the infrastructure and vehicles must be maintained to avoid service disruption. IP-Road Side Unites (IP-RSU) are placed next to the roads; they can act like MAGs and communicate with IP OnBoard Unites (IP-OBU), which are built into the cars. Mobility Anchors (MA) in this architecture behave like an LMA. When a vehicle moves to an area where another IP-OBU serves, then IP-based mobility management can avoid service disruption. IPW A VE architecture is depicted in Figure 38.

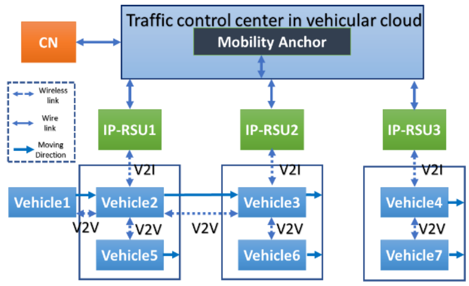

Fig. 38. Example of vehicular network architecture for V2I and V2V [63]

The aviation industry has also been examining the usage of IP- based mobility management. Aeronautical Telecommunication Network with IP (ATN/IP) may also utilizes PMIPv6 [65] [66][67][68], main concepted can be seen in Figure 39.

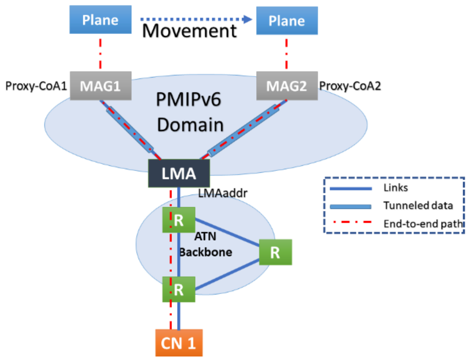

Fig. 39. Aeronautical telecommunication handover [66]

PMIPv6, as a network-based approach, is also intended to solve a mobility problem, specialized when an airplane moves from one aviation control system to another. There were even experiments to change IPv6 in IPv6 tunnel of PMIPv6 to MPLS in aeronautical networks [68].

PMIPv6 has been started to be examined for integrating with 5G networks. Kyoungjae Sun et al.[69] present a distributed PMIPv6 integration to 5G User Plane Functions (UPF) where core and edge sites are considered, presented in Figure 40. They also follow the 5G system design guidelines to separate control and user plane. Distributed LMA (DLMA) is located on the edge side, which receives control messages of PMIPv6; meanwhile, an edge UPF handles the data plane. Their goal is to exchange session handling and QoS based on specific types of IPv6 addresses, defined in RFC 8653 [25].

But SDN brings in a new approach for PMIPv6 too. Including the above-mentioned specialized (emerging) applicabilities and the "ordinary" telecommunications usage (working with 5G, non-3GPP traffic offload). Thus, the domain of PMIPv6 presents several new research topics with SDN. This will not just contain the architecture redesign of PMIPv6 in the SDN context but examine the dynamicity, flow-based, and distributed manner of the SDN-PMIPv6.

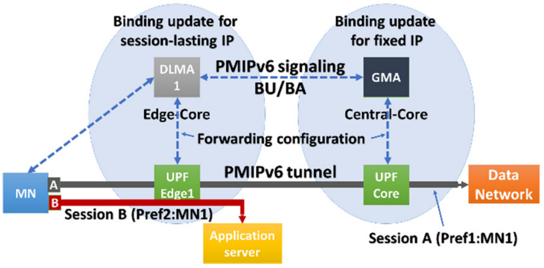

Fig. 40. PMIPv6 based distributed session mobility management [69]

5G is accelerating the cloudification of network services, and Mobile IPv6 and Proxy Mobile IPv6 are not exceptions in this trend [70] [71]. But it highlights new aspects of networking like energy consumption or Total Cost of Ownership (TCO) questions. To our best knowledge, these questions have not yet been addressed so far in the overall IP-based mobility management context. However, with 5G, there are several publications to deal with it (e.g., [72][73][74][75][76]). The ones above present new ways for further research directions of IP-based mobility management. This paper has also concluded that flow mobility has not been considered together so far in a PMIPv6 + SDN environment where multiple interfaces are used. This also opens further research possibilities.

VI. Conclusion

To the best of our knowledge, this paper surveyed all the architectures focusing on PMIPv6 – SDN integration solutions available in the literature.

In Table 3, we summarized the essential characteristics of all the analyzed architectures. The biggest differentiators are whether the architecture proposal keeps PMIPv6 control plane signaling or relies on tunneling elimination. Most of the papers also use Openflow for SDN implementation. From the point of view of standard compatibility and interoperability with legacy systems, keeping the PMIPv6 control plane is crucial.

Deployment of SDN or Openflow controllers has brought in a new type of Single-Point-of-Failure problem. Even though LMA SPOF weakness is solved with SDN, the network operator should solve the SDN controller problem. The reliability of SDN controllers is out of the scope of this paper, but a full-scale, deployment-ready solution must deal with that issue. The surveyed studies clearly show that standardization work must also be considered as inter- (administrative)domain handover needs a common base.

Interesting, but 4G and 5G network compatibility are not widely examined and considered in the surveyed papers. Furthermore, cloud computing compatibility has rarely been mentioned in the available literature. We think this definitely will be an important future resource direction.

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László Bokor received the M.Sc. degree in computer engineering from the Department of Telecommunications, Budapest University of Technology and Economics (BME) in 2004, later the M.Sc.+ degree in bank informatics from the Faculty of Economic and Social Sciences, BME, and the Ph.D. degree from the Doctoral School of Informatics, BME. He has researched in multiple EU-funded and national research and development projects for several years. He is currently with the Department of Networked Systems and Services (HIT) as an Associate Professor. He leads the Commsignia-BME HIT Automotive Communications Research Group at BME and the Vehicle Communication Working Group of the Mobility Platform at KTI Institute for Transport Sciences. He is a member of the HTE, the Hungarian Standards Institution's T echnical Committee for ITS (MSZT/MB 911), the TPEGoverC-ITS Task Force within the TPEG Application Working Group of TISA, the ITS Hungary Association, and the BME's MediaNets Laboratory, where he currently participates in different R&D projects. In recognition of his professional work and achievements in mobile telecommunications, he received the HTE Silver Medal (2013), the HTE Pollák-Virág Award (2015, 2022), and the HTE Gold Medal (2018). He was a recipient of the UNKP-16-4-I. Post-Doctoral Fellowship in 2016 from the New National Excellence Program of the Ministry of Human Capacities of Hungary. In 2018 he was awarded the Dean's Honor (BME VIK) for education and research achievements in the field of communication of autonomous vehicles; in 2020, he received the BME HIT Excellence in Education Award.

TABLE III
SUMMARY OF THE SURVEYED PAPERS WITH KEY FUNCTIONAL INDICATORS

#	The approach	Publication date	Main objective	Main distinguisher	Does it use PMIPv6 signaling?	Tunneling	Protocol	Other comments
1	Seong-Mun Kim et. al [41]	2014 Jan	Integration PMIPv6 to Openflow and avoid tunneling	Control and data planes separation and eliminate IP tunneling	Yes	No	Openflow	Name: OPMIPv6
2	Kyoung-Hee Lee [42]	2014 Jan	Keeping PMIPv6 signaling while moving it into the SDN era	Routeflow as a controller	Yes	No	RouteFlow and Openflow	Control plane elements are VMs
3	Syed M. Raza et al. [44][45]	2014 Jan	Integration PMIPv6 to Openflow to reduce handover latency	Keeping full backward compatibility on PMIPv6	Yes	Yes	Openflow	Name: OF-PMIPv6
4	Hao Yu [46]	2014 May	Solution for inter-domain heterogeneous mobility with SDN and PMIPv6	Heterogenous radio access networks are examined, including EPC	Yes	Yes	It is not mentioned directly.	Vertical handovers
5	You Wang et al. [47]	2014 Aug	PMIPv6-like Mobility Management with Openflow	Binding Cache placement algorithm	No	No	Openflow	Performance compared to PMIPv6 and ILNP[77]
6	Yuta Watanabe, et al.[48]	2015 Jan	Route optimization	Offload LMA by suggesting a route to CN without passing LMA	Yes	No	Openflow	Total throughput increased
7	Sakshi Chourasia et al. .[50]	2015 Apr	New EPC Architecture without MM protocols	PMIPv6 usage at 3GPP S5/S8 interface is also covered	No	No	Openflow	GTP also considered
8	Seong-Mun Kim et al. [51]	2015 Arp	Extended evaluation for Paper #1	Control and data planes separation and eliminate IP tunneling	Yes	No	Openflow	Performance gain compared to ordinary PMIPv6
9	Abbas Bradai et al. [52]	2015 Jun	Dynamic anchor point	Load-balancing considered	No	Yes	Openflow	HMIPv6 is used too
10	Weng-Kang Jia [53]	2015 Nov	PMIPv6 function integration to EPC with SDN	Inter-domain PMIPv6 -based handover with SDN help	partially	partially	Openflow	Performance gain in registration to non-SDN PMIPv6
11	A_Aissioui et al. [54]	2015 Dec	Follow-me-cloud based on PMIPv6	Cloud computing considered	Yes	No	Openflow	Server and mobile user move too
12	Pill-Won Park et al. [55]	2016 Feb	Support mobility in SDN architecture with OpenFlow signaling and PMIPv6 concept	No PMIPv6 signaling messages	No	No	OpenFlow	Name: OMM
13	Kuljaree Tantayakul et al. [56]	2016 Mar	Eliminates PMIPv6 for mobility management in the SDN world	Existing Openflow messages are used	No	No	Openflow	Refers to Seong-Mun Kim et. al and Syed M. Raza et. al
14	Ce Chen .[57]	2016 Apr	Low-Latency Handover in SDN-Based Enterprise Networks	Using and evolving OF-PMIPv6 concepts for IPv4	No	No	Openflow	Name: M-SDN
15	Syed M. Raza et al. [58]	2016 Jun	Improve the PMIPv6 based on OpenFlow to serve inter-domain IP mobility	Inter-domain handover	Yes	Yes	OpenFlow	The architecture of Paper #3 evolved
16	Walaa F. Elsadek et al. [59]	2016 Aug	Mitigating inter-domain handover with an SDN Mobility Framework	Focus on offloading core network	No	No	Openflow	SIPTO/LIPA considered
17	Syed M. Raza et al. [60]	2017 Jan	On-demand way of working is concerned	Inter-domain handover with multiple prefix assignment for the MN	Yes	Yes	OpenFlow	Extension of Paper #15 ( ) IDS-PMIP
18	N. Omheni et al. [61]	2018 Jan	Partially distributed way of working	MIH is used	Yes	Yes	Openflow	The number of handovers is reduced
19	Syed M. Raza et al. [62]	2019 Oct	on-demand inter-domain SDN-PMIPv6	New protocol for controllers communication Prefix retrieval mechanism	Yes	Yes	Openflow C3 between controller	Extension of Paper #15 () and #17 () Name: OIS-PMIP