Computer Science and Information Systems 17(1):51–70 https://doi.org/10.2298/CSIS181101016C

# Towards a software-based mobility management for 5G: An experimental approach for flattened network architectures.

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**Abstract.** The number of mobile subscribers, as well as the data traffic generated by them, is increasing exponentially with the growth of wireless smart devices and the number of network services that they can support. This significant growth is pushing mobile network operators towards new solutions to improve their network performance and efficiency. Thus, the appearance of Software Defined Networking (SDN) can overcome the limitations of current deployments through decoupling the network control plane from the data plane, allowing higher flexibility and programmability to the network. In this context, the process of handling user mobility becomes an essential part of future mobile networks. Taking advantage of the benefits that SDN brings, in this article we present a novel mobility management solution. This proposal avoids the use of IP-IP tunnels and it adds the dynamic flow management capability provided by SDN. In order to analyse performance, an analytical model is developed to compare it with NB-DMM (Network-based DMM), one of the main DMM (Distributed Mobility Management) solutions. Additionally, performance is also evaluated with an experimental testbed. The results allow handover latency in real scenarios and numerical investigations to be measured, and also show that SR-DMM achieves better efficiency in terms of signaling and routing cost than NB-DMM solution.

**Keywords:** SDN, DMM, IPv6 mobility, cost analysis, experimental evaluation.

## 1. Introduction

With the ever more rapid development and innovations of wireless communications, and the advancement of more powerful and smart mobile devices, the future mobile networks are expected to be able to provide new services according to the specific demands of the users. These advances have generated an exponential growth of global mobile data traffic which will increase sevenfold between 2017 and 2022, reaching 77.5 exabytes per month by 2022 [1]. The signaling load is expected to increase almost 50% faster than the growth in data traffic [2]. Driven by this massive wireless data traffic increase, efficient network management mechanisms have been revealed as one of the major challenges in next-generation mobile networks [3, 4]. These mechanisms must be able to dynamically control and allocate network resources to provide flexibility in the new 5G ecosystem [5].

One of these processes, involved in the network management, is the mobility support. Mobility management protocols are responsible for maintaining the active services while the user roams between different networks. For this purpose, the Internet Engineering Task Force (IETF) standardized IP mobility management protocols that are Mobile IPv6 (MIPv6) [6] and Proxy Mobile IPv6 (PMIPv6) [7]. The operation of these solutions is based on the existence of a central entity responsible for managing the movement of the mobile node. This agent maintains the location of MNs and redirects traffic to them. However, these centralized mobility management paradigms are not efficient when handling a large volume of mobile data traffic. Our previous works [8, 9] establish the limitations and problems of these approaches such as non-optimal routes, centrally deployed mobility anchors (single point of failure) and reliability and scalability issues [10].

In order to address these problems, new distributed mobility management approaches are being proposed, in which the mobility anchors are positioned closer to the user with the aim of getting a flatter network. Moreover, SDN has emerged as an efficient network approach capable of supporting the dynamic nature of the next-generation wireless networks. In this article, we propose a mobility management solution, called SR-DMM, that combine SDN and DMM and improves the mobility management process in 5G networks, taking full advantages of the software capabilities of the SDN paradigm. The key benefit of the SR-DMM solution is that it manages to reduce significantly both signaling and routing cost, optimizing control and data plane. The signaling overhead is reduced because our proposal does not require the binding refresh process. Moreover, the complexity of the data plane and the tunnel management is also reduced avoiding the use of IP-IP tunnels during the movement of the users. Due to this, the proposed solution can reduce handover latency. These benefits have also been identified and validated through experimental evaluation in a testbed. In addition, an analytical framework has been developed in order to evaluate and compare our proposal with a previous legacy DMM proposal.

The rest of the paper is organized as follows. In Section 2, we briefly present background information about Distributed Mobility Management protocols. Then, Section 3 describes Software Defined Networking paradigm and SR-DMM is introduced. Section 4 shows the analytical model used to evaluate the proposal, and the numerical results of this analysis. Section 5 presents the performance evaluation through the experimental prototype. Finally, Section 6 concludes the paper.

## 2. Related work

Nowadays, most of the deployed architectures, such as 3GPP (Third Generation Partnership Project) networks, have a small number of centralized anchors managing the traffic of thousands of mobile users, but these centralized approaches have certain problems [8]. The evolution towards DMM approaches has shown improvements in better use of network resources [11, 12, 13, 14, 15]. Additionally, future mobile networks will be driven by software, relying on emerging technologies such as SDN [16, 17, 18].

Similarly to other mobility solutions, distributed mobility management protocols can be broadly classified in two categories, depending on the role of the mobile node in the handover process, namely those that require the active involvement of the MN (Host-

Based DMM) and those that not (Network-Based DMM). Thus, in this section, an overview of the distributed mobility management protocols is presented in order to then discuss its relationship with the Software Defined Networking paradigm and its implications for future mobile networks. A brief description of the existing solutions is also given for comparison with the SDN-based DMM solution proposed in this paper.

## 2.1. Host-Based DMM

This DMM proposal is based on Mobile IPv6 and is detailed in [13, 19] (Host-Based DMM, HB-DMM). HB-DMM extends mobility signaling and reuses many concepts such as the binding cache at the MN, binding cache at the mobility anchor or tunneling. Moreover, in [19], the authors attempt to improve the performance of mobility support by extending the MIPv6s HA to the AMA (Access Mobility Anchor), which is a new mobility anchor defined for the proposed Host-Based DMM approach. These AMAs are distributed at the edge of the access network level and the MN configures its address based on the provided network prefix from the AMA.

When an MN moves to an adjacent access network, served by another AMA, a new address is configured in the MN based on the network prefix obtained from the serving AMA at the new access network, while it keeps the previous address from the origin AMA. As a result of the signaling between the serving AMA and the origin AMA, a bidirectional tunnel is created between them through new signaling messages called Access Binding Update (ABU) and Access Binding Acknowledgement (ABA). As depicted in Fig. 1, this solution creates multiple tunnels between AMAs and, in cases where a high mobility rate exists, the system performance might be critically compromised by the frequent registrations and maintenance of multiple tunnels.

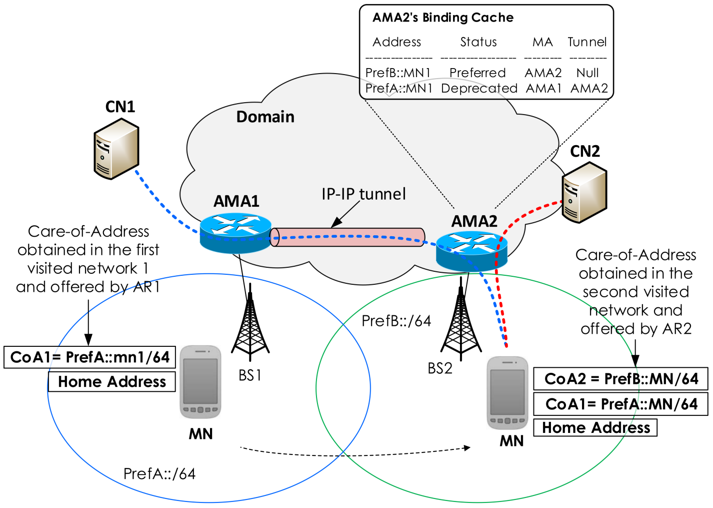

**Fig. 1.** Host-Based DMM

## 2.2. Network-Based DMM

Network-Based DMM (NB-DMM) [20] is a Distributed Mobility Management approach that shares with PMIPv6 the fact that it is network-based. It exempts the MN from participating in any mobility signaling, so no network software upgrade is required at the MN for mobility support because distributed mobility anchors perform mobility signaling on behalf of the MN. This NB-DMM is one of the early proposals designed in the IETF for network-based DMM at the Distributed Mobility Management Working Group. In NB-DMM, the mobility management functionalities are moved to the access routers (AR) level in order to anchor the traffic closer to the MN. Each AR is required to have both mobility anchoring and location functionalities, and it is referred to as a mobility capable access router (MAR).

In NB-DMM, a new session is anchored at the current AR and initiated using the current IPv6 address. When a handover occurs before the end of the session, the data traffic of this session is tunneled between the current MAR and the anchoring MAR for this session. In order to achieve a network-based solution without the participation of the MN in the mobility signaling, the architecture is partially distributed and relies on a centralized database (Mobility Context DB, CMD). This DB stores ongoing sessions for the MNs; it stores the home network prefix currently allocated to the MN and their respective anchoring points. Thus, upon a handover, the new MAR retrieves the IP addresses of the anchoring MAR for the MNs sessions from the database. Then, the new MAR proceeds to update the location by sending a PBU to each anchoring MAR. Each anchoring MAR replies by a PBA. The basic operation of NB-DMM is depicted in Fig. 2.

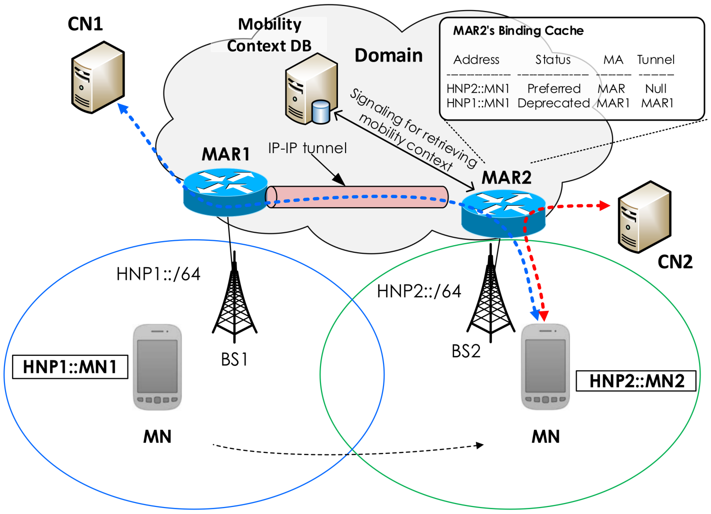

**Fig. 2.** Network-Based DMM

## 3. SDN-Based Distributed Mobility Management

Software Defined Networking is an emerging approach to designing, building and managing networks. This term has been coined in recent years and is currently attracting attention from universities and industry as important architecture for the management of traditional IP networks which are complex and very hard to manage. The SDN architecture is directly programmable, agile, centrally managed and open standards-based.

Furthermore, Fig. 3 describes the SDN functional architecture which consists of three main layers. The Infrastructure layer involves the physical network equipment, the control layer consists of the network controllers and the application layer involves functional applications.

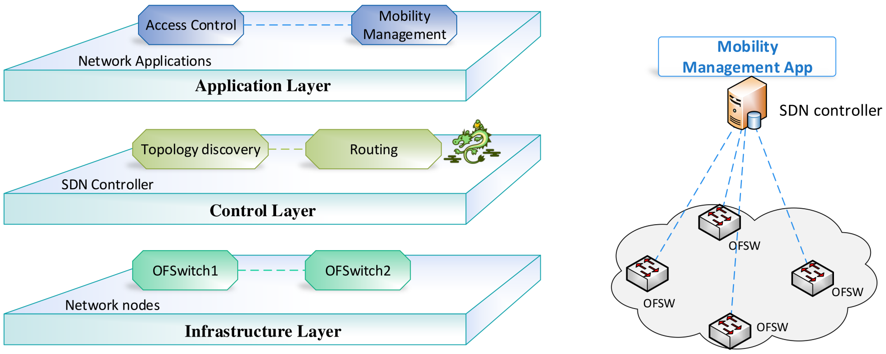

**Fig. 3.** SDN functional architecture

In this way, SDN provides innovation, improved performance and enhanced configurations. Therefore, this paradigm can be seen as a great opportunity to manage mobility efficiently in 5G networks.

### 3.1. SR-DMM solution

The objective of managing the mobility of MNs through SDN technology is to achieve solutions where the control plane is centralized and separated from the data plane, which is distributed. Mobility management is offered based on a service developed as an SDN application that will run on the network controller. This network controller manages a control plane that consists of generic hardware. Therefore, the main objective of our proposal (SDN Redirection DMM) is to provide flexibility, scalability and reliability to the future wireless communications by using SDN capabilities in order to manage mobility as a service. SR-DMM focuses on providing L3 improvements such as L3 handover latency reduction. However, there are other solutions, which include improvements at the link-layer [21, 22], but they are out of the scope of this paper.

In this work, network flexibility refers to the ability of a network to adapt its resources [23, 24]. SR-DMM offers flexibility through SDN programmability. The proposed solution implements a mechanism via open standards to optimally redirect flows when an MN moves through the network domain. Moreover, scalability is defined as the ability to, more specifically in the control plane, handle an increasing workload [25]. SR-DMM provides scalability by reducing the signaling overhead because our proposal does not require the binding refresh process. In the following sections, flexibility and scalability are measured analytically in terms of signaling cost and packet delivery cost respectively. These improvements are also measured experimentally in terms of handover latency. In addition, SR-DMM introduces reliability through centralized network controllers which must be capable of meeting real time requirements of the network [26].

The centralized network controller has a global vision of the entire network. This opportunity is taken advantage of by SDN application through OpenFlow channel. Therefore, mobility service knows the global status of the DMM domain data plane in order to make timely decisions.

On the other hand, the network controller provides capabilities to the edge switches through OpenFlow interfaces by anchoring the packet flow to each mobile node. This solution distinguishes between switches with anchor capabilities (edge switches) and switches without these capabilities. The SR-DMM application is developed on the network controller and it allows flow tables over OpenFlow Switches (OFSwitches) with anchor capabilities to be configured. Moreover, the SR-DMM application provides the edge OFSwitches with other functionalities such as neighbour discovery and access control.

Due to the global vision of the network controller, the proposal avoids overheads introduced by tunneling between mobility anchors in DMM solutions by performing flow redirections.

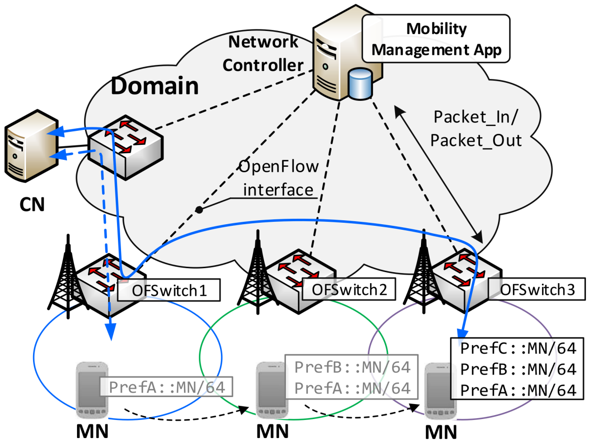

**Fig. 4.** Architecture of SR-DMM proposal

Fig. 4 shows the functional architecture of the SR-DMM solution where the access network consists of OpenFlow switches which are managed by the network controller. In this case, a switch located at the edge of the network (e.g. OF-Switch1) acts as an anchor for the flows opened by the mobile node when connected to this OF-Switch. When the MN moves through the DMM domain, it acquires new IPv6 prefixes from the visited networks.

Clearly, an analogy with the NB-DMM solution can be established: an SDN controller in SR-DMM is a similar entity to CMD (in NB-DMM) and OFSwitches are the entities analogous to the MAARs located on the edge network.

The following subsections show the important tasks of the SR-DMM proposal, such as the initial registration operation and the handover process.

### 3.2. SR-DMM: Initial registration

When an MN connects for the first time to an OFSwitch of the DMM domain, it sends a RS (Router Solicitation) message to this device. This OFSwitch, according to its flow table, encapsulates the RS in an OpenFlow PacketIn message and sends it to the network controller. The MN is authenticated and located by the network controller,which stores a bind with its MAC address, its identifier (MN-ID) and the anchor to which the terminal is currently associated. Then, the network controller retrieves the corresponding network prefix, creates an RA (Router Advertisement) message with this prefix, encapsulates this message into an OpenFlow PacketOut message and finally this message is sent to OF-Switch. When the MN receives the RA, it configures the IPv6 address that anchors to the OFSwitch (see Fig. 5).

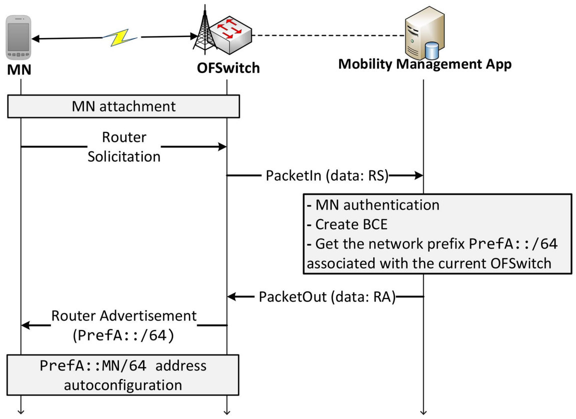

**Fig. 5.** SR-DMM proposal: initial registration operation

### 3.3. SR-DMM: Handover operation

During the handover operation, SR-DMM allows the location of the MN to be detected when the network controller receives a new RS message encapsulated into a PacketIn message. In this moment, the network controller de-encapsulates this message and verifies that the current OFSwitch is different from the previous one. If so, the SDN controller generates as many network prefixes as previously visited OFSwitches by the MN during its movement through the DMM domain. With these network prefixes, the mobile node could configure its IPv6 network addresses. This occurs when the MN receives an RA message from its new mobility agent.

The SR-DMM application sets a flow rule on each previous OFSwitch where the flows are anchored by the MN. The creation of flow rules for the OFSwitches visited by the MN is described in detail in Algorithm 1.

**Algorithm 1:** Flow rules calculation for the OFSwitches visited by the MN

```
Input:
   Mobile Node ($MN$),
   Previous OFSwitches list ($OFS_{list}$),
   Current OFSwitch ($COFS$)
Output:
   Flow rules list to install in OFSwitches ($FR$)
foreach $PrevOFS \in OFS_{list}$ do
    // Get IPv6 address from the MN physical address and network prefix of the PrevOFS
    $MN_{global\_addr} = getIPv6Address(MN_{hw\_addr}, PrevOFS_{prefix})$;
    // Get local address used to connect PrevOFS and COFS
    $MN_{local\_addr} = getIPv6Address(COFS, MN_{Id})$;
    // Build OpenFlow rule to install on OFSwitches
    $Rule = buildOpenFlowRule(PrevOFS, MN_{global\_addr}, MN_{local\_addr})$;
    // Create list of all rules
    $FR[PrevOFS] = Rule$
end
return $FR$;
```

The installed rule allows packets to redirect from previous anchors to current mobility agents of the MN by establishing an IPv6 destination address which is formed by the network prefix associated with the current OFSwitch and the identifier of the MN in the SR-DMM domain (MN-ID). The flow rule installed on the current mobility agent allows the original IPv6 address of the packets belonging to the previous sessions to be restored in order to maintain the continuity of the sessions transparently. Moreover, the flow rules installed on OFSwitches expire when the time elapses and the corresponding match does not exist. This event is received by the network controller and the expired sessions will not have mobility support (see Fig. 6).

Therefore, SR-DMM allows data traffic to be redirected from the previous OFSwitch to the current one transparently according to the MN location and without involving the MN in the control signaling. This process does not overload the network with the control headers introduced by the IP-IP tunnels.

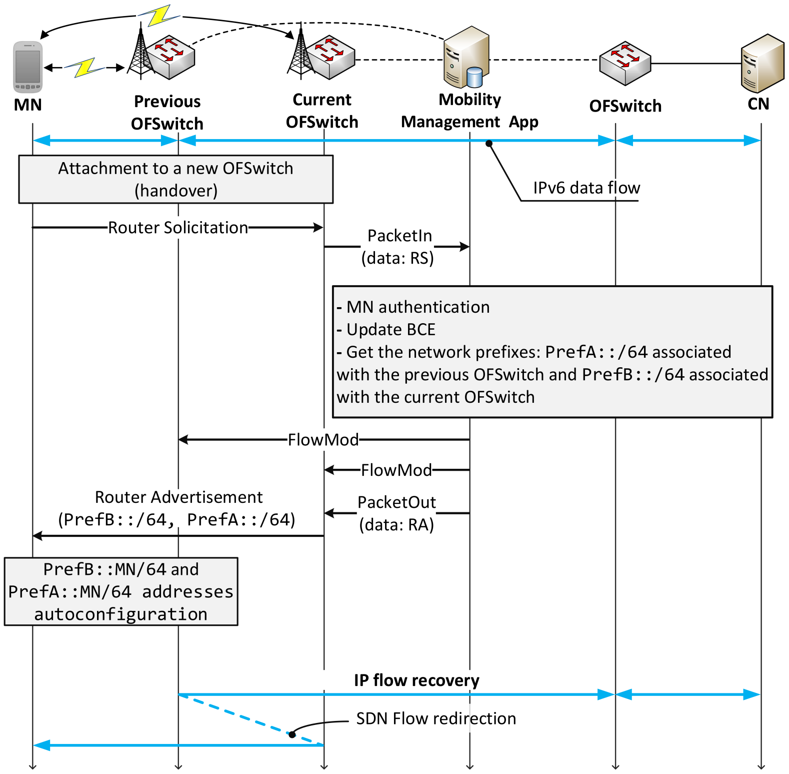

**Fig. 6.** SR-DMM proposal: handover process

Other implementations establish an optimal route by applying flow rules to all OFSwitches involved in the path between CN and MN [27]. With SR-DMM it is only necessary to install new rules on the edge OFSwitches visited by the MN because the paths to each destination network are calculated previously and dynamically by the mobility service in order to calculate the optimal route between the previous OFSwitch and the current one. The SR-DMM solution does not need to use any specialized mobility agent, as distinct from other solutions such as [28]. All network devices of the DMM domain are generic and its functionality is established by the network controller, which chooses whether the switches act as mobility agents or not.

## 4. Analytical model

This section presents a cost analysis in terms of signaling cost and data packet delivery cost of our proposed solution and compares them with NB-DMM solution.

The analysis is performed on a domain which consists of N cells connected to different access nodes. These will be the first network devices with IP capability. The network topology is described in Fig. 7.

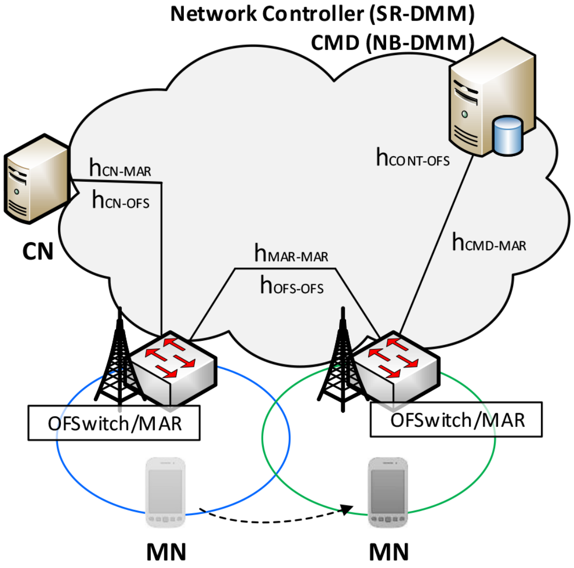

**Fig. 7.** Network topology used in analysis.

NB-DMM and SR-DMM solutions are evaluated through an analytical model in order to calculate signaling cost and packet delivery cost. Both solutions are also analysed on an experimental testbed, which is presented in the following sections.

The analytical model has been developed using the framework described in [15]. The packet transmission cost in IP networks is directly proportional to the number of hops between source and destination nodes. Hence, $h_{x,y}$ is defined as the hop distance between $x$ and $y$ network nodes.

### 4.1. Signaling cost evaluation

One of the main functionalities for any IP mobility management protocol is the process of ensuring that the MNs mobility session is kept up to date while an MN moves among networks. This requires control messages that need to be sent among the mobility agents in the network.

The total signaling cost of registration updates during a session is denoted by $C_s$. The signaling cost is the accumulative traffic load on exchanging signaling messages during the communication session of the MN. This cost depends on the size of the signaling messages and the number of hops in every L3 handover process during the time interval that the MN communication remains active. Therefore, for each movement into a new subnet, the Proxy Binding Update(PBU)/Proxy Binding ACK (PBA) message is sent to the CMD for NB-DMM proposal. Moreover, the binding cache is refreshed during the prefix lifetime (binding refresh process) and the prefix is deleted when there is no active session (deregistration process).

The SR-DMM approach notifies the handover using OpenFlow messages to interact with the forwarding table of the OFSwitches. The signaling control messages exchanged are FlowMod messages, which are typical of SDN architecture. Thus, the path between mobility agents is updated through FlowMod messages. Moreover, inactive network prefixes are removed when the timers of the flow table entries expire. In this case, the binding refresh mechanism is not necessary.

We refer to the total signaling cost as a sum of the three main components: the cost for the binding update after a handover; the cost for terminating a prefix that is no longer active; and the cost required to periodically refresh the bindings. Therefore, the signaling cost during MN movement for both NB-DMM and SR-DMM solutions are summarized in the following expressions:

$$\begin{aligned} C_s^{NB-DMM} &= \mu_c \cdot ((S_{PBU} + S_{PBA}) \cdot h_{CMD-MAR} \\ &\cdot (N_{pr} + 1) + 2 \cdot (S_{PBU} + S_{PBA}) \cdot h_{CMD-MAR} \\ &+ R_{BCE} \cdot (S_{PBU} + S_{PBA}) \cdot h_{CMD-MAR}) \end{aligned} \tag{1}$$

$$\begin{aligned} C_s^{SR-DMM} &= \mu_c \cdot ((N_{pr} + 1) \cdot 2 \cdot S_{FlMod} \cdot h_{CONT-OFS} \\ &+ (S_{P-IN} + S_{RS} + S_{P-OUT} + S_{RA}) \cdot h_{CONT-OFS}) \end{aligned} \tag{2}$$

where $\mu_c$ is the subnet (i.e., cell) border crossing rate and $N_{pr}$ is the number of active prefixes per MN. $N_{pr}$ can be also defined as the number of MARs/OFSwitches which maintain some active session with the MN. According to [29], $N_{pr}$ is calculated as:

$$N_{pr} = \frac{\mu_c}{\delta} \tag{3}$$

where $1/\delta$ is the mean value of the active prefix lifetime while the MN is visiting a foreign network.

### 4.2. Packet delivery cost evaluation

The total data packet delivery cost for a session is defined as $C_{pd}$. This value is influenced by the size of the data messages multiplied by the number of hops needed to forward packets from the CN to the MN and vice versa. Thus, the expressions that represent the cost are as follows:

$$\begin{aligned} C_{pd}^{NB-DMM} &= N_{p/s} \cdot ((N_{pr} - 1) \cdot (S_{DATA} + S_{IP}) \\ &\cdot h_{MAR-MAR} + (S_{DATA} \cdot h_{CN-MAR}) \\ &+ (S_{DATA} \cdot h_{MN-MAR})) \end{aligned} \tag{4}$$

$$\begin{aligned} C_{pd}^{SR-DMM} &= N_{p/s} \cdot ((N_{pr} - 1) \cdot S_{DATA} \cdot h_{OFS-OFS} \\ &\cdot h_{OFS-OFS} + (S_{DATA} \cdot h_{CN-OFS}) \\ &+ (S_{DATA} \cdot h_{MN-OFS})) \end{aligned} \tag{5}$$

where $N_{p/s}$ is the packet transmission rate per active flow and $S_{DATA}$ is the size of these data messages. All parameters used in the analysis are shown in the Notations.

### 4.3. Numerical results

This subsection discusses the performance evaluation of both NB-DMM and SR-DMM proposals. Network topology used for analytical evaluation is shown in Fig. 7. The default values [15] [19] [30] are assumed to be as follows: $E[\mu_c] = [50 - 1800]$ s; $E[\delta] = 60$ s; $E[R_{BCE}] = 60$ s; $N_{p/s} = 3000$; $S_{PBU} = S_{PBA} = 76$ bytes; $S_{RS} = S_{RA} = 52$ bytes; $S_{P-IN} = 92$ bytes; $S_{P-OUT} = 103$ bytes; $S_{FlMod} = 116$ bytes; $S_{DATA} = 120$ bytes; $S_{IP} = 40$ bytes; $h_{CMD-MAR} = h_{CONT-OFS} = 2$ hops; $h_{MAR-MAR} = h_{OFS-OFS} = 2$ hops; $h_{CN-MAR} = h_{CN-OFS} = 5$ hops and $h_{MN-MAR} = h_{MN-OFS} = 1$ hop.

Fig. 8 shows the comparison of signaling cost as a function of the cell residence time, which varies from 50 to 1800 seconds. As could be expected, $C_u$ achieves the highest values when the cell residence time is low.

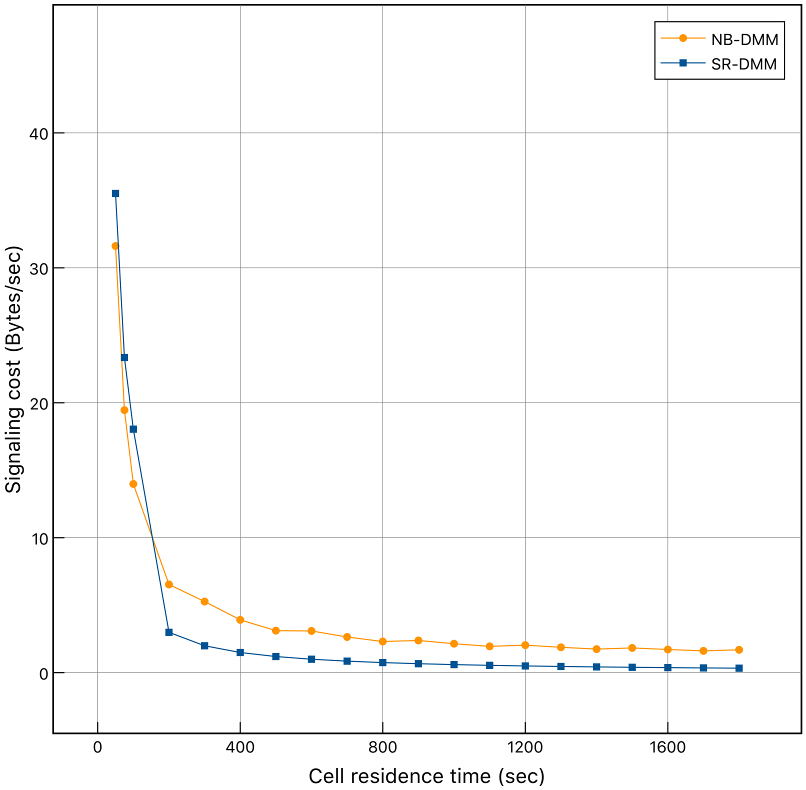

**Fig. 8.** Signaling cost versus cell residence time

When the cell residence time is low, signaling cost for the SR-DMM proposal is greater than the value of NB-DMM solution because NB-DMM is based on IPv6 protocols. Moreover, SR-DMM is an SDN-based proposal and messages exchange is performed through OpenFlow primitives which use TCP protocol.

However, we observe an enhanced performance of our proposal when the value of the cell residence time is increased. SR-DMM benefits from the options included by the SDN paradigm. Thus, our proposal does not require the binding refresh process and its signaling cost is lower than the signaling cost introduced by NB-DMM solution.

On the other hand, data packet delivery cost represents the cost of delivering data packets to an MN per unit time. Fig. 9 depicts the packet delivery cost as a function of the cell residence time. As can be observed, NB-DMM solution implies IP-IP tunneling including an IPv6 header between the previous and current mobility agents. However, with our proposal, additional IPv6 headers are not introduced. This is an important advantage on the data plane of the DMM-based solutions. Clearly, the SR-DMM proposal obtains the best results, optimizing both the control plane and data plane.

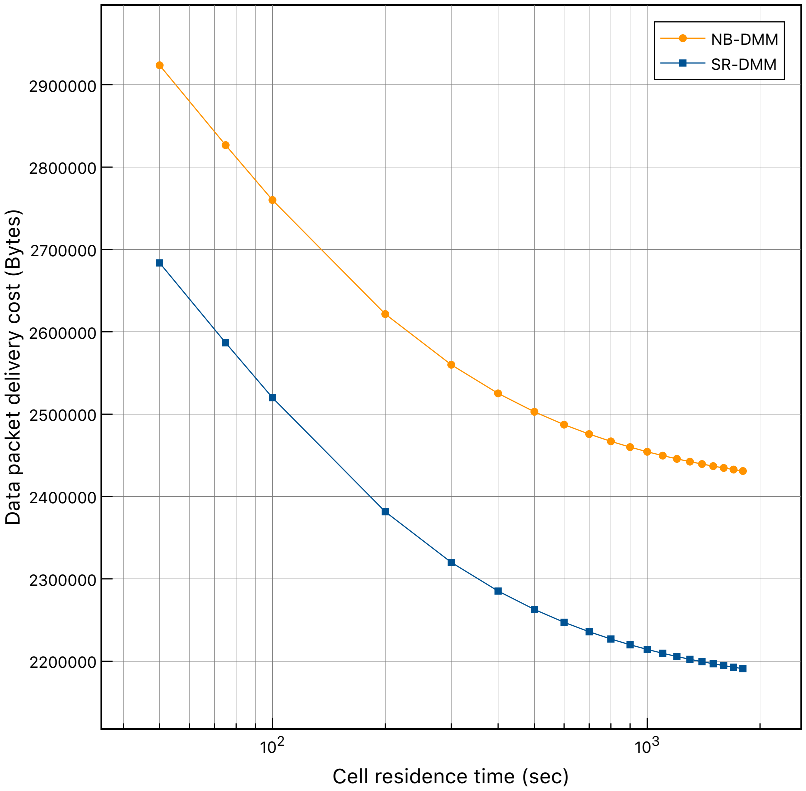

**Fig. 9.** Packet delivery cost versus cell residence time

## 5. Experimental evaluation

This section reports on the experimental evaluation conducted using real implementations of NB-DMM and our solution SR-DMM. The testbed deployed to perform the experiments of both solutions is depicted in Fig. 10. On the one hand, NB-DMM has been analyzed using a DMM implementation for GNU/Linux systems called MAD-PMIPv6 (Mobility Anchors Distribution for Proxy Mobile IPv6) [31]. This solution is written in C and runs on the Linux kernel. On the other hand, the control plane of SR-DMM is implemented through Ryu framework for SDN environments, using OpenFlow protocol as a control interface. Ryu fully supports IPv6. Thus, the SR-DMM service is deployed as an application on the network controller, which is running with Ryu.

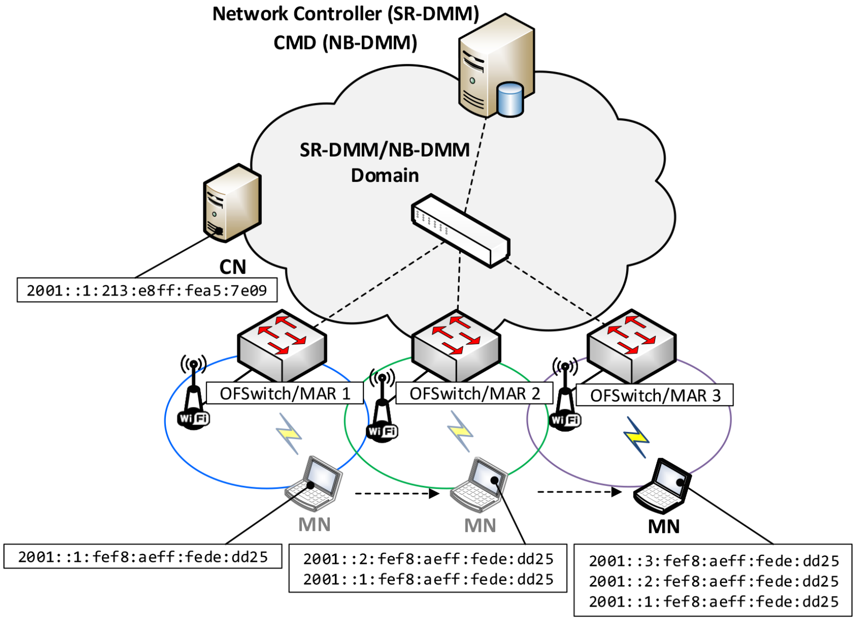

**Fig. 10.** Network topology used in experimental evaluation

Both solutions have been evaluated on the same network topology. This access network consists of three OFSwitches, which provide access to the MNs through wireless interfaces by using IEEE 802.11g technology. A network prefix (64 bits) is associated with each OFSwitch/MAR. This prefix is calculated by the SR-DMM application on the network controller. However, in the NB-DMM implementation, the prefix is calculated by the MAR. Moreover, a CN is responsible for sending flows to the MN. SR-DMM does not require the TCP/IPv6 stack of all devices to be updated. However, MARs and CMD, in NB-DMM solution, run with a compiled Linux kernel with mobility features.

The experimental evaluation focuses on the handover latency. This parameter is defined as the time interval in which an MN does not have IP connectivity as a result of a handover process, which is caused by the nature of the mobility when a MN changes its point of attachment to the network and a disruption time exits. In fact, the number of packets lost during a handover is directly proportional to the handover latency.

In our experimental testbed, we use Wireshark at the MN to extract the events produced when repeating the following sequence: the MN attaches to OFSwitch/MAR 1 and CN starts an UDP stream to the MN. Then, the MN visits OFSwitch/MAR 2 and OFSwitch/MAR 3 before coming back to OFSwitch/MAR 1.

This experiment is repeated obtaining more than 600 handovers for both solutions. Fig. 11 depicts the empirical CDF for the values of the UDP stream recovery time in the testbed for SR-DMM and NB-DMM.

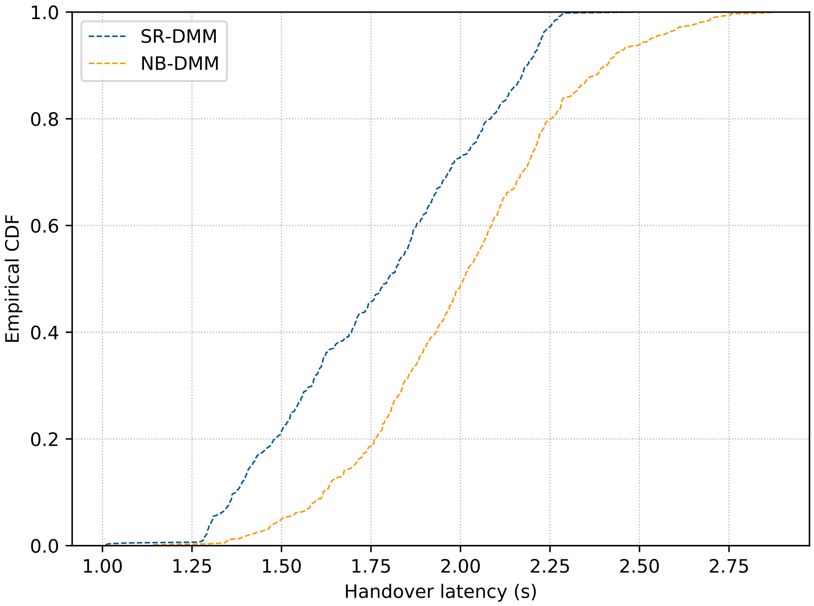

**Fig. 11.** Empirical CDF of the handover measurements

Moreover, Table 1 reports the mean and standard deviation values of these results for SR-DMM and NB-DMM proposals.

**Table 1.** SR-DMM handover latency measurements

| | Mean (s) | Std.Dev. (s) |
|---|---|---|
| SR-DMM | 1.78 | 0.29 |
| NB-DMM | 2.01 | 0.31 |

As can be seen in Table 1, the average handover latency is 1.78 seconds in SR-DMM tests. However, with NB-DMM the average handover latency is higher (2.01 seconds). During this handover disruption time, the mobile node cannot receive IPv6 packets until the session is restored by the SR-DMM/NB-DMM service.

Finally, other tests conducted consisted in measuring the different components of the handover latency while the MN roams among the three OFSwitches/MARs of our testbed (see Fig. 10). UDP traffic has been used in this experiment. We have measured three handover events which are detailed as follows:

- L2: the Layer-2 handover is the time required to perform an L2 switch from one OFSwitch/MAR to another. We measured this as the interval between two IEEE 802.11 control messages.
- LSDN: time between when the MN sends an RS to the OFSwitch in the visited network and the MN receives an RA with all IP parameters. NB-DMM does not spend LSDN time, because it does not use SDN mechanisms.
- L3: is measured as the interval between the last data packet received by the MN before the handover and the first data packet received or sent after the handover.

Fig. 12 explores in detail the components of the handover latency for the SR-DMM and NB-DMM solutions.

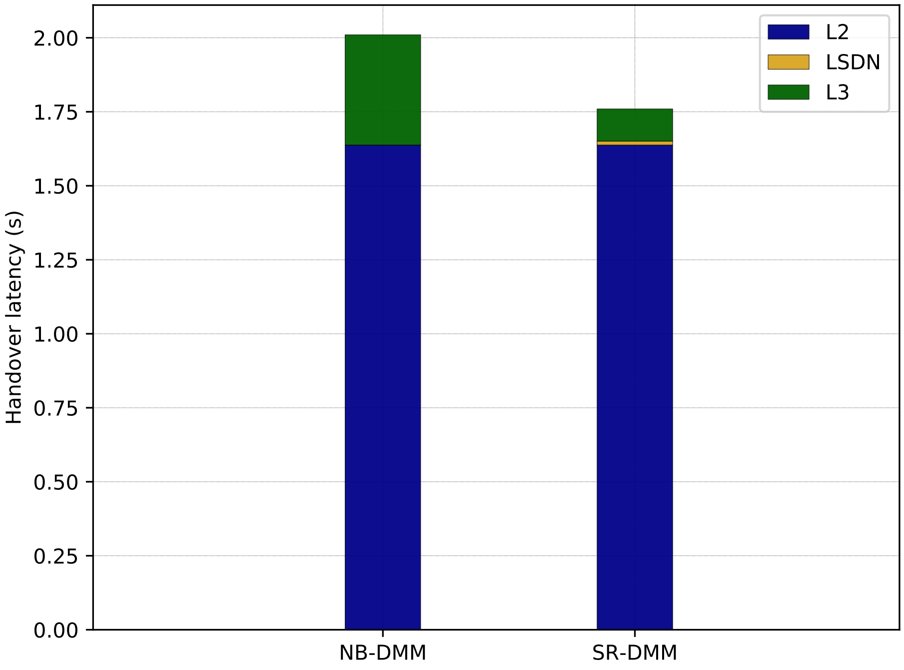

**Fig. 12.** Handover latency composition

As can be seen from the results, the L2 switch time is the major term for both proposals. The technology used in this level is IEEE 802.11g. The processing time of the network controller in SR-DMM (LSDN) is between 0.3 and 0.7 percent of the total handover latency. However, NB-DMM does not spent LSDN time because it does not require any SDN mechanisms. Moreover, IP flow recovery (L3) depends on types of solution: the NB-DMM solution uses 18% of the handover time and SR-DMM only uses 6%. The SR-DMM offers benefits due to SDN capabilities compared with NB-DMM.

## 6. Conclusions

Software-Defined Networking brings a natural solution to decouple the network control plane from the data plane for 5G environments, where Distributed Mobility Management is seen as a necessary paradigm in future mobile network deployments in order to flatten the network.

In this context, this article is focused on an analytic and experimental evaluation of an SDN-based DMM solution, called SR-DMM. The main objective is to provide flexibility and scalability to the mobility process in next generation networks. In order to compare the performance of our proposals with other legacy DMM solution such as NB-DMM, we have formulated an analytical model that reveals the benefits that SR-DMM brings to the network's performance in terms of signaling and packet delivery cost. This improvement can be achieved due to the implementation of SR-DMM, that reduces the complexity of the data plane and the tunnel management avoiding the use of IP-IP tunnels during the movement of the users. In addition, an experimental evaluation of SR-DMM and NB-DMM have been conducted in a real scenario. The results show that the own mechanisms of SDN introduce a minimum latency in the handover process. It also demonstrates that SDN can alleviate the complexity of mobility management and will be a key concept in the design of future mobile networks.

SR-DMM provides a simple implementation of the mobility management protocol without modifying the network nodes. Moreover, the data plane is simplified by avoiding the use of IP-IP tunnels. Thus, the packet delivery cost is improved with our proposal. On the other hand, in the experimental evaluation, SR-DMM also presents an enhanced scalability due to the global vision of the network controller. The SR-DMM offers benefits due to SDN capabilities compared to the legacy DMM approaches.

## Notations

$h_{x-y}$: Average hop distance between $x$ and $y$ nodes.
$N_{pr}$: Number of used active prefixes.
$N_{p/s}$: Packet transmission rate per active flow.
$R_{BCE}$: Rate of BCE refresh operations.
$S_{DATA}$: Size of a data packet.
$S_{PBU}$: Size of the PBU message.
$S_{PBA}$: Size of the PBA message.
$S_{FlMod}$: Size of the FlowMod message.
$S_{P-IN}$: Size of the PacketIn message.
$S_{P-OUT}$: Size of the PacketOut message.

$S_{RS}$: Size of the Router Solicitation message.
$S_{RA}$: Size of the Router Advertisement message.
$S_{IP}$: Size of the IPv6 tunnel header.
$\mu_c$: Subnet border crossing rate.

**Acknowledgments.** This work was supported in part by the Regional Fund, through Computing and Advanced Technologies Foundation of Extremadura (COMPUTAEX), European Regional Development Fund, and the Regional Ministry of Economy and Infrastructure of the Junta de Extremadura under project IB18003.

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*Received: November 1, 2018; Accepted: July 18, 2019.*