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Distributed Mobility Management for the Future Mobile Networks: A Comprehensive Analysis of Key Design Options

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ABSTRACT The design and deployment of a novel mobile network architecture, motivated by the challenges deriving from the explosive increase in data traffic on operator networks, are a pressing problem in today's telecommunications. Distributed mobility management (DMM) introduces a key idea to tackle the traffic bottlenecks that impact current mobile networks by proposing the deployment of distributed mobility anchor points close to terminal locations. There have been many proposals to build DMM solutions, with different focuses and merits for future mobile networks, aimed at overcoming the limitations from current centralized mobility management solutions. To the best of our knowledge, a comprehensive analysis and comparison study systematically analyzing available design options have not yet been provided. In this paper, we identify essential design considerations and their underlying options, comparing their impact on user and network performance. In addition, we provide the recent advances of DMM with emerging trends such as control-/data-plane separation and mobile cloud, which will impact the next generation network paradigm.

INDEX TERMS Distributed mobility management, DMM, 5G networks, IP mobility management, software-defined networking.

I. INTRODUCTION

Mobile data traffic continues its tremendous growth path, requiring increased investments by mobile operators to deal with the subsequent overwhelming capacity requirements. Mobile operators have been looking for intelligent ways to significantly reduce the revenue-outstripping costs while stretching their network capacities with data offloading technologies. Local IP Access (LIPA) and Selected IP Traffic Offload (SIPTO) mechanisms have been developed inside 3GPP networks, particularly focused on the data offloading for mobile core networks [1]. Their ideas aim to enable users to access locally available peering points via small cells, thus freeing up mobile network capacity. Such data offloading solutions are effective to alleviate the traffic pressures over the current mobile architecture, which is hierarchically centralized: the amount of traffic volume going through a centrally deployed mobility anchor, i.e. an IP mobility anchor in an IP-based network and a PDN Gateway (PGW) in 3GPP evolved packet core (EPC), is reduced. However, it is envisaged that such optimizations would not be disruptive enough to cope with the current increasing traffic in the mobile core and to fundamentally resolve the scalability issue from typical centralized mobility management (CMM) architectures, such as single point of failure, sub-optimal routing, and unnecessary use of mobility resources.

Distributed mobility management (DMM) is regarded as one of the alternatives to CMM, facilitating the anchoring of traffic closer to the users point of attachment, contributing to the flattening of the mobile networks architecture. It allows a mobile node (MN) to be associated with multiple mobility anchors, optimizing packet routing as the MN changes its point of attachment. To realize such an architectural concept, there are many proposed solutions with distinct control and data planes management features, covering the introduction of conceptual scenarios, protocol design enhancements and consequent user/network performance improvements:

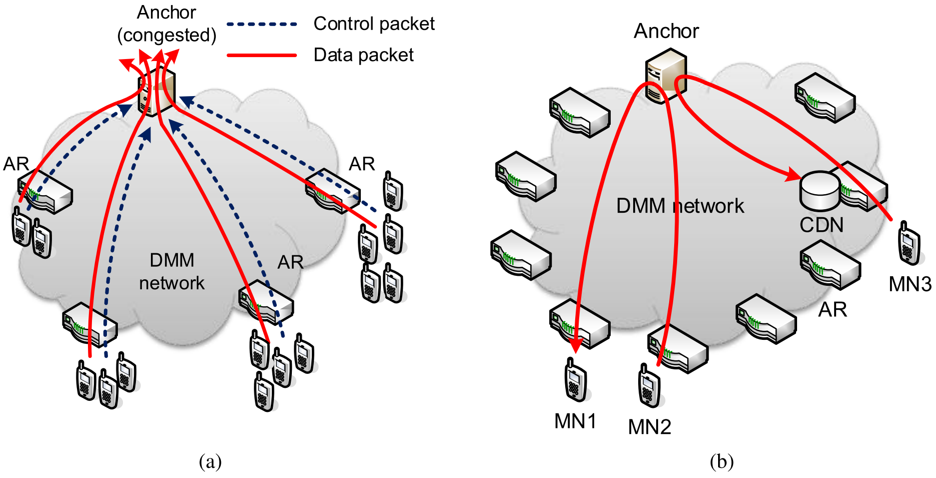

FIGURE 1. **Main issues in centralized mobility management; (a) single point of failure and (b) suboptimal routing.**

some works include the presentation of DMM solutions aimed at efficient handling of mobile video traffic [2] and an overview of standards landscape and progresses regarding DMM [3]. Those works are not dedicated to providing a wider and comprehensive understanding of the main factors that should be considered to build a DMM solution. Nowadays, beyond the effect of the traffic distribution, integrating the technical principle of DMM with new network paradigm such as software-defined networking (SDN) and virtual cloud network are going to be a trend for the next generation mobile network solutions.

Regarding the DMM solutions investigation, some literatures contributing to the review of DMM solutions were identified; however, the associated comparisons were given narrowly with a few target parameters or specific design considerations, not providing a comprehensive analysis. In [45], the comparison was given between the proposed DMM solution and legacy mobility protocols, being restricted to the respective known differences (e.g. distribution of control functions). In [46], a more detailed classification of DMM solutions was presented, but limited to a "client (host)-based vs. network-based" solution category perspective. Therefore, it is time to delve into DMM design issues and identify the resulting impact of different design options on different goals of DMM solutions while thoroughly reviewing the newly proposed ideas enhancing architectural aspects and performances.

This paper contributes to the following points differently from the previous literatures;

- We provide an extended list of design considerations for designing DMM solutions, and describe the competitive approaches per each design option from previous DMM literatures.
- We investigate the main idea of the classified solutions approaches while enumerating pros. and cons. of them.
- We evaluate the solutions approaches in terms of diverse performance metrics and their impact in terminal and network.

In this paper, we first briefly review the major problems in centralized mobility management and introduce the benefits of distributed mobility management in Section II. We then introduce the essential design considerations when developing a DMM solution, enumerate available design options in Section III, and qualitatively assess their impact with comparison table in Section IV. We additionally present DMM research with emerging network trends in Section V and conclude this paper in Section VI. For determining the design considerations of DMM, we mainly refer to progresses inside the IETF DMM working group as the leading standardization community on this topic; however, this paper is not limited to IETF proposals, and further goes through relevant academic proposals.

II. DISTRIBUTED MOBILITY MANAGEMENT

A. LIMITED FEATURES IN CENTRALIZED MOBILITY MANAGEMENT

Centralized IP mobility management solutions leverage on an IP mobility anchor node, which is a network entity that manages forwarding state and forwarding path for all the traffic subject to IP addresses or prefixes of associated MNs. Fig. 1 shows the snapshot of the main issues of the CMM approach; single point of failure and suboptimal routing. The single point of failure means that a mobility anchor takes the binding management (driven by control signaling) and data anchoring for all the MNs, introducing huge burden and congestion at the anchor as illustrated in Fig. 1(a). The suboptimal routing issue usually happens as an MN goes away from its anchor located at the mobile core, as the anchor point is not changed. Particularly as shown in Fig. 1(b), when an MN (MN3) tries to access local contents in a content delivery network (CDN) cache located near the access router (AR) where the MN is attached, the suboptimal routing path could be severe, taking longer packet delivery latency while bringing about the inefficiency of network resource usage. In addition, the suboptimal routing may also happen when the direct communications between MN1 and MN2 is made in Fig. 2(b). Ultimately, they

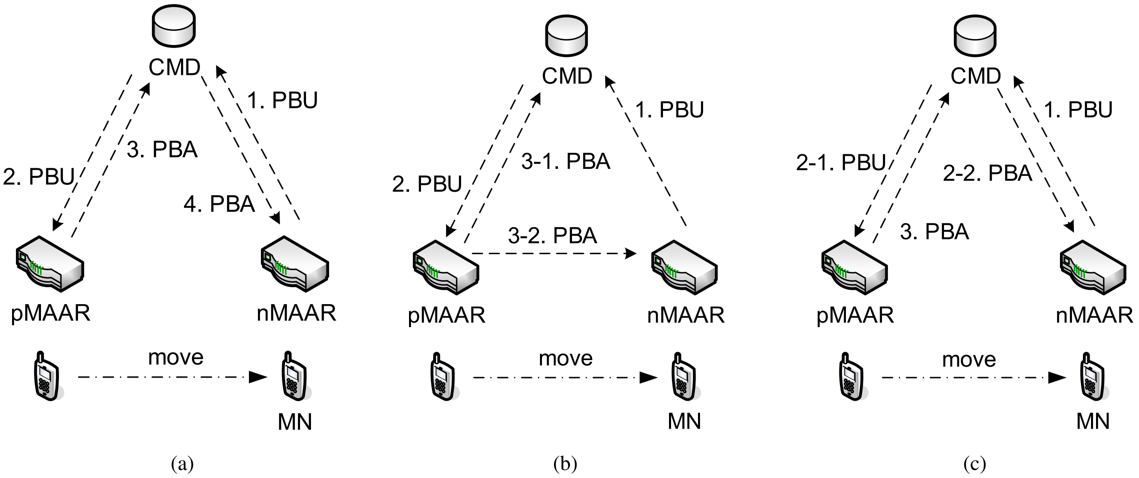

FIGURE 2. **Three available network-based mobility management approaches depending on CMD's role. (a) CMD as relay. (b) CMD as MAAR locator. (c) CMD as proxy.**

do not offer an economically future-proof solution to effectively and efficiently cope with the increasingly absolute traffic volume, which will significantly impact the mobile core.

B. BENEFITS OF DISTRIBUTED MOBILITY MANAGEMENT

Unlike CMM, DMM pursues the distributed deployment of mobility anchor functions near the MNs. Based on this fundamental change of the anchor positioning strategy, we can expect the following benefits:

- **Optimal routing path**: the distributed deployment of mobility anchor points closer to MNs eliminates the need for all traffic to traverse the mobile core, thus facilitating shorter and optimal routing communications. Once the MN initially attached at a DMM-enabled router (DMR)[1] moves to another DMR, an IP tunnel is created between the two DMRs and packet forwarding starts through the tunnel. However, while the MN stays connected at its anchor DMR, the packets are routed by regular IP routing, without the IP tunneling mechanism. In CMM, mobility anchor is usually assigned per MN. In DMM, per-flow anchoring concept can easily be realized as the anchor function is at every DMR, thus optimal routing is easily ensured.
- **Workload distribution**: in DMM, an MN can be associated with multiple anchor DMRs while being attached at a single access DMR, with different granularity, e.g., IP addresses or prefixes. IP sessions on the MN could get distributed through the associated anchor DMRs. It can also contribute to the distribution of mobility signaling and packet processing, as identified in the simulation study [4], [5]. DMM may easily facilitate the on-demand mobility that initiates the IP mobility management procedure when needed, such as when an MN moves to other DMR. Such on-demand mobility feature is effective to avoid tunneling overhead and corresponding processing in the mobility entities.
- **Improved handover performance with shorter packet delivery latency**: distributed deployment of mobility anchor points fits well into accessing both local contents and resources dispersed, e.g., by CDNs or advanced caching techniques. Such forward deployment of mobility anchor functions becomes essential for Internet content acceleration and is expected to be a general trend in future Internet environments as well. It will improve the handover performance of MNs and increase network resource efficiency. A similar trend can nowadays be found in mobile-edge computing (MEC), which presents a new network architecture concept that enables cloud computing capabilities and IT service environment at the edge of the mobile network [6]. But it is introduced with use cases dealing with application processing functions not mobility functions.

III. DESIGN OPTIONS FOR DISTRIBUTED MOBILITY MANAGEMENT

As a general concept, DMM can be instantiated in different ways. In order to design a DMM solution, there are many considerations to be pondered, spanning from the base operation to performance enhancements, with trade-offs with respect to different network performance metrics. We address various DMM design issues that should be considered for a DMM solution: i) host involvement in mobility management;

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[1] There is no standard term for referring to generalized "DMM-enabled router" working on distributed and dynamic mobility management. So, to generically call generic DMM router regardless of specific DMM proposal, we call it DMM router, in short, DMR, covering the different kinds of DMM-oriented mobility anchor/access routers proposed in multiple works. Depending on the role of DMR, i.e. anchor router or access router, we refer to it as "anchor DMR"or "access DMR" respectively, for distinguishing the role of a DMR. But for describing a specific DMM proposal, we call the entity name introduced in the proposal.

ii) distribution of control plane; iii) anchor point change; iv) anchor point selection; v) source IP address selection.

The technical approaches for building a DMM solution can be broadly classified in two different ways: anchorless or anchor-based. The anchorless means that there is no dedicated network entity as the packet re-routing point with binding cache management for keeping IP session continuity. Such an anchorless mobility solution nowadays can also be argued by the SDN technique. Anchorless DMM approaches are still immature, and have not received enough industry recognition and it is hard to find academic papers without SDN consideration. One we could find is from [7], which proposes a flat architecture with BGP, DHCP, and dynamic DNS update. That is, it requires the overall change of intra-/inter-routing protocols deployed over operator networks for a routing path change as an MN continues to move. It could be useful by removing the dedicated anchor point over the network; however, it is still immature and such approach has not received meaningful industry recognition. In this paper, we therefore focus on the anchor-based DMM solution approaches and deal with the design issue for a DMM solution. SDN itself is agnostic from the DMM category so it can belong to both approaches (anchorless vs. anchor-based). Under the anchor-based category, DMM design issues with SDN will be introduced and investigated as the anchor-based approach is significantly studied.

A. HOST INVOLVEMENT IN MOBILITY MANAGEMENT

DMM solutions design can be categorized into network-based and host-based approaches in terms of the host involvement in the mobility management. This design property has been traditionally considered in the design of previous mobility management solutions, e.g., Proxy Mobile IPv6 (PMIPv6) and Mobile IPv6 (MIPv6).

Such property should be considered in a DMM solution design with following points; which functions and information structures can be inherited or what should be differently applied or changed from the design categories. In this section, we address the main properties and differences of a DMM solution design with network-based and host-based approaches.

1) NETWORK-BASED (NO HOST-INVOLVED)

In general, IP mobility management consists of three main steps: movement detection, assignment of IP address/prefix, and binding update. In the network-based approach, these operations are executed by the network on behalf of the MN. So, a network entity performing mobility access and anchor operation in DMM should detect a newly attached MN then perform the binding update procedure for the MN. In [8], central mobility database entity that stores the binding cache entry for MNs in the PMIPv6-based DMM is proposed and introduced as a competing approach for DMM in [2]. The mobility anchor and access router (MAAR) introduced in [8] plays the role of mobility manager for the IPv6 prefixes it anchors and runs the functionalities of PMIPv6s mobile access gateway (MAG) and local mobility anchor (LMA). MAARs follow the same features for the network-based mobility support such as movement detection and home emulation that hides the terminal's mobility by advertising the same prefix the MN has been assigned at the initial MAAR. However, depending on the role definition of central mobility database (CMD), three different network-based DMM solutions are described with the different processing operation of the mobility signaling: CMD as relay, CMD as MAAR locator, CMD as proxy.

When the CMD work as relay as shown in Fig. 2(a), Proxy Binding Update (PBU) and Proxy Binding Acknowledgement (PBA) signaling messages are exchanged via the CMD. For the locator in Fig. 2(b), when the CMD receives a PBU message from the next MAAR (nMAAR), it will add nMAAR's IP address in the option field of the PBU message and send the extended PBU message to the previous MAAR (pMAAR), allowing the pMAARR to send the PBA message directly to the nMAAR. Lastly, when the CMD works as proxy as shown in Fig. 2(c), the CMD is required to determine the handover operation from a PBU message received and send the PBA message to the nMAAR for the fast preparation of tunneling, regardless of receiving the PBA message from the pMAAR.

In [9], a similar solution has been proposed for PMIPv6-based DMM. It also relies on a central database managing the attached MN's anchor router, but only taking a role of simple database whereas the CMD proposed in [8] has diverse options.

Regarding the home emulation for network-based mobility support, it is important to hide the changed layer-2 information, i.e. MAC address of MAGs when the MN attaches to a new MAG in the same DMM domain, not to make the MN recognize its movement. One easy solution is to configure all the mobility anchor routers'MAC addresses with the same one virtually created. Otherwise, following the distributed logical interface (DLIF) concept proposed in [10], a new mobility anchor router will get the same number of logical interfaces corresponding to the number of anchored prefixes on the MN. Each logical interface is mapped to the anchored prefix the MN is holding. So, the MN will not notice its moving.

2) HOST-BASED (HOST-INVOLVED)

Compared with network-based approaches, host-based approaches require modifications and intelligence in MNs for taking care of initiating and processing the consequences of IP mobility, such as managing the binding update lists associated with the established sessions and mobility resources in use for packet tunneling [11]. In [3], the host-based DMM approach is depicted with the deployment model that Home Agent (HA) and AR, introduced in Mobile IPv6, are co-located and distributed. The MN inherits Mobile IPv6 client function but are additionally required to have the managing capability of multiple addresses for the simultaneous use and initiating required network operation.

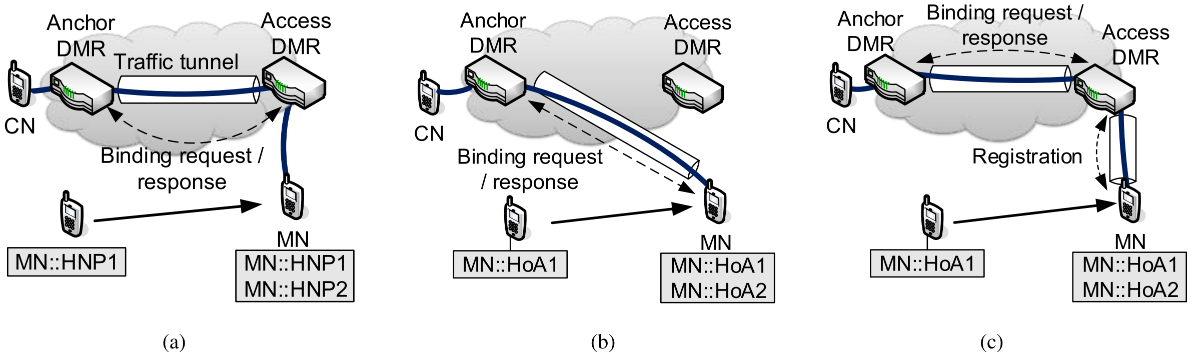


FIGURE 3. **Rough comparison of the binding update design in network-based mobility, host-based mobility, and semi host-based mobility. (a) Network-based mobility management. (b) Host-based mobility management. (c) Semi host-based mobility management.**

In [12], a new host-based DMM design was proposed, which can be called a semi host-based DMM approach, proposing access mobility anchor (AMA) with the extended HA functionality from Mobile IP for partially taking up the binding update procedure on behalf of the MN. That is, the MN interacts with the AMA for the registration signaling (host-based) and the rest of the binding update is made between the serving AMA and anchor AMA (network-based) to deliver the information regarding MN's context. This model is shown in Fig. 3(c) with other DMM approaches. Note that other DMM papers have used different terms for the same entity having mobility access and anchor router functionality.

Therefore, in the comparison among the approaches, we use the DMR instead of their defined entity names. In the semi host-based approach, packet tunneling technique is not employed between the MN and serving DMR but used between serving DMR and anchor DMR, so it achieves better efficiency in terms of radio resources consumption than the host-based mobility DMM solution approach.

B. DISTRIBUTION OF CONTROL PLANE

The distribution of the data plane is commonly accepted in all DMM approaches, but the control plane design may be implemented in distinct ways, being subject to the network deployment and operation strategies. The control plane functions include the tracking and maintenance of the mapping between the MNs ID, its location and anchoring information: IP address(es) or prefix(es), and IP address of associated access and anchoring DMRs. As such, the control plane design pertains to the logical organization of this information. There are two main control plane models in the legacy trend for mobility management architecture: partially-distributed and fully-distributed, with the main difference between the two models concerning whether control and data planes are loosely or tightly coupled, respectively [2]. The control plane for DMM can be implemented by SDN, which makes network behaviors controlled and managed by a centralized controller with a holistic view of the network, based on the control plane and data plane separation.

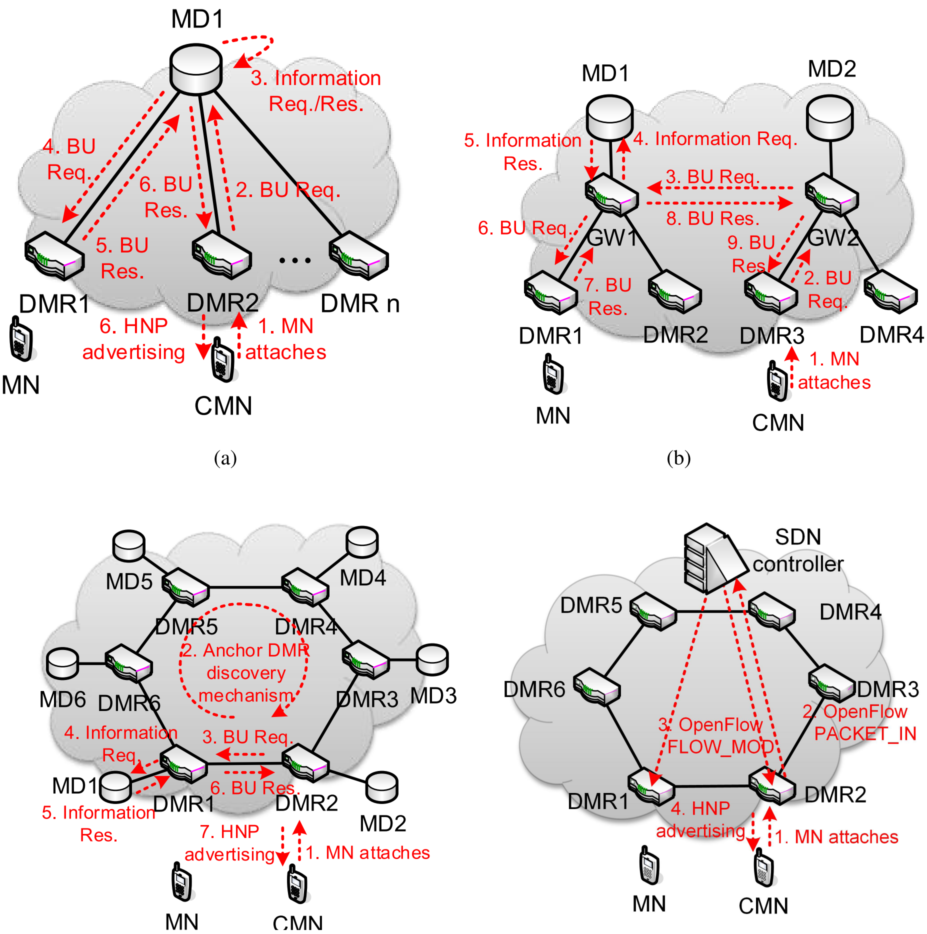
1) PARTIALLY-DISTRIBUTED (CENTRALIZED CONTROL PLANE AND DISTRIBUTED DATA PLANE)

In partially-distributed models, the MNs mapping information is centralized in an external mobility database, which is accessed and updated through the mobility management signaling. There are different design options depending on the role and signaling involvement carried out by the mobility database. One option is deploying a single mobility database from where DMRs obtain the necessary binding information for the attached MNs [2], [3], [12], as shown in Fig. 4(a). In [8], the mobility database is divided with three possible roles (i.e. relay, locator, and proxy) as previously described in the network-based DMM solution comparison. This model is simple and easy to implement, but it may lead to a single point of failure due to mobility signaling storms. This issue may be minimized by segmenting the managed DMM area by placing multiple mobility databases into the segmented DMM area, as shown in Fig. 4(b). For the data communication between MNs under the different gateways (GWs), the mobility database (MD) entity connected to each gateway is accessed by a proper signaling mechanism [13].

As shown in Fig. 4(b), on receiving the binding update request from correspondent mobile node (CMN)'s access DMR, it figures out the mapping information associated with the requested MN's anchor DMR (DMR1) does not exist and then forwards the request to GW1 where the MN's HNP is managed and maintained. By accessing MD1, GW1 gets to know who the MN's anchor DMR is. Then, the mapping information is delivered to the serving DMR (DMR3). Multiple MDs approach may mitigate load but will not be enough to address huge number of mobile devices.

2) FULLY-DISTRIBUTED (DISTRIBUTED CONTROL PLANE AND DISTRIBUTED DATA PLANE)

Unlike the partially-distributed mobility database model, in a fully-distributed model, the information pertaining to the mobility bindings is "distributed" throughout all DMRs and the mobility signaling takes place between these entities. One critical issue in the fully-distributed model is to find the MNs anchor DMR. As shown in Fig. 4(c), CMN attaches to DMR2,



(a) (b)

(c) (d)

FIGURE 4. **Design comparison of control plane for DMM. (a) Partially distributed model (with single mobility database). (b) Partially distributed model (with multiple mobility databases). (c) Fully distributed model. (d) SDN-based (control plane) model.**

but DMR2 does not know which DMR it should contact to get the anchor DMRs of the associated MNs flows.

In [8], such a fully distributed model is briefly discussed, with the introduction of alternative methods for retrieving and storing MNs binding information into DMRs are proposed, including distributed and autonomous mechanisms such as distributed hash table (DHT) [14], multicast or broadcast query mechanism [15] or external mechanism such as IEEE 802.21 MIH [16]. The fully-distributed DMM model may guarantee the higher scalability but is prone to incur significant signaling overhead than the partially-distributed DMM model, caused by the unnecessary signaling propagation to discover and update the MD holding the MNs mobility binding information.

In [43], distributed IP mobility approach (DIMA) based on a DHT overlay for binding cache distribution has been proposed. The main idea is similar with [14]–[16] as it leverages on DHT. But the key benefit is DIMA remains compatible to Mobile IP variants so it can be used for Hierarchical MIP (HMIP) and PMIP. In [17], timer-based bloom filter aggregation scheme using multicast has been proposed to mitigate the signaling overhead impact. Once receiving the MNs location update request, the proposed mobility anchor router hashes the MNs ID and sets the corresponding bit in Bloom filter and stores the indexes in the changed index store. With time periodicity, the mobility router shares its changed indexes with other mobility routers, thus considerably saving the unnecessary signaling overhead with the cost of timer interval.

3) SDN-BASED CONTROL PLANE MODEL

SDN has been applied for designing the DMM control plane. The overall shape for control plane is as shown in Fig. 4(d). In [39], it contributed to the design and implementation of the lightweight mobility control application working in ONOS [40]. The proposed mobility manager detects a terminal attachment with ICMPv6 router solicitation (RS) signaling message generated by the IPv6 host and determines a terminals attach or mobility. Accordingly, the controller configures a routing path between two mobile terminals

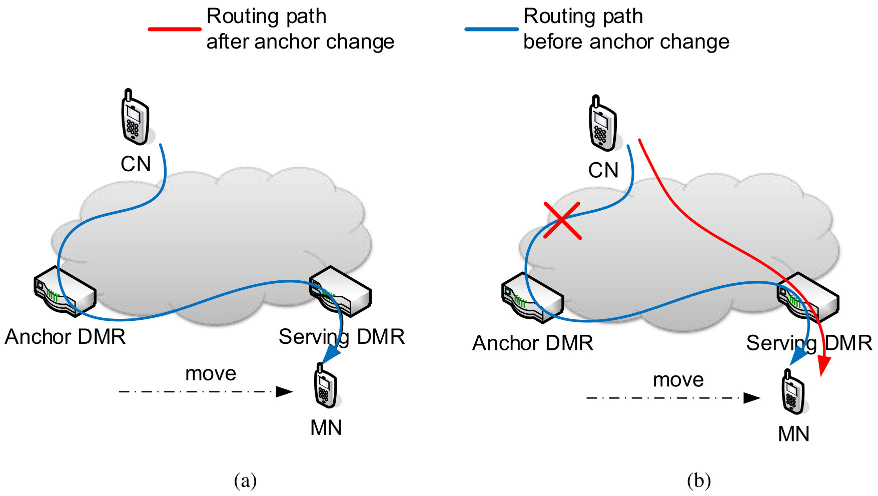


FIGURE 5. **Comparison of fixed anchoring and dynamic anchoring approaches. (a) Long routing issue in fixed anchoring approach. (b) Routing distance shorten by dynamic anchoring approach.**

over SDN. In [31], two design models are proposed; the first one supports IP tunneling in OpenFlow switches for less signaling overhead in the flow modification while the other does not support it for optimal routing path support. Though it has shown they have signaling cost, handover latency, and end-to-end latency during a handover event, each of them is meaningful to be employed depending on the usage purpose. In [45], the same control plane mechanism with OpenFlow has been proposed. In addition, taking into consideration the TCAM constraint and reduced round trip time of mobility control signaling messages in the switch, a binding cache placement idea has also been proposed.

C. ANCHOR POINT CHANGE (FIXED ANCHORING VS. DYNAMIC ANCHORING)

In the CMM solution approach such as with MIPv6 and PMIPv6, once the anchor point is determined and assigned to an MN, the anchor point becomes fixed until the MN de-registers the anchored IP session, though the serving anchor point initially determined of each MN might be different. In many DMM solutions from the literature review, for reducing the routing distance between the MN and mobility anchor point, IP anchoring works "per flow", which can be called per-flow anchoring, whereas it is generically done "per terminal" in CMM [8]. Per-flow anchoring in DMM facilitates the dynamic change of anchor point of a flow. We investigate two operational approaches, i.e., fixed anchoring and dynamic anchoring for DMM with their merits and limitations.

1) FIXED ANCHORING

The fixed anchoring means the anchor point is determined for an MN and is not changed until the MN closes the anchored IP session. The fixed anchoring approach is easy to deploy and the data-plane anchor function can easily be inherited from HA in MIPv6 or LMA in PMIPv6. But when the session duration of an IP flow gets longer with MN's mobility in the fixed anchoring approach, the routing distance also might get longer, as depicted in Fig. 5(a), where it is based on the anchor deployment closers to the MN. Different anchor point selection such as placing the anchor point closer to CN might mitigate the long routing issue much; however the main issue causing such long routing situation still remains as the anchor point has not been changed depending on MN's context.

2) DYNAMIC ANCHORING (RE-ANCHORING)

Unlike the fixed anchoring approach, dynamic anchoring (that can be called re-anchoring) means the anchor point initially determined is changed based on certain conditions or user/network parameters. The objective of the dynamic anchoring is to make better routing situation in terms of reduced packet delivery latency of MNs, as depicted in Fig. 5(b).

In [18], a mobility re-anchoring solution is proposed to improve the delivery of sessions requiring IP session continuity. The proposed algorithm works based on the MNs context, i.e., required IP session capability composed of IP address reachability or IP session continuity, where the IP address reachability is the ability to maintain the same IP address for applications running as servers in an extended period of time while the IP session continuity means the IP session is kept without the session disruption [19]. Initially, the determined mobility anchors differ depending on the IP session capability; a mobility anchor close to the MN for applications requiring the IP session continuity but a mobility anchor, i.e., rather centralized anchor for applications requiring the IP address reachability is determined. The initially determined mobility anchor is changed by the mobility anchor that provides an improved IP delivery path in the data offloading perspective.

In the dynamic anchoring solution, it is challenging to change the anchored routing path of the ongoing IP session while keeping the session continuity as packets sent by the CN has been reached to the original anchor router. Specifically, there are two issues: updating the forwarding table in the network and transferring IP anchoring role from the old anchor router to a new anchor router. In the combined structure of control plane and data plane, it is not easy to make it, because there is no entity to know and control the whole end-to-end routing path. In [18], it is assumed that the MN knows which mobility anchor router it should select based on its context and the current routing path is optimal or not. So, it does not provide the deployable solution.

Therefore, for the dynamic anchoring, the control plane and data plane is required to be separated with SDN because the separated control facilitates the smooth change of re-routing point with the flow modification in the forwarding table. For the latter issue, one solution is anchor switching method delegating a managed IP prefix from the current anchor router to a new anchor router over SDN environments [20], [21]. For the prefix delegation, Dynamic Host Configuration Protocol v6 (DHCPv6) Prefix Delegation (PD) has been employed. Specifically, as the MN moves to a new DMR, the DHCPv6 release procedure is initiated between the current anchor DMR and DHCPv6 server. Then, the new anchor router sends DHCPv6-PD request and receives DHCP-PD reply to/from the DHCPv6 server.

In [22], it emphasizes on the need of dynamic anchoring to improve handover performance while reducing the network complexity in mobility management, while mentioned in [18]. But it focuses on the anchor point selection algorithm that minimizes packet delivery cost, signaling cost, and handover latency, not dealing with how the re-routing point in SDN can be smoothly changed in details. Regarding the selection criteria of the anchor point, it will be covered in the next section.

D. ANCHOR POINT SELECTION

In DMM, the anchor point selection affects the communication performance as well as the handover performance. In this section, we categorize what possible reference criteria and investigate their general differences with impact on mobility support architecture and user QoE.

1) DISTANCE-BASED

A simple option for the DMM anchor point selection is to pick up an anchor router based on the distance between a reference host and candidate DMRs, where the reference host can be MN (MNs nearest anchor) or CN (CN's nearest anchor). The main benefit of selecting MN's nearest anchor is that it can be effective to access local contents placed closers to the MN's location from the selected anchor DMR [23]. Besides, the IP session connectivity after mobility can easily be provided due to shorter signaling path between the anchor DMR and a new access DMR, as depicted in Fig. 5(a), as long as the MN is not too far from its anchor DMR. However, this approach may cause a suboptimal routing issue by not considering CNs location but MNs location only.

Unlike the MNs nearest anchor selection, the selection of CN's nearest anchor can be advantageous to avoid the potential suboptimal routing raised in the MNs nearest anchor point selection scheme.

In [24], it proposes to select the corresponding home agent (CHA), i.e., the HA closest to the CN. If there are multiple IP sessions running on the MN, each of them may get different HA being the closest to the CN of each session. In [22], a dynamic anchor point selection scheme has been proposed over a SDN environment. The main idea is to create and maintain the optimal routing path with the proposed anchor point selection algorithm while the MN communicates with the CN. The algorithm computes the packet transmission cost in terms of routing hop between the source and anchor point candidates, and between the anchor point candidates and the destination. From that, it picks up the anchor point that minimizes the added cost among the ones.

2) LOAD-BASED

The anchor point can be selected by taking into account the load condition at each anchor, since MNs are not uniformly distributed neither do they have similar traffic consumption patterns. The load-balanced anchor point selection allows more reliable mobility management and contributes to better user and network performances.

In [25], a LMA selection algorithm for a load-balancing PMIPv6 network has been proposed by the proposed mobility session redirection mechanism with the runtime mobility signaling procedure. Simply, when the load of an LMA reaches the absolute maximum capacity, the proposed LMA redirection procedure is activated; once a binding update signaling is received at the current LMA, the PBU signaling message is redirected to another LMA. To measure the load information of each LMA, it employs the load monitoring server that periodically receives the load information from the deployed LMAs. It contributes to the substantiation of the load-based anchor point (LMA) selection. Therefore, it could get lower blocking probability of the new sessions and dropping probability of the ongoing sessions from the performance evaluation.

3) CONTEXT-BASED

Context information such as MN's velocity (user context) and requested applications (application context) can be decision criteria for anchor point selection. For supporting them in a network-based approach, the network needs to obtain necessary context, through intelligent monitoring mechanisms. In the host-based approach, certain explicit indication mechanism, e.g. extended router solicitation message or external solution like Media Independent Handover (MIH) will be required to deliver the MNs context to the related network entity.

In [26], as a merit of SDN-based mobile networking for cellular operators, the mobility anchor selection with context

TABLE 1. **Comparison of anchor point selection criteria from target solutions.**

	Distance-based	Load-based	Context-based
PMIPv6-DMM [8]	✓ (MN's nearest)		
DMA [9]	✓ (MN's nearest)		
Corresponding network homing [24]	✓ (CN's nearest)		
Dynamic anchor point selection [22]	✓ (Optimal routing path)		
DD-PMIPv6 [11]	✓ (MN's nearest)		
LB-PMIPv6 [25]		✓ (Anchor (LMA)'s load)	
SDN-Cellular [26]			✓ (Terminal speed)
Context-aware adaptive IP mobility anchoring [18]			✓ (IP session capability, terminal speed)
SDN-DMM-5G [31]	✓ (MN's nearest in the tunnel mode)		

information of the MN has been suggested in the partially-separated SDN mobile architecture that reuses the legacy mobility control plane. When the MN is moving with high mobility speed (as the MNs context), the mobility anchor (i.e., centralized mobility anchor) not causing frequent handover with the scarification of the long routing path is selected, thus avoiding the session disruption in mobility. But when the MN is moving with relatively slow mobility speed, the anchor point being the closest to the MN is selected, thus securing the optimal routing path. In [18], terminal speed is also considered but the IP session capability mentioned in the previous subsection is importantly considered as context information.

Table 1 summarizes and shows where each solution belongs to which anchor point selection category with what metric.

E. SOURCE IP ADDRESS SELECTION

In DMM, an MN is prone to have multiple IP addresses in case its IP sessions are anchored at multiple DMRs, i.e., per-application anchor assignment. Such situation may raise the source IP selection issue; what source should IP address each application use and how the preferred source IP address can be selected. In this section, we categorize available source address selection mechanisms with two following approaches from the relevant literature review: application-agnostic source address selection and application-based source address selection.

1) APPLICATION-AGNOSTIC

In the application-agnostic source IP address selection, the application type is not taken into account. When an application is initiated, it will be assigned to an IP prefix or address newly received from the network, thus the prioritized factor in the source address selection will be made with prefix/address freshness. The main benefit is that it is simple and requires no implementation change in the legacy devices. The application-agnostic approach can also be substantiated by following the default address selection mechanisms [27], which specifies the rules such as address scope, longest-matching prefix, public/temporary address type, and so on for selecting an IPv6 address among available ones. The drawback of the application-agnostic approach is that the source IP address is configured without regard to the application-level preferences. Most literatures introduced in this manuscript implicitly follow the application-agnostic approach, not considering the existence and/or availability of source IP addresses previously configured, and additional information based on which the selection can be realized.

2) APPLICATION-BASED

The application-based source IP address selection approach takes ‘‘application preferences’’ into consideration in the source IP address selection of an MN. One easy way is extending the socket API, in order to allow applications to override the default choice of source address selection [28]. Such extension provides options to DMM applications, compared with the application-agnostic approach, but it may not be enough to satisfy new needs created by the DMM nature pursuing the on-demand mobility.

In [19], it is argued that IP addresses over mobile networks have two important capabilities; IP address reachability and IP session continuity. The need of those capabilities may depend on aspects like required session duration and sensitivity to IP address change. According to the definition, it proposes three types of IP addresses, i.e., fixed IP address, session-lasting IP address, non-persistent IP address with the necessary flags to be added in RFC 5014 [28]. The fixed IP address supports the both IP session continuity and IP reachability, and the session-lasting IP address supports only IP session continuity while the non-persistent IP address does support nothing. With the proposed source IP address selection, the network can assign a proper mobility capability with the corresponding mobility entity for an application, so it is helpful to avoid unnecessary network resource waste. In [29], use cases with the three source IP address types defined in [19] and derived selection issues are presented through the case study.

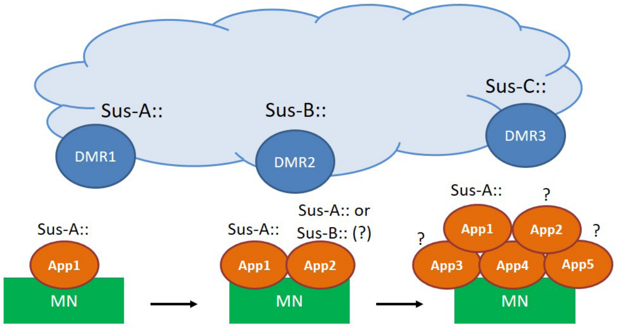


FIGURE 6. Source IP selection issue with session-lasting IP address type.

Fig. 6 shows a selection issue associated to the session-lasting IP address. Suppose that an MN is now connected at DMR1 and an application (App1) is initiated with the session-lasting IP address request as source IP address type. So, it gets `Sus-A::` prefix and App1 is assigned with `Sus-A::` prefix. Then, the MN moves and attaches to DMR2. A new application (App2) is initiated with the same IP address request, so `Sus-B::` prefix is assigned to the MN. Taking into consideration the priority with the newly received prefix, as one of the application-agnostic approaches, `Sus-B::` prefix should be assigned for App2. Obtaining a new session-lasting IP address (`Sus-B::`) may take some time due to the exchange with the network while using the existing one (`Sus-A::`) is instantaneous, and it spends the IP address resource a lot as it is expected that a new app will try to get a new session-lasting IP prefix [19]. If the MN moves to DMR3, the address selection becomes more complicated as many available IP addresses already configured in the IP stack. On the other hand, using the existing one might yield less optimal routing while saving the address resource. Depending on the performance characteristics and its sensitivity, the selection of source IP prefix should differ. Following the default address selection mechanism does not represent the selection preference of the application, so additional flag called "ON_NET" has been proposed, exposing the application preference, triggering the IP stack to get an IP prefix from the current serving network [29].

In [30], to reduce the longer routing path and save the corresponding the network resource as the MN moves farther from the initial anchor router, the Router Advertisement (RA) signaling message extension has been proposed with the prefix cost option. The proposed prefix cost option is intended to deliver the communicating cost between the current MN and advertised prefix. By exposing those information, the MN can make an optimal decision for the address assignment and release, thus maintaining the optimal routing path with the cost information. But it is not clearly defined what the cost means, though there are many network parameters affecting the optimal routing path, like routing hop, delay, network bandwidth. If the metric is defined as the cost, it could be used to actually improve the MNs performance. In addition, it is well aligned with the current network solutions, not changing huge modification in networks and terminals.

IV. EVALUATION OF THE DESIGN OPTIONS

This section discusses qualitatively the impact of design choices, based on the identified features in each DMM design issue. We also evaluate the DMM solutions approaches with the different design aspects in terms of various performance factors.

A. HOST INVOLVEMENT IN MOBILITY MANAGEMENT

Removing the host involvement in mobility management eliminates the complexity of developing costly functions and firmware updates in the host. Also, it will contribute to better user QoE since mobility signaling delay over the air is avoided. Besides, following an evolution strategy of DMM-based mobility management, it easily facilitates mobility functions upgrade for extending and optimizing the mobility management operation, without restrictions of the host modifications. On the contrary, the host-based approach enables MNs to easily express their application preferences with existing mobility signaling mechanisms or small extension of them as needed, though a fair amount of complexity and incremental battery consumption will be required. Nowadays, pursuing network-based only or host-based only may be no longer wise, as their complementary aspects are needed, So, designing the hybrid approach that accommodates those two aspects is expected to improve the user/network performance while minimizing the drawbacks of them.

B. CONTROL PLANE DISTRIBUTION

Partially-distributed model gives a reliable and realistic option for deploying and running a mobility database by mobile operators. It enables easy installation and control over additional functionality that can enhance the mobility performance. It does not need to install additional protocol or software for the mobility anchor discovery of attached MNs. As suggested in [8], the mobility database can be diverse, i.e., relay, locator, or proxy. On the contrary, to facilitate the fully-distributed model, using a P2P strategy as a representative distributed autonomous mechanism is not a convincing approach for operators, due to its complexity and potentially unreliable mobility management support [26]. In addition, a large volume of control signaling messages can be introduced when managing distributed mobility databases, with binding cache updates and synchronization between DMRs, representing potential broadcast storms in the network. Therefore, enhanced DHT approaches reducing the excessive signaling overhead can be illuminated as promising solutions [14]–[17], as introduced in the fully-distributed control plane model.

C. ANCHOR POINT CHANGE

The fixed anchoring approach facilitates the implementation of a DMM protocol; but not addressing the non-negligible issue, i.e., suboptimal routing as the MN moves farther from the initial anchor router. In addition, it does not require additional control signaling operation to change the current anchor router. On the contrary, the dynamic anchoring approach requires the additional control plane mechanism to change the anchor role from the old anchor router to a new one. With the combined control and data plane structure, it is hard to realize the anchor switching operation, as such operation can be possible with a controller having a holistic view of the network based on the control and data plane separation. The literatures in [18] and [20] basically assume the SDN environment for dynamic anchoring; but the difference is that the former proposal employs the BGP routing protocol to update the routing domain while the latter proposal is based on OpenFlow to enforce flow modification in the forwarding table in the OpenFlow switches.

D. ANCHOR POINT SELECTION

Regarding anchor point selection, there are many performance factors influencing terminal and network and but those depend on the context of user and application. The distance-based anchor point selection is easy to implement without additional procedure for the selection. But in the CNs nearest anchor point selection [24], to find CN's HA, the DNS should be able to deliver the host name of the requested CN's HA and the MN should be able to resolve the received host name in the stack. This might impact on DNS and MNs, requiring some modification or changes insides.

The load-based and context-based anchor point selection approaches may introduce additional monitoring and decision engine over DMM networks, requiring careful integration with existing network entities and consequently causing complexity. However, the load-based anchor point selection might enhance the network scalability, allowing more sessions to be anchored and thus more mobile users to be supported while assuring the performance in mobile. Such intelligence-boosted decision will improve throughput and packet loss rate. In the context-based selection, if an MN is highly mobile, selecting an anchor close to the MN would cause frequent handover and consequently service disruption and many signaling overhead, which is critical to the application performance. In such a situation, keeping the routing optimality will be in a trade-off with signaling overhead. In case that routing optimality is more prioritized in the selection design, the distance-based selection could be generally effective, contributing to the efficient network resource usage and faster packet delivery for the MN.

E. IMPACT OF SOURCE ADDRESS SELECTION

The application-agnostic approach may not provide optimized connection for an application, though there are some rules considering Mobile IP communications in [32]. In the application-based approach, extensions to the socket API will enable application developers to make applications optimized to the on-demand mobility nature [19]. Such source address selection in accordance with application purpose will also contribute to the reduction of network resources by avoiding unnecessary mobility session initiation. However, it may lead to additional signaling for the required address configuration procedures between the MN and the network, as proposed for extended neighbor discovery protocol (NDP) and DHCP in [33] and [34]. With the concern of increasing data traffic volume, increasing signaling traffic over operator networks impacts on the current deployed network. So, it should be considered minimized extension and less exchange of signaling from the existing protocols.

Table 2 summarizes the impact of each design issue to a set of relevant performance factors; routing distance, packet loss, complexity, scalability, efficiency in signaling and data delivery.

V. DMM WITH EMERGING NETWORKING TRENDS

DMM was raised to tackle the drawbacks of the CMM solutions, i.e., MIPv6 and PMIPv6, exclusively from an "IP mobility management" angle. However, recent advances such as SDN, NFV, and Cloud have been greatly influential to more recent proposals, which couple the distribution of mobility functions included as an essential property to next generation network architectures with orthogonal features (e.g. virtualization) and benefits (e.g. elasticity). In this section, we introduce and analyze recent advances of DMM in light of emerging networking trends, including extended research trials based on the DMM concept.

A. SDN FOR MOBILE OPERATOR NETWORKS

In the many literatures, the protocols with signaling operation and packet delivery are specified, based on the legacy architecture composed of mobility entities combined with control plane and data plane. Such combined structure prevents flexible control management, which is expected to effectively deal with mobility routing path and link failure on demand. Such features are essentially required and will be considered in 5G networks. In [26], possible mobile networking approaches using SDN are proposed over different deployment types of IP mobility anchors, i.e. CMM and DMM. It proposed two approaches applying SDN with DMM, depending on the accommodation of the existing mobility management entities: partially-separated and fully-separated models where the former integrates the SDN with legacy mobility control plane while all the control is dominated by a SDN controller

TABLE 2. **Comparison of the impact of the design issues.**

	Design Options for DMM Solution				
Influencing Factors / Performance Factors	Host involvement in mobility management	Control plane distribution	Anchor point change	Anchor point selection	Source IP address selection
Routing distance	N/A	N/A	Improved in dynamic anchoring approach	Depending on distance between anchor and MN or CN path	Improved in application-based method
Packet loss	Increased in host-based approach	N/A	Increased in dynamic anchoring approach	Could be improved in the load-based (network-aware) selection than other selection approaches	N/A
Complexity	Host complexity increased in host-based approach	Network complexity increased in fully-distributed approach and decreased in SDN-based control plane model	Network complexity increased in dynamic anchoring approach	Network complexity increased but depending on nature of information used for decision	Increased in application-based method for an address decision
Scalability	N/A	Increased in fully-distributed approach	N/A	System scalability increased in the load-based selection	N/A
Efficiency in signaling and data delivery	Decreased in host-based approach	Decreased in fully-distributed approach	Decreased in dynamic anchoring approach	Increased or decreased depending on nature of information used for decision	Decreased with application-agnostic approach

without taking the legacy mobility control plane into consideration in the latter. Technical challenges include the provision of handover management and data path management over the given SDN environment. In [42], an OpenFlow-based DMM architecture for an advanced mobile network is proposed. The authors put the OpenFlow network at the SGi-LAN between the PGW and Internet for flexible traffic steering during a terminal handover. In [35], a protocol for forwarding policy configuration (FPC) of the data-plane nodes is proposed with client/agent functions. To configure data-plane nodes and functions, the data-plane is abstracted by an agent interface to the client. The FPC client can be integrated with mobility management system to control forwarding policy and mobility session. The FPC agent manages the data-plane nodes and provides abstracted data-plane network to mobility management systems through FPC clients. FPC can be used and aligned in diverse DMM deployment models in [44]. The deployment models presented accommodate diverse mobile network use cases based on the type of composition and connection among the mobility components for advanced mobile networks.

B. DISTRIBUTED MOBILE CLOUD NETWORK

Follow-Me-Cloud (FMC) proposes the interworking of federated clouds and distributed mobile networks for ensuring an optimal mobile connectivity service [36]. FMC basically takes a basis of distributed deployment of Serving GWs (SGWs) and PDN GWs (PGWs), which serve their regional clouds. The purpose of FMC is to make mobile terminals always connected to the optimal SGW/PGW in the mobile networks. It is designed with SDN for effective and flexible change of the IP sessions with the proposed ID mechanism that combines session and service to overcome the inflexibility from the current IP address being used as ID and locator together.

Considering the future demands such as cost-efficiency, flexibility, agility for operators, cloud platforms are frequently mentioned in industry as well as research communities. Combining the mobile networks and cloud technologies leads to a new technology paradigm NFV in which mobile network functions are virtualized, allowing the decentralization of mobile networks and to meet the demands and requirements mentioned above. From the perspective of a mobile operator, one of the important aspects and capabilities expected from NFV is easy and efficient scaling (in/out or up/down) of mobility management function resource.

In [37], the separation and distribution of 3GPP Mobility Management Entity (MME) is proposed, taking a key control plane element of location management and mobility management of mobile terminals over cloud. The current MME entity is combined with several internal entities such as signaling processing and managing database. In the proposal, the MME is divided with three entities; front end, signaling processor called worker, and state database, where the front end keeps the interface with other 3GPP entities, the worker performs the signaling message processing, and the state database keeps and manages the stored information. And importantly, they work on different virtual machines empowered by the cloud infrastructure technology. In [38], it exposes the same research interest with [37], but with the different focus of scaling operations.

VI. CONCLUSION

The concept of distributed mobile networking is essentially considered for evolving the mobile network architecture. This paper provides a brief overview of the design considerations for distributed mobility management solutions. We first introduced the limitations of centralized mobility management and benefits of distributed mobility management. On the benefits of such deployment strategies, we presented four fundamental design considerations when defining a DMM solution, while introducing proposed solutions on the design issues. In addition, we provided the qualitative analysis of each enumerated design options in different operational metrics. Finally, we introduced recent advances of DMM associated with two key technological trends, which are importantly considered for building future mobile networks. Additional open issues may emerge in future progress; however, the presented design issues represent the pillars for a DMM solution. The presented DMM study is expected to be used as a guideline for designing future mobile network solutions.

REFERENCES

[1] K. Samdanis, T. Taleb, and S. Schmid, "Traffic offload enhancements for eUTRAN," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 3, pp. 884–896, 4th Quart., 2012.

[2] D.-H. Shin, D. Moses, M. Venkatachalam, and S. Bagchi, "Distributed mobility management for efficient video delivery over all-IP mobile networks: Competing approaches," *IEEE Netw.*, vol. 27, no. 2, pp. 28–33, Mar. 2013.

[3] J. C. Zuniga, C. J. Bernardos, A. De La Oliva, T. Melia, R. Costa, and A. Reznik, "Distributed mobility management: A standards landscape," *IEEE Commun. Mag.*, vol. 51, no. 3, pp. 80–87, Mar. 2013.

[4] S. Jeon, S. Figueiredo, and R. L. Aguiar, "On the impacts of distributed and dynamic mobility management strategy—A simulation study," in *Proc. IFIP Wireless Days (WD)*, Nov. 2013, pp. 1–6.

[5] E. Logota, D. Corujo, S. Jeon, J. Rodriguez, and R. L. Aguiar, "The 5G Internet," in *Fundamentals of 5G Mobile Networks*. Hoboken, NJ, USA: Wiley, 2015, pp. 29–62. [Online]. Available: http://onlinelibrary.wiley.com/doi/10.1002/9781118867464.ch2/summary

[6] *Mobile Edge Computing: A Building Block for 5G*, AA Houten, The Netherlands, Telecompaper, Jul. 2015.

[7] P. J. McCann, "Design of a flat wireless Internet service provider network," in *Proc. IEEE WPMC*, Oct. 2011, pp. 1–5.

[8] C. Bernardos *et al.*, "A PMIPv6-based solution for distributed mobility management," draft-bernardos-dmm-pmip-08, IETF Personal Draft, Mar. 2017.

[9] P. Seite and P. Bertin, "Distributed mobility anchoring," draft-seite-dmm-05, IETF Personal Draft, Jul. 2012.

[10] C. Bernardos and J. Zuniga, "PMIPv6-based distributed anchoring," draft-bernardos-dmm-distributed-anchoring-08, IETF personal draft, Sep. 2016.

[11] H. Ali-Ahmad, M. Ouzzif, P. Bertin, and X. Lagrange, "Distributed dynamic mobile IPv6: Design and evaluation," in *Proc. IEEE WCNC*, Apr. 2013, pp. 2166–2171.

[12] J.-H. Lee, J.-M. Bonnin, P. Seite, and H. A. Chan, "Distributed IP mobility management from the perspective of the IETF: Motivations, requirements, approaches, comparison, and challenges," *IEEE Wireless Commun.*, vol. 20, no. 5, pp. 159–168, Oct. 2013.

[13] P. P. Ernest, H. A. Chan, and O. E. Falowo, "Distributed mobility management scheme with mobility routing function at the gateways," in *Proc. IEEE GLOBECOM*, Dec. 2012, pp. 5254–5259.

[14] H. Luo, Y. Qin, and H. Zhang, "A DHT-based identifier-to-locator mapping approach for a scalable Internet," *IEEE Trans. Parallel Distrib. Syst.*, vol. 20, no. 12, pp. 1790–1802, Dec. 2009.

[15] M. Gohar and S. Koh, "Network-based distributed mobility control in localized mobile LISP networks," *IEEE Commun. Lett.*, vol. 16, no. 1, pp. 104–107, Jan. 2012.

[16] *Final Operational Mobility Architecture*, EU FP7 MEDIEVAL Project, Deliverable D4.4, Dec. 2012. [Online]. Available: www.ict-medieval.eu/resources/MEDIEVAL_D4.4_Final.pdf

[17] H. Ko, G. Lee, S. Pack, and K. Kweon, "Timer-based bloom filter aggregation for reducing signaling overhead in distributed mobility management," *IEEE Trans. Mobile Comput.*, vol. 15, no. 2, pp. 516–529, Feb. 2016.

[18] T. Condeixa and S. Sargento, "Context-aware adaptive IP mobility anchoring," *Comput. Netw.*, vol. 71, pp. 84–99, Oct. 2014.

[19] A. Yegin, D. Moses, K. Kweon, J. Lee, J. Park, and S. Jeon, "On demand mobility management," draft-ietf-dmm-ondemand-mobility-10, IETF WG draft, Jan. 2017.

[20] H. Chan, X. Wei, J. Lee, S. Jeon, A. Petrescu, and F. Templin, "Distributed mobility anchoring," draft-ietf-dmm-distributed-mobilityanchoring- 03, IETF WG draft, Dec. 2016.

[21] H. Chan, X. Wei, J. Lee, S. Jeon, and F. L. Templin, "A systematic classification of distributed IP mobility," in *Proc. IEEE INFOCOM Workshop*, Apr. 2016, pp. 455–460.

[22] A. Bradai, A. Benslimane, and K. D. Singh, "Dynamic anchor points selection for mobility management in software defined networks," *J. Netw. Comput. Appl.*, vol. 57, pp. 1–11, Nov. 2015.

[23] H. Chan, D. Liu, P. Seite, H. Yokota, and J. Korhonen, "Requirements for distributed mobility management," IETF RFC 7333, Aug. 2014.

[24] A. Yegin, K. Kweon, J. Lee, and J. Park, "Corresponding network homing," draft-yegin-dmm-cnet-homing-02, IETF personal draft, Jul. 2014.

[25] S. Jeon, R. L. Aguiar, and N. Kang, "Load-balancing proxy mobile IPv6 networks with mobility session redirection," *IEEE Commun. Lett.*, vol. 17, no. 4, pp. 808–811, Apr. 2013.

[26] S. Jeon, C. Guimaraes, and R. L. Aguiar, "SDN-based mobile networking for cellular operators," in *Proc. ACM MobiArch Workshop*, Sep. 2014, pp. 13–18.

[27] D. Thaler, R. Draves, A. Matsumoto, and T. Chown, "Default address selection for internet protocol version 6 (IPv6)," IETF RFC 6724, Sep. 2012.

[28] E. Nordmark, S. Chakrabarti, and J. Laganier, "IPv6 socket API for source address Selection," IETF RFC 5014, Sep. 2007.

[29] S. Jeon, S. Figueiredo, Y. Kim, and J. Kaipallimalil, "Use cases and API extensions for source IP address selection," *IETF Personal Draft*, Oct. 2016.

[30] P. McCann and J. Kaippallimalil, "Communicating prefix cost to mobile nodes," draft-mccann-dmm-prefixcost-03, Apr. 2016.

[31] T. Nguyen, C. Bonnet, and J. Harri, "SDN-based distributed mobility management for 5G networks," in *Proc. IEEE WCNC*, Apr. 2016, pp. 1–7.

[32] E. Nordmark, S. Chakrabarti, and J. Laganier, "IPv6 socket API for source address selection," IETF RFC 5014, Sep. 2007.

[33] J. Korhonen, S. Gundavelli, P. Seite, and D. Liu, "IPv6 prefix properties," *IETF Personal Draft*, Feb. 2016.

[34] D. Moses and A. Yegin, "DHCPv6 extension for on demand mobility exposure," *IETF Pers. Draft*, Feb. 2017.

[35] M. Liebsch, S. Matsushima, S. Gundavelli, D. Moses, and L. Bertz, "Protocol for forwarding policy configuration (FPC) in DMM," draft-ietf-dmm-fpc-cpdp-07, IETF personal draft, Mar. 2017.

[36] T. Taleb and A. Ksentini, "Follow me cloud: Interworking federated clouds and distributed mobile networks," *IEEE Netw.*, vol. 27, no. 5, pp. 12–19, Sep./Oct. 2013.

[37] G. Premsankar, K. Ahokas, and S. Luukkainen, "Design and implementation of a distributed mobility management entity on OpenStack," in *Proc. IEEE CloudCom*, Nov. 2015, pp. 487–490.

[38] Y. Takano, A. Khan, M. Tamura, S. Iwashina, and T. Shimizu, "Virtualization-based scaling methods for stateful cellular network nodes using elastic core architecture," in *Proc. IEEE ICCCTS*, Dec. 2014, pp. 204–209.

[39] Y. Yang, S. Jeon, D. Kim, and H. Choo, "Design and implementation of SDN-based lightweight IPv6 mobility manager in ONOS," in *Proc. ACM IMCOM*, Jan. 2017, p. 107.

[40] P. Berde *et al.*, "ONOS: Towards an open, distributed SDN OS," in *Proc. ACM HotSDN*, Aug. 2014, pp. 1–6.

[41] Y. Wang and J. Bi, "A solution for IP mobility support in software defined networks," in *Proc. ICCCN*, Aug. 2014, pp. 1–8.

[42] L. Valtulina, M. Karimzadeh, G. Karagiannis, G. Heijenk, and A. Pras, "Performance evaluation of a SDN/OpenFlow-based distributed mobility management (DMM) approach in virtualized LTE systems," in *Proc. IEEE Globecom Workshop*, Dec. 2014, pp. 18–23.

[43] M. Fischer, F.-U. Andersen, A. Kopsel, G. Schafer, and M. Schlager, "A distributed IP mobility approach for 3G SAE," in *Proc. IEEE PIMRC*, Sep. 2008, pp. 1–6.

[44] S. Gundavelli and S. Jeon, "DMM deployment models and architectural considerations," draft-ietf-dmm-deployment-models-01, IETF WG draft, Feb. 2017.

[45] H. Ali-Ahmad, M. Ouzzif, P. Bertin, and X. Lagrange, "Distributed mobility management: approaches and analysis," in *Proc. IEEE ICC Workshop*, Jun. 2013, pp. 1297–1302.

[46] F. Giust, C. J. Bernardos, and A. Oliva, "HDMM: Deploying client and network-based distributed mobility management," *Telecommun. Syst.*, vol. 59, no. 2, pp. 247–270, Jun. 2015.

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